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Automated air pressure control system in a motorised breathing apparatus

Abstract. The relevance of the study is to develop an effective system for controlling the pressure in the air supply in motorised breathing apparatus to ensure effective protection of employees from dangerous aerosols and improve their health. The goal was to create an automated air pressure control system in a motorised breathing apparatus using a proportional-integral-derivative controller. For this purpose, the simulation method was used. In order to avoid unforeseen situations of deterioration of the level of protection, the structure of the pressure control system of a motorised respirator has been developed with the selection of the appropriate controller based on the obtained dependences of the influence of the parameters of the breathing mode and the amount of pressure in the under-mask space of the respirator, which ensures an appropriate comfortable mode of operation. This allowed developing a simulation model with a PID controller that would provide the appropriate pressure values within the permissible limits (50-370 Pa). It is proved that the proportional-integral-derivative controller maintains the pressure in the respirator mask within certain limits both with an increase and with a decrease in the control signal, preventing excessive fluctuations in the controlling variable, which leads to an extension of the service life of the filter elements and a reduction in electricity consumption for the operation of the fan motor. Based on modelling the operation of the pressure control system in different modes of operation, it is shown that when using a PID controller with defined parameters, the system provides compensation for changes in air

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*Corresponding author

pressure in the under-mask space of the respirator in different breathing modes of the user. The results can find practical applications in the field of safety and health, in industrial environments where workers are at risk of inhaling dangerous aerosols, such as toxic particles, gases, or other harmful substances

Keywords: identification; simulation model; motorised respirator; controller; setpoint; pressure

INTRODUCTION

The need to ensure effective protection of employees from potentially dangerous aerosols and pathogens that can cause diseases of the pulmonary system makes this problem relevant. The use of motorised respirators is determined by their efficiency, comfort, and performance, depending on the pressure in the air supply system. High pressure reduces the protection efficiency and reduces the operating time, since increasing the resistance on the filters leads to battery power consumption. In this regard, there is a need to develop an automated air pressure control system in motorised respirators. This system allows controlling the period of protective action, which is critical for the safe operation of respirators. Existing models of respirators have limited control systems that do not consider all possible use situations. For example, insufficient pressure can cause untreated air to enter, and lack of respiratory rate control can cause discomfort and disability. Thus, the task of developing an air pressure control system for motorised respirators, which considers the variability of the parameters of the human breathing cycle under variable physical activity, environmental pollution, and climatic conditions, becomes urgent.

Many studies have been devoted to the issue of determining parameters and configuring the control system for various technological processes. S.S. Zhou *et al*. (2018), P. Otrisal *et al*. (2021) proposed a model for simulating breathing based on the user's physical activity. Their development is quite interesting for building simulation models that allow selecting parameters for the pressure control system in motorised respirators. The disadvantages of the proposed model include the lack of a description of the effect on the dynamics of the respiratory rhythm of the interaction of central circuits that generate biomechanics through feedback from peripheral signalling pathways, as indicated by the authors of another study (Brook *et al*., 2017).

An interesting problem was solved by P. Otrisal *et al.* (2020), which consisted in evaluating the performance of a pneumatic installation for transporting various materials. The researchers used a stimulation approach to solve the problem, which they implemented in the Matlab Simulink software suite. The value of the proposed approach is to develop a flexible model for evaluating the effectiveness of moving materials in pneumatic installations, which considers various parameters: changes in the resistance of the system, the weight of materials, the amount of air, and energy costs for moving materials. However, the use of the proposed model for controlling the pressure in the system of a motorised respirator, unfortunately, is only partially possible to determine the cost of electricity due to changes in parameters. Unfortunately, the system does not provide for dynamic fluctuations in the human breathing process and requires appropriate processing.

The study by R. Weiss *et al*. (2021) developed a model for regulating the air supply to the under-mask space of a respirator based on the design of a blower, which can control the centrifugal fan in automatic mode, in accordance with the breathing patterns. The researchers obtained several important conclusions, which were later used in the development of a new simulation model. In particular, they established a relationship between the duty cycle and the fan speed (W410F1) from the respiratory flow. It was noted that the control system, which is based on a single-chip microprocessor (STM32F103VET6), creates prerequisites for delaying the supply of air flow due to a sharp change in load. This disadvantage was proposed to be reduced by the presence of an additional control system, which will reduce the amount of delay.

G. Gheorghe *et al*. (2021) simulated the operation of a motorised respirator on a dummy with three different breathing modes to build an appropriate mathematical model that will allow for the control process of air purification. However, when considering the process of correcting aerosol particles into the under-mask space, the researchers did not consider the dynamics of changes in respiratory modes due to stress in the mathematical model.

N. Al-Naggar (2015) conducted a simulation study of the work of anesthesiologists who used motorised respirators to determine the comfort of their use. Ease of breathing, noise, heat changes, visibility, and speech intelligibility were evaluated. In one of the conclusions of the study, it was noted that the rapid discharge of the battery leaves users defenceless, which requires further improvement of the design, which would ensure the operability of the motorised respirator in a given service life. Similar conclusions regarding the provision of a comfortable feeling when using motorised respirators were obtained by S. Cheberyachko *et al*. (2020) and A. Licina & A. Silvers (2021), where participants in the experiment also addressed the need to ensure the required duration of their work.

The analysis of the conducted studies confirmed a significant interest in the development of motorised respirators that ensure their comfortable use, based on working conditions, physical activity, and breathing patterns. A study of the effectiveness of using such devices by users showed an inappropriate level of electrical charge of batteries, which did not allow them to work out the entire required service life. Analysis of other papers has shown that such a situation can occur when there is no effective pressure control system or other variable parameters.

The purpose of the study was to develop an automated air pressure control system in a motorised breathing apparatus based on a proportional-integral-derivative controller (PID controller).

In order to achieve the research objective, the following tasks need to be completed:

- to develop the structure of the air pressure control system of a motorised respirator with the selection of the appropriate controller and to obtain the dependences of the influence of the parameters of breathing modes on the functioning of the control system, based on the initial conditions;
- to select the characteristics of the controller that ensure the approximation of the air pressure value to rational values based on the analysis of the dependence of the influence of the parameters of breathing modes on the functioning of the control system;
- to compare the simulation results with experimental data on changes in air pressure in the respirator mask under different operating modes.

MATERIALS AND METHODS

An experimental stand with a physical model of a motorised respirator was used for the study (Fig. 1), the design of which was described in the paper by S. Cheberyachko *et al*. (2020).

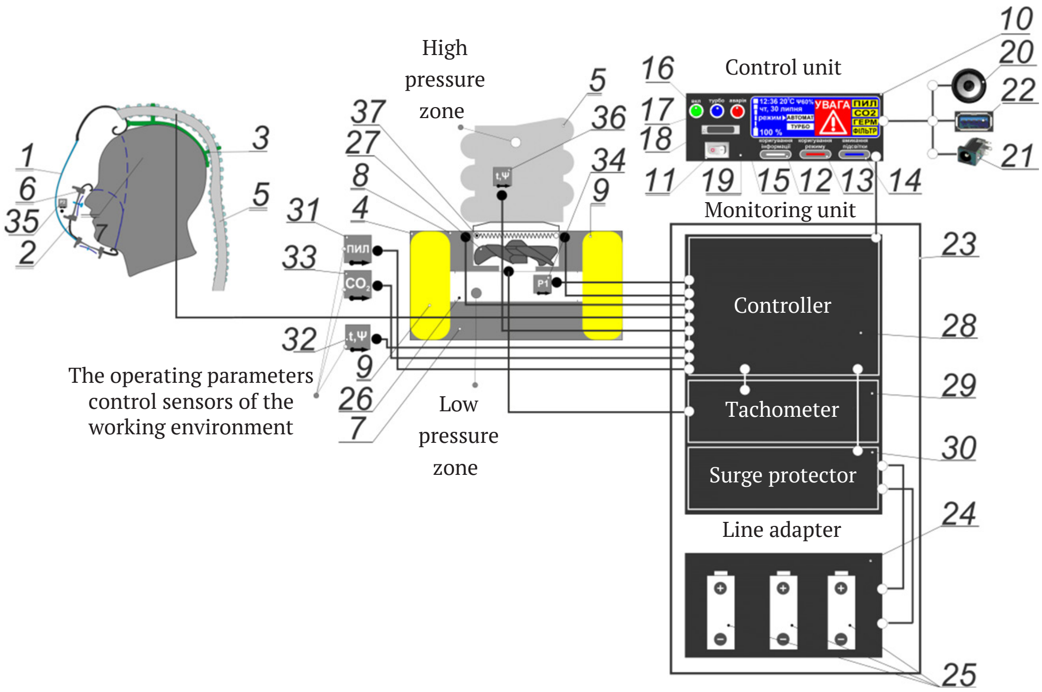

Figure 1. Test stand with a physical model of a motorised respirator

Note: helmet mask (1), gas seal (2), headband straps (3), air purification device (4), flexible corrugated duct (5), inhalation valve (6), exhalation valve (7), air purification device housing (8), filter elements (9), control unit (10), toggle switch "on/off" (11), button No. 1 (12) – "Information adjustment" (time, day of the week, month, ambient temperature, humidity); button No. 2 (13) "Mode adjustment" (automatic mode, turbo mode, emergency mode); button No. 3 (14) – "Display backlight"; light indicators: red indicator light (15) – "Accident", blue indicator light (16) – "Turbo", green indicator light (17), memory card (18), display (19) speaker (20), battery charger (21), USB connector for connecting to a PC for configuring and adjusting the software of the air purification device (22), monitoring unit (23), power supply unit (24) consisting of three batteries (25), channel (26), fan (27), controller (28), tachometer (29), surge protector (30), sensor for monitoring the presence of dust in the atmosphere of the working area (31), sensor for monitoring temperature and humidity in the atmosphere of the working area (32), sensor for monitoring the concentration of carbon dioxide in the atmosphere of the working area (33), pressure monitoring sensor in the low pressure zone (34), pressure monitoring sensors in the high pressure zone (35), temperature and humidity monitoring sensor in the high pressure zone (36), purified air heater (37)

Source: S. Cheberyachko *et al*. (2020)

To create a control system that would qualitatively regulate the selected technological parameters of motorised filtering respirators, it was necessary to obtain detailed information about the dynamic properties and behaviour of the control object: changes in air pressure in the mask of a motorised respirator developed by J. Schumacher *et al.* (2020), which depend on the depth and frequency of human breathing during different work (Fig. 2), characterised by the minimum pressure (during inhalation, p_{min}, Pa); maximum pressure (during exhalation, p_{max}, Pa); inhalation duration (t_{inh}, s); exhalation duration, (t_{exh}, s).

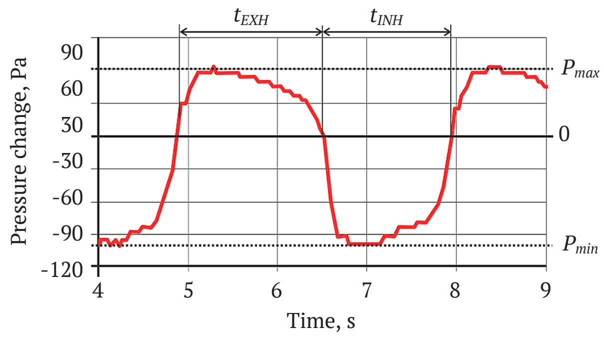

Figure 2. Pressure changes during breathing

Note: the vertical line shows the change in pressure (Pa) in the respirator mask during the process of inhalation and exhalation of air from the lungs: p_{max} – maximum exhalation pressure and p_{min} – maximum rarefaction that is formed during inhalation; the horizontal line shows time interval of exhalation (t_{exh}) and inhale (t_{inh})

Source: I. Dediv (2012), J. Schumacher *et al.* (2020)

To build a simulation model of a motorised filtering respirator, the human breathing process is given in the form of an equation (Cheberyachko *et al.*, 2022):

$$p(t) = A \cdot \sin(2\pi nt/60) - h, \tag{1}$$

where $p(t)$ – pressure created during breathing, Pa; A – respiratory amplitude, Pa; n – respiratory rate, $n = 60/T$, min^{-1}; T – period of the breathing cycle, s; h – signal displacement, which depends on the ratio of respiratory phases (exhalation/inhalation), Pa; t – time, s.

The signal offset was defined as:

$$h = (h_{inh} - h_{exh})/2, \tag{2}$$

where h_{inh} – rarefaction during inhalation, Pa; h_{exh} – exhalation pressure, Pa.

At the same time, h_{inh} and h_{exh} are calculated as the average value of the maximum values of rarefaction and pressure of the respiratory cycle over the selected time interval of experimental data, for example, when performing light physical work (Fig. 3):

$$h_{inh} = \frac{1}{N}\sum_{i=1}^{N} h_{inh} i \text{ and } h_{exh} = \frac{1}{N}\sum_{i=1}^{N} h_{exh} i, \tag{3}$$

where $h_{inh}i$ – maximum inhalation dilution for i-th cycle of breathing, Pa; $h_{exh}i$ – maximum exhalation pressure for i-th cycle of breathing, Pa; N – number of breathing cycles on the selected time interval of experimental data; i – breathing cycle number, $i = 1,2 \ldots N$.

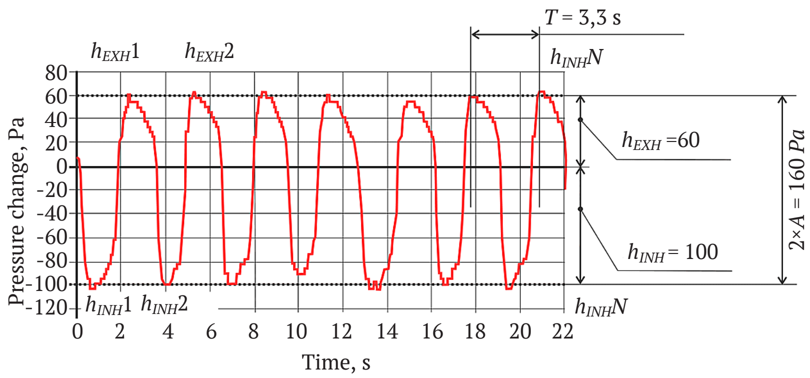

Figure 3. Characteristics of human breathing when performing work of the category "Light physical work 1b"

Note: T – period of the breathing cycle, s; $h_{inh}i$ – maximum inhalation dilution for i-th cycle of breathing, Pa; $h_{exh}i$ – maximum exhalation pressure for i-th cycle of breathing, Pa; N – number of breathing cycles on the selected time interval of experimental data; i – breathing cycle number, $i = 1,2 \ldots N$; experimental data were obtained in the process of human respiration when performing work of the 1b category of severity, which is determined based on the requirements of State Sanitary Standards 3.3.6.042-99 (1999); the period of the inhalation-exhalation process is 3.5 seconds; the change in pressure drop reaches 160 Pa

Source: S.S. Zhou *et al.* (2018), P. Otrisal *et al.* (2021)

Considering the given model of the respiratory signal in accordance with equation (1), a simulation model of a motorised filter respirator was developed (Fig. 4), which shows the relationship between the fan speed (u, rpm) applied to the input of the motorised respirator as a task signal and the pressure that the fan creates (p_{fan}, Pa), and the pressure created by a person during breathing ($p_{breathing}$, Pa), which together allows determining the total pressure in the under-mask space of the respirator (y, Pa), which is based on the fact that breathing effort increases by 60% at rest and up to 35% during physical activity. This was due to both the structural elements of the respirator (filter, inhalation/exhalation valves) and the presence of a "dead" space in the respirator mask – the remaining oxygen-depleted air after exhalation.

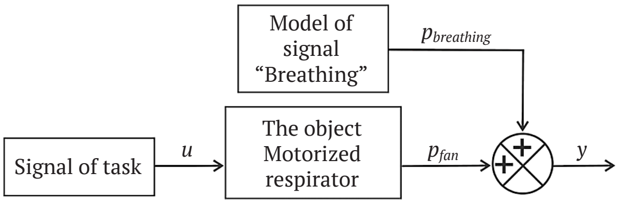

Figure 4. Block diagram of the simulation model

Note: the relationship between the fan speed is shown (u), which is applied to the input of the motorised respirator as a task signal, and the pressure p_{fan}, which at the same time creates a fan based on the resistance of filters and channels, and the amount of derivative pressure that the user creates ($p_{breathing}$), which ensures the appropriate mode of operation of the research object

Source: developed by the authors based on P. Otrisal *et al*. (2020), S. Cheberyachko *et al*. (2022)

Since a harmonic signal was used for the simulation, this allows reproducing the breathing mode in a motorised respirator for the category "Light physical work 1b", with an air flow rate (200 l/min) at the limit of rarefaction with breathing pressure drop amplitude not exceeding 60 Pa. While for the breathing mode for the categories of work "Moderate severity 2a" and "Moderate severity 2b", characterised by a pressure amplitude of up to 90 Pa, the second level of air flow rate (250 l/min) and for the categories of work "Heavy 3" – the third level: 120 Pa and 320 l/min, respectively (Makaveckas *et al*., 2023; Lee, 2024). With this approach, the user may not always be able to switch the device to the required flow rate in a timely manner, which can cause outside air to enter the mask through leaks when inhaling. This requires the development of a new motorised respirator control system that maintains the required air pressure in the under-mask space by changing the speed of rotation of the fan turbine. To solve this control problem, it is proposed to use two types of controllers: two-position and PID (proportional-integral-derivative).

Quality criteria that the air pressure control system in the respirator mask must meet:

1. Static accuracy (steady-state accuracy):

- established error or mismatch error (ε_{est}) – the maximum permissible deviation of the air pressure in the mask from the set value in the steady-state mode should not exceed 25 Pa.

2. Dynamic accuracy (transition quality):

- transition time (t_{tr}) – time it takes for the motorised respirator to reach the operating mode (the constant value of the corresponding parameter is the pressure in the mask), no more than 0.5 s;
- re-regulation (σ) – maximum permissible pressure deviation in the mask during operation should not exceed 20 Pa.

Approximation of experimental and theoretical data was performed using the normalised root-mean-square error (NRMSE), which was calculated in MATLAB using the "goodnessOfFit" function (Lutska *et al*., 2019).

RESULTS AND DISCUSSION

In general, the system of automatic control of air pressure in the under-mask space of a motorised respirator with feedback is shown in Figure 5.

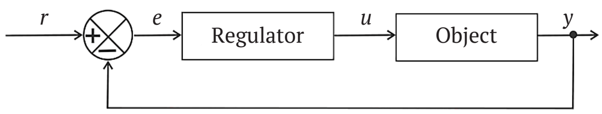

Figure 5. Block diagram of the automatic control system with feedback

Note: the difference between the setpoint (reference, r) of the pressure that must be maintained in the under-mask space of the respirator and the current value of the controlled value (y) determines the error or mismatch signal (e), based on which the output value of the controller or the controlling influence (u) is formed on the control object – a motorised respirator

Source: compiled by the authors

To adjust the two-position controller due to the setpoint U_{set} and deviations ΔU. The value of ΔU is selected equal to 0.5-0.7 of the permissible deviation range of the adjustable value. Reduction in ΔU leads to an increase in the frequency of operation of the controller, and the expansion of the zone ΔU may lead to an undesirable deviation of the adjustable value. Value of U_{set} is selected if:

$$U_{set} = U_{avg} + 0.5 \cdot U, \tag{4}$$

where U_{avg} – average value of the regulated value:

$$U_{avg} = (U_{max} + U_{min})/2. \tag{5}$$

That is, with an acceptable pressure fluctuation range of 20 Pa, the deviation will be ±10 Pa. Hence, the first block diagram of the simulation model of the control system of a motorised respirator with a two-position controller is shown in Figure 6. A block diagram of the simulation model of the control system of a motorised respirator with a PID controller is shown in Figure 7.

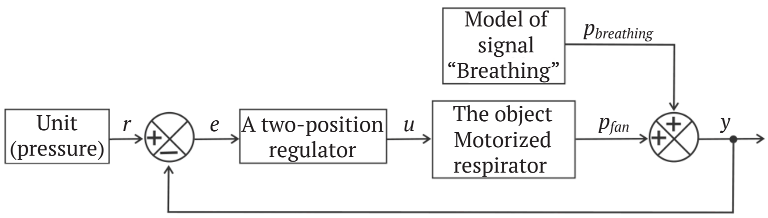

Figure 6. Block diagram of a control system with a two-position controller

Note: based on the pressure setpoint (r), which must be maintained in the under-mask space of the respirator, and the current pressure value in the mask (y), which is determined by the pressure generated by the fan (p_{vent}) and the user's breathing modes ($p_{breathing}$), the output value of the controlling influence (u) from the two-position controller is determined – the fan speedr

Source: compiled by the authors

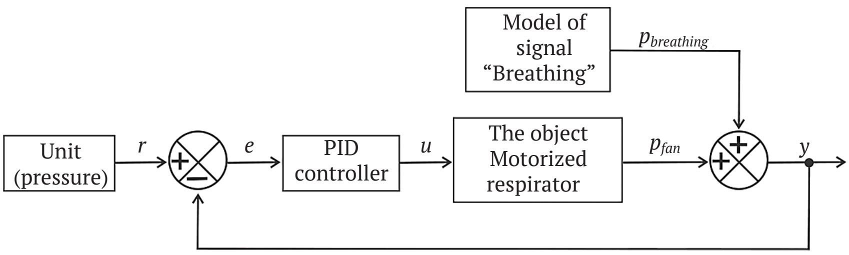

Figure 7. Block diagram of a simulation model of a control system with a PID controller

Note: based on the pressure setpoint (r), which must be maintained in the under-mask space of the respirator, and the current pressure value in the mask (y), which is determined by the pressure generated by the fan (p_{fan}) and the user's breathing modes ($p_{breathing}$), the initial value of the controlling influence (u) from the proportional-integral-derivative (PID) controller is determined

Source: compiled by the authors

The use of a PID controller requires appropriate configuration, which is performed using empirical and heuristic methods. It is proposed to change the controller parameters in the following sequence: first, adjust the gain of the proportional component K_p, when other channels are turned off, the gain of the integral component K_i is adjusted, and the last one determines the gain of the derivative component K_d. The controlling influence u(t), generated at the output of the PID controller, contains proportional and integral components:

$$u(t) = k_p \cdot e(t) + k_i \cdot \int_0^t e(t)dt + k_d \cdot \frac{de(t)}{dt}, \tag{6}$$

where $u(t)$ – controlling influence; $e(t)$ – error (discrepancy between the setpoint and the actual value); k_p – gain of the proportional component; k_i – gain of the integral component; k_d – gain of the derivative component.

This provides the necessary level of control over the air pressure in the respirator mask, based on the user's preset breathing modes. At the first stage, to identify the dependence of the influence of environmental parameters on the functioning of the air pressure control system during the respiration process, the experimental data of pressure changes were compared when performing works of the category “Light physical work 1b”, which are published in the study N.M. Lutska *et al*. (2019) with a pressure change curve defined by a mathematical model, which is mapped by equations (1-3). The results of the approximation of experimental and theoretical data shown in Figure 8 are 58.74%, the correlation coefficient is 0.915, and the Fisher statistical criterion is 10273 (Lima *et al*., 2023). This indicates sufficient reliability of the mathematical model, which allows it to be used in further studies of the air pressure control system in motorised personal respiratory protection equipment (PRPE).

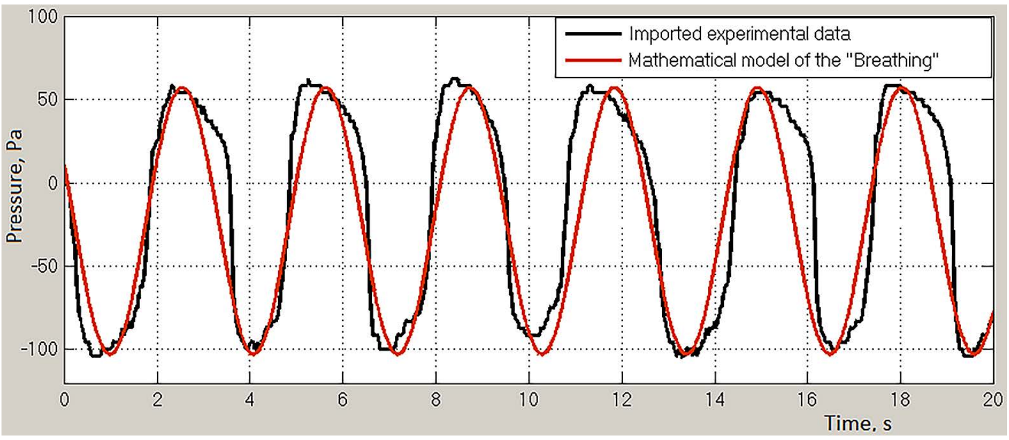

Figure 8. Experimental data for the category of "Light physical work 1b" and data from the mathematical model
Source: compiled by the authors

The next step was to test the operation of the motorised respirator on its simulation model, the block diagram shown in Figure 7, under different air supply modes (Fig. 9).

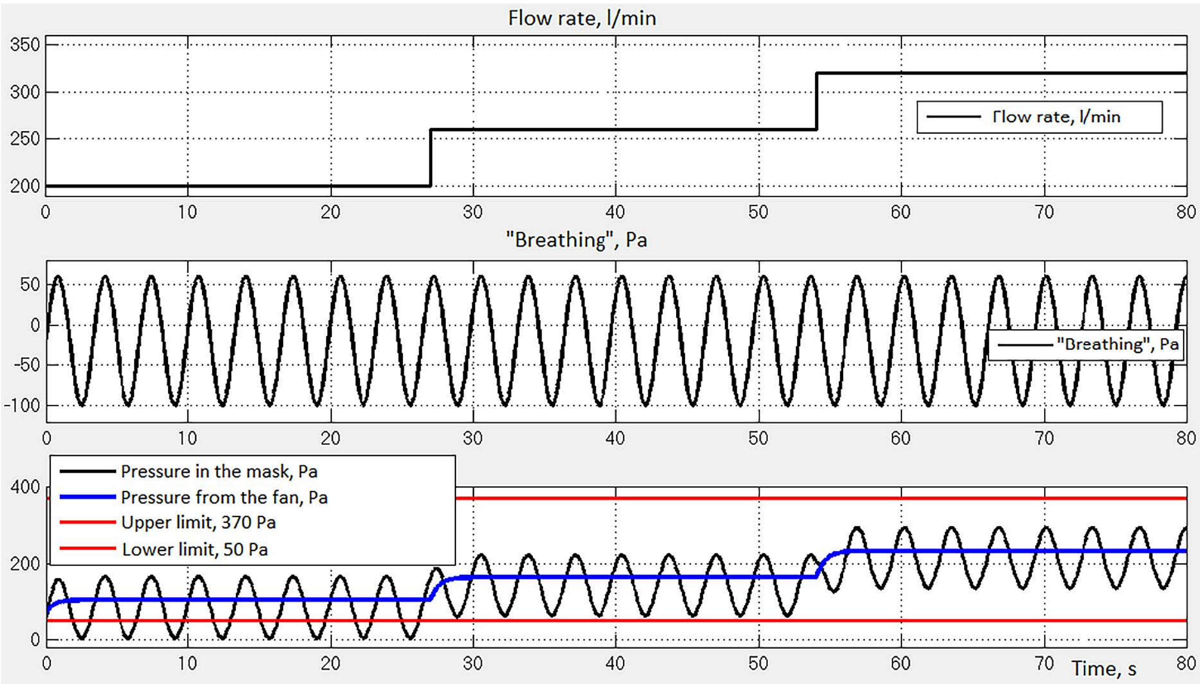

Figure 9. Result of the simulation model when changing the flow rate
as a controlling influence under different operating modes
Source: compiled by the authors

Figure 9 shows that the disadvantage of the functioning of the simulation model of a motorised respirator is the drop in air pressure in the mask beyond the lower permissible limit (below 50 Pa), which can cause the suction of external polluted air into the mask, and there is also no compensation for forces during inhalation/exhalation.

Studies of the operation of the control system with a two-position air pressure controller in motorised respirators when performing work of the category "Light physical work 1b" and category "Heavy 3", considering the respiratory rate of 15 cycles per minute at a pressure amplitude of 60 Pa and 30 l/min at an amplitude of 120 Pa, respectively, are shown in Figures 10 and 11. However, the air pressure value was set for light physical work of 120 Pa, with fluctuations in the permissible range of 110-130 Pa, and for heavy physical work – 260 Pa with fluctuations in the range of 250-270 Pa.

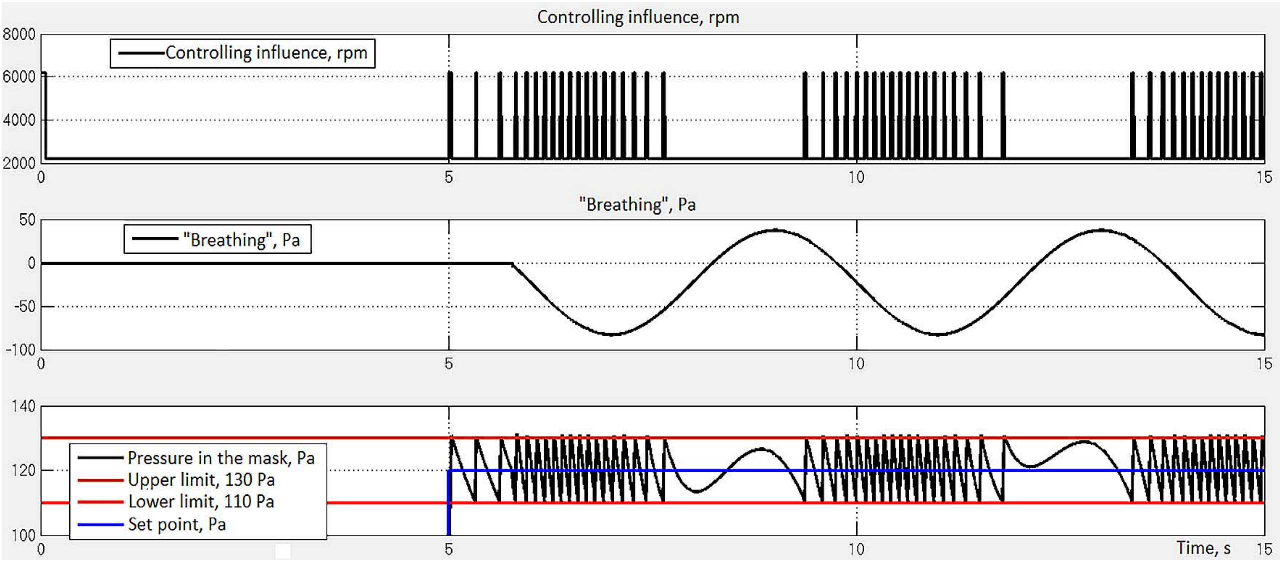

Figure 10. Simulation results at a sinusoid frequency corresponding to respiration of 15 cycles per minute with an amplitude of 60 Pa, a setpoint of 120 Pa

Source: compiled by the authors

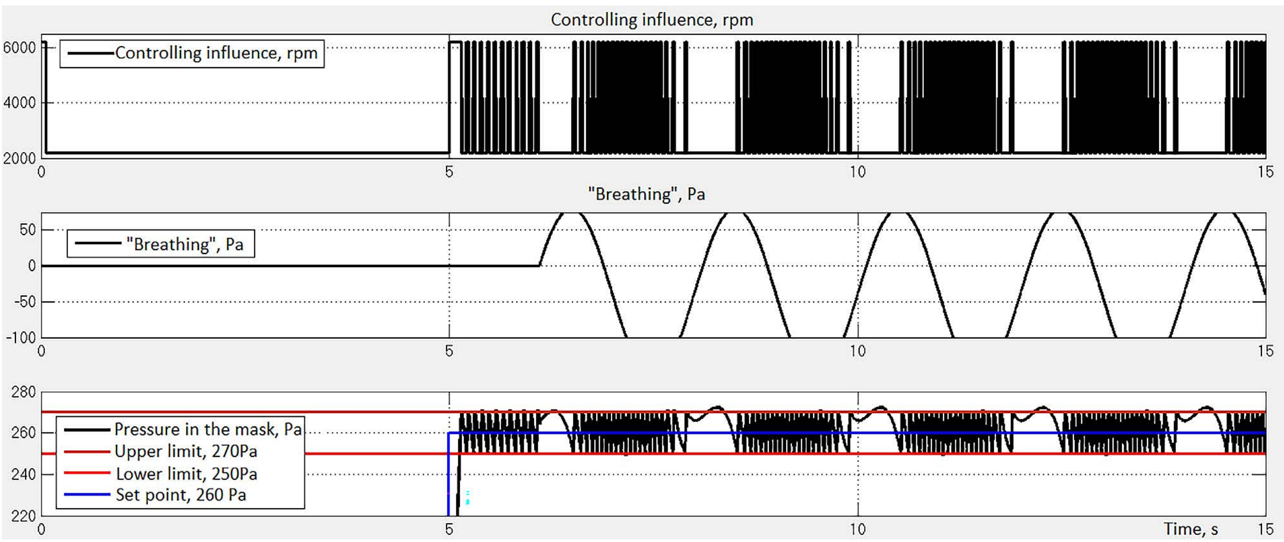

Figure 11. Simulation results at a sinusoid frequency corresponding to respiration of 30 cycles per minute with an amplitude of 120 Pa, a setpoint of 260 Pa

Source: compiled by the authors

Analysis of the results obtained when modelling a control system with a two-position controller showed that during operation there are exceeding the control limits up to 1 Pa during inhalation compensation and up to 2 Pa during exhalation. In addition, the fan is in the mode of constant fluctuations in the speed of rotation (min/max), up to 20 Hz, which can lead to premature exhaustion of the working life and its failure, cause additional noise and vibration.

Studies of the operation of the control system under the air pressure controller in motorised respirators when performing work of the category "Light physical work 1b" and category "Heavy 3" are shown in Figures 12 and 13.

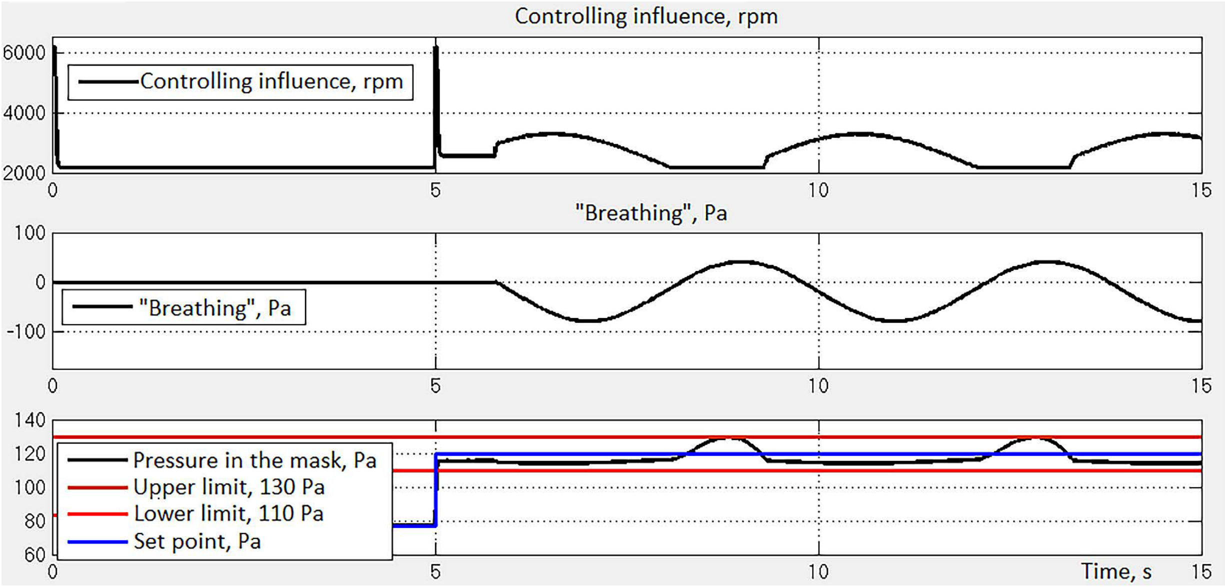

Figure 12. Simulation results at a sinusoid frequency corresponding to respiration of 15 cycles per minute with an amplitude of 60 Pa, a setpoint of 120 Pa

Source: compiled by the authors

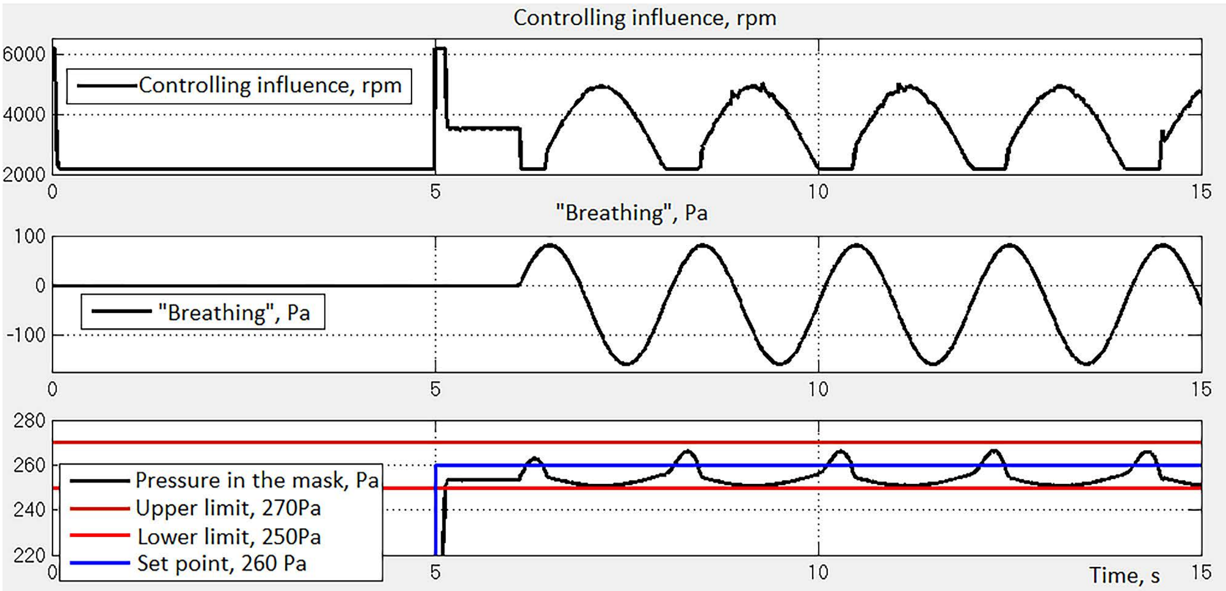

Figure 13. Simulation results at a sinusoid frequency corresponding to respiration of 30 cycles per minute with an amplitude of 120 Pa, a setpoint of 260 Pa

Source: compiled by the authors

Based on the results of modelling the air pressure control system in the mask of a motorised respirator using a PID controller, it was found that:

- gain of the proportional component K_p of the PID controller significantly affects the established error: within the coefficient values *Kp* from 50 to 967, the steady-state error varies from -60 Pa to -1 Pa. When the value is K_p more than 250, there is an appearance of minor fluctuations, which gradually increase until the appearance of system overshoot at K_p above 967;

- the gain of the integrating component in the range of 0.1-10 affects the static accuracy of the system, reducing the established error. An increase in K_i, when changing the setpoint due to an increase/decrease in physical load on the user (changing the amplitude and frequency of breathing), increases the established error;
- when increasing the gain of the derivative component K_d from 0.01 to 5, the established error decreases. A further increase causes fluctuations to appear; while a decrease in K_d allows expanding the boundaries of changes K_p up to 500 without any fluctuations;
- changing the breathing mode causes the need to increase the setpoint to compensate for the exhalation pressure and decrease it to prevent useless operation of the fan at high speeds (saving battery power).

The next step was to compare the results of simulation models of control systems with a two-position and PID controller, respectively, as shown in Figure 14, where the advantage of using a PID controller in air pressure control systems is demonstrated, which eliminates fluctuations in the controlling influence – the fan speed and reduces the deviation of the air pressure in the mask from the set value (air pressure setpoint).

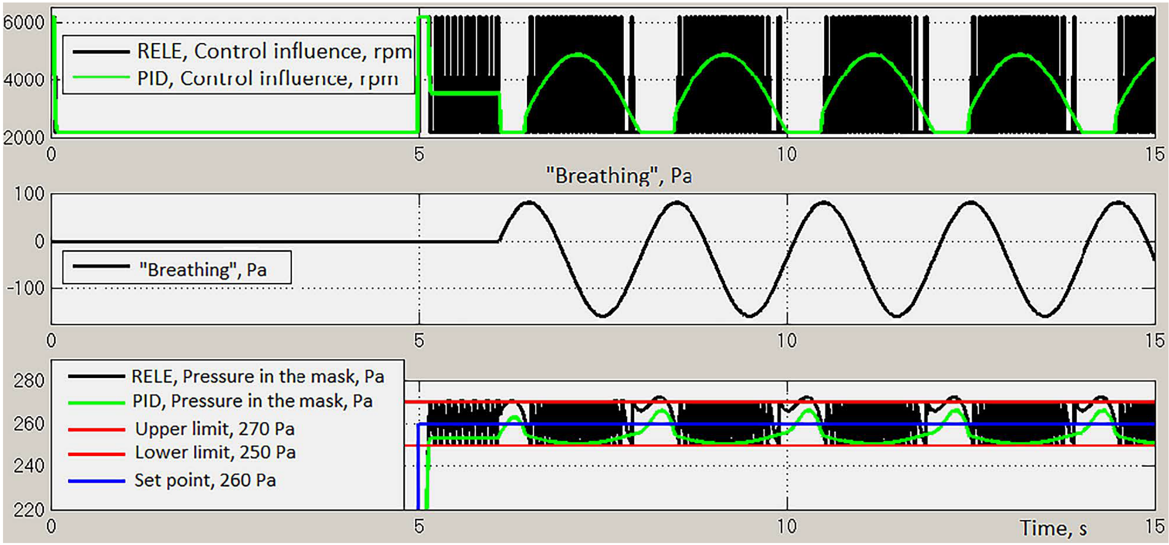

Figure 14. Comparison of the results of simulation models of control systems with a two-position and PID controller
Source: compiled by the authors

At the last stage, the operation of the simulation model of the control system was checked when providing experimental data – the "Breathing" test signal. The test results, shown in Figure 15, showed that when using a PID controller with defined parameters, the control system compensates for changes in air pressure in the under-mask space of the respirator under different respiratory modes of the user (changes in breathing frequency and depth). The air pressure is within certain limits (50-370 Pa).

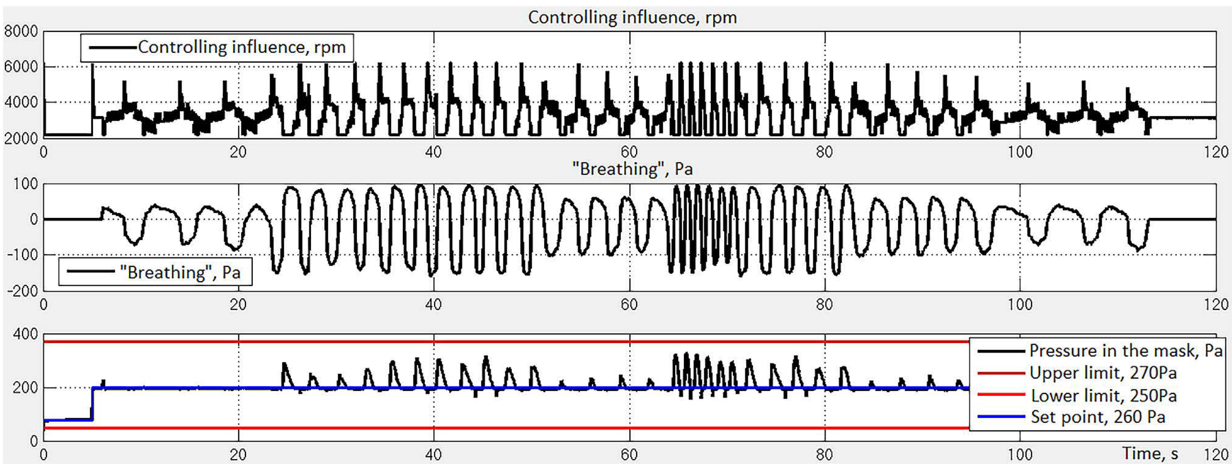

Figure 15. Operation of the control system simulation model when a test signal is sent
Source: compiled by the authors

Studies have shown that the process of human breathing in a motorised respirator can be set by a harmonic signal in the form of a sinusoid with a frequency and amplitude corresponding to different modes of physical activity of the user while working in a motorised respirator. The obtained conclusion does not contradict a number of studies conducted on changing the respiratory mode when the load changes, which indicate the possibility of calculating changes in air pressure according to the harmonic law, considering coefficients that reflect the sinusoid (Vitazkova *et al*., 2024). This allows using the proposed model to test the effectiveness of various simulation models. At the first stage, it was found that the well-known simulation model for controlling air pressure does not allow providing the necessary air flow rates when changing signals to maintain both the required pressure level in the under-mask region and when increasing the filter resistance. Similar results, which showed the presence of problems in the control system of motorised respirators, were obtained by G. Teng *et al*. (2023), who investigated the effect of various artificial ventilation regimens on the effectiveness of nebulised bronchodilators in the treatment of intubated adult patients with obstructive pulmonary disease.

According to M. Bergman *et al*. (2017), the structure and configuration of the respirator blower monitoring system requires refinement and verification in real process conditions. This allows adjusting the parameters based on the appropriate working conditions. S. Xu *et al*. (2019), N.A. Kamaluddin *et al*. (2022) note the need to create systems that will adapt to the individual parameters of the user, and to external influences, such as filter contamination, the presence of moisture, etc.

The paper by L.F. Miles *et al*. (2021) proposed a mathematical model of mechanical air supply for artificial ventilation with various modes of pressure-controlled ventilation (PCV). The model considers the possibility of obtaining dynamic signals to monitor the amount of air that needs to be supplied to the under-mask space. However, the model does not provide for the possibility of increasing the resistance of filters due to dust, which does not allow it to be used to describe the operation of motorised respirators. The study by C. O'Toole *et al.* (2020) included an analysis of a number of key indicators, such as inhalation and exhalation volume, respiratory rate, and analysis of oxygen and carbon dioxide concentrations in the exhaled air. The obtained data help to determine the effectiveness of the respirator in simulating situations associated with possible equipment failure. Analysis of these ventilation parameters under controlled conditions allows understanding how the system responds to stressful scenarios and determines how effectively it provides volunteers with the necessary amount of fresh air and appropriate gas levels during respiration. These results can be useful for further improving the design and functionality of respirators, which will provide optimal protection and comfort for users in various situations.

C. Pintavirooj *et al.* (2022) reviewed an emergency ventilator based on a fan with a sensor and ventilation drive of a new design. They described in detail the emergency ventilator, which uses a new fan with an innovative sensor and ventilation drive. This device is designed for use in emergency situations and is highly efficient and reliable due to the use of advanced technologies in the sensor and ventilation control system. The integration of these innovations into the design of the device ensures a fast and accurate response to the patient's needs, making it an effective tool in emergency medical cases. X. Zhao *et al.* (2024) describe the improvement of power supply systems for electric respirators for air purification, which involves optimising the design parameters of the impeller of a centrifugal fan. This allows increasing the efficiency and productivity of the ventilation system, ensuring an optimal volume of air supply with minimal energy consumption. Optimisation of impeller parameters involves manufacturing elements based on their shape, size and material, which maximises air movement and ensures optimal pressure. This helps to increase productivity and ensure efficient operation of the respirator in air purification from contaminants and particles. This approach to optimising the fan design ensures a reliable and energy-efficient operating process of the respirator power system, which is important in the context of ensuring the safety and comfort of users in situations related to air pollution.

To avoid these shortcomings in this study, it was proposed to develop new simulation models of the control system of a motorised respirator with a two-position controller and a PID controller. As a result of the conducted research, it was found that the simulation model of the air pressure control system in a respirator mask with a configured PID controller fully meets the quality criteria put forward: static error of 0.3 Pa (average value), transition time of 0.135 s, and no system overshoot. However, to determine the parameters of the PID controller, it is not possible to use analytical calculation methods due to the non-linearity and unsteadiness of processes to ensure the necessary compensation by the control system for pressure fluctuations in the mask caused by the user's breathing during various physical exertion, which are responsible for the air supply to motorised respirators, as an object of control. This requires additional research to determine the parameters of the controller that allow maintaining the air pressure in the under-mask space of a motorised respirator within acceptable limits (50-370 Pa), which will ensure the comfort of using a motorised respirator (Teng *et al*., 2023). Preventing excessive fluctuations in the controlling variable also helps to reduce the wear and breakage of system elements, which can occur due to constant loads and instability in operation (Diekman *et al*., 2017; Damiani *et al*., 2023). This can significantly reduce the time and cost of equipment maintenance and repair, and ensure smooth and efficient operation of the system for a long time. This management approach is key to production and helps to conserve resources and energy, which is critical in modern industry.

CONCLUSIONS

The structure of the pressure control system in the middle of a motorised respirator is developed with the selection of the appropriate controller based on the obtained dependencies between the change in the breathing mode and the pressure value in the under-mask space, which allows providing an appropriate comfortable mode of operation for users. It is determined that the simulation model with a PID controller will provide appropriate pressure values within the permissible limits (50-370 Pa), which increases the comfort of using a motorised respirator, providing the necessary compensation by the control system for pressure fluctuations in the mask caused by the user's breathing during various physical exertion, characterised by changes in the pressure drop and the volume of air consumed.

It is proved that the PID controller maintains the pressure in the respirator mask within certain limits, both with an increase and with a decrease in the control signal, preventing excessive fluctuations in the controlling variable, which leads to an extension of the service life of the filter elements and a reduction in electricity consumption for the operation of the fan motor. Based on modelling the operation of the pressure control system in different modes of operation, it is shown that when using a PID controller with defined parameters, the system provides compensation for changes in air pressure in the under-mask space of the respirator in different breathing modes of the user. It was found that the simulation model of the air pressure control system in a respirator mask with a configured PID controller fully meets the quality criteria put forward: static error of 0.3 Pa (average value), transition time of 0.135 s, and no system overshoot.

Future studies may include the evaluation of the effectiveness of the system during different physical activities and in different climatic conditions, to determine the optimal regulation parameters for maximum user comfort and safety. Another possible area for further research is to expand the functionality of the control system, considering the individual characteristics of users and the dynamics of their breathing. The integration of additional sensors and algorithms can further improve the system and expand its capabilities to provide the highest level of comfort and protection for respirator users.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Al-Naggar, N. (2015). Modelling and simulation of pressure controlled mechanical ventilation system. *Journal of Biomedical Science and Engineering*, 8, 707-716. doi: 10.4236/jbise.2015.810068.

[2] Bergman, M., Basu, R., Lei, Z., Niezgoda, G., & Zhuang, Z. (2017). Development of a manikin-based performance evaluation method for loose-fitting powered air-purifying respirators. *Journal of the International Society for Respiratory Protection*, 34(1), 40-57.

[3] Brook, R.D., Newby, D.E., & Rajagopalan, S. (2017). The global threat of outdoor ambient air pollution to cardiovascular health: Time for intervention. *JAMA Cardiology*, 2(4), 353-354 doi: 10.1001/jamacardio.2017.0032.

[4] Cheberyachko, S., Cheberyachko, Y., Deryugin, O., Slavinskyi, D., & Klimov, D. (2020). Filtering respirator with forced air supply. *Reporter of the Priazovskyi State Technical University. Section: Technical Sciences*, 41, 155-171. doi: 10.31498/2225-6733.41.2020.226205.

[5] Cheberyachko, S., Cheberyachko, Y., Naumov, M., & Deryugin, O. (2022). Development of an algorithm for effective design of respirator half-masks and encapsulated particle filters. *International Journal of Occupational Safety and Ergonomics*, 28(2), 1145-1159. doi: 10.10 80/10803548.2020.1869429.

[6] Damiani, L., Revetria, R., & Giribone, P. (2023). Dynamic simulation of a pneumatic transport plant powered by PV panels and equipped with electro-chemical storage. *Electrochem*, 4(2), 239-254. doi: 10.3390/electrochem4020016.

[7] Dediv, I. (2012). Computer simulation model of respiratory signal noise. *Bulletin of Sumy State University. Series: Technical Sciences*, 3, 160-164.

[8] Diekman, C.O., Thomas, P.J., & Wilson, C.G. (2017). Eupnea, tachypnea, and autoresuscitation in a closed-loop respiratory control model. *Journal of Neurophysiology*, 118, 2194-2215. doi: 10.1152/jn.00170.2017.

[9] Gheorghe, G., Ilie, M., Bungau, S., Stoian, A.M.P., Bacalbasa, N., & Diaconu, C.C. (2021). Is there a relationship between COVID-19 and hyponatremia? *Medicina (Kaunas)*, 57(1), article number 55. doi: 10.3390/medicina57010055.

[10] Kamaluddin, N.A., Kassim, M., & Shahbudin, S. (2022). A review on 3D augmented reality design technique and inward leakage testing on protective face mask. *Pertanika Journal of Science & Technology*, 30(4), 2639-2658. doi: 10.47836/pjst.30.4.19.

[11] Lee, K. (2024). A new test statistic to assess the goodness of fit of location-scale distribution based on progressive censored data. *Symmetry*, 16(2), article number 202. doi: 10.3390/sym16020202.

[12] Licina, A., & Silvers, A. (2021). Use of powered air-purifying respirator (PAPR) as part of protective equipment against SARS-CoV-2-a narrative review and critical appraisal of evidence. *American Journal of Infection Control*, 49(4), 492-499. doi: 10.1016/j.ajic.2020.11.009.

[13] Lima, C.A., Campos, S.L., Bandeira, M.P., Leite, W.S., Brandão, D.C., Fernandes, J., Fink, J.B. & Dornelas de Andrade, A. (2023). Influence of mechanical ventilation modes on the efficacy of nebulized bronchodilators in the treatment of intubated adult patients with obstructive pulmonary disease. *Pharmaceutics*, 15(5), article number 1466. doi: 10.3390/pharmaceutics15051466.

[14] Lutska, N.M., Ladanyuk, A.P., & Savchenko, T.V. (2019). Identification of the mathematical models of the technological objects for robust control systems. *Radio Electronics, Computer Science, Control*, (3), 163-172. doi: 10.15588/1607-3274-2019-3-18.

[15] Makaveckas, T., Bliūdžius, R., Alavočienė, S., Paukštys, V., & Brazionienė, I. (2023). Investigation of microclimate parameter assurance in schools with natural ventilation systems. *Buildings*, 13(7), article number 1807. doi: 10.3390/buildings13071807.

[16] Miles, L.F., Makar, T., Oughton, C.W., & Peyton, P.J. (2021). Ventilatory parameters measured during a physiological study of simulated powered air-purifying respirator failure in healthy volunteers. *Anaesthesia and Intensive Care*, 49(3), 206-213. doi: 10.1177/0310057X20978982.

[17] O'Toole, C., McGrath, J.A., Joyce, M., Bennett, G., Byrne, M.A., & MacLoughlin, R. (2020). Fugitive aerosol therapy emissions during mechanical ventilation: *In vitro* assessment of the effect of tidal volume and use of protective filters. *Aerosol and Air Quality Research*, 20(12), 2604-2613. doi: 10.4209/aaqr.2020.04.0176.

[18] Otrisal, P., Bungau, C., Obsel, V., Melicharik, Z., & Tont, G. (2021). Selected respiratory protective devices: Respirators and significance of some markings. *Sustainability*, 13(9), article number 4988. doi: 10.3390/su13094988.

[19] Otrisal, P., Friess, K., Urban, M., Bungau, S., Tit, D.M., Mosteanu, D.E., Melicharik, Z., Bungau, C., & Aleya, L. (2020). Barrier properties of anti-gas military garments, considering exposure to gas organic compounds. *Science of the Total Environment*, 714, article number 136819. doi: 10.1016/j.scitotenv.2020.136819.

[20] Pintavirooj, C., Maneerat, A., & Visitsattapongse, S. (2022). Emergency blower-based ventilator with novel-designed ventilation sensor and actuator. *Electronics*, 11(5), article number 753. doi: 10.3390/electronics11050753.

[21] Schumacher, J., Arlidge, J., Dudley, D., Sicinski, M., & Ahmad, I. (2020). The impact of respiratory protective equipment on difficult airway management: A randomised, crossover, simulation study. *Anaesthesia*, 75, 1301-1306. doi: 10.1111/anae.15102.

[22] State Sanitary Standards 3.3.6.042-99. (1999). *Sanitary standards for the microclimate of industrial premises*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=14283.

[23] Teng, G., Shi, G., Zhu, J., & Zhao, C. (2023). Research on the air supply adjustment technology of breath-following powered air-purifying respirators. *Scientific Reports*, 13, article number 12219. doi: 10.1038/s41598-023-39411-z.

[24] Vitazkova, D., Foltan, E., Kosnacova, H., Micjan, M., Donoval, M., Kuzma, A., Kopani, M., & Vavrinsky, E. (2024). Advances in respiratory monitoring: A comprehensive review of wearable and remote technologies. *Biosensors*, 14(2), article number 90. doi: 10.3390/bios14020090.

[25] Weiss, R., Guchlerner, L., Weissgerber, T., Filmann, N., Haake, B., Zacharowski, K., Wolf, T., Wicker, S., Kempf, V.A.J., Ciesek, S., Stöver, T., & Diensthuber, M. (2021). Powered air-purifying respirators used during the SARS-CoV-2 pandemic significantly reduce speech perception. *Journal of Occupational Medicine and Toxicology*, 16, article number 43. doi: 10.1186/s12995-021-00334-y.

[26] Xu, S.S., Lei, Z., Zhuang, Z., & Bergman, M. (2019). Numerical simulations of exhaled particles from wearers of powered air purifying respirators. *Journal of the International Society for Respiratory Protection*, 36(2), 66-76.

[27] Zhao, X., Guan, J., Wang, T., Liu, X., Xu, Q., & Zhou, J. (2024). Optimization of impeller structure parameters of a centrifugal fan in a powered air-purifying respirator power system. *Processes*, 12(2), article number 353. doi: 10.3390/pr12020353.

[28] Zhou, S.S., Lukula, S., Chiossone, C., Nims, R.W., Suchmann, D.B., & Ijaz, M.K. (2018). Assessment of a respiratory face mask for capturing air pollutants and pathogens including human influenza and rhinoviruses. *Journal of Thoracic Disease*, 10(3), 2059-2069. doi: 10.21037/jtd.201.

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Автоматизована система керування тиском повітря у моторизованому дихальному апараті

Анотація. Актуальність дослідження полягає в розробці ефективної системи керування тиском в подачі повітря у моторизованих дихальних апаратах для забезпечення ефективного захисту працівників від небезпечних аерозолів та покращення їхнього здоров'я. Метою було створення автоматизованої системи управління тиском повітря в моторизованому дихальному апараті, використовуючи пропорційно-інтегрально-диференціальний регулятор. Для цього було використано метод імітаційного моделювання. Щоб унеможливити непередбачені ситуації з погіршення рівня захисту, розроблено структуру системи керування тиском моторизованого респіратора з обранням відповідного регулятора на основі отриманих залежностей впливу параметрів режиму дихання та величину тиску у підмасковому просторі респіратора, що дозволяє забезпечити відповідний комфортний режим роботи. Це дозволило, розробити імітаційну модель з ПІД-регулятором, яка забезпечить відповідні величини тиску в допустимих межах (50-370 Па). Доведено, що пропорційно-інтегрально-диференціальний регулятор забезпечує підтримку тиску в масці респіратора у визначених межах як при збільшенні так і при зменшенні сигналу керування, запобігаючи зайвим коливанням керуючої величини, що призводить до подовження ресурсу фільтрувальних елементів та зменшення витрат електроенергії на роботу двигуна вентилятора. Показано на основі моделювання роботи системи керування тиском при різних режимах роботи, що при використанні ПІД-регулятора з визначеними параметрами, система забезпечує компенсацію змін тиску повітря в підмасковому просторі респіратора при різних режимах дихання користувача. Отримані результати можуть знайти практичне застосування в сфері безпеки та охорони здоров'я, в промислових умовах, де працівники піддаються ризику вдихання небезпечних аерозолів, таких як токсичні частки, гази чи інші шкідливі речовини

Ключові слова: ідентифікація; імітаційна модель; моторизований респіратор,; регулятор; уставка, тиск

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Investigation of deformation of the spring tooth of agricultural implements from the action of the force applied to it

Abstract. The relevance of the study lies in the need to investigate the dependence of the force applied to the spring tooth on its parameters, which is an important task due to the widespread use of spring teeth in agricultural implements, such as balers, reapers, rakes, etc. The purpose of the study is to establish an analytical description of the spring tooth deformation depending on the amount of applied force. For this purpose, the theory of bending rods from the resistance of materials was applied, without simplifying it, as is common in construction, where the deflection of a beam is small compared to its length. The calculation is based on the well-known dependence of the curvature of the elastic axis of the beam (tooth) on the applied moment and the stiffness of its cross-section. The study considers a cantilevered tooth, which at the point of pinching is a spring with several turns, followed by a smooth transition to a rectilinear shape. The

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tooth is divided into two parts along its length: curvilinear and rectilinear. Calculation of the deformation, i.e., finding the shape of the elastic axis after the action of the applied force, is carried out for both parts separately. The need for this approach is dictated by the fact that the curvature of the elastic axis of the tooth in the free state changes abruptly from the stable value of the curvilinear part to a zero value of the straight part. The main result of the study is to find the shape of the elastic axis of individual parts of the tooth under the action of the applied force and combine them into one whole. This helps to determine the amount of movement of the free end of the tooth depending on the amount of force applied to it. The application of the obtained data can help in the development of more efficient and productive agricultural tools, and increase their durability and efficiency when interacting with the soil

Keywords: curvature; elastic axis; applied force; moment

INTRODUCTION

In agriculture, in particular in the mechanisation of processes, it is important to understand and improve the parameters of agricultural tools. The effectiveness of these tools is directly related to the reliability of their components. The investigation of spring tooth deformation due to applied force determines not only the stability and efficiency of tools, but can also help improve their design and functionality. Tools with optimised spring teeth can provide increased productivity and reduce wear, which are key factors in modern farming. The use of new technological solutions in agriculture can help to increase yields, reduce resource costs, and improve the environmental sustainability of agricultural activities. Thus, the study is an important step towards optimising and modernising agricultural production.

The results of the study of the influence of operational factors on the technical condition of agricultural machinery in the process of its use are described in detail by L. Semenenko *et al.* (2021). Based on a systematic analysis of methods for increasing the durability and wear resistance of the working bodies of tillage machines, it is established that their increase in 90% of cases is achieved by technological methods. According to S. Mudarisov *et al.* (2019), a new area in the development of agriculture is emerging in the world, in fact, it is a new strategy based on the use of modern innovative technologies for tillage and the development of combined units for their implementation. However, the study of the process of interaction of tillage working bodies with the soil when designing new structures requires simple analytical physical and mathematical models of such a process. Thus, K. Aikins *et al.* (2023) modelled the interaction process of the most common tillage implements, such as cultivator tine, disc harrow on an elastic rack, deep ripper (chisel plough), mouldboard plough, and smooth roller. Analysing the interaction of these working bodies with the soil, the researchers paid attention to such parameters as the depth of cultivation, the degree of soil destruction, rolling resistance, energy costs, and other characteristics. They found that the efficiency of tillage significantly depends on the selection and adjustment of working bodies, as well as on soil parameters such as humidity and soil type. The results of the study helped to improve tillage technologies and reduce energy consumption, which corresponds to modern principles of sustainable agriculture. S. Cao *et al.* (2022) analysed the trajectory of the hook-shaped teeth, and determined the optimal operating parameters of the harvesting device. The results of the study showed that the optimal operating parameters of the harvesting device significantly affect the harvesting efficiency, reducing plant damage and grain loss. Analysis of the trajectory of the hook-shaped teeth determined the optimal depth of penetration of the teeth into the soil, the angle of inclination, and the speed of movement of the device. Q. Wang *et al.* (2021) proposed a new method for modelling the clutch for a pickup baler using automatic dynamic analysis of mechanical systems and the discrete element method.

The speed of movement of the strip, filling of buckets with seeds, backflow, surface areas of working bodies, clamping of grains in the gaps between the bucket and the strip, and other factors in the aggregate and relationship with the biological and mechanical-technological properties of grain seeds affect the injury of grains and their quality indicators. I. Rogovskii *et al.* (2020) investigated the modes of interaction of an elastic riser pipe of a spherical disk with the ground medium using ballast loading when the translational velocity of a mobile energy vehicle changes.

Spring teeth play a key role in the tillage process, providing the necessary flexibility and adaptability in harsh working conditions. Their certain ordered number forms rakes, which are the working bodies of balers, reapers, rakes, cultivators, and harrows. An important function of mulching the soil in the spring-autumn period, and the effective distribution of stubble in autumn after harvesting, is most effectively performed by heavy wide tooth harrows, the tools of which consist of a pivotally installed conical spring with one or two free tips (a tool with a spring tooth). The study by L. Tulaganova *et al.* (2022) is devoted to improving the resource performance of cultivator legs when using a combined strengthening method. The article presents a scheme of combined three-layer cultivator blade formation, which ensures an increase in resource indicators due to the application of powdered abrasion-resistant materials by arc surfacing. V. Bulgakov *et al.* (2018) proposed the design of a new spring-toothed harrow that has mechanical selectivity for weed germination. The study by H. Sheng *et al.* (2022) is devoted to the construction of mathematical models of the stability of the functioning of a mechanical rotor system. In the paper, a dynamic model of the rotor is developed using the theory of blade elements.

The elasticity of the material must be considered in many cases. For example, S. Pylypaka *et al.* (2020) considered the movement of a flexible strip up the surface of a horizontal cylinder. Moving along the inner surface of the cylinder, the strip is forced to take on its shape. Additional force is required to overcome the elasticity of the strip, unlike a completely flexible strip. The elastic bending of the riser of the cultivator tine is discussed by S. Pylypaka *et al.* (2023). The study considers the elastic axis of the tine when it is bent during operation. The study by V. Khopost & I. Demchuk (2023) is devoted to the search for the elastic axis of a spiral spring in a free state. A characteristic feature of these studies is that the elastic element is not divided into parts, that is, the change in the curvature of the elastic axis is natural.

The spring tooth of an agricultural tool consists of two sections: rectilinear and curvilinear in the form of a spring. The curvature of the elastic axis of these sections at the junction point changes abruptly from zero to a stable value. This circumstance does not allow considering the tooth as a single whole, in mathematical terms. All this determines the purpose of the study aimed at mathematically describing the deformation of the tooth, which consists of rectilinear and curvilinear sections, under the action of a force applied to it.

MATERIALS AND METHODS

The elastic tooth of an agricultural machine can be made either paired or not paired. Figure 1 shows the tooth variants and the solid model of the unpaired tooth, which was tested for bending in this study.

Figure 1. Spring tooth options and its solid-state model
Note: this model was adopted for bending tests under the applied force
Source: compiled by the authors

The tooth is conventionally divided into two parts: rectilinear and curvilinear in the form of a spring. Given that the spring pitch is a small value compared to other dimensions, a simplification was adopted, according to which it is equal to zero. From the design of the teeth, it can be seen that the end of the curvilinear part of the tooth is rigidly attached to the shaft on which the rake is located, that is, it is cantilevered.

An elastic tooth with the dimensions given on the Lidius website (n.d.) was used for consideration. Figure 2 shows a paired tooth for a heavy harrow in two projections with the required dimensions.

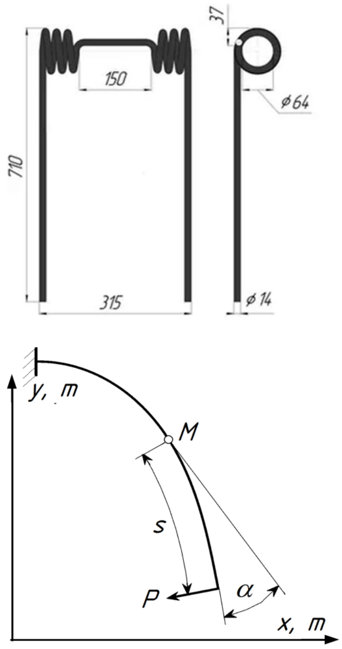

Figure 2. Spring tooth
Note: the dimensions required to calculate tooth bending under the applied force are provided
Source: Lidius (n.d.)

The radius of its elastic axis can be found from a given internal diameter of the spring: $r_o = 0.039\ m$. Value k_o can be defined as the inverse of r_o: $k_o = 25.64\ m^{-1}$. The cross-section of the tooth is a circle. Its moment of inertia I is known: $I = \pi r^4/4$, where $r = 0.007\ m$ according to Figure 2. The tooth material is spring steel. Its Young's modulus is also known: $E = 2.2 \cdot 10^{11}\ N/m^2$. Hence, the stiffness of the tooth is: $EI = 414.9\ N \cdot m^2$.

The research methods were based on the theory of material resistance and differential geometry of curves. The first part was based on the position of the resistance of materials, in relation to which the relationship between the curvature of the elastic axis of the beam, the moment applied to it, the shape of the cross-section of the beam and the Young's modulus of the material from which it is made are established. This relationship has a form:

$$k(s) = \frac{M(s)}{EI}, \tag{1}$$

where $k = k(s)$ – dependence of the curvature k of the elastic axis depends on the length of its arc s; $M(s)$ – dependence of the applied moment M to the beam from the arc length of its elastic axis; EI – stiffness of the beam, which is the product of the Young's modulus E at the moment of inertia I of the beam cross-section. In this case, the cross-section is constant along the entire length of the beam, hence the stiffness EI is also a constant value.

The second part was based on the position of differential geometry, which establishes a relationship between the natural equation of the elastic axis, that is, the dependence of its curvature on the arc length, and parametric equations. Deformation of a cantilevered rectilinear beam under the action of an applied force P is shown in Figure 3.

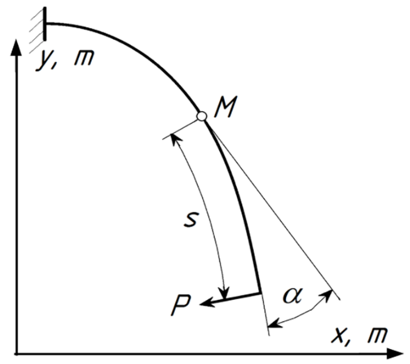

Figure 3. Graphic illustration for determining the curvature of the elastic axis of a beam at the current point
Note: under the action of the applied force P cantilevered rectilinear beam has acquired a curvilinear shape. P – applied force; M – current point on the elastic axis of the beam; s – length of the elastic axis from the point of application of the force to the current point; α – angle by which the elastic axis deviated, starting from the current point M, due to the action of force P
Source: compiled by the authors

By drawing a tangent at the current point M and at the point where the force P is applied, an angle α will be created between them. The value of this angle over the arc length interval s characterises the degree of deviation of the curve from the rectilinear shape, and their ratio is the average curvature. When moving to the boundary, the exact value of the curvature can be obtained at the current point:

$$k(s) = \frac{d\alpha}{ds}. \qquad (2)$$

Given (2), expression (1) can be rewritten as follows:

$$\frac{d\alpha}{ds} = \frac{M(s)}{EI}. \qquad (3)$$

If the dependency α=α**(s)** is known, which is found by integrating expression (3), then the parametric equations of the curve have the form of the following integrals:

$$x = \int \cos\alpha(s)\, ds; \; y = \int \sin\alpha(s)\, ds. \qquad (4)$$

Even for the simplest cases of rod bending, expressions (4) cannot be integrated and require the use of numerical methods. With the advent of computer technologies, it became possible not only to numerically integrate expressions, but also to visualise the results obtained, which for this case is the construction of curvilinear elastic axes when bending rods.

RESULTS AND DISCUSSION

First, it is advisable to consider the cantilevered rectilinear part of the tooth. Under the action of the applied force P, which can be the reaction of the soil, it will take on a curvilinear shape (Fig. 3). Moment of force M_1 is determined from the dependence:

$$M_1 = Ps_1, \qquad (5)$$

where s_1 – length of the elastic axis, which starts from the point of application of the force P.

After substituting (5) into (3) and integrating:

$$\alpha = \frac{Ps_1^2}{2EI}. \qquad (6)$$

Further substitution of expression (6) in (4) provides parametric equations of the elastic axis, for the construction of which it is necessary to apply numerical integration methods. Arc length s_1 changes from zero to the value of the length of the rectilinear part of the tooth.

The second part of the tooth is a cantilevered spring. In the free state, it has an initial constant curvature k_o, which is the inverse of the radius r_o of the circle, the spring axis. The same force P will be applied to it, which is called a tracking force because it remains perpendicular to the elastic axis when it is deformed. Moment of force M_2 can increase or decrease the curvature of the elastic axis of the spring depending on how the force P is directed – on "twisting" or "untwisting" the spring. With this in mind, it can be written as:

$$\frac{d\alpha}{ds} = k_0 \pm \frac{M_2(s_2)}{EI} = k_0 \pm \frac{Ps_2}{EI}, \qquad (7)$$

where s_2 – length of the elastic spring axis.

Equation (7) describes the shape of the elastic axis of a spring, provided that the force P is applied at the opposite end from fitting, that is, without considering the additional action from the rectilinear part of the tooth. This action is determined by the numerical value of the moment M_1, which can be found by equation (5). Therefore, the equation of the elastic axis of the curvilinear part of the tooth, considering the transfer of force from the rectilinear section, is written:

$$\frac{d\alpha}{ds} = k_0 \pm \frac{Ps_2 + M_1}{EI}. \qquad (8)$$

Under the transfer of force from a rectilinear section of the tooth, it should be understood that this section was such before the deformation. After the applied moment, it also becomes curvilinear. After integrating expression (8):

$$\alpha = k_0 s_2 \pm \frac{Ps_2^2 + 2M_1 s_2}{2EI}. \qquad (9)$$

Further application of equations (4) to construct the elastic spring axis after deformation requires numerical integration.

Firstly, it is necessary to consider the deformation of the rectilinear part of the tooth under the action of the applied force P. The length of its axis according to Figure 3 is $s_1 = 0.664$ *m*. The force $P = 200$ *N was assumed.* Equation (6) determines the angle α between tangents at the start and end points of the elastic axis: $\alpha = 0.11$ *rad* $= 6.3°$. The shape of the elastic axis can be found by numerically integrating equations (4) by substituting expression (6) in them and changing s_1 within $s_1 = 0 \ldots 0.664$. The integration result is shown in Figure 4a. It shows that with increasing distance s_1, the curvature of the axis increases as the moment M_1 increases.

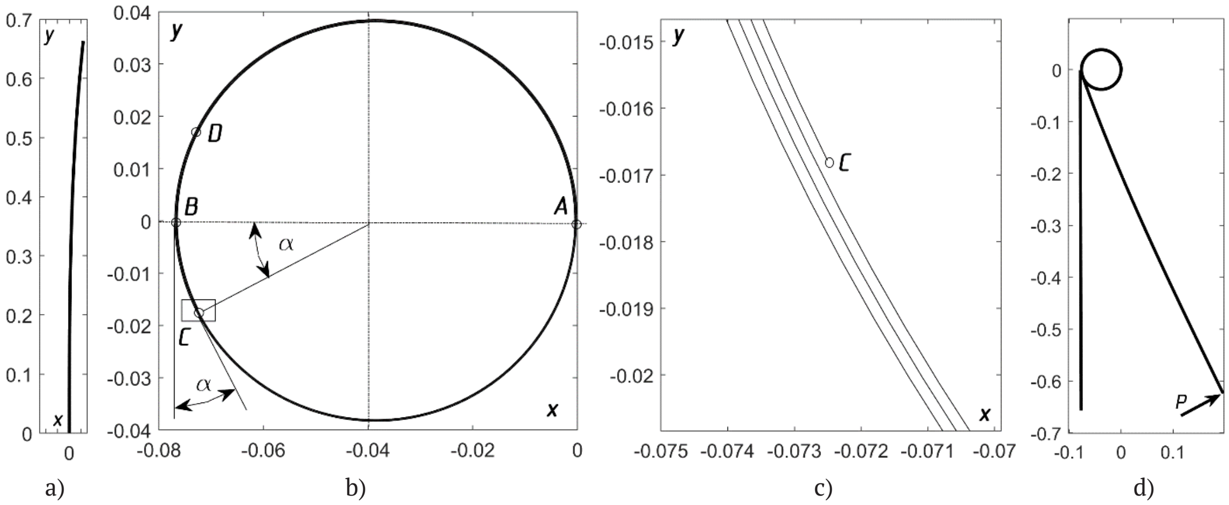

Figure 4. Graphic illustrations for finding the shape of the elastic axis of individual parts of the tooth and the tooth as a whole after the applied force of *P=200 N*

Note: a) elastic axis of the rectilinear section of the tooth after deformation; b) elastic axis of the curvilinear section of the tooth after deformation; c) enlarged fragment in the vicinity of the point *C*; d) elastic axis of the tooth

Source: developed by the authors based on research

The next step is to consider the deformation of the curvilinear part of the tooth in the form of a spring. The length of the elastic axis of 3.5 turns in the free state at $r_o = 0.039$ is $s_2 = 0.858$. The angle of rotation of the tangent corresponding to 3.5 turns is *22 rad*. After "twisting" the spring (i.e., with the "+" sign in equation (9), the new angle value is *22.45 rad*. The difference between these values: $\alpha = 0.45$ *rad* $= 25.8°$. After numerical integration of equations (4), after substituting the dependence (9) in them, it is possible to obtain the shape of the elastic axis of the spring after "twisting" due to the action of the applied force *P* (Fig. 4b). At first glance, it may seem that no changes have occurred. However, the twisting angle increased by α, that is, the free end of the spring has moved from point *B* to point *C*. Point *A* is the point of cantilever attachment of the spring to the harrow body. Figure 4b shows a repeatedly enlarged fragment that is located near point *C* highlighted with a rectangle. It shows that the elastic axis of the spring has turned from a circle into a spiral with a very high density of twists, which can be approximately determined from the scale of the enlarged fragment. To get an image of the elastic axis of the tooth as a whole after deformation by its force $P = 200$ *N*, it is necessary to combine the two parts shown in Figure 4a and 4b. This connection should occur at the top point of the first tooth element (Fig. 4a) with the second element (Fig. 4b) at the point *C* along the first order of smoothness, i.e., with a common tangent to both curves at this point. Based on known coordinates and angles α, this connection is shown in Figure 4d. It shows the spring tooth before and after deformation. From the obtained images, it can be concluded that the deviation of the tooth from its original position in the free state largely depends on the curvilinear part, that is, on the spring and the number of its turns. The total deviation for the given example in angular measurement is $25.8° + 6.3° = 32.1°$.

Reversing the direction of the force *P* to the opposite direction will not change the shape of the elastic axis of the straight part of the tooth, but will simply change its curvature to the opposite direction. In the curvilinear part, instead of "twisting", there will be "untwisting". Equation (9) with the "-" sign gives the value *21.55 rad.* The difference is $21.55 - 22 = -0.45$ *rad* $= -25.8°$. Thus, "twisting" and "under-twisting" occurs at the same angle. For the case of "under-twisting" in Figure 4b corresponds to the point *D*. In general, for both the first and second parts of the tooth, the law of angle growth α it is linear with different proportionality coefficients. The incremental angle α is denoted by α_1 for the rectilinear part of the tooth and by α_2 – for a curvilinear part:

$$\alpha_1 = \frac{s_1^2}{2EI} P; \;\; \alpha_2 = \pm \frac{s_2^2 + 2s_1 s_2}{2EI} P. \tag{10}$$

The graph of the angle α growth depending on the amount of applied force *P* is shown in Figure 5.

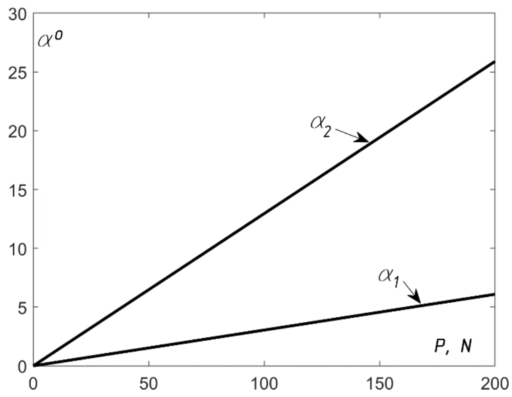

Figure 5. Graph of dependence of angle α on force P
Notes: for rectilinear (α_1) and curvilinear (α_2) areas of the tooth
Source: developed by the author based on research

From the graph in Figure 5 it can be seen that the intensity of angle growth α on a curvilinear section is several times higher than on a rectilinear one. From the second equation (10), it can be seen that its value largely depends on the length s_2 of the elastic axis of a curvilinear section, i.e., a spring. As its length decreases, the angle α_2 decreases. However, it is possible to reduce the stiffness proportionally by reducing the cross-sectional diameter of the tooth. This can achieve virtually the same effect, i.e., for a given force P, the angle α_2 will remain the same. As the stiffness decreases, the angle α_1 will increase according to the first equation (10). It is necessary to reduce the length of the spring by one twist. Then its length will be $s_2=0.61\ m$. Next, substitute the expression of the moment of inertia in the second equation (10) $I=\pi r^4/4$ and solve it with respect to r:

$$r = \sqrt[4]{\frac{2Ps_2(2s_1+s_2)}{\pi\alpha_2 E}}. \tag{11}$$

All previous values of the values included in expression (11) must be taken into account, and the new value $s_2=0.61\ m$. After substituting in (11) and calculating, it is possible to obtain: $r=0.0062\ m$. Instead of the previous wire diameter *14 mm* to make a tooth, it requires *12.4 mm*. Next, the first equation (10) determines the value of the angle α_1 with a new stiffness value: $\alpha_1=9.9°$. Thus, the deformation of the rectilinear part of the tooth increased slightly – increased from $\alpha_1=6.3°$ to $\alpha_1=9.9°$.

In the future, the elastic axis calculations were performed according to the previous algorithm for new values $s_2=0.61\ m$ and $EI=255.3\ N\cdot m^2$. Figure 6 shows the same images as in Figure 4, but with the new data, i.e., the tooth diameter is *12.4 mm* and the spring has 2.5 twists instead of 3.5. For clarity, an image of the tooth and its elements with preliminary data is shown next to dashed lines. In both cases, the applied force is the same: $P=200\ N$. The figures show that the differences between the shape of the tooth for the first and second cases are not significant. Figure 6c shows that with fewer twists, the distance between them increases, and the diameter of the shaft on which they should be fitted should be smaller. However, this difference can be seen under multiple magnifications. However, this must be considered, because the lack of clearance between the shaft and the spring in the free state will cause the spring to not work on twisting.

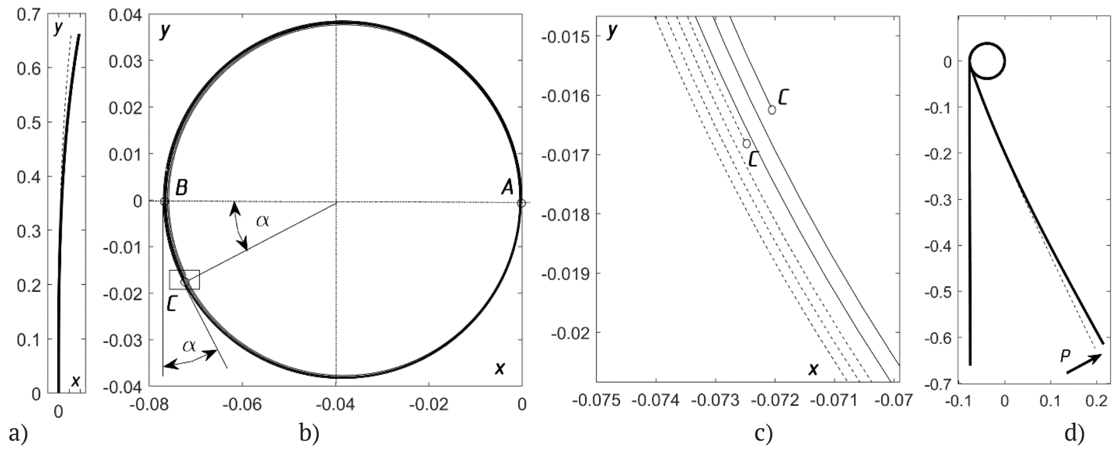

Figure 6. Comparative images of elastic axes of two tooth variants after applied force $P=200\ N$
Notes: a) elastic axis of the rectilinear section of the tooth after deformation; b) elastic axis of the curvilinear section of the tooth after deformation; c) enlarged fragment in the vicinity of the point C, highlighted by a rectangle; d) elastic axis of the tooth
Source: developed by the author based on research

This study showed that with a slight decrease in the length of the curvilinear part (spring) and a corresponding decrease in the thickness of the tooth, it is possible to achieve almost the same power characteristics of the tooth, namely, the amount of movement of its free end under the action of a given force. In this case, the curvature of the elastic axis of the rectilinear section of the tooth is insignificant. This reduces the consumption of material for its manufacture and the weight of the finished product.

The studies by L. Babitskiy *et al.* (2020) and Ch. Li *et al.* (2021) are devoted to the investigation of the process of wear of the blades of cultivator tine blades under various types of strengthening and their influence on changes in the traction resistance of a tillage unit. The papers present dependences for predicting changes in the thickness of cutting edges reinforced with various options, on the linear wear of the blade in width and angle of its sharpening. Increasing the wear resistance of the working bodies can also be implemented by using the latest structural materials (Antoszewski *et al.*, 2017) and methods of surface nanostructuring of working surfaces (Gaponova *et al.*, 2019; Martsynkovskyy *et al.*, 2020).

B. Antoszewski *et al.* (2017) investigated the use of a UV laser with picosecond pulses to create microstructures on the surface of elastomeric plastics, which opens up new prospects in the field of material modification. This approach allows creating precise and detailed microstructures that can be used to improve the adhesion, hydrophobicity, antibacterial properties, and other characteristics of materials. The use of picosecond pulses reduces the thermal effect on the material, which ensures accuracy and control in the formation of microstructures, and also reduces the risk of deformation or damage to elastomeric plastics.

V. Martsynkovskyy *et al.* (2020) developed technological solutions to protect the contact surfaces of the coupling from fretting wear, which opens up opportunities to ensure long-term and reliable operation of mechanical connections. These technological innovations aim to prevent or minimise the impact of fretting wear on contact surfaces by applying appropriate coatings, surface treatment, or the use of special materials. This allows increasing the efficiency and service life of mechanical connections and reducing the cost of their maintenance and repair. O. Gaponova *et al.* (2019) evaluated the quality parameters of an aluminised coating produced by the electric spark alloying method, which is an important stage in the research and production process. This method allows influencing the properties of the material by injecting aluminium into the surface of the part by spark discharge. Evaluation of the quality of an aluminised coating includes analysis of parameters such as coating thickness, structure, adhesion to the substrate, microhardness, and other characteristics. Using this method improves the quality and functionality of products with an aluminised coating and ensures high quality of production.

The problem of determining deflections of beams under the action of an applied force is common in construction mechanics. However, there the deflections in comparison with the length of the beams are insignificant, that is, the curvature of the elastic axis of the beam is close to zero, that is, to a straight line. The expression of the curvature of the axis includes the first and second derivatives of its equations. Due to the fact that the deflections of the beams are small, respectively, the curvature of the axis is small, in the construction industry it is customary to neglect the second derivative, since it does not matter significantly. The problem of determining deflections is greatly simplified, that is, there is a transition from the theory of nonlinear bending to linear. If this simplification gives practical results for small deflections, then this approach is not acceptable for large deflections.

In the case of significant deflections of the rods, a nonlinear bending theory is applied. The simplest case of bending a cantilevered rod occurs when it has a rectilinear elastic axis in the free state. The study by V. Khopost & I. Demchuk (2023) considered the bending of the rod, which is the riser of a cultivator tine. The curvature of its elastic axis in the free state is constant, that is, the riser of the cultivator tine is outlined in an arc of a circle. A force is applied to the attachment point of the tine, the moment from which "spins" the riser, that is, reduces its curvature. If the initial curvature value is equated to zero, then the dependences obtained in this study describe the bending of a rectilinear rod. What is common to the current study is that the applied force changes during operation, since the working elements in the form of elastic elements interact with the soil environment, which resists variable values.

An important practical task is to determine the vibrations of elastic rods of considerable length in deep drilling structures. In them, the role of elastic rods is played by drill columns, the length of which can reach tens of meters, as noted by O. Vlasiy *et al.* (2017), M. Vasilenko *et al.* (2021). The researchers suggest that optimising the shape and size of the protective ring, which increases its thickness, is important for improving the stability of aluminium drill pipes. This optimisation is aimed at reducing the risk of damage and wear to pipes during drilling. By improving the design of the protective ring, it is possible to provide more effective protection of pipes from external influences such as friction, shock, and other mechanical loads. This approach helps to increase the service life of drill pipes and reduce the cost of their maintenance and replacement. For example, T. Wang & J. Ye (2023) consider the oscillation of a rod with a length of 100 metres. In this case, the solution to the problem is reduced to finding the functions that most accurately describe the shape of the bend line. Such a function can be polynomial. The study notes that for rods of small length, a full-scale function of the 6^{th} order can be used. However, for rods of considerable length, this function can give a significant error. Therefore, in such cases, the bend line should be considered as a spline divided into several spline functions.

An analytical description of the problem of nonlinear rod bending is given in the paper by Q. Wang *et al.* (2021). The description is based on the dependence of the curvature of the elastic axis on the applied moment and stiffness, i.e., equation (1). However, if in the current study the arc length of the elastic axis, which is natural, is taken as an independent variable, then in this paper such a variable is the coordinate "x". Accordingly, the curvature of the elastic axis is determined by the well-known equation, if the axis is defined by the dependence $y = y(x)$. Further transformations lead to a single parametric form and are expressed in terms of Jacobi elliptic functions. This approach is cumbersome and complex. The study considers three cases of rod loading: 1) bending of the rod occurs as a result of the action of a constant force in the direction, when its vector moves parallel to itself during deformation of the elastic axis; 2) bending of the rod occurs by a tracking force. In this case, the force vector retains a constant angle to the tangent of the elastic axis at the point of its application. In a special case, this angle can be a straight line. As for the conducted studies, the calculations consider the tracking force, which is perpendicular to the elastic axis at the point of its application. In general, an elastic tooth is affected by the resistance force of the soil medium, which can be decomposed into two components: perpendicular to the tooth axis and tangent to it. The ratio of these forces is of no interest, since the purpose of this study is to establish an analytical description of the deformation of a spring tooth depending on the magnitude of the applied force, which has certain limits; 3) the general case of bending is considered, when the force vector changes its direction according to a certain law, i.e., it does not follow the rotation of the elastic axis of the rod.

Characteristic of these papers is that the curvature of the rod, which can be constant or variable, is described by one equation. A characteristic difference of this study is that the elastic axis of the existing spring tooth shape cannot be described by one equation, since there is a point at which the curvature changes abruptly from zero to a certain constant value. This point is the transition from a rectilinear shape of an elastic tooth to a curvilinear one in the form of a spring. To solve such a problem, which is fundamentally different from the ones considered, it was proposed to conditionally divide the elastic axis of the tooth into two parts: curvilinear and rectilinear. When considering the deformation of a rectilinear part, it was assumed that the point of cantilever fitting is the point of interface with the curvilinear part. The expression of the change in angle α (Fig. 3) was found according to equation (6). Numerical integration of parametric equations (4) revealed a curvilinear elastic tooth axis that was rectilinear before the action of the force.

When considering the deformation of the curvilinear part of an elastic tooth, the point of cantilever attachment is the place where the tooth is attached to the unit frame. The initial curvature of the elastic axis is constant, and with this in mind, the change in the angle α was calculated using equation (9). A special feature of this equation is that, firstly, it considers the deformation of the elastic axis during "twisting" – the "+" sign, or when "untwisting" – the "-" sign. Secondly, the transfer of force from the area of the tooth that is in contact with the soil is considered. If for some reason the ground resistance force is zero, this part of the tooth becomes rectilinear and does not transmit any force to the curvilinear section of the tooth. The final stage is the connection of two sections of the tooth after deformation into a single whole along the common tangent at the point of their interface.

CONCLUSIONS

To solve the problem of mathematical description, the tooth was conventionally divided into two sections: rectilinear and curvilinear in the form of a spring. These two sections were considered separately. For this purpose, the well-known statement of the theory of material resistance on the dependence of the curvature of the elastic axis on the applied moment was applied. First, the deformation of the rectilinear section of the tooth was determined, and then the curvilinear one. However, the effect of the first section on the second was considered, since they are rigidly connected to each other, that is, they form a single whole. For both sections, it was necessary to apply numerical integration methods to find the shape of the elastic axis after their deformation. After that, both sections of the elastic axis were connected into a single whole. This approach provided an idea of the deviation of the tooth from its original position under the action of an applied force to its free end.

The proposed approach allows modifying the spring tooth, while maintaining its functionality. In particular, a variant is considered when the tooth diameter can be reduced and at the same time the length of its curvilinear section can be reduced, provided that the deviation value of its free end is commensurate with the unmodified version under the action of the same force. At the same time, it is necessary to consider the side effect, which is that the curvature of both parts of the tooth increases. This growth is characterised by the value of the angle between the tangents at the initial and final points of the elastic axis of the tooth. In the course of the study, it was found that the growth rate of this angle is much higher for the curvilinear section of the tooth. In practice, this means that the rectilinear area of the tooth has little effect on its deviation from its original position. The determining value of this deviation is the deformation of the curvilinear section of the tooth in the form of a spring. This leads to a smooth reduction in the radius of the elastic axis of the spring, which must be considered to ensure the necessary clearance between the spring and the shaft on which it is attached. If the tooth works to "untwist" the spring, that is, the applied force is directed in the opposite direction, there is a smooth increase in the radius of the elastic axis of the spring and the size of the gap or its absence does not matter.

Future studies should open up opportunities for developing new technological solutions in the field of agricultural machinery aimed at improving productivity, reducing wear, and improving consistency with other machine elements.

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None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Aikins, K., Ucgul, M., Barr, J., Awuah, E., Antille, D., Jensen, T., & Desbiolles, J. (2023). Review of discrete element method simulations of soil tillage and furrow opening. *Agriculture*, 13(3), article number 541. doi: 10.3390/agriculture13030541.

[2] Antoszewski, B., Tofil, S., Scendo, M., & Tarelnik, W. (2017). Utilization of the UV laser with picosecond pulses for the formation of surface microstructures on elastomeric plastics. *IOP Conference Series: Materials Science and Engineering*, 233, article number 012036. doi: 10.1088/1757-899X/233/1/012036.

[3] Babitskiy, L., Moskalevich, V., & Belov, A. (2020). Results of research of working bodies with increased reliability of tillage and sowing machines. *E3S Web of Conferences,* 193, article number 01042. doi: 10.1051/e3sconf/202019301042.

[4] Bulgakov, V., Ivanovs, S., Bandura, V., & Ihnatiev, Ye. (2018). Experimental investigation of harrow with spring teeth for cultivation of sugar beets. In *17th International scientific conference engineering for rural development* (pp. 215-220). Jelgava, Latvia. doi: 10.22616/ERDev2018.17.N259.

[5] Cao, S., Xie, J., Wang, H., Yang, Yu., Zhang, Ya., Zhou, J., & Wu, Sh. (2022). Design and operating parameters optimization of the hook-and-tooth chain rail type residual film picking device. *Agriculture*, 12(10), article number 1717. doi: 10.3390/agriculture12101717.

[6] Gaponova, O., Kundera, Cz., Kirik, G., Tarelnyk, V., Tarelnyk, V., Martsynkovskyy, V., Konoplianchenko, Ie., Dovzhyk, M., Belous, A., & Vasilenko, O. (2019). Estimating qualitative parameters of aluminized coating obtained by electric spark alloying method. In A.D. Pogrebnjak & V. Novosad (Eds.), *Advances in thin films, nanostructured materials, and coatings. Lecture notes in mechanical engineering* (pp. 249-266). Singapore: Springer. doi: 10.1007/978-981-13-6133-3_25.

[7] Khopost, V., & Demchuk, I. (2023). Elastic bending of a curved strip with a given initial curvature of its elastic axis. *Applied Geometry and Engineering Graphics*, 104, 183-189. doi: 10.32347/0131-579x.2023.104.183-189.

[8] Li, Ch., Cao, H., Han M., Qin, P., & Liu, X. (2021). Analytical method for geometric nonlinear problems based on offshore derricks. *Mathematics*, 9(6), article number 610. doi: 10.3390/math9060610.

[9] Lidius. (n.d.). Retrieved from http://lidius.com.ua/index.php?route=product/product&path=60_67_123_134&product_id=1022.

[10] Martsynkovskyy, V., Tarelnyk, V., Konoplianchenko, Ie., Konoplianchenko, I., Gaponova, O., & Dumanchuk, M. (2020). Technology support for protecting contacting surfaces of half-coupling –shaft press joints against fretting wear. In V. Ivanov (Eds.), *Advances in design, simulation and manufacturing II* (pp. 216-225). Cham: Springer. doi: 10.1007/978-3-030-22365-6_22.

[11] Mudarisov, S., Gabitov, I., Lobachevsky, Y., Mazitov, N., Rakhimov, R., Khamaletdinov, R., Rakhimov, I., Farkhutdinov, I., Mukhametdinov, A., & Gareev, R. (2019). Modeling the technological process of tillage. *Soil and Tillage Research*, 190, 70-77. doi: 10.1016/j.still.2018.12.004.

[12] Pylypaka, S., Volina, T., Hropost, V., Babka, V., & Hryshchenko, I. (2023). Determination of the form of a spiral spring in a free state. *ScienceRise*, 3, 3-9. doi: 10.21303/2313-8416.2023.003213.

[13] Pylypaka, S., Zaharova, T., Zalevska, O., Kozlov, D., & Podliniaieva, O. (2020). Determination of the effort for flexible strip pushing on the surface of a horizontal cylinder. In *Advanced manufacturing processes* (pp. 582-590). Cham: Springer. doi: 10.1007/978-3-030-40724-7_59.

[14] Rogovskii, I., Titova, L., Trokhaniak, V., Haponenko, O., Ohiienko, M., & Kulik, V. (2020). Engineering management of tillage equipment with concave disk spring shanks. *Inmateh – Agricultural Engineering*, 60(1), 45-52. doi: 10.35633/inmateh-60-05.

[15] Semenenko, L., Tarasov, O., Vasylenko, S., Cherep, V., & Polishchuk, V. (2021). Mathematical models for assessing the reliability of agricultural machinery, taking into account the influence of military factors in the front-line territory. *Scientific Horizons*, 24(9), 55-62. doi: 10.48077/scihor.24(9).2021.55-62.

[16] Sheng, H., Zhang, Ch., & Xiang, Yu. (2022). Mathematical modeling and stability analysis of tiltrotor aircraft. *Drones*, 6(4), article number 92. doi: 10.3390/drones6040092.

[17] Tulaganova, L., Yunushuzhaev, S., & Juraeva, G. (2022). Improving the wear resistance and durability of cultivator tools. *Journal of Physics: Conference Series,* 2373, article number 022026. doi: 10.1088/1742-6596/2373/2/022026.

[18] Vasilenko, M., Rogovskii, I., Voinash, S., & Maksimovich, K., Sokolova, V.A., Garbuzova, T.G., Meshcheryakov, S.A., & Ariko, S.Ye. (2021). Research of weight and linear wear from resource indicators of cultivator paws hardened by combined method. *IOP Conference Series Earth and Environmental Science*, 677(3), article number 032025. doi: 10.1088/1755-1315/677/3/032025.

[19] Vlasiy, O., Mazurenko, V., Ropyak, L., & Rogal, O. (2017). Improving the aluminum drill pipes stability by optimizing the shape of protector thickening. *Eastern-European Journal of Enterprise Technologies*, 1/7(85), 25-31. doi: 10.15587/1729-4061.2017.65718.

[20] Wang, Q., Bai, Z., Li, Zh., Xie, D., Chen, L., & Wang, H. (2021). Straw/Spring teeth interaction analysis of baler picker in smart agriculture via an ADAMS-DEM coupled simulation method. *Machines*, 9(11), article number 296. doi: 10.3390/machines9110296.

[21] Wang, T., & Ye, J. (2023). Numerical analysis of bending property of bi-modulus materials and a new method for measurement of tensile elastic modulus. *Journal of Rock Mechanics and Geotechnical Engineering*, 15(10), 2539-2555. doi: 10.1016/j.jrmge.2023.03.003.

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Дослідження деформації пружинного зуба сільськогосподарських знарядь від дії прикладеної до нього сили

Анотація. Актуальність дослідження полягає в необхідності вивчення залежності сили, яку застосовують до пружинного зуба, від його параметрів, що є важливою задачею у зв'язку з широким застосуванням пружинних зубів у сільськогосподарських машинах, таких як прес-підбирачі, жатки, граблі та інші. Метою роботи є встановлення аналітичного опису деформації пружинного зуба в залежності від величини прикладеної сили. Для цього було застосовано теорію згину стержнів із опору матеріалів, при цьому вона не спрощується, як це прийнято в будівельній справі, де прогин балки в порівнянні з її довжиною є величина мала. За основу розрахунку взято відому залежність кривини пружної осі бруса (зуба) від прикладеного моменту і жорсткості його поперечного перерізу. В статті розглянуто консольно защемлений зуб, який в точці защемлення представляє собою пружину з декількома витками з подальшим плавним переходом до прямолінійної форми. Зуб по довжині розбивається на дві частини: криволінійну і прямолінійну. Розрахунок деформації, тобто знаходження форми пружної осі після дії прикладеної сили здійснюється для обох частин окремо. Необхідність у такому підході продиктована тим, що кривина пружної осі зуба у вільному стані змінюється стрибкоподібно від сталого значення криволінійної частини до нульового значення прямолінійної частини. Основним результатом дослідження є знаходження форми пружної осі окремих частин зуба під дією прикладеної сили та їх об'єднання в одне ціле. Це дає можливість визначити величину переміщення вільного кінця зуба в залежності від величини прикладеної до нього сили. Застосування отриманих даних може допомогти в розробці більш ефективних та продуктивних сільськогосподарських інструментів, а також підвищити їхню довговічність та ефективність при взаємодії з ґрунтом

Ключові слова: кривина; пружна вісь; прикладена сила; момент

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Integration of advanced technologies to improve the efficiency of gas condensate field development

Abstract. In the context of constantly growing global energy demand and rapid changes in the energy sector, the study and implementation of advanced technologies in the development of gas condensate fields is of critical importance. The purpose of this study is to investigate methods to increase the efficiency of production and sustainable use of energy resources by optimising the development of gas condensate fields using advanced technologies. The methods used include analytical method, classification, functional method, statistical method, synthesis. Within the framework of this study, the technological aspects of using wells of the Altyguyi gas condensate field were investigated and extensive laboratory and field analyses were conducted aimed at the correct implementation of the double injection method for simultaneous extraction of gas from one reservoir and oil from another, with an emphasis on their contribution to the development of wells through this approach. The paper also considers aspects of operation and technology, including hydrodynamic and thermohydrodynamic studies, when analysing well designs considering compatibility intervals and mining and geological drilling conditions, based on predictive curves of reservoir pressure and rock fracture pressure. As a result of the analyses, studies and calculations, the implementation of the method of intensification of gas condensate field production using the oil and gas approach of dual injection in one well was substantiated. This approach is focused on reducing capital investments and accelerating the development process. The practical significance of this research lies in the development and implementation of innovative technologies to optimise the production processes of gas condensate fields, which contributes to improving the efficiency of hydrocarbon production and promotes the sustainable use of energy resources

Keywords: sustainable use; optimisation of processes; double injection; prognostic curves; production intensification

INTRODUCTION

The study of technologies for the development of gas condensate fields and their optimisation through the integration of advanced methods is an integral aspect in the context of dynamic changes in the energy sector and the ever-growing global demand for energy. Efficient use of gas condensate resources is becoming a key element for ensuring energy sustainability and promoting sustainable development. Approaches such as double injection, hydrodynamic research, and the integration of innovative technologies not only contribute to improving production efficiency, but also reduce capital investment and accelerate the development process, which is critically important in the context of the current challenges of the energy industry and rapid changes in the global energy paradigm.

The research focuses on identifying and solving complex technological and organisational issues related to the development of gas condensate fields. These difficulties include not only technical aspects, such as optimising the processes of extraction, processing, and transportation of gas condensate, but also organisational issues related to project management, interaction with stakeholders, and ensuring compliance with regulatory requirements and environmental standards. Solving these problems requires an integrated approach that includes both scientific research

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and practical expertise, and consideration of economic and social factors.

A. Deryaev (2023a) considers in detail the effectiveness of the double injection method in gas condensate fields, analysing its pros and cons in detail and offering recommendations for optimising its application. The study does not address alternative methods for optimising the production processes of gas condensate fields, which may limit the understanding of possible effective strategies. V.G. Golubev *et al.* (2020) consider the technological aspects of wells using the example of a gas condensate field, paying attention to the influence of mining and geological conditions on the choice of well designs. However, due attention is not paid to the diversity of geological conditions, which may reduce the generality of the results obtained.

A study conducted by B.R. Pulatov (2021) emphasises the hydrodynamic and thermohydrodynamic aspects of the exploration of gas condensate fields, substantiating their importance for determining optimal solutions in the development process. The study does not consider thermohydrodynamic aspects sufficiently, which may be key in adapting technologies to various thermal conditions of deposits. R. Al Dhaif *et al.* (2022) argue that forecasting of surface oil flows in unstable oil and gas condensate reservoirs using artificial intelligence methods is an advanced approach with significant potential in the modern oil and gas industry. This method is based on the use of artificial intelligence algorithms such as machine learning and neural networks to analyse complex and multidimensional data related to oil and gas fields. One of the advantages of using artificial intelligence methods in forecasting of oil flow rates is their ability to identify complex relationships between various parameters and factors affecting production. This includes not only the geological and physico-chemical characteristics of deposits, but also dynamic changes in production conditions (Kondrat & Matiishyn, 2023).

The purpose of this study is to explore the possibilities of increasing the efficiency of production and sustainable use of energy resources through optimising the development of gas condensate fields using advanced technologies.

MATERIALS AND METHODS

In the study conducted on the territory of the western region of Turkmenistan, the main attention was paid to two deposits: Altyguyi and Korpedje. Data from several wells in each of these fields were analysed. During the study, information was collected on the geological characteristics of deposits, gas composition, and data on temperature and pressure in wells. These data were used to assess potential gas condensate reserves at the sites under consideration.

The analytical method helped in a detailed review of the existing production parameters of gas condensate fields, which helped to identify key factors affecting the efficiency of development processes. This method contributed to the development of optimisation strategies and became the basis for making informed decisions on the introduction of advanced technologies aimed at increasing the efficiency and sustainability of the use of energy resources. Comprehensive data studies were carried out using the statistical method, which identified trends and patterns in the production of gas condensate fields. These statistical patterns helped to assess the current efficiency of processes and predict possible development scenarios, which significantly enriched the knowledge base and provided the basis for developing strategies to improve the extraction and sustainable use of energy resources.

Using the functional method, the main functions and parameters affecting the efficiency of the development of gas condensate fields were identified. This method helped to systematise mining processes and identify optimal strategies for the introduction of advanced technologies. The results obtained using the functional method provided the basis for the development of innovative solutions aimed at optimising processes and increasing the sustainability of the use of energy resources in the context of gas condensate fields.

The deduction method helped in the systematic identification of general patterns and principles underlying the efficient production of gas condensate fields. This method helped formulate the fundamental principles of optimising development processes by logically establishing causal relationships. Employing the deduction method yielded a deeper understanding of the key factors impacting production efficiency and facilitated the development of strategies promoting the sustainable use of energy resources in gas condensate production.

By applying the synthesis method, various aspects of the development of gas condensate fields were combined into a single whole. This method provided a comprehensive view of the relationship between technological, environmental, and economic factors in the mining process. The results of the synthesis revealed optimal solutions that ensure not only increased efficiency, but also compliance with the principles of sustainable use of energy resources in the development of gas condensate fields.

The classification method helped in the systematisation and grouping of various factors affecting the development of gas condensate fields. This method identified key categories and parameters, which made it easier to assess the importance of each element in the context of optimisation. The results of the classification method provided the basis for developing individual strategies for the introduction of advanced technologies, depending on the specifics of each group of factors, thereby contributing to increasing the efficiency and sustainability of the use of energy resources in the development of gas condensate fields.

Using the induction method, general patterns were derived based on observations and specific cases of the development of gas condensate fields. This method allowed identifying the main trends and successful practices that can be applied in a broad context. The insights gained through the induction method pave the way for the development of general guidelines for optimizing gas condensate field development, incorporating advanced technologies. As such, this method plays a crucial role in establishing overarching strategies to improve efficiency and sustainability in the use of energy resources during gas condensate production.

The following equation was used in the study (1-5):

$$T_{sep} = T_{ent.} - \Delta T_{thr.} - \Delta T_{TO}, \quad (1)$$

where $T_{ent.}$ – gas temperature at the inlet to the gas processing point (GPP); $\Delta T_{thr.}$ – throttle temperature drop due to the Joule Thompson effect; ΔT_{TO} – gas temperature drop in the heat exchanger.

$$\Delta T_{thr.} = \frac{\Delta P_{thr.}}{\varepsilon}, \quad (2)$$

where $\Delta P_{thr.}$ – throttle pressure drop (MPa) and Joule-Thompson coefficient (ε): $\varepsilon = 0.27$ MPa/°C (assumed based on throttling conditions).

$$\Delta T_{thr.} = 2\Delta T_{thr.}, \quad (3)$$

$$P_{ent.cr.} = P_{req.} + P_{thr.}, \quad (4)$$

where $P_{req.}$ – outlet pressure of the gas processing plant (GPP).

$$P_{req} = P_{ter.} + \Delta P_{g.p.}, \quad (5)$$

where $P_{ter.}$ – final pressure allowed under gas supply conditions, equivalent to 5.6 MPa.

The key benefit of these calculations lies in their ability to illuminate the impact of various factors on gas condensate field development processes.

RESULTS

A full range of studies and systematic measurements are carried out at the gas condensate fields of Turkmenistan. These activities are designed to complement the main complex of hydrodynamic and field geophysical studies and measurements. They have received the approval of the relevant authorities and strictly comply with the requirements set out in the approved project document for the development of the field. This complex of studies and measurements covers various important aspects, including the rapid detection of wells that may be sources of underground leaks and interplastic flows. Implementing such a comprehensive approach is vital for achieving the sustainable and safe development of these gas condensate fields.

Table 1 comprehensively details the operational and technical specifications of Altyguyi's productive oil wells. It is noteworthy that the flow rates of 24 fountain wells in the field range from 82 to 6 tonnes per day, the watercut varies from 1% to 30%. It is worth emphasising that the watercut in three of these wells (designated as wells 7, 16, and 18) is 73%, 71%, and 77%, respectively. The gas factor for these wells ranges from 205 to 1129 m^3 per tonne, and the solidification temperature of the oil ranges from 36 to 37°C. These detailed characteristics provide valuable information about the operational characteristics and composition of productive wells of the Altyguyi field, which are necessary for effective field management and production optimisation.

Table 1. Key operational and technical details of Altyguyi's high-performing wells

No. of well	Work method	Horizon	Borehole, m	Fitting diameter, mm	Gas supply depth, m	Note
21	fountain	PC-8	4007	5	2200	
3	fountain/gas lift	PC-9	3757	4		
4	fountain	PC-9	3770	8		
7	fountain	PC-9	3758	5		
10	fountain	PC-9	3674	6		
11	fountain	PC-9	3868	6		
12	fountain	PC-9	3740	8		
16	fountain/gas lift	PC-9	3875	5		Punch 2000 m
17	fountain	PC-9	3860	8		
18	fountain	PC-9	3905	4		
19	fountain	PC-9	3910	8		
24	fountain	PC-9	3751	8		
51	fountain/gas lift	PC-9	3685	5		Punch 2000 m
52	gas lift	PC-9	3685	6	2200	Punch 2000 m
102	fountain	PC-9	3727	6		
104	fountain	PC-9	3760	4		
105	fountain	PC-9	3860	8		
106	fountain	PC-9	3810	5		
107	fountain	PC-9	3885	5		
108	fountain	PC-9	3829	6		
110	fountain	PC-9	3820	4		

Continued Table 1.

No. of well	Work method	Horizon	Borehole, m	Fitting diameter, mm	Gas supply depth, m	Note
111	fountain	PC-9	3880	8		
112	fountain	PC-9	3771	4		
113	fountain	PC-9	3705	8		
114	fountain	PC-9	3700	6		

Note: PC – pumping and compressor equipment
Source: developed by the author based on A.R. Deryaev (2023b)

In 2011, two wells numbered 3 and 51 underwent significant changes in operation as a result of switching to gas lift mode. However, in 2014, these wells were switched to semi-spontaneous operation, which led to the termination of the supply of working agent. As a result, these wells are now operating in fountain mode (Deryaev, 2023c). During the use of the gas lift method, a number of notable transformations have occurred, marking a dynamic evolution over time. A gradual decline in annular pressure caused gas to come out of the oil, while the amount of dissolved gas in the extracted products simultaneously increased. These developments necessitated a shift from gas lift to fountain operation in the wells (Sahu *et al.*, 2021).

Due to the decrease in reservoir pressure in productive formations, it becomes necessary to carry out measures to restore gas supply, which necessitates a return to the gas lift method of operation. This adaptive strategy is of paramount importance to ensure the sustainable efficiency and productivity of these wells. Due to the flexibility of operational methodologies, the goal is to optimise the production process in direct response to fluid and changing conditions within the reservoir. This adaptive approach serves as a strategic imperative, ensuring that mining operations remain finely tuned and aligned with the ever-changing dynamics of the reservoir, which ultimately supports the overall efficiency of the mining process. The field currently boasts 52 operational wells. In line with the field's meticulous development plan, a comprehensive evaluation is being conducted to determine if all existing naturally flowing wells can be converted to gas lift operation. This potential change is being meticulously evaluated with the primary objective of boosting industry-wide productivity and efficiency (Syed *et al.*, 2022). Such a step will not only increase operational efficiency, but will also meet the changing needs and requirements of the field's development strategy.

Table 2 provides a detailed overview of proposed strategies for the systematic transition to gas lift operation in the field's existing flowing wells. The subtleties of this gas lift method are revealed as a well-thought-out operational paradigm strategically focused on improving the efficiency of production at the Altyguyi field. In this innovative gas lift method, a decisive shift in operation occurs in the depth range of 2000-2200 m. Here, a carefully selected working agent, often in the form of a heated gas, becomes a catalyst for improving extraction dynamics. The introduction of this agent is carefully controlled using specialised gas lift valves temporarily installed on the drilling site with precision (Giglio *et al.*, 2021). This thoughtful operational plan is not just a procedural adjustment, but represents a fundamental aspect of a comprehensive field development strategy. A special infrastructure has been carefully created to ensure the smooth execution of gas lift operations at the field. This infrastructure is designed in such a way as to ensure uninterrupted and efficient gas supply to gas lift wells. The gas supplied at an operating pressure of 70 to 85 kgf/cm^2 passes through specialised gas compressor lines to reach its destination. It is important to note that each well within the framework of gas lift operation requires an average gas consumption of about 15 thousand m^3/day. This infrastructure is not just a logistical basis; it is an integral component that ensures the viability and sustainability of the gas lift method throughout the field. The significance of this operational transition goes beyond just improving efficiency. This is a strategic step that meets the changing requirements of field management, optimising production volumes while maintaining environmental considerations. The careful implementation of the gas lift method, combined with a reliable infrastructure supporting its implementation, is evidence of the field's commitment to advanced technologies and best practices in the field of oil production (Borj *et al.*, 2024). As the industry continues to evolve, these strategic operational shifts highlight the adaptive nature of resource management, ensuring that the Altyguyi field remains at the forefront of efficient and sustainable energy production.

Table 2. Proposed option for conversion of flowing wells at the Altyguyi field to gas lift operation mode

Indicators	Unit of measurement	2022	2023	2024	2025	2026	2027
Oil production	thousand tonnes						
Liquid extraction	thousand tonnes						
Gas related resources	million m^3						
Conversion of wells to gas lift method	well		5	6	7		

Continued Table 2.

Indicators	Unit of measurement	2022	2023	2024	2025	2026	2027
Fund of gas lift wells that will be put into operation by the end of the year	well	1	6	12	19	19	19
Average oil flow rate of operating wells	t/day						
Liquid	t/day						
Water restriction	%						
Gas resource required for the gas lift	million m^3	1.9	5.9	30.2	32.3	43.1	41.7

Source: developed by the author based on A.R. Deryaev (2023b)

The ideal flow rate is crucial for the most efficient operation of the gas lift system, which requires a reduction in specific consumption. For optimal flow rate, the gas lift needs to be submerged as deeply as possible below the dynamic fluid level. Ideally, the lift's length should closely match the well's depth. In scenarios where maximum flow rate is required while minimising specific flow, a relative immersion value of $\xi = 0.5$ is ideal. For optimal efficiency, a relative maximum flow rate of $\xi = 0.6$ is employed (Rodrigues *et al.*, 2021). Efficiently operated gas lift wells need careful optimisation using proven techniques. Based on calculations, gas lift wells where the gas is injected at a depth between 2300 and 2500 meters, specific operating pressures $P_{work} = 6.4$, 7.4, and 8.4 MPa are considered feasible. For wells with gas receivers at depths from 3000 to 3500 m, the standard operating pressures range from 10 to 12 MPa. Gas condensate fields benefit significantly from the implementation of closed-cycle compressor gas lift systems (Wang *et al.*, 2022). To effectively support gas lift operations and guarantee export-quality gas delivery to the pipeline, this system necessitates the incorporation of advanced gas treatment technologies. Such an integrated approach not only improves operational efficiency, but also meets environmental and safety standards, contributing to the overall success of the gas condensate field development.

The Altyguyi field's wellhead infrastructure for product collection and processing is seamlessly integrated with the adjacent Korpedje field's systems. This compatibility allows for a unified and standardized approach to handling products from both regions, leading to improved operational efficiency and enhanced resource utilization. Figure 1 illustrates the Altyguyi field's gas condensate collection and processing technology. The collected gas and condensate from the Altyguyi field's wells are directed through pipelines to sophisticated measuring equipment. Subsequently, they are transported via collectors to the Korpedje field's gas treatment plant for initial processing. This interconnected system simplifies the transportation and processing of gas condensate, optimising the use of resources and contributing to increased overall operational efficiency.

As a sample of gas condensate field development technology in the energy sector, a study of a gas field in the Western region of Turkmenistan was conducted. Part of this is the inspection of production wells, collection systems, treatment systems, and compression of produced gas. The purpose is to assess the practicality and necessity of potential modifications or reconstruction in the context of future field development projects. Such an assessment is crucial to ensure that the field's energy infrastructure remains adaptive and efficient in response to changing operational requirements and environmental considerations. Such a far-sighted approach helps to maintain the sustainability and competitiveness of the operation of gas condensate fields in the long term.

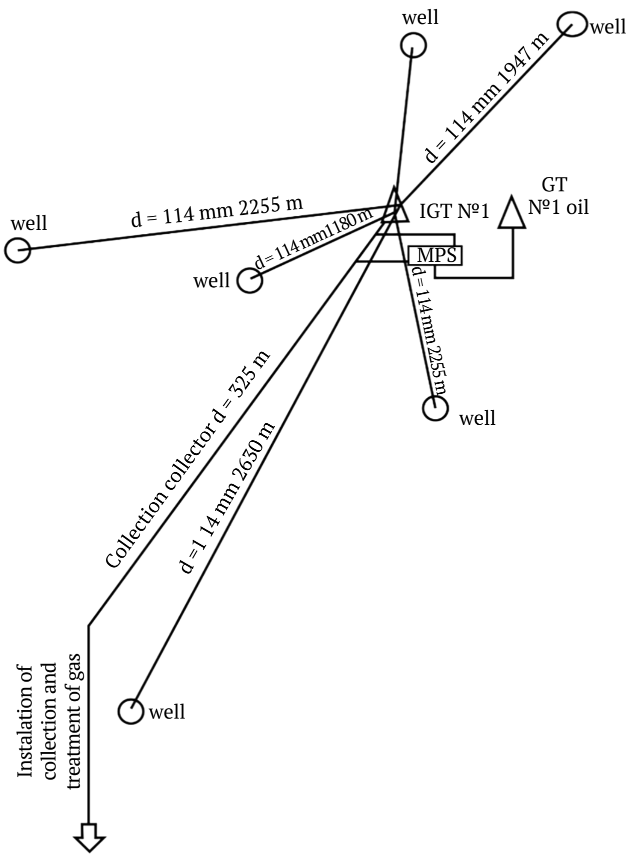

Figure 1. ltyguyi field gas condensate well collection and processing system

Note: IGT – industrial gas turbine, MPS – multiprocessor system, GT – gas turbine

Source: developed by the author based on A.R. Deryaev (2023b)

The compressor station (CS) plays a crucial role in ensuring the efficient operation of the gas processing complex (Zhou *et al.*, 2021). The main function is to compress the associated gas when it enters the station via a gas pipeline. This process is carried out in three separate compression stages. During compression, the gas undergoes transformations as its pressure rises from 0.3 MPa to 7.5 MPa. This compression procedure is crucial to ensure the flow and utilisation of the appropriate gas inside the installation. The CS is also responsible for the compression of associated gas entering the station from several oil and gas collection points, namely, a conventional pumping compressor station 1 and 2 located near the respective fields. These integrated gas pipelines combine several associated gas sources, consolidating their flows and subjecting them to the necessary compression. The CS also compresses natural gas directly produced at the gas condensate field. This gas arrives at the station through a dedicated combined gas pipeline, meticulously connected to the corresponding group measuring equipment (GME) for accurate flow measurement. This compression operation ensures that the natural gas from the field is under sufficient pressure for further processing and transportation, which corresponds to the overall operational objectives of the facility. The multifaceted functions of the compressor station are an integral part of the uninterrupted processing and transportation of various gas flows, which contributes to improving the overall efficiency and productivity of the gas processing complex.

The CS has a number of technical and technological characteristics necessary for its effective operation. The CS is equipped with two separate installations, each of which has cooling systems responsible for the first and second stages of associated gas compression. The CS is also responsible for compressing the corresponding gas entering the station from the oil and gas collection stations of the production pumping station 1 and 2. This intermediate pressure serves as the inlet pressure for the subsequent final or third compression stage. To guarantee optimal efficiency by keeping the equipment within its operating temperature range, cooling systems are indispensable. The compressor station features three dedicated units for the third compression stage: one for associated gas and two for natural gas directly from the pipeline. This design enables efficient and separate compression of different gas streams, contributing to optimized operations.

A noteworthy feature of the CS is its low-temperature mechanical cooling system. This system employs steam compression technology with a refrigerant, often freon, to achieve low-temperature condensation for cooling purposes. This cooling system is crucial to maintain the proper gas temperature, prevent overheating, and protect the integrity of the compressor station equipment. Together, these technical and technological characteristics allow the CS to effectively manage and process associated and natural gas flows, while maintaining the necessary operating conditions and equipment integrity. The cooling systems and compression stages are carefully designed to improve the overall efficiency of the gas processing complex. The gas resources that can be efficiently shipped to consumers with a given gas quality exactly correspond to the annual design capacity of the CS. A constant pressure is maintained at the inlet of the CS by utilizing two distinct gas streams, which helps preserve equilibrium (Moldabayeva *et al.*, 2021).

The integrated gas treatment plant at the current development stage faces a unique challenge: maintaining the required inlet pressure while guaranteeing export gas quality. This pressure ensures the gas meets the specified water and hydrocarbon dew point parameters outlined in the gas supply contract, crucial for reliable and compliant gas delivery to consumers. The GPP plays a key role in achieving these standards and maintaining stable export gas quality. However, a current study of the GPP's operational parameters reveals insufficient reservoir pressure at the inlet compared to the original design plan. This pressure shortfall impacts the overall efficiency of the gas cooling process, which utilizes low-temperature gas separation technology with regenerative heat exchange. It's crucial to recognize that the specific heat exchanger employed plays a significant role in the cooling process efficiency. This dependence is directly linked to the heat exchanger's design and the surface area of its heat exchange plates. In simpler terms, the choice and characteristics of the heat exchanger directly impact the gas cooling process efficiency.

Integrated heat exchangers within the GPP are crucial for this cooling process, significantly lowering the gas temperature before it enters the low-temperature separator. This reduction is achieved using a method known as regenerative heat transfer and results in a temperature reduction of almost half compared to the traditional Joule-Thompson throttling effect. The introduction of these state-of-the-art heat exchangers underlines the plant's commitment to improve cooling efficiency and maintain the necessary quality standards for the processed gas. Using equation (1), the required operating temperature of gas separation was calculated, especially in a low-temperature separator. The decrease in throttle temperature due to the Joule-Thompson effect is calculated using equation (2). Based on operational data, equation (3) describes the decrease in gas temperature occurring within the heat exchanger. The reference pressure at the inlet of the integrated gas treatment plant, where the gas is conditioned to meet the required specifications, depends on two factors. Then, a specific ratio is evaluated based on equation (4). Then the estimated pressure at the pipeline's end (obtained from equation (5)) and the total pressure losses throughout the pipeline are considered.

Based on the calculated ratios, obtaining conditioned gas with a specific water dew point requires $T_{d.w.} = 0°C$, the required pressure drop at the GPP installation is approximately DR~3 MPa in the summer months and about DR~1.5-2 MPa in the winter months. To meet these conditions, the pressure at the inlet to the GPP should be approximately $P_{ent.}$~9.5 MPa in summer and $P_{ent.}$~8.5 MPa in winter. To ensure the inclusion of suitable high-pressure gas resources in the current field development project, this document defines the necessary criteria. These resources must be treatable to meet the specified GPP conditions and align with the calculated inlet pressure values

(Leontidis *et al.*, 2023). To ensure export-quality gas is delivered even with the anticipated decrease in high-pressure gas supplies, the gas compressor station needs to maintain operation in gas treatment modes. To address this critical challenge, the immediate construction of a booster compressor station is essential. It's important to note that gas lift wells receive their supply through dedicated gas pipelines connected to the main pipeline. These injection lines operate at pressures from 6.2 to 11 MPa, providing gas supply to gas lift wells. Effective operation of gas lift wells requires optimisation based on proven techniques. Calculations show that for gas lift wells with gas injection points at depths from 2300 to 2500 m, the recommended operating pressures are $P_r = 6.4$, 7.4, and 8.4 MPa. For wells with a gas inlet depth of 3000 to 3500 m, the operating pressure should be in the range of 10 to 12 MPa.

DISCUSSION

The integration of advanced technologies into the development of gas condensate fields represents a key aspect in the modern oil and gas industry. This topic is highly relevant, since oil and gas companies face the constant challenge of increasing production efficiency under conditions when gas condensate fields present complex technological and engineering tasks. The integration of advanced technologies included a variety of innovations, ranging from the use of modern methods of geophysical research and seismic analytics to accurately determine the structure of the field, to the introduction of automated well management systems and the use of advanced production methods such as hydraulic fracturing. One of the important aspects of the study was to reduce the environmental impact of hydrocarbon production. The use of advanced technologies allowed for more precise control of production processes, reducing the risks of leaks and minimising the impact on the environment (Shmandii *et al.*, 2022).

According to S. Matkivskyi *et al.* (2021), methods for extracting hydrocarbon resources are evolving rapidly, investigating the impact of CO_2 injection rates on water pressure system behavior during gas condensate field development is becoming increasingly crucial. The growing popularity of CO_2 injection to enhance gas condensate production necessitates a thorough understanding of its effects on the field's water management system. (Dzhalalov *et al.*, 2021). One of the key aspects of the study under discussion is the assessment of the effect of different injection rates of CO_2 on hydrodynamic processes in the water pressure system. This includes studying pressure changes, water flow rates, and interactions with the reservoir and adjacent gas condensate layers. The data obtained can significantly influence the development of optimal CO_2 injection strategies that ensure efficient extraction of gas condensates with minimal negative impacts on the water supply. These data are consistent with the theses given in the previous section. This study represents an important step towards improving the efficiency of gas condensate production, while emphasising the importance of balancing technological advantages and environmental sustainability of water supply.

Referring to the definition of L. Jia *et al.* (2021), the application of changing the wettability of gas to improve the efficiency of methane drainage is an innovative approach that can significantly improve the efficiency of natural gas production processes. This method uses the possibility of changing the interaction of gas with the surface of a porous medium, which contributes to more efficient displacement and drainage of methane from gas fields. A practical example of the application of this method may include the use of modified surfactants or coatings capable of affecting the wettability of gas in porous formations. Such technologies can be applied in field conditions where conventional methods of methane extraction face limitations. For example, changing the wettability can increase the permeability of rocks, which, in turn, will reduce the resistance to gas flow and increase its yield (Tileuberdi *et al.*, 2021). It should be noted that when implementing such innovative methods, it is important to consider potential challenges. These include the need for thorough testing and adaptation to specific geological and technological features of the deposit, and an assessment of the environmental consequences of the impact of new substances on the environment. Effective management and optimisation of these technologies require a systematic approach and balanced attention to technical and environmental aspects.

A.R.B. Abad *et al.* (2021) have shown that the use of hybrid machine learning algorithms for predicting condensate viscosity in the bottomhole zone of gas condensate deposits is a promising approach aimed at improving the accuracy and reliability of estimates in conditions of complex geological formations. These hybrid algorithms combine the advantages of various machine learning methods, which makes it possible to better understand a variety of factors affecting the viscosity of condensate. One of the key advantages of hybrid algorithms is their ability to process large amounts of data, including a variety of formation parameters and mining conditions. This is especially important for gas condensate fields, where the complexity of geological structures and variable operating conditions can significantly affect the viscosity of condensate. It can be agreed with this view that successful implementation of hybrid algorithms requires good quality training data and constant updating of models to reflect changes in mining conditions. Such an approach to predicting condensate viscosity can significantly reduce time and resource costs in the production process and ensure more efficient management of gas condensate fields.

As noted by M.Z. Kamali *et al.* (2022), forecasting of the permeability of inhomogeneous carbonate gas condensate reservoirs using a group data processing method is a significant step in the field of accurate modelling and management of hydrocarbon production. Carbonate gas condensate reservoirs have a complex structure and heterogeneity, which complicates the prediction of their permeability, an important parameter for optimising production. The group data processing method is an innovative approach that allows considering groups of variables and dependencies between them when predicting permeability. This method can efficiently process large amounts of data, including various reservoir characteristics, geological parameters, and mining conditions. The use of the group method in predicting the permeability of carbonate gas condensate reservoirs can improve the accuracy of forecasts by considering many factors affecting this parameter (Ismailova *et al.*, 2021). It also provides the ability to adapt to changes in the geological structure and operating conditions, which is key to successful production management over time. Analysing the results and conclusions obtained, it is necessary to have high-quality and detailed data on the geological characteristics of the deposit for effective implementation. The application of the group data processing method in predicting the permeability of carbonate gas condensate reservoirs is a promising tool for improving production strategies and optimising the operation of deposits.

J. Tongwen *et al.* (2021) determined that the development of a three-element mechanism for cyclic injection of gas into condensate-gas formations represents an innovative approach to optimising the extraction of hydrocarbons from complex formations. This mechanism is based on the cyclic introduction of gas into the reservoir and its subsequent extraction, which contributes to the efficient production of condensate and gas. Such a method can provide better control of production processes and increase oil recovery, especially in conditions where conventional methods are ineffective. A new method of increasing condensate oil recovery, associated with a three-element mechanism of cyclic gas injection, provides an opportunity to optimise reservoir pressures and control the migration of hydrocarbons (Matkivskyi & Kondrat, 2023). This is especially true for condensate and gas fields, where proper pressure balancing can significantly increase the volume of extracted resources.

In addition, the successful implementation of this three-element mechanism requires a detailed study of the geological and physico-chemical properties of the deposit and the supporting infrastructure. The new method of condensate extraction through cyclic gas injection represents a promising way to optimise hydrocarbon production and can make a significant contribution to the sustainable and efficient use of energy resources.

CONCLUSIONS

The study investigated how integrating advanced technologies can improve the efficiency of developing gas condensate fields. One key finding is that using innovative methods to optimize production is crucial, as demonstrated by analyzing the technological aspects of well operation at the Altyguyi gas condensate field.

Utilizing gas lift appears to be a promising approach for improving the efficiency of hydrocarbon extraction. This method provides the possibility of effective pressure control and improved extraction of oil and gas, especially in gas condensate fields. Studies of hydrodynamic and thermohydrodynamic provide a deeper understanding of the impact of gas lift on the characteristics of wells and the field as a whole. This provides the necessary basis for the optimal choice of gas lift system parameters, considering the features of geological conditions.

Operational and technological aspects of hydrodynamic and thermohydrodynamic studies also make a significant contribution to the optimisation of field development. The analysis of well designs, considering the mining and geological conditions of drilling, opens up opportunities for improving processes. Data analysis allowed assessing the current state and efficiency of well operation, which is important for optimising hydrocarbon production processes. The results of the study highlighted the importance of further improving technological solutions and maintenance methods to increase the durability and productivity of wells.

An important result of the study is the development of intensification of a gas condensate field using oil and gas dual completion method with one well. This approach, the first in world practice, is focused on reducing capital investments and accelerating the development of deposits, which represents a significant contribution to the energy industry. This study not only expands the scientific understanding of the technological aspects of gas condensate field production, but also provides practical recommendations for integrating advanced technologies in order to increase efficiency and sustainable use of energy resources.

A complete understanding necessitates further research on the influence of various gas lift system parameters on the effectiveness of well conversion to gas lift. This research should also encompass a long-term analysis of the impact of gas lift on field production.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Abad, A.R.B., Mousavi, S., Mohamadian, N., Wood, D.A., Ghorbani, H., Davoodi, S., Alvar, M.A., & Shahbazi, K. (2021). Hybrid machine learning algorithms to predict condensate viscosity in the near wellbore regions of gas condensate reservoirs. *Journal of Natural Gas Science and Engineering*, 95, article number 104210. doi: 10.1016/j.jngse.2021.104210.

[2] Al Dhaif, R., Ibrahim, A.F., & Elkatatny, S. (2022). Prediction of surface oil rates for volatile oil and gas condensate reservoirs using artificial intelligence techniques. *Journal of Energy Resources Technology*, 144(3), article number 033001. doi: 10.1115/1.4051298.

[3] Borj, B.P., Fanaei, M.A., Esdandyari, M., Naddaf, A., Jafari, D., & Baghmisheh, G. (2024). Machine learning-assisted methods for prediction and optimization of oxidative desulfurization of gas condensate via a novel oxidation system. *Journal of Sulfur Chemistry*, 45(1), 84-100. doi: 10.1080/17415993.2023.2257827.
[4] Deryaev, A. (2023a). Dual completion operation technology for two gas condensate reservoirs with production lifting by one column of pumping and compressor pipes. *Machinery & Energetics*, 14(4), 33-41. doi: 10.31548/machinery/4.2023.33.
[5] Deryaev, A.R. (2023b). Features of forecasting abnormally high reservoir pressures when drilling wells in areas of south-western Turkmenistan. *Innovaciencia*, 11(1), 1-16. doi: 10.15649/2346075X.3605.
[6] Deryaev, A.R. (2023c). Prospect forecast for drilling ultra-deep wells in difficult geological conditions of western Turkmenistan. *Sustainable Engineering and Innovation*, 5(2), 205-218. doi: 10.37868/sei.v5i2.id237.
[7] Dzhalalov, G.I., Kunayeva, G.E., & Moldabayeva, G.Zh. (2021). Fluid influx to a battery ofincomplete horizontally branched wells in deformed formation. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 3(447), 29-33. doi: 10.32014/2021.2518-170X.58.
[8] Giglio, E., Pirone, R., & Bensaid, S. (2021). Dynamic modelling of methanation reactors during start-up and regulation in intermittent power-to-gas applications. *Renewable Energy*, 170, 1040-1051. doi: 10.1016/j.renene.2021.01.153.
[9] Golubev, V.G., Sadyrbaeva, A.S., Baibotayeva, S.Y., Turebekova, A.M., Besbayeva, N.A., & Aikenova, S.Zh. (2020). The technique and description of the experimental setup for conducting research on the process of oil displacement with aqueous solutions of the tested components. *Bulletin of KazNRTU*, 138(2), 257-260.
[10] Ismailova, J.A., Delikesheva, D.N., Akhymbayeva, B.S., Logvinenko, A., & Narikov, K.A. (2021). Improvement of sweep efficiency in a heterogeneous reservoir. *Smart Science*, 9(1), 51-59. doi: 10.1080/23080477.2021.1889259.
[11] Jia, L., Li, K., Shi, X., Zhao, L., & Linghu, J. (2021). Application of gas wettability alteration to improve methane drainage performance: A case study. *International Journal of Mining Science and Technology*, 31(4), 621-629. doi: 10.1016/j.ijmst.2021.04.002.
[12] Kamali, M.Z., Davoodi, S., Ghorbani, H., Wood, D.A., Mohamadian, N., Lajmorak, S., Rukavishnikov, V.S., Taherizade, F., & Band, S.S. (2022). Permeability prediction of heterogeneous carbonate gas condensate reservoirs applying group method of data handling. *Marine and Petroleum Geology*, 139, article number 105597. doi: 10.1016/j.marpetgeo.2022.105597.
[13] Kondrat, R., & Matiishyn, L. (2023). Analysis of conditions for stable operation of water-cut gas and gas condensate wells. *Prospecting and Development of Oil and Gas Fields*, 1(86), 46-53. doi: 10.31471/1993-9973-2023-1(86)-46-53.
[14] Leontidis, V., Niknam, P.H., Durgut, I., Talluri, L., Manfrida, G., Fiaschi, D., Akin, S., & Gainville, M. (2023). Modelling reinjection of two-phase non-condensable gases and water in geothermal wells. *Applied Thermal Engineering*, 223, article number 120018. doi: 10.1016/j.applthermaleng.2023.120018.
[15] Matkivskyi, S., Kondrat, O., & Burachok, O. (2021). Investigation of the influence of the carbon dioxide (CO_2) injection rate on the activity of the water pressure system during gas condensate fields development. *E3S Web of Conferences*, 230, article number 01011. doi: 10.1051/e3sconf/202123001011.
[16] Matkivskyi, S.V., & Kondrat, O.R. (2023). The influence of the net density of injection wells on the efficiency of the cycling process in the development of gas condensate deposits. *Prospecting and Development of Oil and Gas Fields*, 2(87), 41-50. doi: 10.31471/1993-9973-2023-2(87)-41-50.
[17] Moldabayeva, G., Suleimenova, R., Sadvakasov, M., & Jalalov, G. (2021). Features of planning and implementation of energy-saving measures at compressor stations of main gas pipelines. *Complex Use of Mineral Resources*, 317(2), 46-56. doi: 10.31643/2021/6445.17.
[18] Pulatov, B.R. (2021). Technological aspects and complications arising when drilling wells in rapon-bearing zones. *Innovations in the Oil and Gas Industry*, 2(3), 103-114.
[19] Rodrigues, H.T., Almeida, A.R., Barrionuevo, D.C., & Fraga, R.S. (2021). Effect of the gas injection angle and configuration in the efficiency of gas lift. *Journal of Petroleum Science and Engineering*, 198, article number 108126. doi: 10.1016/j.petrol.2020.108126.
[20] Sahu, C., Kumar, R., & Sangwai, J.S. (2021). A comprehensive review on well completion operations and artificial lift techniques for methane gas production from natural gas hydrate reservoirs. *Energy & Fuels*, 35(15), 11740-11760. doi: 10.1021/acs.energyfuels.1c01437.
[21] Shmandii, V., Titova, H., Kharlamova, O., & Ryhas, T. (2022). Ensuring environmental safety through utilization of drilling waste. *Ecological Safety and Balanced Use of Resources*, 13(1), 42-48. doi: 10.31471/2415-3184-2022-1(25)-42-48.
[22] Syed, F.I., Alshamsi, M., Dahaghi, A.K., & Neghabhan, S. (2022). Artificial lift system optimization using machine learning applications. *Petroleum*, 8(2), 219-226. doi: 10.1016/j.petlm.2020.08.003.
[23] Tileuberdi, N., Zholtayev, G.Z.H., Abdeli, D.Zh., & Ozdoev, S.M. (2021). Investigation of drainage mechanism of oil from pores of oil saturated rocks using nitrogen at the laboratory condition. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 5(449), 146-152.

[24] Tongwen, J., Longde, S., Wei, X., Xiangjiao, X., Yong, W., & Jing, X. (2021). Three-element development mechanism of cyclic gas injection in condensate gas reservoirs and a new technique of enhancing condensate oil recovery. *Acta Petrolei Sinica*, 42(12), 1654-1664. doi: 10.7623/syxb202112010.
[25] Wang, J., Sun, J., Xie, W., Chen, H., Wang, C., Yu, Y., & Qin, R. (2022). Simulation and analysis of multiphase flow in a novel deepwater closed-cycle riserless drilling method with a subsea pump+gas combined lift. *Frontiers in Physics*, 10, article number 946516. doi: 10.3389/fphy.2022.946516.
[26] Zhou, J., Peng, J., Liang, G., Chen, C., Zhou, X., & Qin, Y. (2021). Technical and economic optimization of natural gas transmission network operation to balance node delivery flow rate and operation cost. *Journal of Intelligent & Fuzzy Systems*, 40(3), 4345-4366. doi: 10.3233/JIFS-201072.

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Інтеграція передових технологій для покращення ефективності розроблення газоконденсатних родовищ

Анотація. В умовах постійно зростаючого світового попиту на енергію та стрімких змін в енергетичному секторі, вивчення та впровадження передових технологій у розробку газоконденсатних родовищ набуває критичного значення. Мета даної роботи полягає в дослідженні методів збільшення ефективності видобутку та сталого використання енергетичних ресурсів шляхом оптимізації процесів розроблення газоконденсатних родовищ з використанням передових технологій. Серед використаних методів слід відзначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу. У рамках цього дослідження вивчено технологічні аспекти використання свердловин Алтигуїнського газоконденсатного родовища, проведено широкі лабораторні та промислові дослідження, спрямовані на правильну реалізацію методу подвійного закачування для одночасного видобутку газу з одного пласта та нафти з іншого, з акцентом на їхній внесок у розробку свердловин за допомогою цього підходу. У роботі також розглянуто аспекти експлуатації та технології, включно з гідродинамічними і термогідродинамічними дослідженнями, під час аналізу конструкцій свердловин з урахуванням інтервалів сумісності та гірничо-геологічних умов буріння, з основою на прогностичних кривих пластового тиску і тиску руйнування гірських порід. У результаті проведених аналізів, досліджень і розрахунків обґрунтовано впровадження методу інтенсифікації видобутку газоконденсатного родовища з використанням нафтогазового підходу подвійного закачування в одній свердловині. Цей підхід орієнтований на скорочення капітальних вкладень і прискорення процесу розвитку. Практичне значення цього дослідження полягає в розробці та впровадженні інноваційних технологій для оптимізації процесів видобутку газоконденсатних родовищ, що сприяє підвищенню ефективності видобутку вуглеводнів, а також сталому використанню енергетичних ресурсів у сучасній енергетиці

Ключові слова: стале використання; оптимізація процесів; подвійне закачування; прогностичні криві; інтенсифікація видобутку

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Application of the regression neural network for the analysis of the results of ultrasonic testing

Abstract. Conducting a study on this topic becomes relevant due to the great importance of the safety of critical infrastructure facilities and the presence of operational defects in equipment elements and pipelines, which poses serious threats, including the possibility of equipment destruction and negative environmental impact. The purpose of this work is to study the possibility of using the diffraction-time technique of ultrasonic non-destructive testing together with a deep convolutional neural network to accurately determine the numerical value of the height of an operational crack. The methods used include the analytical method, classification method, functional method, statistical method, synthesis method, and others. The study found that an automated approach to measuring crack height, based on diffraction signals and the use of neural networks, significantly improved the quality and accuracy of non-destructive testing. Ultrasonic testing is one of the most common inspection methods for detecting service cracks and is considered to be the most effective. It allows for reliable detection of defects and determination of their size without destroying the product. The results of the study emphasize the high potential and efficiency of the method in analysing the data obtained and provide confirmation of its applicability for determining the condition of objects during ultrasonic inspection. The paper emphasizes that these technologies are particularly important and effective. It is noted that their widespread use

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in various industries, such as medicine, aviation, and machine learning, demonstrates their power in solving complex problems. The practical significance of the work lies in the development of advanced approaches that provide new insights and methods to improve the efficiency of analysing the results, which can be applied in industry to improve the quality of control and reliability of technical facilities

Keywords: non-destructive testing; operational defects; diagnostic efficiency; Data Processing; automation of procedures; industrial monitoring

INTRODUCTION

The use of regression neural networks significantly improves the efficiency of ultrasonic data analysis, helping to detect operational defects, thereby ensuring safety and reliability. Automated analysis enables faster defect detection, reducing inspection and maintenance time and costs. Deep neural networks provide high accuracy in detecting even small defects, contributing to reliable diagnostics. The study of this topic promotes the use of innovative technologies in the security of critical facilities and contributes to progress in science and technology. All this is aimed at ensuring more efficient and safer monitoring of the condition of infrastructure facilities. The challenge of this study is the difficulty of detecting operational defects, in particular cracks, which may be hidden or invisible using traditional inspection methods. In addition, the challenge is to develop ultrasonic inspection methods that effectively detect defects and guarantee reliability and accuracy to avoid potential errors and incorrect results.

According to D.V. Pronyaev & V.V. Melnyk (2022), artificial neural networks have provided unique opportunities to improve healthcare systems and increase the effectiveness of medical education. They have been introduced into the training process of medical specialists to simulate real-life clinical scenarios. This has allowed students to gain practical experience in a safe environment and develop diagnostic and treatment skills. However, this study did not address the security and reliability of AI algorithms in the context of medical data, which is a key aspect in the use of such technologies in sensitive areas.

The purpose of the study by A. Atamanchuk (2022) was to develop and test a method for detecting and identifying an unmanned aerial vehicle (UAV) based on neural networks, aimed at improving the efficiency and accuracy of the recognition process. An effective method has been developed that can be used to detect and identify UAVs with high accuracy. The results obtained have practical applications in various industries where they detect and recognize unmanned aerial vehicles. However, this work did not take into account the possible challenges and threats associated with the analysis of unmanned aerial vehicles, which may raise questions about the protection and confidentiality of the information revealed.

In their study, O.M. Berezsky *et al.* (2021) apply the linear regression method to analyse the quantitative characteristics of cytological images in order to obtain objective indicators and improve diagnostic capabilities. The use of linear regression in the analysis of cytological images simplified the interpretation of quantitative data and allowed for objective comparisons between different cellular structures. The research is aimed at improving the methods of analysing cytological images, which is essential for the development of modern medicine. The application of the linear regression method is an important step in improving the objectivity and speed of diagnosis based on cytological data. However, the study did not conduct a comparative analysis with other machine learning methods to determine the advantages and disadvantages of using linear regression.

In their study, O. Burlieiev *et al.* (2021) determine the level of efficiency and benefits of using artificial neural networks in various sectors of the economy, including market analysis, forecasting economic indicators, and financial management. The study highlights the high potential and efficiency of using artificial neural networks in the economy, with the ability to analyse complex relationships and make accurate forecasts, making them a key tool for solving the problems of the modern economic environment. However, the authors did not consider all aspects and specific cases of application of artificial neural networks.

In their paper, N.V. Kuznietsova & Z.S. Chernysh (2020) analyse the use of regression models in the financial analysis of enterprises and determine their effectiveness in predicting financial performance indicators. As a result, the use of regression models has allowed enterprises to more accurately analyse and forecast financial performance indicators, which, in turn, will help improve management strategies and make informed decisions. However, the study lacked additional analysis, which could include a comparison of the effectiveness of regression models with other methods, such as time series analysis or machine learning methods.

The purpose of this study is to determine the feasibility of using the diffraction-time technique of ultrasonic non-destructive testing in combination with a deep convolutional neural network to accurately determine the numerical value of crack height.

MATERIALS AND METHODS

This study was carried out by applying methods that reveal the theoretical and practical content of the object, providing a comprehensive view of innovative approaches to the use of a regression neural network for analysing ultrasonic inspection results. The analytical method in this study was used to thoroughly review the theoretical aspects of regression neural networks used for the analysis of ultrasonic inspection results. This method made it possible to understand and describe the mathematical foundations of the functioning of neural networks in the context of studying ultrasonic inspection. The analysis of the mathematical foundations of regression neural networks in the context of ultrasonic control contributed to the understanding of their potential in accurate analysis and processing of results.

The classification method made it possible to systematize different types of ultrasonic data and define their categories for the needs of applying regression neural networks. The classification results helped to determine the optimal network parameters for specific data classes. The application of this method made it possible to identify different types of ultrasound images and to distinguish their main categories, depending on the needs of regression neural network analysis. This method made it possible to adapt the structure and parameters of regression neural networks to different types of information, which increased their efficiency and accuracy of analysis of the results.

The functional method considered the existing capabilities of regression neural networks and their application to analyse the results of ultrasonic testing. This method considered how the regression neural network performed specific tasks and solved problems related to ultrasonic inspection. The functional method determined the effectiveness and efficiency of regression neural networks in solving specific ultrasonic data analysis tasks. This method made it possible to determine how the neural network adapts to various conditions and identifies key functions during information processing, which provides important guidance for further improvement of its performance.

The statistical method allowed combining the data obtained, and identifying statistical patterns and risks associated with the use of regression neural networks in the context of ultrasound inspection, which is important for assessing the reliability and validity of the results. The synthesis method in this study was used to create and optimize regression neural networks for ultrasound data analysis. This includes the synthesis of network parameters, structure, and weights to achieve optimal performance.

In the study, ultrasonic data obtained using diffraction time-of-flight technique was collected. The data was carefully processed and prepared for further use in the neural network. A deep convolutional neural network was tuned and trained using the ultrasound data. A regression approach was used to accurately determine the crack parameters. The results were validated and analysed to determine the effectiveness of the regression neural network for analysing ultrasonic data and determining crack heights. The results of the regression neural network application were compared with other approaches and methods of ultrasonic inspection to determine the advantages and disadvantages.

A thorough review and analysis of the diffraction-time technique used to measure crack parameters in materials was carried out. Different approaches and techniques that use ultrasound for defect detection are considered. The paper uses a deep convolutional neural network to analyse and process the received diffraction signals. The application of a regression neural network allows accurately determining the height of cracks in materials based on the obtained ultrasonic data.

In this work, a convolutional neural network for image recognition was developed and used to reduce errors in determining the height of the defect. To train a neural network, it is necessary to have so-called labelled data, i.e. data for which the correct answer is known in advance, in this case, the height of the crack. For this purpose, the training data were modelled using the CIVA software. Experimental measurements with real defects would have been more efficient, but this would have required ultrasonic equipment, transducers, and a huge number of samples with real defects. CIVA is a platform for non-destructive testing tasks consisting of modules: modelling, visualization, and analysis. In this study, the software was used to model rectangular defects with different heights, lengths, and defect angles (Table 1). In the end, the artificial crack database consisted of 3 sets: test, validation, and training. In total, the database contains approximately 100 images and took about 30 hours to generate.

Table 1. Parameters of the training model

Model parameters	
Sample form	Rectangular
Material	Steel
Length	200 mm
Thickness	100 mm
Height	30 mm
Converter parameters	
Type	Contact
Emitter shape	Disk
Diameter	6.35 mm
Angle of refraction	60°
Angle of incidence	23.165°

Continued Table 1.

Model parameters	
Scanning scheme	
Location	Symmetrical
Distance between centres	38 mm
Initial position	71×37 mm
Scan move	along the axis
Step (x-axis)	0.5 mm
Number of steps (on the x-axis)	120
Simulated defect	
Height	0-30 mm
Length	30 mm, 40 mm
Angle of inclination of the crack	0°, 2°, 4°

Source: created by the authors

The structural similarity index (SSIM) was used to quantify the structural similarity between images, which allows determining the degree of correspondence between the structures and content between them. In this study, a convolutional neural network (CNN) was developed to solve the problem of determining the height of cracks using the Keras library, TensorFlow framework. The training process of this neural network was performed on an Intel Core i5-7300HQ CPU. Despite the fact that the CPU training speed is less efficient compared to using graphics cards, it was sufficient in this case. This is due to the small number of parameters in the neural network structure and the size of the training set, which contained only 52 images. In general, the training process for 100 epochs usually takes from 10 to 30 minutes.

RESULTS

A crack is one of the most dangerous operational defects, which, depending on its size, particularly its height, can lead to equipment failure. Non-destructive testing tasks play a key role in ensuring the safety, reliability, and efficiency of NPP equipment. Non-destructive testing is the inspection of the quality of products using various fields or radiation. The ultrasonic inspection method is based on the ability of high-frequency vibrations to penetrate the material and reflect scratches from the surface.

Time-of-flight diffraction (TOFD) technology, in turn, is used to record diffraction signals that occur at the edges of a defect using two sensors (Fig. 1). This technique makes it possible to establish the coordinates of cracks quite accurately (Hecht, 1997). The system of this method contains a transmitter and a receiver of ultrasonic waves, which are directed to a single point inside the welded joint. If no defect is present, then after the compression wave is emitted from the transmitter, the first signal to reach the receiver is a side wave representing the outer surface, and the second signal to reach the receiver is an echo from the back wall representing the inner surface. If a defect is present, the diffraction signal is generated at the top of the defect and arrives before the signal generated at the bottom of the defect.

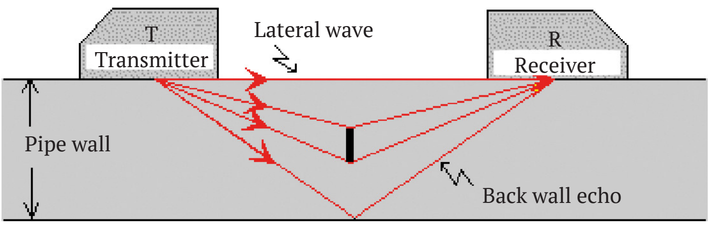

Figure 1. The working principle of TOFD technology

Source: created by the authors

Simple geometric considerations can be used to estimate the height of a crack, knowing the scan angle, the difference in the arrival time of the two signals, and a constant, the speed of sound propagation in the material. However, in reality, the signals are very difficult to recognize (Fig. 2).

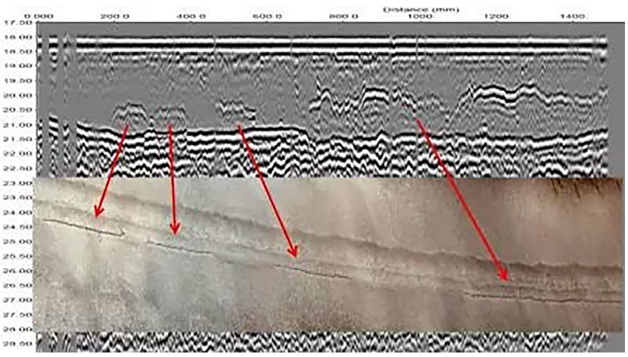

Figure 2. Real TOFD signal

Source: created by the authors

Deep learning is a machine learning technique that is one of the best for solving problems of processing large amounts of data, processing speed, and reducing error. Deep learning models are often called deep neural networks because they consist of a multi-layered architecture. Each layer of the network receives input and performs a certain operation before passing the results to the next layer. As mentioned earlier, a convolutional neural network specializes in image analysis. The peculiarity of this architecture is that it highlights the features of images and at the same time reduces the amount of information by identifying the most informative part of it. In fact, each convolutional layer of a neural network is a set of digital filters whose kernels are optimized during training (Protsenko, 2022). Examples of modelling control results are shown in Figure 3. It is possible to see a slight difference between the results, but calculating the height of the defect without significant errors is a task beyond the reach of humans. Therefore, computer processing is used in this work (Bowles, 2015; Yousefi *et al.*, 2018; Lee *et al.*, 2023).

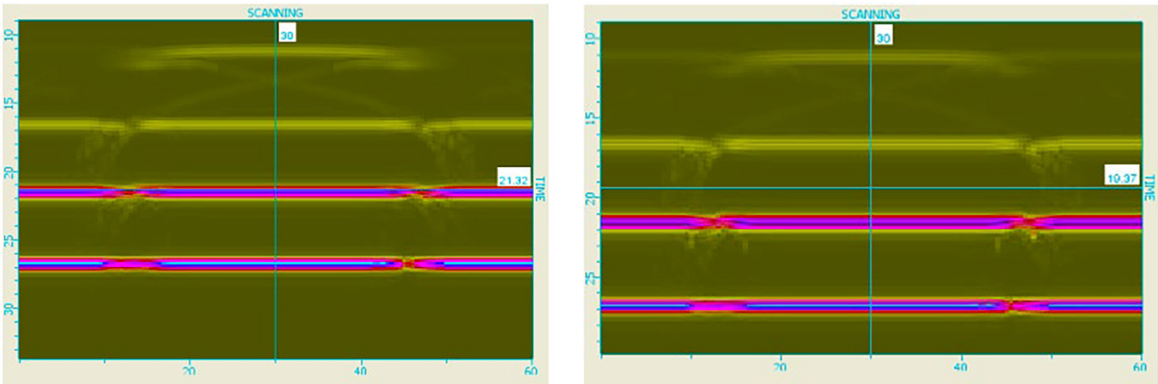

Figure 3. The result of ultrasonic control in the form of an amplitude image for defects with a height of 3 mm and 4 mm, respectively

Source: created by the authors

As a result of the modelling in the CIVA software, a dataset was obtained that contained 118 images, each of which was uniquely indexed (labelled), i.e. had unique parameters of the crack for which the signal was modelled. The modelling itself is manual and contains many procedures and processes involving humans, so errors are possible when generating, naming result files. Therefore, to exclude their influence on the study, all photos were analysed for uniqueness by comparing each photo with all others using a code. In the process, only 52 images were found to be unique. Since the rest of the photos had at least one duplicate (the same photo), but with different indexing, none of them could be used, as it was no longer possible to establish which indexing was correct. Therefore, all non-unique images were excluded from the database that would be used to train and test the neural network.

For the selected 52 images, Figure 4 shows the so-called heat similarity matrix – how similar one photo is to another. The Structural Similarity Index (SSIM) is then used to quantify the similarity between the photos, which allows finding out the degree of correspondence between the structure and content between them. Usually, in such cases, it is possible to use a comparison by calculating the mean square error (MSE), but this means only a pixel-by-pixel comparison of images with complete disregard for the structures on it. Unlike MSE, SSIM gives more weight to structures than to the colour of a single pixel pair. That is, this similarity assessment is better at recognizing similar photos that are similar to the human eye than MSE, i.e. it calculates the so-called perceived similarity (Wang *et al.*, 2004; Wang & Bovik, 2009). According to the obtained SSIM index, a cell on the similarity matrix is coloured. Red indicates full similarity, and blue indicates the least similarity of all. Ideally, only the main diagonal should be red, i.e. the photo should be similar only to itself. In the matrix above, it is possible to see other red cells, but the similarity coefficient is different, which means that the data is not identical.

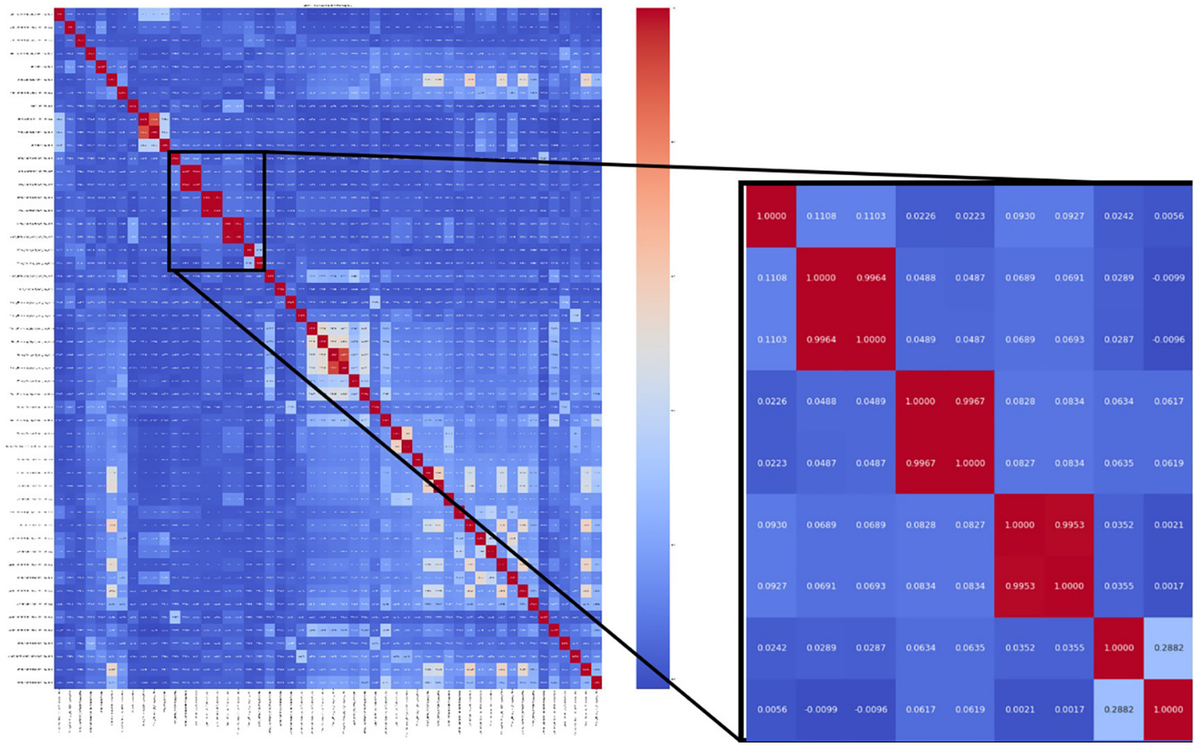

Figure 4. Thermal similarity matrix of the used data set

Source: created by the authors

The dataset was divided into three smaller datasets: a training dataset of 39 images, a validation dataset of 7 images, and a test dataset of 6 images. The training set is used to train the neural network, the validation set is used to evaluate the trained models and compare them with each other to select the best hyperparameters, and the test set is used to evaluate the final neural network with the hyperparameters already selected. To train the neural network, it was decided not to use any augmentation, i.e. artificially expanding the database by enlarging/decreasing, shifting, rotating the image. Despite the small dataset, augmentation would not be very correct in this case. In contrast to object classification tasks, where augmentation is almost always a standard approach and can be applied to object images without losing their essence, this task analyses an ultrasound signal (Wong *et al.*, 2016). Any manipulation of the data can lead to signal distortion, which in turn can affect the accuracy of its analysis. This data-driven approach ensures that the network training is based on original, untouched data, and thus maximizes its accuracy in recognizing ultrasound signals.

Modern machine learning methods make heavy use of frameworks such as TensorFlow, which provide powerful tools for developing and training neural networks. Achieving optimal results required careful selection of hyperparameters. This included determining the optimal number of Conv2D and MaxPooling2D convolutional layers, adjusting the number of filters and kernel sizes for each Conv2D layer, defining the parameters of fully connected layers, dropout values, and batch sizes. After that, the best configuration was selected based on the results of testing on the validation dataset. The structure of the best neural network is shown in Table 2 and schematically depicted in Figure 5.

Table 2. Architecture of classification convolutional neural network

Layer	Activation function	Characteristics
Conv2D	ReLU	The number of filters – 64 The core size – 6×6
MaxPooling2D	-	The core size – 2×2
Conv2D	ReLU	The number of filters – 32 The core size is 5×5
MaxPooling2D	-	The core size – 2×2
Conv2D	ReLU	The number of filters – 32 The core size – 4×4
Flatten	-	-
Dense	ReLU	The number of neurons – 64
Dropout	-	Rate – 0.4
Dense	ReLU	The number of neurons – 32
Dropout	-	Rate – 0.4
Dense	Softmax	The number of neurons – 6
Number of parameters		3,124,390

Source: created by the authors

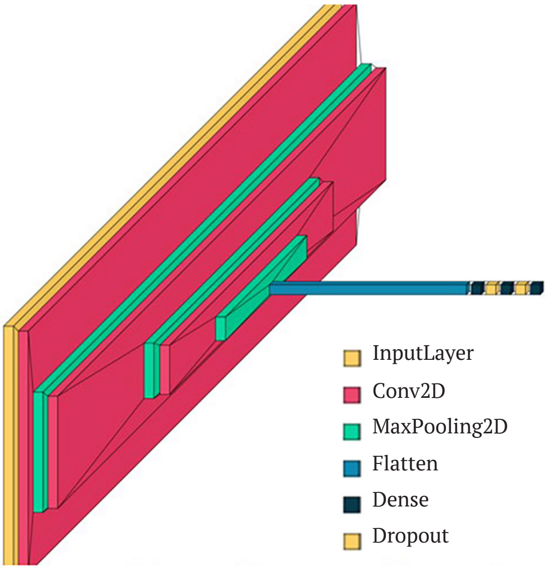

Figure 5. Classification model architecture

Source: created by the authors

The results of testing the checkpoint-preserved classification network after training for 100 epochs are shown in Table 3.

The error of the model in classifying one image, which was assigned to a class located at a distance of only 1 mm from the actual crack height, indicates the importance of further improvement and development of the system. In order to quantify the error and improve the accuracy of predictions, it is worth considering the use of a regression neural network (Fig. 6).

Table 3. Results of training the classification model

Cracked Test ID	Crack height, mm	Height class	Estimated height class	Classification result
1	3 mm	0-5 mm	0-5 mm	True
2	9 mm	5-10 mm	10-15 mm	False
3	11 mm	10-15 mm	10-15 mm	True
4	17 mm	15-20 mm	15-20 mm	True
5	19 mm	15-20 mm	15-20 mm	True
6	25 mm	25-30 mm	25-30 mm	True
7	29 mm	25-30 mm	25-30 mm	True
Precision				85.71%

Source: created by the authors

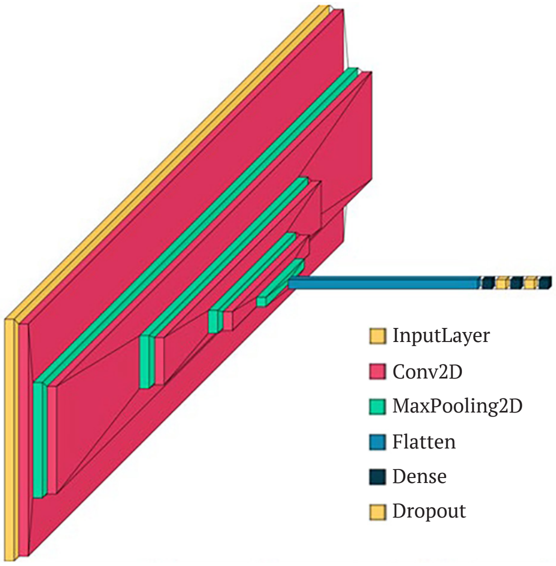

Figure 6. Architecture of the regression model

Source: created by the authors

Regression neural networks allow solving problems related to the prediction of numerical values, which in this case is ideal for determining the specific height of a crack. Compared to classification, where only two categories are possible (correct/incorrect), the regression approach provides quantitative values that determine the degree of deviation of the predicted value from the actual value. The changes in the architecture that provided for the transition from the classification to the regression model included important modifications that contributed to the solution of the problem of predicting numerical values, namely the height of a crack in the material. The original six-neuron output layer that used the softmax activation function for classification was replaced by a single output neuron without an activation function responsible for predicting the numerical value. During the hyperparameter selection, the dropout value was reduced and another convolutional layer Conv2D and MaxPooling2D were added (Table 4).

Table 4. Architecture of regression convolutional neural network

Layer	Activation function	Characteristics
Conv2D	ReLU	The number of filters – 64 The core size – 6×6
MaxPooling2D	-	The core size – 2×2
Conv2D	ReLU	The number of filters – 32 The core size – 5×5
MaxPooling2D	-	The core size – 2×2
Conv2D	ReLU	The number of filters – 32 The core size – 4×4
MaxPooling2D	-	The core size – 2×2
Conv2D	ReLU	The number of filters – 32 The core size – 4×4
Flatten	-	-
Dense	ReLU	The number of neurons – 64
Dropout	-	Rate – 0.1
Dense	ReLU	The number of neurons – 32
Dropout	-	Rate – 0.1
Dense	-	The number of neurons – 1
Number of parameters		393,745

Source: created by the authors

The results of testing the regression network stored by the checkpoint after training for 100 epochs are shown in Table 5. The average absolute error was 0.46 mm, and the average relative error was 4.86%, which indicates that this neural network is well-trained to determine the crack height, but only in the material sample specified in the simulation. Therefore, it is important to consider that the results obtained on this specimen may not be equally transferable to other specimens due to variations in the material. For a wider and more universal application of the model, it is necessary to expand the size of the training dataset and consider the variability of material properties. The findings show that the regression neural network performs well in the task of determining the crack height on a given material sample. Scaling to other materials can be achieved by expanding the training set and optimizing the network parameters.

Table 5. Results of regression model training

ID test with a crack	Height, real value, mm	Height, predicted value, mm	Absolute error, mm	Relative error, %
1	3	3.49	0.49	16.39
2	9	8.47	0.53	5.87
3	11	10.47	0.53	4.82
4	17	17.18	0.18	1.05
5	19	19.16	0.16	0.84
6	25	25.72	0.72	2.89
7	29	28.39	0.61	2.12
	Average values		0.46	4.86

Source: created by the authors

In order to successfully scale the developed model to other materials and inspection conditions, two key steps are required. First, the training dataset should be expanded to include different defect shapes and sizes. This will help the model to adapt to the different nature of materials and avoid transferring sample properties to a specific material only. Second, it is important to optimize the neural network parameters. This involves experimenting with hyperparameters, such as network architecture, learning rate, and other parameters that affect its performance. These steps can be used not only to achieve high accuracy on a particular material, but also to ensure the overall adaptability of the model to different conditions and types of materials, which would make it more versatile and effective in practical applications (Erkmen & Yildirim, 2008; Qiao *et al.*, 2020). Additionally, the modelling allowed determining the optimal size of the training set to achieve maximum efficiency. Sensitivity analysis of hyperparameters, such as training speed and data set size, revealed their impact on the model's performance and identified optimal values. Validation on real data confirmed the model's adaptability to new conditions and data, which will enhance its applicability in real-world scenarios. Comparison with other methods of analysing ultrasonic inspection results also shows the high efficiency of the developed neural network. In general, the results obtained confirm the great potential and practical value of the regression neural network for analysing ultrasound data, and also indicate ways to further improve and expand its applications in various fields of technical diagnostics and control.

The paper emphasizes the importance and effectiveness of advanced deep learning and neural network technologies. It is noted that their widespread use in various fields, such as medicine, aviation, and machine learning, indicates their power in solving high-level problems. In medicine, they help automate diagnostics and develop effective treatments. In the aviation industry, these technologies ensure efficient monitoring and maintenance of aircraft, increasing safety. In machine learning, they expand the possibilities in forecasting and task classification. The paper highlights that these technologies are key to solving modern challenges in science and technology. Their widespread adoption in various industries demonstrates a deep approach and potential for solving various problems, emphasizing the importance of their application in the modern technological environment.

DISCUSSION

This research article discusses a key topic in the field of non-destructive testing, namely improving the accuracy of crack height measurements using diffraction signals and the use of neural networks to optimize this process. Much emphasis was placed on analysing the methodology of using machine learning technologies, in particular neural networks, which can improve the efficiency of the inspection procedure. Specific aspects of the use of neural networks in crack height measurement were discussed in detail. The peculiarities of diffraction signals were carefully considered, and machine learning-based models were developed to accurately determine the size of cracks in materials. The regression neural network is highly effective in determining the parameters of ultrasonic inspection, which has led to a significant increase in measurement accuracy, a critical aspect for ensuring the reliability and safety of industrial facilities (Fomin *et al.*, 2023). The use of neural networks has made it possible to automate the process of analysing ultrasonic data, reducing dependence on the human factor, and speeding up the time to detect defects (Smailov *et al.*, 2023). This contributed to the efficient use of resources and optimization of production processes. The results of the study indicate that the regression neural network can be scaled up and applied to different materials and conditions. This makes it a versatile tool for solving control problems in various industries.

One of the key advantages of this study is its relevance in the modern context. In particular, measuring the height of cracks turns out to be a critical task in ensuring the safety and reliability of infrastructure facilities (Babak *et al.*, 2021). The importance of this study is emphasized by the fact that in the nuclear industry, this issue is becoming particularly relevant to prevent possible accidents. It is noted that solving the problems of crack measurement has the potential to improve safety and reliability in these strategically important industries (Ripetskyi *et al.*, 2023). The paper identifies new opportunities for applying modern technologies and studying their impact on the sustainability and safety of infrastructure systems.

In their study, O. Tymchuk *et al.* (2023) developed a model that uses recurrent neural networks to accurately estimate the value of real estate. The developed RNN model is capable of accurately predicting the value of real estate objects, considering various factors and variables, which contributes to improving real estate decision-making processes and improving the accuracy of valuations. This study is aimed at expanding the possibilities of using recurrent neural networks in the field of real estate valuation. These results are expected to improve the accuracy and objectivity of real estate pricing, which opens new prospects for market participants. The regression neural network demonstrates high efficiency in detecting and analysing defects, and the recurrent neural network is successfully used to accurately estimate the value of real estate (Shults *et al.*, 2023). Both studies harness the power of neural networks to solve important problems in their respective fields. The regression and recurrent neural networks demonstrate high accuracy and efficiency in solving the problems of ultrasonic inspection and real estate valuation, respectively.

The work by V. Gerus & S. Vitruk (2022) on the study of the effectiveness of neural networks in economics and their impact on the analysis and forecasting of economic indicators reveals significant aspects, contributing to the development of new methods and approaches in this area. As a result, the use of neural networks in the economy has led to improved forecast accuracy, increased decision-making speed and optimization of economic processes. The research of these authors focuses on the effectiveness of neural networks in economic analysis and decision-making, as well as on the accuracy of defect detection in materials. The study of the effectiveness of neural networks in economics is important for understanding the potential of these technologies in improving economic processes and making informed management decisions. The regression neural network has been shown to be effective for physical analysis of materials, while the application of neural networks in economics can improve analysis and management decision-making in the financial sector (Petchenko *et al.*, 2023).

In his study, M. Gertsiuk (2022) described the development and use of a mathematical model based on a neural network to predict the effects of river pollution. As a result, mathematical modelling based on a neural network is a promising approach for predicting the effects of river pollution, and this study aims to further develop this area in the field of water resources protection. Both studies use neural networks for different tasks, but they both demonstrate the power of these methods to solve important problems in their respective fields. The use of regression neural networks in technical applications and mathematical modelling for environmental research are promising areas of neural network use in various fields.

The study by U.M.R. Paturi *et al.* (2018) was aimed at comparing the effectiveness of regression analysis and integral numbers of microgeometry (INM) in modelling the surface roughness of AISI 52100 steel during hard turning. As a result, the regression analysis and INM proved to be effective in modelling the dependence of surface roughness on turning parameters, and INM demonstrated higher accuracy for complex nonlinear dependencies between turning parameters and roughness. The work is relevant in the context of improving turning and manufacturing technologies, which can lead to higher quality of manufactured parts and reduced production costs. Both studies are distinguished by their relevance and importance for certain industries but have differences in the areas of application and approaches to solving the relevant problems.

In their study, N. Ceryan *et al.* (2012) described the development and application of generalized regression neural networks for predicting the unconfined compressive strength of carbonate rocks. The results of this study are useful for geologists, engineers, and material manufacturers working with carbonate rocks. The model serves as a tool for fast and accurate prediction of mechanical properties of materials. The research aims to develop knowledge in the use of neural networks for predicting the mechanical properties of rocks, contributing to the further development of methods and technologies in the field of geology and mining. Both studies consider the use of regression neural networks in different areas: determining ultrasonic inspection parameters and predicting the mechanical properties of carbonate rocks. These two studies demonstrate the importance and effectiveness of using regression neural networks in solving analysis and prediction problems in various fields. They complement each other, providing a valuable contribution to the development of materials control and research methods.

An analysis of various studies on the use of neural networks in various industries has shown that these technologies do indeed have high potential and efficiency in solving complex problems. These studies not only demonstrate the power of neural networks in their respective fields, but also point to their versatility and applicability in various contexts. These technologies have the potential to revolutionize approaches to analysis, forecasting and management in a variety of industries, from industry to the environment to finance. This article provides an understanding of how diffraction signals are generated and measured, making the findings and research methodology accessible to a wide range of readers. This approach promotes mutual understanding and popularization of the topic among specialists and researchers working in the field of non-destructive testing. An interesting aspect is the use of neural networks to analyse diffraction signals and determine the height of cracks. Automating the process and improving the accuracy of measurements using this approach may prove to be key to the further development and improvement of inspection systems. Overall, the study not only solves an urgent problem in the field of non-destructive testing, but also offers a technological approach that has the potential for widespread practical implementation and improved accuracy of crack height measurements, which can have a positive impact on safety and efficiency.

CONCLUSIONS

A study on the use of a regression neural network to analyse the results of ultrasonic testing has revealed the great potential of this technology in the field of non-destructive testing. Using advanced deep learning and neural network techniques, it was possible to significantly improve the accuracy and efficiency of determining the parameters of controlled objects. The results obtained allow concluding that the regression neural network is successful in detecting defects using ultrasonic inspection. This opens prospects for the widespread adoption of this technology in various industries, including industry, construction, and infrastructure.

In the course of the work, an ultrasonic inspection dataset was generated, analysed, and cleaned using TOFD technology and developed a convolutional neural network architecture for classifying defect heights based on ultrasonic inspection signals. The architecture and hyperparameters of the created convolutional neural network were improved to classify cracks in materials by their height. The resulting neural network showed a result of 85.61% accuracy on the test dataset. Based on the developed classification convolutional neural network, a regression model was developed to determine the exact numerical value of the crack height, which is an important aspect in non-destructive testing. After selecting the hyperparameters, testing on the test dataset showed the result: the average absolute error in determining the crack height was only 0.46 mm, the average absolute error was 4.86%.

The obtained results confirm the possibility of successfully using convolutional neural networks to determine the crack height from ultrasonic inspection signals and provide grounds for further research into the use of neural networks in the analysis of ultrasonic inspection results. To further improve the accuracy of predictions, the training dataset should be expanded and improved by adding data from different samples: different materials, different shapes, and sizes with a wider range of crack characteristics, and real ultrasonic inspection data of the corresponding TOFD technology.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Atamanchuk, A. (2022). *Method of detection and identification UAV with using a neural network*. Ternopil: Ternopil Ivan Puluj National Technical University.

[2] Babak, V.P., Babak, S.V., Eremenko, V.S., Kuts, Y.V., Myslovych M.V., Scherbak, L.M., & Zaporozhets, A.O. (2021). Models of measuring signals and fields . *Studies in Systems, Decision and Control*, 360, 33-59. doi: 10.1007/978-3-030-70783-5_2.

[3] Berezsky, O.M., Pitsun, O.Yo., Melnyk, G.M., & Datsko, T.V. (2021). Application of linear regression method for analysis of cytological images quantitative characteristics. *Ukrainian Journal of Information Technology*, 3(1), 73-77. doi: 10.23939/ujit2021.03.073.

[4] Bowles, M. (2015). Machine learning in python: Essential techniques for predictive analysis. Retrieved from https://www.wiley.com/en-be/Machine+Learning+in+Python%3A+Essential+Techniques+for+Predictive+Analysis-p-9781118961742.

[5] Burlieiev, O., Vasylenko, O., & Ivanenko, R. (2021). Efficiency of using artificial neural networks in the economy. *Economy and Society*, 31, 67-72. doi: 10.32782/2524-0072/2021-31-27.

[6] Ceryan, N., Okkan, U., & Kesimal, A. (2012). Application of generalized regression neural networks in predicting the unconfined compressive strength of carbonate rocks. *Rock Mechanics and Rock Engineering*, 45, 1055-1072. doi: 10.1007/s00603-012-0239-9.

[7] Erkmen, B., & Yildirim, T. (2008). Improving classification performance of sonar targets by applying general regression neural network with PCA. *Expert Systems with Applications*, 35(1-2), 472-475. doi: 10.1016/j.eswa.2007.07.021.

[8] Fomin, O., Speranskyy, V., Krykun, V., Tataryn, O., & Litynskyi, V. (2023). Models of dynamic objects with significant nonlinearity based on time-delay neural networks. *Bulletin of Cherkasy State Technological University*, 3, 97-112. doi: 10.24025/2306-4412.3.2023.288284.

[9] Gertsiuk, M. (2022). A mathematical modeling model of river's water pollution consequences with use of neural network, which based on regression problem. In *Collection of Scientific Works "Control, Navigation and Communication Systems"* (pp. 95-98). Poltava: National University "Yuri Kondratyuk Poltava Polytechnic". doi: 10.26906/SUNZ.2022.2.095.

[10] Gerus, V., & Vitruk, S. (2022). Effectiveness of neural networks in the economy. In *Proceedings of the1stInternational Scientific and Practical Conference "Science: Development and Factors its Influence"* (pp. 389-394). Amsterdam: InterConf.

[11] Hecht, A. (1997). Time of flight diffraction technique (TOFD) – An ultrasonic testing method for all applications. *NDTnet*, 2(9), 55-90.

[12] Kuznietsova, N.V., & Chernysh, Z.S. (2020). Regression models application for analysis and forecasting of the financial activity quality indicators of the company. *System Research & Information Technologies*, 2, 67-81. doi: 10.20535/SRIT.2308-8893.2020.2.05.

[13] Lee, S.E., Park, J., Yeom, Y.T., & Kim, H.J. (2023). Sizing-based flaw acceptability in weldments using phased array ultrasonic testing and neural networks. *Applied Sciences*, 13(5), article number 3204. doi: 10.3390/app13053204.

[14] Paturi, U.M.R., Devarasetti, H., & Narala, S.K.R. (2018). Application of regression and artificial neural network analysis in modelling of surface roughness in hard turning of AISI 52100 steel. *Materials Today: Proceedings*, 5(2), 4766-4777. doi: 10.1016/j.matpr.2017.12.050.

[15] Petchenko, M., Yakushev, O., Yakusheva, O., & Bilichenko, A. (2023). A neural network model of economic growth. *Economic Bulletin of Cherkasy State Technological University*, 23(2), 51-60. doi: 10.24025/2306-4420.69.2023.288489.

[16] Pronyaev, D.V., & Melnyk, V.V. (2022). Application of artificial neural networks in health care and medical education. In *Current Issues of Science, Education and Society: Theory and Practice* (pp. 48-49). Uman: Center for Financial-Economic Research.

[17] Protsenko, O. (2022). *Information technology of machine learning in problems of bioengineering*. Sumy: Sumy State University.

[18] Qiao, L., Liu, Y., & Zhu, J. (2020). Application of generalized regression neural network optimized by fruit fly optimization algorithm for fracture toughness in a pearlitic steel. *Engineering Fracture Mechanics*, 235, article number 107105. doi: 10.1016/j.engfracmech.2020.107105.

[19] Ripetskyi, Ye., Ripetskyi, R., & Korobkov, O. (2023). Prediction of the stressed and deformed state of hanging gas pipes under changes in the external load. *Prospecting and Development of Oil and Gas Fields*, 1(86), 29-37. doi: 10.31471/1993-9973-2023-1(86)-29-37.

[20] Shults, R., Ormambekova, A., Medvedskij, Y., & Annenkov, A. (2023). GNSS-assisted low-cost vision-based observation system for deformation monitoring. *Applied Sciences (Switzerland)*, 13(5), article number 2813. doi: 10.3390/app13052813.

[21] Smailov, N., Dosbayev, Z., Omarov, N., Sadykova, B., Zhekambayeva, M., Zhamangarin, D., & Ayapbergenova, A. (2023). A novel deep CNN-RNN approach for real-time impulsive sound detection to detect dangerous events. *International Journal of Advanced Computer Science and Applications*, 14(4), 271-280. doi: 10.14569/IJACSA.2023.0140431.

[22] Tymchuk, O., Pylypenko, A., & Kicha, A. (2023). A recurrent neural network for real estate price estimation. *Energy and Automation*, 5, 88-99. doi: 10.31548/energiya5(69).2023.088.

[23] Wang, Z., & Bovik, A. (2009). Mean squared error: Love it or leave it? A new look at Signal Fidelity Measures. *IEEE Signal Processing Magazine*, 26(1), 98-117. doi: 10.1109/MSP.2008.930649.

[24] Wang, Z., Bovik, A., & Sheikh, H. (2004). Image quality assessment: From error visibility to structural similarity. *IEEE Transactions on Image Processing*, 13(4), 600-612. doi: 10.1109/TIP.2003.819861.

[25] Wong, S., Gatt, A., Stamatescu, V., & McDonnell, M. (2016). Understanding data augmentation for classification: When to warp? In *International Conference on Digital Image Computing: Techniques and Applications* (pp. 1-6). Gold Coast: IEEE. doi: 10.1109/DICTA.2016.7797091.

[26] Yousefi, B., Kalhor, D., Usamentiaga, R., Lei, L., & Ibarra Castanedo, C. (2018). Application of deep learning in infrared non-destructive testing. In *14th Quantitative InfraRed Thermography Conference* (pp. 97-105). Berlin: IRT. doi: 10.21611/qirt.2018.p27.

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Застосування регресійної нейронної мережі для аналізу результатів ультразвукового контролю

Анотація. Проведення дослідження на цю тему стає актуальним у зв’язку з великим значенням безпеки об’єктів критичної інфраструктури та наявністю експлуатаційних дефектів у елементах обладнання та трубопроводах, що створює серйозні загрози, включаючи можливість руйнування обладнання та негативний вплив на навколишнє середовище. Мета даної роботи полягає у вивченні можливості використання дифракційно-часової техніки ультразвукового методу неруйнівного контролю разом з глибокою згортковою нейронною мережею для точного визначення числового значення висоти експлуатаційної тріщини. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. В ході дослідження було виявлено, що автоматизований підхід до вимірювання висоти тріщин, який базується на дифракційних сигналах та використанні нейронних мереж, суттєво покращив якість та точність неруйнівного контролю. Одним з розповсюджених методів контролю для виявлення експлуатаційних тріщин є ультразвуковий контроль, який вважається найбільш ефективним. Він дозволяє надійно виявляти дефекти та визначати їхні розміри без руйнування виробу. Результати дослідження підкреслюють високий потенціал та ефективність методу в аналізі отриманих даних та надають підтвердження його застосовності для визначення стану об’єктів під час ультразвукового обстеження. Робота підкреслює, що ці технології є особливо важливими та ефективними. Зазначається, що їх широке застосування у різних галузях, таких як медицина, авіація та машинне навчання, свідчить про їх потужність у розв’язанні складних завдань. Практичне значення роботи полягає в розвиненні передових підходів, що надають нові інсайти та методи для покращення ефективності аналізу результатів, які можуть бути застосовані в промисловості для поліпшення якості контролю та надійності об’єктів технічного призначення

Ключові слова: неруйнівний контроль; експлуатаційні дефекти; ефективність діагностики; обробка даних; автоматизація процедур; індустріальний моніторинг

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Welding processes in the restoration of industrial and energy facilities

Abstract. The research relevance is determined by the constant development and changes in the production environment and technological requirements to ensure increased safety, durability, and efficiency of industrial and energy facilities. The study aims to analyse methods and strategies for improving the efficiency of welding and joint quality control, to achieve greater stability and reliability of energy facilities. The methods used include observation, comparative and descriptive, monitoring, abstraction, and others. The study analysed various welding technologies and their impact on the quality of welded joints. Various methods of calculating welded structures concerning materials and technical requirements were considered. In addition, various methods of quality control of welded joints, including visual inspection and non-destructive testing, were investigated. The study determined that the correct choice of technology, calculations and quality control can improve the strength, reliability, safety, and economic feasibility of welded structures. The studied welding technologies and quality control methods used are more effective for use in specific conditions and there is no general solution. In addition, the proper application of these methods demonstrated that they can significantly reduce the recovery time and increase the overall productivity of the process of restoring industrial and energy facilities. Therefore, the optimal use of welding technologies and quality control methods can significantly improve the efficiency and durability of industrial and energy facilities. The practical significance of the study is to contribute to improving the safety, reliability, and efficiency of the rehabilitation of industrial and energy facilities by improving the quality control procedures for welded joints

Keywords: non-destructive testing; microstructure; bond strength; electrodes; quality control methods

INTRODUCTION

The application of welding processes in the restoration of industrial and energy facilities is critical in the modern technological context. This aspect is becoming increasingly important as infrastructure wear and tear increases and the need for efficient rehabilitation. Welding is a key process in many industries, including construction, engineering, shipbuilding, and energy. Weld quality determines the safety, strength, and durability of welded structures, as well as the efficiency of industrial and energy facilities. Welded joints that do not meet quality standards can lead to serious accidents, injuries and even death. Studying welding technologies and quality control methods helps ensure the safe operation of welded structures. Welds must have sufficient homogeneity and chemical composition similarity to the base metal to withstand operational loads. The calculation of welded structures helps to determine the required welding parameters and weld dimensions at the design stage. The right choice of welding technology and quality control methods can significantly reduce the cost of welding, as well as the maintenance and repair of the entire structure. Welding technologies are constantly being improved, and new technological solutions are emerging that are changing welding and quality control methods for the better. It is necessary to constantly increase the level of knowledge and improve skills to meet modern requirements.

The research addresses the need to adapt welding methods to modern requirements of technological development and standards, as well as to ensure the quality,

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safety, and efficiency of the infrastructure rehabilitation process. With the development of technology, new welding methods and materials are emerging that can be more efficient and safer. The research aims to adapt these innovations to the needs of infrastructure rehabilitation. Welding standards are constantly being reviewed and updated to ensure that production and quality are maintained. Therefore, it is important to continuously monitor and modify welding process flow charts in production to meet new requirements. Defects and damage in welded joints can lead to serious accidents and damage. The development of welding methods should aim to minimise these risks. Efficient use of materials and optimisation of work time is important for the economic viability of the infrastructure rehabilitation process.

Following V. Korzhyk *et al.* (2024), the development of new welding technologies and the improvement of quality control methods for welded joints are important to ensure the reliability and safety of industrial and energy facilities. The study does not consider the impact of environmental variables on welding quality. V. Kachynskyi & M.P. Koval (2021) emphasise the need to consider the individual characteristics of each welding process and choose the optimal approach to quality control. The paper does not focus on the need to further investigate the impact of welding defects on the service life of structures. According to A.S. Novodranov *et al.* (2023), the developed conditions and criteria for assessing the effectiveness of welding technologies and inspection methods can increase production efficiency and ensure high-quality welded joints. The study does not address the possibility of introducing new methods of non-destructive testing of welded joints.

O.F. Kryvyi & Yu.O. Morozov (2022) note that ensuring the stability and uniformity of the quality of welded joints is a key task in the implementation of any project. The researchers do not mention the need to further study the impact of vibrations on the strength and reliability of welded structures. Yu.K. Bondarenko & Yu.V. Loginova (2022) emphasises the importance of continuous monitoring and updating of welding quality control methods by modern standards and technologies. However, the study does not provide sufficient information on the possibility of using new materials in welding. V. Lebedev *et al.* (2022) raise the important issue of developing effective quality management systems aimed at continuous improvement of welding processes and quality control of welded joints. The study does not address the important issue of the influence of preliminary mechanical stresses on welding quality.

The study aims to evaluate methods and strategies aimed at improving the efficiency of welding and quality control of joints, ensuring greater safety and reliability of energy facilities.

MATERIALS AND METHODS

Using the observation method, the welding processes were studied in detail in practice. The observation took place at the E.O. Paton Electric Welding Institute, Kyiv, during May-July 2023. During this method of direct observation of the workflow, the various stages of welding were monitored, and any deficiencies or malfunctions identified were carefully considered. This method was used to obtain important practical information about real welding conditions that cannot always be reflected in theoretical models.

A detailed study of different types of welding was carried out using comparative and descriptive methods. The characteristics of each method, including its advantages and disadvantages, as well as the impact on the quality and reliability of welded joints, were studied. This method made it possible to make an objective assessment of different welding technologies and determine the best approach for a particular task.

Using the monitoring method, various welding parameters were checked over a long period, from September 2023 to February 2024. During the welding process, continuous monitoring was carried out, during which data on temperature, welding electrode speed and other important parameters were recorded. This contributed to the timely detection of changes in the quality of the welded joints and was used to respond promptly to any deviations from the optimal parameters.

The abstraction method was used to identify the main general principles and patterns of welding processes and their impact on the rehabilitation of industrial facilities. By separating the essentials from the details of specific situations, this method was used to focus on the key aspects of welding and to consider them in a generalised way, which contributed to the development of general principles and recommendations for industrial site restoration.

The functional method was used to determine the optimal welding quality functions and their dependence on various process parameters. This method was used to study the functional dependencies between the input welding parameters and the output quality of the joints. Synthesis methodology was used to combine various aspects of welding and joint quality control to create a comprehensive strategy. This method was used to compare different methods and approaches to optimise the use of resources and achieve maximum results. The classification method was used to help structure various aspects of the welding and joint quality control processes. By grouping the input data according to certain criteria, a structured picture of the processes was obtained, and the main trends and patterns were identified. The analogy method was used to establish parallels between already known and new situations in the field of welding and industrial facilities restoration. This method was used to transfer the knowledge and experience gained in previous cases to new conditions, which contributed to a more effective understanding and solution of problems in the restoration process.

The induction method was used to thoroughly investigate the available data and examine their interrelationships to formulate general statements and conclusions. By studying the experience and observations already made in the field of welding, the main regularities and principles governing the processes of welding and joint quality control were identified. This was used to draw conclusions about the effectiveness of certain welding methods and identify key areas for further research.

RESULTS

Welding plays are valuable in the restoration of industrial and energy facilities that have been worn out due to various factors. This technology opens up wide opportunities for the restoration and improvement of metal structures, allowing for effective solutions to several problematic situations. Welding is used to repair damaged components (Tanasković *et al.*, 2021). This can include repairing cracks, tears, distortions, and other types of defects in metal structures such as beams, pipes, machine bodies, and tanks. A wide range of welding processes allows for effective repair of various types of damage, ensuring their strength and durability. In addition, welding can be used to manufacture new parts to replace worn or damaged ones. This provides effective restoration of the functionality of an object and extend its service life. Welding can be used to produce exact replicas or modified versions of parts that meet the specific needs of the facility. Finally, welding can be used to connect new components to existing structures when a facility is being modernised or expanded. This process allows new elements to be integrated into existing infrastructure, ensuring their reliability and interaction with the entire system.

Manual metal arc welding (MMA) is the most common and versatile method used in refurbishment (Fig. 1). It allows welding different types of metals and repairing different parts and structures (Nalle *et al.*, 2024). This technique enables welding in hard-to-reach places, even in the ceiling position, which is often necessary to avoid an emergency.

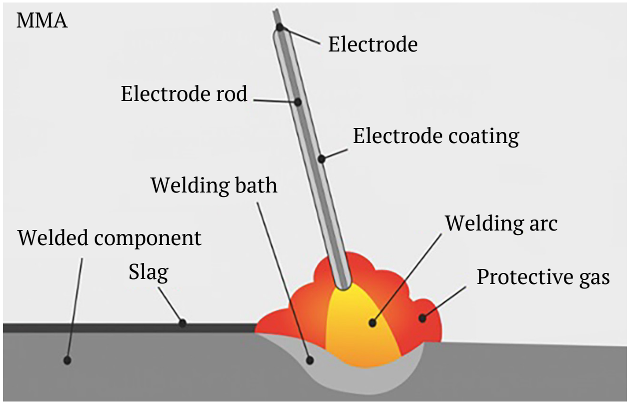

Figure 1. MMA (manual metal arc)
Source: Main types of welding (2020)

Metal inert gas (MIG) and metal active gas (MAG) use an automatically fed electrode wire that delivers a higher welding quality than manual arc welding (Fig. 2). This welding method is widely used in remanufacturing applications where production and cost-effective processes with high quality are important.

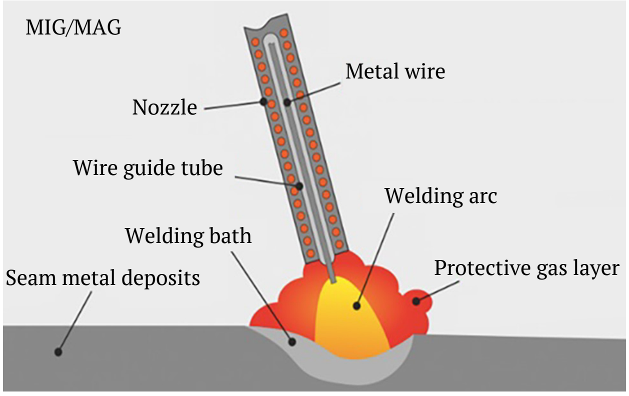

Figure 2. Metal inert gas (MIG) and metal active gas (MAG)
Source: Main types of welding (2020)

Automatic submerged arc welding uses a flux that protects the weld pool from weathering. This method is designed for thick-walled structures, special steels, and high-performance welds in industrial environments where maximum welding quality and uniformity are required. Each of these methods has its advantages and limitations, and the choice of a specific welding method in the rehabilitation process depends on the welding quality requirements, the characteristics of the object being repaired and the availability of equipment. The use of welding in the restoration of metal structures has several significant advantages that make it the only effective method.

Welding ensures a high-quality joint that is comparable to the strength of the base metal. This guarantees a long-lasting repair and high resistance to stress and environmental influences. Welding can be a more cost-effective way to repair damage, especially in cases where replacing entire components is not cost-effective or an option. The use of welding can save money while maintaining the functionality and useful life of the facility. Welding is a versatile method that can be used to repair a wide range of metal components, from the smallest parts to large structures (Chludzinski *et al.*, 2021). This versatility makes welding an important tool in the restoration of a wide variety of objects.

Thus, welding proves to be not only an effective but also a practical solution for the restoration of damaged metal structures due to its durability, cost-effectiveness, versatility, and speed of repair work. The choice of welding type for a particular project or restoration work is influenced by several important factors that determine the quality and efficiency (Ghiasvand *et al.*, 2021):

- chemical and physical parameters of the base metal;
- operating conditions of the structure;
- conditions of repair operations;
- welding position;
- units in the repair batch;
- availability of qualified employees;
- repair timeframes.

Furthermore, the choice of welding type may be limited by budgetary considerations. Some methods can be costly in terms of equipment and materials, so it is important to balance cost with capability. Welding work should be carried out by qualified specialists with relevant experience and certificates. Welding plays an important role in the rehabilitation and maintenance of industrial and energy facilities.

Welding can effectively repair and strengthen boiler and turbine vessels that have been damaged by cracks or other defects. Welds reliably seal damaged areas, ensuring the safe and efficient operation of the equipment. Welding is used to repair and strengthen damaged or old pipelines. This prevents leakage of liquids or gases and ensures reliable and safe operation of the system. Welding can be used to manufacture and install new parts on machines, machinery, and other equipment that have worn out or failed (Zhang *et al.*, 2021). This extends the service life of the equipment and ensures its efficient operation. Welding is used to connect new structures or parts to existing systems when modernising or expanding industrial and energy facilities. This ensures the stability and reliability of structures that can withstand heavy loads and keep the facility running smoothly. All of these examples demonstrate the possibilities and diversity of welding applications in the rehabilitation and maintenance of industrial and energy facilities.

When repairing and restoring industrial and energy facilities, the choice of welding technology is one of the key aspects of project success. A variety of welding processes, including arc, gas, surfacing and electron beam welding, offer a wide range of possibilities for the restoration of various types of structures and materials (Skoblo *et al.*, 2001). The choice of a particular technology depends on several factors. The material to be welded is important in determining the most effective method. Different materials have different properties and react differently to different welding processes. For example, different methods can be used to weld steels, such as Tungsten Inert Gas (TIG) for high quality and precise welding, or Metal Inert Gas (MIG) for fast and high productivity welding (Kesse, 2021). An important aspect is the size and shape of the welded joint. For large structures or bulky components, automated methods such as submerged arc welding or laser welding can be effective, allowing for faster turnaround times without sacrificing quality. At the same time, for small or complex parts, more precise methods such as spot welding or vacuum welding can be chosen. The technical requirements for a welded joint include requirements for strength, tightness, thermal effects and other parameters. The choice of technology must meet these requirements and ensure compliance with quality and safety standards. All of these factors are considered when choosing a welding technology for the rehabilitation of industrial and energy facilities. The right choice of technology not only allows for efficient performance of the task but also ensures high quality and durability of the restored facilities, which is important for the stable operation of industrial systems (Korzhyk *et al.*, 2017).

The calculation of welded structures is an integral part of the process of rehabilitation and construction of industrial and energy facilities. There are various welding methods used for this purpose. Today, the most common are electric welding, which can be arc or resistance welding, and gas welding. In addition, there are manual, semi-automatic and automatic welding methods. Depending on how the elements to be welded are arranged, there are different types of joints: butt, corner, lap and tack. Before starting welding, a set of calculations must be performed that consider various aspects and requirements of the structure. The calculations include the choice of materials. This is important because the material determines the strength, durability, and other characteristics of the structure. For example, corrosion-resistant materials can be used for facilities that operate in aggressive environments, and heat-resistant materials can be used for structures that are exposed to high temperatures. The next important step is to determine the dimensions of the welded joints. This includes selecting the optimal weld parameters, such as penetration depth, width, and length. The correct weld size ensures not only strength but also ease of use during the welding process (Li *et al.*, 2022). Another important aspect is the calculation of material thickness. The thickness of the material determines not only the strength but also the resistance of the structure to external influences. When restoring industrial or energy facilities, properly performed calculations ensure the required strength, reliability, and safety of the structure. They are used to avoid unforeseen situations and ensure the long-term and efficient operation of the facility throughout its entire service life.

Reliability is assessed by the ability of a product to perform its functions over a certain period of service life while maintaining its characteristics within the limits provided for its operation. The quality of welded joints depends on many factors, which can be divided into two main categories: technological and structural and operational. Technological factors include welding materials, equipment, preparation, and execution of welding operations, as well as the experience and qualifications of the operator. As for the design and operational aspects, these include the properties of the base material, product design, operating conditions, quality control methods and system, and the requirements of standards. All of these factors must be considered and controlled to effectively manage welding quality. After the welding process is complete, quality control of welded joints is an important step. This is a necessary procedure to ensure that the welded joint meets the established standards and is free from defects that could adversely affect the safety and reliability of the structure.

Product quality is defined as a set of characteristics that affect its suitability to meet the established needs following its intended use. Product quality control is aimed at ensuring that these characteristics meet the established requirements, which can be defined in standards, drawings, specifications, product passports and other regulatory and technical documentation. Quality parameters of welded joints are established based on various characteristics shown in Figure 3.

Weld strength

- Physical and chemical properties of the weld should be close to the properties of the base metal of the structure
- Homogeneous structure of the seam and the seam zone
- Absence internal residual stresses

Reliability of the received connection

- Ability to withstand repeated cyclic applied loads
- Ability to operate within guarantee period without visual changes

Absence of defects

- Visual absence of pores and cracks
- No detected defects on special inspection equipment

Correct chemical composition of the weld

- Particularly important for operating conditions in harsh corrosive or thermal industries

Figure 3. Criteria that determine the quality of weld seams
Source: compiled by the author

One of the inspection methods is visual inspection, during which the inspector assesses the appearance of welded joints for cracks, unsuitability, and other defects. In addition, non-destructive testing methods are also used, including ultrasonic and radiographic inspection. These methods can reveal internal defects that may not be visible by visual inspection, providing a more complete assessment of the quality of welded joints. It is also important to conduct mechanical tests, such as tensile or impact tests, which allow us to assess the strength and deformation properties of welded joints (Ran *et al.*, 2021). Quality control of welded structures is not only a means of verifying compliance with standards, but also an important component in the process of ensuring the safety and reliability of industrial and energy facilities. Responsible implementation of this procedure is key to preventing potential industrial accidents and ensuring the long-term and safe operation of structures. As shown in Figure 4, inspection methods are divided depending on where they are applied in the production process, at a certain stage of the technological process.

Stage 1. Initial control

- Quality control and conformity of welded materials
- Certification of the main materials and surface cleanliness
- Analysis of the conformity of drawings and the quality of design development
- Inspection of the quality of pre-assembled components (if any)
- Confirmation of the quality of personnel training for a particular type of work

Stage 2. Operational process control

- Compliance of welding parameters with the specified and applied ones
- Consistency of assembly quality (gaps)

Stage 3. Final

- Hardness of the weld and weld zone
- Compliance with geometric parameters
- Visual absence of pores and cracks

Stage 4. Control by special equipment (if necessary)

- Ultrasonic inspection or ultrasonic diagnostics
- Destructive

Figure 4. The general approach to welding quality control depends on the complexity of the structure
Source: compiled by the author

Initial inspection includes inspection of both the basic and welding materials that make up the products and the finished welded assemblies and parts that come from other enterprises or sites. At this stage, the operating capability of the welding equipment and the qualifications of the workers are also assessed. Operational inspection includes an assessment of the welding process that is carried out after a specific operation has been performed (e.g., pre-welding preparation inspection, weld seam assembly inspection), as well as inspection during the welding process itself. Final testing is the evaluation of the finished weld after all manufacturing processes have been completed. This stage includes an external inspection of the product, measurement of its dimensions and testing. During acceptance testing, it is checked whether the manufactured product meets the requirements set out in the regulatory and technical documentation.

Based on this inspection, a decision on the suitability of the structure for use is made. Acceptance testing is the final and most critical step in the production of welded joints. Thus, welding technologies, calculation of welded structures and quality control of welded joints are key stages in the restoration of industrial or energy facilities that ensure their strength, reliability, and safety.

DISCUSSION

The use of welding processes in the restoration of industrial or energy facilities is a key aspect of maintenance and repair in modern industrial production. It is an effective way to repair damaged components and ensure their functionality and durability. It is important to note that welding is an extremely effective method of repairing damaged parts or components of industrial structures. It produces strong welded joints that can withstand heavy loads and operating conditions. Various welding methods, such as arc welding, gas welding, surfacing and others, enable the restoration of various types of materials and structures, making them versatile in various manufacturing industries. The use of welding in the restoration of industrial facilities can significantly reduce repair costs compared to replacing damaged parts. This is a cost-effective approach, especially in cases where replacing components requires significant time and resources.

Welding processes used in the restoration of industrial and energy facilities have a significant impact on the efficiency of production processes and resource conservation. This approach allows elements and structures that have been damaged or worn out to be preserved and restored instead of being completely replaced. This saves resources that would otherwise be spent on manufacturing new components, as well as reducing waste and negative environmental impact (Mehmeti *et al.*, 2019). Keeping facilities running smoothly is another important aspect of the use of welding in remanufacturing. Replacing damaged or worn components without delay avoids production downtime and ensures continuous operation of industrial and energy facilities (Sidliarenko, 2023). This approach to maintenance and repair helps to ensure production stability, reduce maintenance costs, and increase the overall efficiency of industrial enterprises. Thus, welding processes in the restoration of industrial or energy facilities are a necessary and effective means of ensuring the reliability and productivity of industrial equipment. This approach helps to conserve resources, reduce costs, and ensure the smooth operation of production processes.

According to A. Ahola *et al.* (2022), study of the fatigue characteristics of welded parts of an old, deteriorated steel railway bridge is an important aspect when considering its rehabilitation. Fatigue performance determines the ability of a material to withstand repetitive loads, which is critical for the safety and durability of a structure. In the context of a railway bridge, which is subjected to significant dynamic loads from trains, the fatigue analysis of the joints and welds plays a crucial role in determining the extent of damage and the possibility of repair. These data are consistent with the theses presented in the previous section. The study of fatigue performance of welded bridge components involves the analysis of many factors, including the geometry of the welded joints, the type of materials used, the load history and the operating conditions. Understanding these characteristics helps engineers develop rehabilitation strategies and ensure the safety of the rehabilitated structure.

Referring to the definition of K. Łyczkowska & J. Adamiec (2022), the phenomena associated with the cracking of repair welds are an important aspect of welding technologies. Cracking can occur as a result of various factors, such as incorrectly selected welding parameters, the presence of internal stresses in the material, insufficient surface preparation, and metal structure features. These phenomena can lead to the formation of microcracks in the welded joint, which can significantly reduce the strength characteristics of the weld and impair its durability. It is worth noting that several criteria must be considered, and appropriate measures taken to prevent cracking of welds in repair. This may include the correct choice of welding materials, considering their composition and heat treatment, optimal adjustment of welding equipment, control of stresses in the material, as well as ensuring sufficient surface pretreatment and removal of possible defects. This approach minimises the risk of cracking and ensures a high-quality repair joint.

H. Zhou *et al.* (2021) determined that predicting and reducing out-of-plane welding deformations are key challenges in the manufacture of typical blocks such as semi-submersible lifting and dismantling platforms. These deformations can occur due to uneven thermal effects during welding, leading to distortion of geometric parameters and structural failure. Even minor deformations can have a significant impact on the subsequent assembly and operation of the platform, so their prediction and control are important stages of the production process. These results confirm the above study, as various methods and technologies are used to reduce out-of-plane welding deformations. This may include optimising the welding process by selecting optimal parameters, using special clamping, and fixing devices, as well as applying local heating and stress control methods. In addition, preliminary modelling and analysis of potential deformations using modern software tools plays an important role (Kostenko *et al.*, 2023). This integrated approach allows for effective control of the welding process and minimisation of the negative effects of deformation on the quality and reliability of the final product.

B.E. Kogo (2021) demonstrated that the analysis of thermal and residual stresses in welded joints of clad pipelines is a key aspect of the welding process. Clad pipelines, consisting of a base steel pipe and a protective coating layer, pose special technological challenges during the welding process. When heated during the welding process, the materials expand and contract, which can lead to thermal stresses in the welded joints. Residual stresses in welded joints can occur due to uneven cooling and shrinkage of the metal during the cooling process after welding. These stresses can affect the mechanical properties of the joint and the ability of the pipeline to withstand operational loads such as pressure and temperature. In agreement with this opinion, various numerical modelling and experimental analysis methods are used to analyse thermal and residual stresses in welded joints of clad pipelines. Numerical models based on finite element methods allow for predicting the stress distribution in the joints and optimising the welding process to minimise their impact. Experimental methods, such as strain measurements and bell tensile testing, are used to verify and validate the results of numerical modelling and assess the quality of welded joints (Oliinyk & Tuts, 2023).

As noted by Y. Li *et al.* (2022), a new approach to occupational health risk assessment in welding projects includes a comprehensive approach to analysing the potential hazards faced by welders in the work environment. This approach considers not only the physical aspects of the job, such as exposure to hazardous substances and working conditions but also the psychological and social factors that can affect the overall well-being of welders. The application of a new approach to occupational health risk assessment in welding projects allows for a more accurate and comprehensive assessment of potential health hazards to welders and the development of appropriate measures to prevent and minimise them. Analysing the results and conclusions obtained, it is possible to note that such an approach may include training personnel in safe working practices, the use of special protective equipment, regular medical examinations and health monitoring, as well as regular audits of the working environment to identify and eliminate potential hazards.

J. Choi *et al.* (2023) determined that modelling predictive maintenance systems for laser welders on continuous galvanising lines based on machine learning with welder control data is an important area of research in industrial production. This system can predict possible failures or malfunctions in the equipment used for laser welding based on data collected in real-time from the welding process systems. One of the main advantages of using machine learning models in predictive maintenance systems is their ability to process large amounts of data and identify complex relationships between various welding process parameters and possible malfunctions. This allows for a quick response to potential problems and minimises equipment downtime, which in turn helps to improve production efficiency.

CONCLUSIONS

Welding processes are a critical aspect of modern engineering practice in the rehabilitation of industrial and energy facilities. Not only does it allow for the restoration of damaged or consumable components, but it also ensures their durability and functionality. Welding is a technology that creates stable and strong joints that can withstand significant mechanical loads and harsh environments, making them indispensable for industrial applications. This is especially important in industrial production environments where equipment and structures are subject to significant wear and tear and require reliable connections to ensure smooth operation and worker safety.

For decades, around the period 1950-2000, welding trends were directed in two aspects: increasing productivity and quality of the joint, where the amount of applied metal was given precedence, and this was the impetus for the development of submerged arc welding, electro slag welding. However, this required highly skilled workers and high equipment costs. In recent years, advances in inverter technologies, a reduction in the metal intensity of structures, and a shift from specific welder skills to semi-automation, even manual welding was observed. Further development of welding is seen in the robotisation of the process and the unification of welding materials. Various welding methods, such as arc welding, gas welding, surfacing and others, provide versatility in restoring different types of materials and structures, which allows them to be widely used in various industries. In addition, welding in the restoration of facilities can significantly reduce repair costs compared to replacing damaged parts, making it a cost-effective solution.

Welding processes used in the refurbishment of industrial and energy facilities help to conserve resources, increase the efficiency of production processes, and ensure production stability. This maintains the uninterrupted operation of facilities and ensures the reliability and performance of industrial equipment. Thus, the use of welding processes in the rehabilitation of industrial and energy facilities is an important element of modern industrial practice, ensuring efficiency, cost-effectiveness, and reliability in production processes. In addition, the use of welding processes opens up opportunities for the introduction of innovative technologies and methods in the restoration of industrial and energy facilities. This contributes to the continuous improvement of the quality and efficiency of repair work, which in turn contributes to the competitiveness of enterprises. Thus, the use of welding in the rehabilitation of industrial and energy facilities plays an important role in ensuring the sustainability and development of the industrial sector. The impact of the welding process parameters on the structure and properties of the restored materials should be further studied.

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CONFLICT OF INTEREST

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REFERENCES

[1] Ahola, A., Lipiäinen, K., Afkhami, S., Lilja, H., & Björk, T. (2022). Fatigue performance of the welded details of an old, demolished steel railway bridge. *Engineering Structures*, 256, article number 113966. doi: 10.1016/j.engstruct.2022.113966.

[2] Bondarenko, Yu.K., & Loginova, Yu.V. (2022). Use of statistical methods to support the required quality of welded products (Review). *Technical Diagnostics and Non-Destructive Testing*, 2, 44-53. doi: 10.37434/tdnk2022.02.06.

[3] Chludzinski, M., dos Santos, R.E., Churiaque, C., Ortega-Iguña, M., & Sánchez-Amaya, J.M. (2021). Pulsed laser welding applied to metallic materials – A material approach. *Metals*, 11(4), article number 640. doi: 10.3390/met11040640.

[4] Choi, J.S., Choi, S.W., & Lee, E.B. (2023). Modeling of predictive maintenance systems for laser-welders in continuous galvanizing lines based on machine learning with welder control data. *Sustainability*, 15(9), article number 7676. doi: 10.3390/su15097676.

[5] Ghiasvand, A., Yavari, M.M., Tomków, J., Grimaldo Guerrero, J.W., Kheradmandan, H., Dorofeev, A., Memon, S., & Derazkola, H.A. (2021). Investigation of mechanical and microstructural properties of welded specimens of AA6061-T6 alloy with friction stir welding and parallel-friction stir welding methods. *Materials*, 14(20), article number 6003. doi: 10.3390/ma14206003.

[6] Kachynskyi, V.S., & Koval, M.P. (2021). Registration of technological parameters and quality control in the process of press welding of pipes with a magneto-controlled arc. In *Proceedings of the 21st International Scientific and Practical Conference "Quality, Standardisation, Control: Theory and Practice"* (pp. 25-29). Kyiv: Association of Machinery Technologists of Ukraine.

[7] Kesse, M.A. (2021). *Artificial intelligence: A modern approach to increasing productivity and improving weld quality in TIG welding*. Lahti: LUT University Press.

[8] Kogo, B.E. (2021). *Thermal and residual stress analysis of welded joints in cladded pipelines*. London: Brunel University London.

[9] Korzhyk, V., Khaskin, V., Voitenko, O., Sydorets, V., & Dolianovskaia, O. (2017). Welding technology in additive manufacturing processes of 3D objects. *Materials Science Forum*, 906, 121-130. doi: 10.4028/www.scientific.net/MSF.906.121.

[10] Korzhyk, V.M., Khaskin, V.Yu., Illyashenko, E.V., Peleshenko, S.I., Grynyuk, A.A., Babych, O.A., Alyoshin, A.O., & Voitenko, O.M. (2024). Hybrid laser-plasma welding: Efficiency and new possibilities (review). *The Paton Welding Journal*, 1, 13-21. doi: 10.37434/tpwj2024.01.02.

[11] Kostenko, M.V., Sheveleva, A.E., Gergel, I.Y., & Loboda, V.V. (2023). Plane deformation of a piezoelectric bimaterial with two electrically conductive and charged interface cracks. *Bulletin of Cherkasy State Technological University*, 2, 146-154. doi: 10.24025/2306-4412.2.2023.278565.

[12] Kryvyi, O.F., & Morozov, Yu.O. (2022). Mathematical modeling of the influence of structural inhomogeneities on the strength of welded joint so. In *Proceedings of the International Scientific and Technical Conference "Ship Electrical Engineering, Electronics and Automation"* (pp. 44-47). Odesa: Odesa Maritime Academy.

[13] Lebedev, V., Brykov, M., & Makarenko, N. (2022). Combination of processes and combined solutions in improving the technique and technology of arc welding and fusion. In *Proceedings of the International Scientific and Technical Conference "Strength and Durability of Modern Materials and Structures"* (pp. 134-136). Ternopil: V.A. Palianytsia.

[14] Li, Y., Liu, W., Chen, Z., Jiang, L., & Ye, P. (2022). A novel approach for occupational health risk assessment and its application to the welding project. *Journal of Cleaner Production*, 378, article number 134590. doi: 10.1016/j.jclepro.2022.134590.

[15] Łyczkowska, K., & Adamiec, J. (2022). The phenomena and criteria determining the cracking susceptibility of repair padding welds of the Inconel 713C nickel alloy. *Materials*, 15(2), article number 634. doi: 10.3390/ma15020634.

[16] Main types of welding. (2020). Retrieved from https://plasmatec-weld.com.ua/news/osnovni-vidi-zvaryuvannya.

[17] Mehmeti, B., Kelmendi, J., Iiljazi-Shahiqi, D., Azizi, B., Jakovljevic, S., Haliti, F., & Anić-Milošević, S. (2019). Comparison of shear bond strength orthodontic brackets bonded to zirconia and lithium disilicate crowns. *Acta Stomatologica Croatica*, 53(1), 17-27. doi: 10.15644/asc53/1/2.

[18] Nalle, C.Y., Aditya, M.B., Putra, F.G., Nalle, M.N., & Sumarta, R.P. (2024). Analysis of electric current on aluminum plate welding using MMA (Manual Metal Arc) method. In *Proceeding of 1st International Conference on Artificial Intelligence, Navigation, Engineering, and Aviation Technology (ICANEAT)* (pp. 144-146). Rogojampi: Akademi Penerbang Indonesia Banyuwangi.

[19] Novodranov, A.S., Topchev, D.D., Mangold, A.M., Shapovalov, E.V., & Kolyada, V.O. (2023). Use of welding additive technologies in manufacture of metal parts of a complex shape (Review). *Automatic Welding*, 1, 16-21. doi: 10.37434/as2023.01.03.

[20] Oliinyk, A., & Tuts, O. (2023). Complex mathematical process of harmful substances spread during main gas pipelines accidents. *Ecological Safety and Balanced Use of Resources*, 14(1), 54-60. doi: 10.31471/2415-3184-2023-1(27)-54-60.

[21] Ran, M.M., Sun, F.F., Li, G.Q., & Wang, Y.B. (2021). Mechanical behaviour of longitudinal lap-welded joints of high strength steel: Experimental and numerical analysis. *Thin-Walled Structures*, 159, article number 107286. doi: 10.1016/j.tws.2020.107286.

[22] Sidliarenko, A. (2023). Mathematical models of road construction, reconstruction and repair under conditions of uncertainty. *Bulletin of Cherkasy State Technological University*, 3, 113-127. doi: 10.24025/2306-4412.3.2023.287845.

[23] Skoblo, T.S., Vlasovets, V.M., & Moroz, V.V. (2001). Structure and distribution of components in the working layer upon reconditioning of parts by electric-arc metallization. *Metal Science and Heat Treatment*, 43(11), 497-500. doi: 10.1023/a:1014857107509

[24] Tanasković, D., Petrović, S., Đorđević, B., Matavž, A., & Mijatović, T. (2021). Algorithm for defining quality of base material for repair welding. *Structural Integrity and Life*, 21(3), 279-284.

[25] Zhang, Y.M., Wang, Q.Y., & Liu, Y.K. (2021). Adaptive intelligent welding manufacturing. *Welding Research*, 100(1), 63-83. doi: 10.29391/2021.100.006.

[26] Zhou, H., Wang, J., Zhang, H., Liu, J., & Mo, Z. (2021). Prediction and mitigation of out-of-plane welding distortion of a typical block in fabrication of a semi-submersible lifting and disassembly platform. *Marine Structures*, 77, article number 102964. doi: 10.1016/j.marstruc.2021.102964.

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Застосування процесів зварювання у відновленні промислових та енергетичних об'єктів

Анотація. Дослідження є необхідним у зв'язку з постійним розвитком і змінами у виробничому середовищі та технологічних вимогах для забезпечення підвищення безпеки, міцності та ефективності промислових та енергетичних об'єктів. Мета даного дослідження – аналізувати методи та стратегії, спрямовані на підвищення ефективності зварювання та контролю якості з'єднань, з урахуванням досягнення більшої стабільності та надійності енергетичних об'єктів. Серед використаних методів слід зазначити, такі як спостереження, порівняльно-описовий, моніторинг, абстрагування та інші. У дослідженні було проведено аналіз різних зварювальних технологій та їх вплив на якість зварних з'єднань. Розглянуті різні методи розрахунку зварних конструкцій з урахуванням матеріалів та технічних вимог. Крім того, було досліджено різні методи контролю якості зварних з'єднань, зокрема візуальний огляд та неруйнівний контроль. В результаті дослідження було встановлено, що правильний вибір технології, розрахунків та контролю якості дозволяє підвищити міцність, надійність, безпеку та економічну обґрунтованість зварених конструкцій. В досліджених зварювальних технологіях та використаних методах контролю якості є більш ефективні для застосування в специфічних умовах і не існує загального рішення. Крім того, виявлено, що правильне застосування цих методів може значно скоротити час відновлення та підвищити загальну продуктивність процесу відновлення промислових та енергетичних об'єктів. Отже, оптимальне використання зварювальних технологій та методів контролю якості може значно покращити ефективність та довговічність промислових та енергетичних об'єктів. Практичне значення дослідження полягає в сприянні підвищенню безпеки, надійності та ефективності відновлення промислових та енергетичних об'єктів шляхом вдосконалення процедур контролю якості зварних з'єднань

Ключові слова: неруйнівний контроль; мікроструктура; міцність з'єднання; електроди; методи контролю якості

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Analysis and optimization of torsion shafts in the context of improving the strength and durability of a light armoured vehicle

Abstract. In the context of the continuous development of armoured vehicles and the increasing requirements for the strength and efficiency of armoured vehicles, the study and improvement of torsion shafts becomes relevant to ensure high service life and optimal functioning. The aim of this study is to analyse the torsion shafts of light armoured vehicles to identify possible areas of optimization to increase the strength and durability of these vehicle elements. The methods used include the analytical method, classification method, functional method, statistical method, synthesis method, and others. As a result of the study, a comprehensive analysis and optimization of torsion shafts for light armoured vehicles was carried out to increase their strength and durability. The choice of high-strength material and weight consideration helped to reduce the weight of the vehicle, increasing its efficiency. Geometric design included the use of advanced techniques to optimize the shaft shape, and stress and strain analysis helped determine the optimum parameters. The use

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of computer modelling and simulation simplified the analysis of the shaft's behaviour under load. The use of safety factors and consideration of impact loads during operation helped to improve the reliability and durability of the structure. The use of the latest materials and manufacturing technologies allowed achieving the optimum parameters of the transmission element. Testing of the prototypes in real conditions confirmed their efficiency and durability. The optimization of weight and weight distribution was aimed at improving the stability of the armoured vehicle, taking into account the requirements of a particular application and manufacturer. The results indicate the potential for improving the design of torsion shafts to increase the performance and stability of light armoured vehicles. This study makes an important contribution to science, as the identified optimizations and improvements in the design of torsion shafts of light armoured vehicles contribute not only to increasing their strength and durability, but also to the rational use of resources and increasing the overall performance of the vehicle

Keywords: geometry; composite materials; suspension; smoothness of movement; tension; deformations

INTRODUCTION

A detailed study of the aspects of torsion shafts, especially in the context of their use in light armoured vehicles, is an important task. This is due to the constant development of modern armoured vehicles and the growing requirements for their strength and efficiency. Consideration of this topic allows identifying the most effective ways to improve the design and use of torsion shafts to ensure high performance and stability of armoured vehicles in modern conditions. Torsion shafts, as key components of the transmission, are important parts that carry a significant part of the mechanical load. Their role is to transmit rotational motion and influence the overall performance and stability of the vehicle. Improvements in their design can lead to significant improvements in strength, durability, and weight and size characteristics.

Considering the aspects of the study, an important task is to address specific challenges, namely, improving the configuration of torsion shafts for light armoured vehicles. One of the key issues is to achieve an appropriate balance between the strength and weight of torsion shafts to ensure high durability and efficiency under heavy loads. Another important issue is the selection of a suitable material for the shafts that has high strength and endurance under various operating conditions. These problems define the current research objectives aimed at improving the design and functional characteristics of torsion shafts in the context of the requirements of modern armoured vehicles.

According to the study by M. Manziak *et al.* (2021), the importance of optimizing torsion shafts for light armoured vehicles is gaining special emphasis due to the increasing technical requirements for armoured personnel carriers. The need to improve these elements to meet modern requirements for vehicle efficiency and durability is emphasized. The study does not consider aspects related to the impact of the operating environment on the strength of torsion shafts and their possible adaptation to different operating conditions of armoured vehicles. In the work by I. Polyak *et al.* (2023), the authors emphasize that a detailed analysis of the geometry and materials used in torsion shafts is a key step in finding optimal solutions to ensure their strength and reliability. The importance of a systematic analysis of these parameters to achieve optimal shaft characteristics in the context of their operation in armoured vehicles is indicated. The paper does not address issues related to the dynamics of torsion shaft operation and the possibility of their optimal adaptation to different modes of operation of armoured vehicles.

According to the study by I. Kyrychenko *et al.* (2021), the importance of using computer modelling to estimate stresses and strains at different points of the shaft emphasizes the need for modern approaches to studying this topic. The need to apply modern methods in the study of this topic to achieve more accurate and comprehensive results in analysing the behaviour of these elements is highlighted. The study does not take into account the impact of external factors, such as temperature changes or exposure to aggressive environments, on the strength and service life of these elements. Researchers M.V. Sklyarov & O. Shapovalov (2021) note that improved geometry and the use of high-strength composite materials are becoming key factors in reducing shaft weight and improving the efficiency of an armoured vehicle. The importance of these aspects for achieving optimal transmission element parameters was emphasized. The researchers do not consider the possible effects of operating conditions, such as wear or abrasion, on the strength and service life of the torsion shaft and composite materials.

A study by M. Hrubel *et al.* (2023) emphasizes that prototype testing plays a crucial role in confirming the effectiveness of proposed changes and their impact on durability and sustainability. The importance of conducting comprehensive testing to reliably assess the response and practical effectiveness of the modifications is highlighted. The paper does not consider the possibility of adapting the test results to different operating conditions of armoured vehicles in real-life scenarios. The paper by M. Tkachuk *et al.* (2022) raises an important question about the potential for improving the design of torsion shafts as a way to increase the performance and sustainability of light armoured vehicles in the modern military context. The researchers identify the relevance of developing technologies to optimize shafts in order to improve their functionality within current military requirements. The study does not take into account ergonomics and safety in the design of shafts, which is significant in military use.

This study aims to analyse torsion shafts used in light armoured vehicles. To achieve this goal, the following tasks have been identified:

1. To conduct a safety analysis, considering the relevant safety factors and assessment of impact loads during operation.

2. To determine a high-strength material for the torsion shaft, providing high strength and endurance under heavy loads, considering the lightness of the selected material to reduce the overall weight of the vehicle.

3. To analyse in detail and evaluate the possibilities of using modern technologies such as composite as or high-tech alloys, and implement advanced manufacturing methods, including additive technologies and CNC machining.

MATERIALS AND METHODS

The analytical method helped to identify potential weaknesses and determine the optimal parameters, including stress concentration points and other possible problems. The study of material selection contributed to the selection of a high-strength material that meets the requirements for sustained loading, thereby ensuring increased strength and service life of the torsion shafts.

Using a statistical method, the critical parameters and their interaction were identified, which allowed the development of optimization strategies to achieve the best results in the production of torsion shafts. The study of safety factors proved to be key to ensuring the reliability and durability of the design in real-world operation. The deduction method helped to formulate general principles and approaches to optimizing torsion shafts. Determining the cause-and-effect relationships between the shaft parameters and its characteristics made it possible to consider the influence of various factors on its functionality. The functional method was used to determine the parameters and configurations of torsion shafts aimed at achieving maximum strength and optimal performance. The functional method made it possible to take into account the influence of various factors, such as load, rotational speed and temperature conditions, on the operation of torsion shafts.

By applying the synthesis method, new concepts and strategies for optimizing torsion shafts were developed, considering a comprehensive approach to their improvement. This method allows combining various aspects, such as material properties, geometrical parameters, safety factors and the use of the latest technologies, to achieve optimal results. The classification method helped to define the main characteristics of torsion shafts and their properties, considering the various factors that affect their functioning. The study of a large amount of data using this method allowed creating a classification system that takes into account different types of shafts, materials, geometry and operating conditions. The induction method was used to generate new ideas and concepts aimed at improving torsion shafts in light armoured vehicles. This method provided new insights into potential areas of improvement in shaft geometry, materials, and manufacturing techniques.

The use of the generalization method in the context of the study of torsion shafts in light armoured vehicles allowed systematizing and summarising the results obtained to determine the chosen optimization path. This method allows for a detailed study of a large amount of data and takes into account the various influences of factors on torsion shafts. Geometric design, based on advanced techniques, helped to achieve the optimal shaft shape, ensuring efficient load distribution, and increasing its stability. The use of computer modelling and simulation software ensured high accuracy in assessing the performance of torsion shafts under various operating conditions. The use of the latest technologies in production, such as additive technologies and computer numerically controlled machines (CNC), contributed to the accurate implementation of the designed parameters and ensured the high quality of the manufactured torsion shafts.

This comprehensive approach to the study and optimization of torsion shafts for light armoured vehicles takes into account important aspects necessary to improve the performance, strength, and durability of vehicles in a military context.

RESULTS AND DISCUSSION

Optimization of structures and characteristics of the suspension of light armoured vehicles to improve passability and dynamic properties

Traditionally, the main design parameters and suspension characteristics of general-purpose vehicles have been formulated taking into account the rated loads and driving conditions on Category I and II roads with asphalt concrete pavement. At the same time, all-wheel drive modifications, known as multipurpose vehicles, which have remained the basis of the Armed Forces of Ukraine's fleet since the days of the Union of Soviet Socialist Republics (USSR), were based on the use of the maximum equipment with basic general-purpose models with minor modifications. These modifications included changes to the drive axles, a lower transmission range, a single-slope layout to meet off-road requirements and allow for a 6×6-wheel configuration, a centralized tyre pressure management system and other similar changes. These additional changes were introduced to improve the vehicle's off-road capability. However, in the case of off-road driving, in addition to the issues of off-road traction, the actual maximum speed is limited by an artificially set crew corresponding to the wheeled vehicles. This limitation is due to the achievement of extreme driving discomfort due to significant vibration oscillations caused by bumps in the road. These limits of vibration load and the permissible duration of their impact on the crew are already known and described in the modern scientific literature on wheeled vehicles (Nussupbek *et al.*, 2023).

The development of a new generation of tactical vehicles was determined by significant requirements for mine and ballistic protection, which were taken into account at the conceptual and working design stage for new models. The traditional way to protect against mines and bullets was to improve the existing vehicles of the previous generation by installing modern protective equipment and making appropriate changes to the serial designs of the chassis, frame, suspension, and other components. However, this approach is complicated because it significantly affects the driving dynamics of vehicles that were not designed to accommodate the increase in overall weight. Another important aspect was the increase in maximum driving speeds, especially off-road. This is because when driving on paved roads, the maximum speed is limited primarily by engine power, and there is a steady upward trend in this parameter. This also applies to heavy tactical vehicles with a GVWR of 12 to 40 tonnes, which have changed their top speeds from 70-80 km/h to 105-120 km/h over the past fifty years with the introduction of the KAMAZ-4310 model (Krainyk *et al.*, 2022).

In today's world, light armoured vehicles are becoming an increasingly important component of the transport environment, especially in the face of growing demand for safety and mobility (Fig. 1). The efficient operation of such vehicles depends on numerous factors, among which the design and quality of the components used, in particular, the torsion shafts, are of key importance. The analysis and optimization of these shafts are becoming an integral part of the development process to improve the strength and durability of light armoured vehicles. To achieve this goal, an important step is the selection of suitable materials for the torsion shaft construction. The use of high-strength alloys or special composite materials can significantly improve the strength and lightness of the shaft, providing an optimal balance between functionality and service life (Feyye *et al.*, 2021). Optimizing the torsion shaft geometry plays a key role in achieving high performance. Taking into account stress concentration points, load analysis, and the influence of external factors allows for optimal shaft shapes and geometries designed for maximum strength and durability. The use of computer modelling and simulation software plays an important role in the development of torsion shafts. It allows virtually testing different designs and materials, determining the optimal parameters, and predicting the behaviour of the shaft under different loading conditions. Another important aspect is the consideration of safety factors. The use of safety factors helps ensure that the torsion shaft can withstand not only standard operating conditions, but also unforeseen situations that may arise during extreme conditions. The final stage is the development of prototypes and their intensive testing in real-world conditions. This stage allows verifying the actual efficiency and strength of the optimized torsion shaft, identifying possible shortcomings, and making the necessary adjustments.

Figure 1. Light armoured vehicle
Source: Light armoured vehicles for the Armed Forces are undergoing the final stage of national trials (2019)

The analysis and optimization of torsion shafts for light armoured vehicles is a multidisciplinary task that requires the interaction of various engineering disciplines. By integrating aspects of material science, geometric design, software modelling and prototype testing, engineers can create torsion shafts that meet high standards of strength and durability, ensuring optimum performance of light armoured vehicles.

Material selection for torsion shaft optimization: balance of strength and lightness

In today's world, where technology is improving every day, the development of vehicles, especially light armoured vehicles, is a task that requires high engineering and scientific expertise. Optimization of torsion shafts, as key elements of the drivetrain, is becoming an important aspect to ensure the efficiency, strength, and durability of vehicles.

In this context, the choice of material for torsion shafts is determined not only by its strength, but also by its lightness, where the balance of these characteristics becomes the key to success.

The strength of torsion shafts is a crucial factor, as these elements are subjected to significant rotational loads during the movement of an armoured vehicle (Huda, 2021). Stress and strain analysis allows engineers to determine how the material can withstand these loads and avoid possible flaws or loss of efficiency. Thus, choosing a material with high strength and fatigue resistance is a top priority. However, the issue of material lightness is equally important. In modern automotive and military equipment, great attention is paid to weight reduction to improve fuel consumption and manoeuvrability. Torsion shaft optimization, which includes the selection of lightweight yet highly durable materials, can play a key role in achieving these goals.

An important aspect of material selection is the engineering ability to take into account the conditions of actual operation. Consideration of temperature fluctuations, aggressive environments and other factors is essential to ensure the reliability and durability of torsion shafts in a variety of conditions. The material choice for optimizing torsion shafts can also include the use of modern composite materials that combine high strength and lightness. This opens new horizons for engineers and designers, allowing them to create vehicles with an optimal combination of properties.

According to the results of recent research by H. Bankar *et al.* (2013), material optimization and weight reduction of the drive shaft using composite materials is an important area of technology development. Composite materials consist of two or more components with different physical properties that interact to create a material with improved characteristics. The use of composite materials in drive shafts allows for an optimal balance between strength and weight. Composites often have a high relative modulus of elasticity and strength at low weight, making them an attractive choice for applications where equipment weight is important. Optimizing drive shaft material and weight can also help reduce fuel consumption and improve system efficiency, which is critical for vehicles and other mechanical systems.

Material selection for torsion shaft optimization in light armoured vehicles requires a careful balance between strength and lightness. Engineers must carefully analyse the operating conditions and use advanced material technologies to create optimal designs that meet the high performance and safety requirements of today's world.

Geometric design of torsion shafts: a path to optimization and performance improvement

The geometric design of torsion shafts is recognized in modern mechanical engineering as a key step in the development of efficient and reliable transmission systems for light armoured vehicles. The use of advanced design techniques is essential to achieve an optimal shaft geometry that maximizes strength and efficiency in real-world applications. The use of advanced design techniques is an important step in the geometric design of torsion shafts. Engineers use computer programmes and engineering solutions to create three-dimensional models of shafts, taking into account various aspects such as geometric parameters, materials and operating conditions.

Stress and strain analysis is an important step in determining the optimal shaft shape in the geometric design of torsion shafts. By using mathematical models and computational software, engineers can determine how different torsion shaft shapes affect the stress and strain distribution in the structure. This allows them to choose a geometry that minimizes stress concentrations and increases the shaft's resistance to fatigue. One of the most advanced techniques is the finite element method (FEM), which allows engineers to virtually simulate stresses and strains in real-world operating conditions (Kushwah *et al.*, 2021). This method considers a variety of factors such as loads, temperature changes, and other operating conditions, allowing engineers to more accurately determine the optimal geometry. It is important to note that the design of torsion shafts is not a static task. As technology advances and new materials become available, engineers must constantly improve their geometric design techniques. Regular updates and adaptations to shaft geometry can not only improve strength, but also reduce weight, which is important for light armoured vehicles.

Referring to the definition of D.E. Osakue *et al.* (2015), shaft fatigue testing, considering its bending and torsion, is a key step in the development of mechanical systems. A shaft that is subjected to constant loads must be thoroughly tested for the possibility of deformation and material fatigue. During bending tests, it is important to consider the loads that may occur during operation and to check whether the shaft can withstand these loads without damage or deformation. Torsional testing, on the other hand, is important for determining the selective rotational stability of the shaft and for preventing possible problems related to torsional loads. These tests help to confirm the reliability and stability of the shaft design under real-world operating conditions, as well as identify possible areas for improvement to optimize its performance and service life. The geometric design of torsion shafts is a key element in optimizing the transmission systems of light armoured vehicles. The use of advanced techniques and mathematical methods allows engineers to create efficient and fatigue-resistant designs that meet the high demands of modern technical development.

Modelling and simulation in the design of torsion shafts: strength analysis and improvement

In today's rapidly evolving engineering environment, the use of computer modelling and simulation software is an essential component of torsion shaft design. This stage not only provides the ability to analyse the shaft's behaviour under load, but also allows engineers to identify and resolve potential problems, ensuring optimum strength and safety. It is to be started with the use of computer modelling software, which gives engineers the ability to create virtual models of torsion shafts. This includes taking into account shaft geometry, materials, and factors such as loads and operating conditions. Computer simulation software allows engineers to reproduce real-time operating conditions and evaluate the impact of various factors on shaft strength and reliability.

Simulation, in turn, is a key step in analysing the behaviour of a torsion shaft (Wang *et al.*, 2022). Using the resulting models, engineers can perform virtual tests by subjecting the shaft to various loads and operating conditions. The simulation allows them to identify stress concentration points, determine areas of maximum force, and identify possible problems that may arise as a result of material deformation or fatigue. The assessment of stress concentration points is particularly important in the design of torsion shafts. These points can indicate where stresses may be highest, which can lead to damage or fatigue of the material in the future. Simulation allows engineers to effectively correct these problems by optimizing the shaft geometry, selecting the best materials, or making other design changes (Hajiyev & Damirov, 2023).

Researchers M. Liang *et al.* (2022) determined that modelling the torsional resistance of a small-diameter hollow shaft using ABAQUS software is an important step in the design and analysis of mechanical systems. ABAQUS is a powerful engineering tool for numerical modelling and simulation of the behaviour of materials and structures under various loading conditions. When modelling the torsional resistance of a hollow shaft, a variety of parameters such as shaft geometry, material properties, loading conditions and boundary conditions must be taken into account. ABAQUS allows engineers to create sophisticated models that consider real-world operating conditions. Analysing the torsional resistance of a hollow shaft can provide important data on its strength and deformation characteristics, which helps to improve the design and ensure a high level of reliability in operation. This approach allows engineers to optimize designs and improve their efficiency before physically manufacturing prototypes.

In modern engineering practice, the use of computer modelling and simulation software is becoming a key element in the optimization of torsion shafts. This allows not only to increase their strength and durability, but also to effectively deal with potential problems, ensuring safety and reliability in operation.

Consideration of safety factors in the design of torsion shafts: ensuring reliability and durability

In the field of mechanical engineering, where high reliability and durability are key success parameters, consideration of safety factors in the design of torsion shafts is a mandatory component. The application of safety factors and careful consideration of impact loads allow for not only optimal shaft performance, but also its reliability in real-world operating conditions (Nuraliyev *et al.*, 2023). The first step in taking safety factors into account is to establish safety factors for all key parameters of the torsion shaft design. These factors consider the various uncertainties and variations that can occur during design and manufacturing. In addition, they provide an additional safety margin to ensure the shaft's reliability in extreme conditions and when exposed to unforeseen factors.

Considering the magnitude of impact loads is another important aspect in the design of torsion shafts. In the operating environment of light armoured vehicles, a variety of situations can arise, such as jolts, obstacles, or unforeseen explosions, which can cause impact loads on torsion shafts (Chovnyuk *et al.*, 2022). Analysing these scenarios allows engineers to consider these safety factors and incorporate them into the shaft design, ensuring reliability and durability. It is important to emphasize that safety factors are determined not only on paper, but also by experimental studies and prototype testing. Consideration of real-world operating conditions and the ability of the design to withstand unexpected loads are important to ensure the safety and reliability of the shaft in the real world.

Researchers A. Koch *et al.* (2023) have shown through their work that identifying safety issues related to torsional side shafts in electrified vehicles plays an important role in ensuring reliable and safe system operation. Side shafts in electrified vehicles, such as electric or hybrid vehicles, are subject to particular dynamic and thermal loads due to their interaction with electric motors. Systems for detecting side shaft torsion problems can include sensors that measure torsional parameters and monitoring algorithms that analyse this data for deviations from normal operation. Prompt detection of such problems allows timely measures to be taken to prevent accidents and improve the safety of passengers and the vehicle as a whole. The development and implementation of effective systems for detecting torsional problems in side shafts in electrified vehicles is an important aspect of engineering work in the field of electromobility aimed at improving the safety and reliability of new technologies.

Consideration of safety factors in the design of torsion shafts is a critical element to ensure the reliability and durability of the structure. The application of safety factors and careful consideration of impact loads allow creating not only technically advanced shafts, but also those that can operate effectively in real-world conditions where safety is a priority.

The use of the latest technologies in the design of torsion shafts: innovations for efficiency and quality

In today's industrial landscape, the use of the latest technology is key to achieving high efficiency, durability, and product quality. In the context of torsion shaft design, the use of the latest materials and manufacturing technologies plays an important role in improving their performance and functionality. An innovative area is the use of advanced materials such as composites or alloys with high performance characteristics. Composite materials, which combine different components to achieve optimum properties, can be used to create lighter but stronger torsion shafts. High-strength alloys can withstand heavy loads, ensuring high safety and reliability (Pavlikov *et al.*, 2019).

An important innovation is the use of advanced manufacturing technologies, such as additive technologies or CNC machining. Additive technologies, such as 3D printing, allow for the creation of complex geometries and optimized shaft design to accommodate internal cavities and structures, which improves weight and mechanical performance. CNC technologies, on the other hand, provide high machining accuracy and the ability to produce complex parts (Zhu *et al.*, 2022). The use of the latest technologies also includes the application of manufacturing methods that allow for the use of thin and resistant materials, ensuring efficiency and minimizing weight. Engineers and designers must constantly improve their approaches and use advanced technologies to optimize and meet the challenges in torsion shaft design.

As noted by E. Bilalis *et al.* (2022), optimizing the design of drive shafts made of composite materials is a hot topic in the engineering and manufacturing industries, aimed at increasing the strength and lightness of the elements. Composite materials consist of a combination of two or more different materials, usually fibres and a matrix, working together to achieve optimum properties (Skorokhod *et al.*, 1995). Optimizing the design of a drive shaft involves considering various parameters such as geometry, fibre orientation, fibre type and number, and the composite matrix. These parameters can be carefully tuned to achieve the desired mechanical characteristics, including high strength at low weight. The use of composite materials in the design of drive shafts allows for weight reduction while maintaining the required strength, which is important in the production of vehicles, aircraft, power generation equipment and other industries (Averin & Borovytskyi, 2023). This approach helps to improve the efficiency and service life of mechanical systems.

The use of the latest materials and production technologies allows us to create not only strong, but also lightweight and efficient shafts that meet the high standards of modern mechanical engineering.

Testing torsion shaft prototypes: ensuring high efficiency and strength

Prototype testing is a critical step in the torsion shaft development process, as it provides an opportunity to determine the real-world performance of a design and refine it before large-scale production. This approach allows engineers not only to identify possible shortcomings, but also to improve and optimize torsion shafts to achieve the highest efficiency and durability. Manufacturing physical prototypes of torsion shafts is the first step in this process. The use of advanced manufacturing technologies, such as additive manufacturing or CNC machining, allows for the precise realization of structural elements that meet the project requirements (Kaššay *et al.*, 2023). However, prototype production is only the beginning of the process, as its effectiveness and durability must be objectively verified.

Intensive tests play a key role in ensuring the quality and reliability of torsion shafts. These tests must reflect the actual operating conditions as well as additional factors that may affect the product in real life. Loads, temperature effects, vibrations, and impact loads should all be taken into account during testing. The test results provide engineers with important data on the operating strength and efficiency of the torsion shaft. They can identify weaknesses, optimize the design, and improve material and geometric aspects. This iterative approach allows for high quality and efficiency in the design of torsion shafts. Prototype testing also opens up opportunities to improve technical solutions and use the latest technologies. Engineers can implement changes in real time, refining and optimizing the design of torsion shafts based on the data obtained.

Researchers A. Wieczorek *et al.* (2022) determined tha t vibration analysis of a drive system equipped with an innovative prototype of a flexible torsion coupling is an important step before implementing this element in real-world applications. Flexible torsion couplings are used to transmit torque between shafts, while providing some flexibility to compensate for vibrations and torsional oscillations. It is important to conduct a vibration analysis to determine how well a new coupling prototype will meet the performance and durability requirements under various operating conditions. Analysis methods can include measuring vibration frequency, amplitude, and shape, as well as taking into account the dynamic properties of the prototype material. Such analysis allows engineers to refine the design and parameters of the flexible torsion coupling prototype, ensuring its optimal performance and durability in real-world applications. Preliminary vibration tests help to identify and eliminate potential problems during the development phase, contributing to the further efficiency and safety of the drive system.

Prototype testing of torsion shafts determines the success of their functionality and durability in real-world conditions. This stage allows confirming concepts, identifying weaknesses, and achieving high standards of efficiency and quality in the manufacture of torsion shafts.

Optimization of mass and weight distribution in the design of torsion shafts: impact on the efficiency and stability of an armoured vehicle

In today's engineering world, mass optimization and weight distribution has become a key aspect in the development of torsion shafts for armoured vehicles (Venczel *et al.*, 2022). This optimization is crucial to ensure not only high efficiency and strength of the shaft, but also to improve the overall stability of the armoured vehicle. Optimizing the torsion shaft mass with respect to efficiency and fuel consumption is one aspect of this process. It is important to strike a balance between strength and lightness of the shaft, as this directly affects the overall performance of the armoured vehicle. The use of high-strength materials and optimized geometry can help reduce shaft weight while still providing the required strength.

Uniform weight distribution is an important factor in improving vehicle stability, especially when driving on uneven roads or in combat situations. Optimal weight distribution can be achieved by taking into account not only the weight of the torsion shaft but also other components of the suspension system. Additive manufacturing and CNC machining technologies can be used to create optimized shaft geometries that contribute to weight reduction. It is also important to use analytical methods and computer modelling programmes to accurately determine the optimal shaft parameters, considering its functionality and interaction with other armoured vehicle systems.

In their study, W. Zeng *et al.* (2023) found that Optistruct-based modelling and lightweight design of automotive transmission shafts is a state-of-the-art approach to optimize weight and maintain the required strength of these important automotive transmission components. Optistruct is a topological and topographic optimization software that allows engineers to automatically structure material and geometry to optimize part properties. Modelling shafts with Optistruct allows engineers to perform topological optimization by considering various parameters such as shape, dimensions, and materials. This approach helps reduce shaft weight while maintaining the required strength and stiffness. The lightweight design process is made more efficient by using the optimization tools offered by Optistruct. The use of this software not only improves the mechanical properties of transmission shafts, but also reduces their weight, which contributes to the efficiency of the automotive transmission and the fuel efficiency of the vehicle as a whole.

By considering the above aspects, engineers can create torsion shafts that not only meet high standards of strength and efficiency, but also make a significant contribution to improving the stability and control of an armoured vehicle. Optimization of weight and weight distribution is becoming a strategic approach in the development of torsion shafts that meets the modern requirements of high-performance and stable armoured vehicles. The development and optimization of torsion shafts for light armoured vehicles is a task that requires a thorough understanding of the specific application of these components and the manufacturer's capabilities. Taking into account the requirements of a specific application ensures that the engineering challenges associated with armoured vehicles are addressed accurately and efficiently.

Engineers must examine the characteristics and features of the light armoured vehicle for which the torsion shafts are being designed. This includes the weight and dimensions of the vehicle, the types of materials used in the construction, the anticipated operating conditions, and the specific tasks the vehicle performs. Next, engineers must carefully analyse the manufacturer's capabilities, which include process limitations, available materials, production methods and technical capabilities. Taking these factors into account allows for optimized solutions that consider realistic production capabilities and deliver efficiency in terms of serviceability and cost. When optimizing torsion shafts, the specifications and requirements of the specific application should be the focus. For example, if a light armoured vehicle has high requirements for speed and manoeuvrability, optimizing shaft weight may be a priority. In a case where safety and stability play an important role, weight distribution and shaft strength may be key factors.

All these aspects interact in the development and optimization of torsion shafts, where balancing the requirements of the specific application with the capabilities of the manufacturer is essential to achieve high standards of quality and performance in the light armoured vehicle sector.

CONCLUSIONS

The analysis and optimization of torsion shafts in the context of improving the strength and durability of a light armoured vehicle is an important step in the development of vehicles designed to operate in high-risk environments. It is a key aspect of the engineering approach, as torsion shafts play an important role in the mechanical structure of vehicles, providing torque transmission and supporting loads during movement. The analysis of torsion shafts involves the study of their geometry, material properties, and operating conditions. This process allows engineers to identify potential problems, such as stress or strain points, that could lead to damage or material exhaustion of the shaft. The detailed analysis is also aimed at determining the optimal shaft design for maximum strength and efficiency.

The use of the latest technologies in the design of torsion shafts is a key stage in the development of transmission systems and mechanisms for light armoured vehicles. Innovations in this area are aimed at improving the efficiency, durability, and overall quality of shafts to optimize their performance in the high-risk conditions and requirements of military operations. Prototype testing of torsion shafts is a critical step in their development process to ensure high efficiency and durability. This process allows engineers to evaluate the actual performance of the shafts when operating under conditions that most closely replicate real-world operating conditions.

Optimization of torsion shafts, in turn, involves the use of advanced engineering methods such as topological optimization or finite element analysis. These methods help reduce shaft weight while maintaining the required strength and stability. The use of new materials such as composites or high-strength alloys can also make a significant contribution to improving the performance of torsion shafts. This analysis and optimization are important steps in ensuring that armoured vehicles are as strong and durable as possible, with a high level of safety for their crews. This helps to improve the design and functionality of the vehicles, ensuring they have the optimum parameters for optimal performance in the causal environment.

When developing the next generation of tactical vehicles, the importance of mine protection and torsion shaft optimization for improved strength should be considered. Changes in the suspension design of general-purpose vehicles and all-wheel drive modifications are aimed at increasing the off-road capability, but the limitation of the artificially installed crew of military vehicles arises when driving off-road due to vibration. This aspect, together with the increase in maximum speeds, defines important areas of research and improvement in the development of transport for combat operations. Additional areas of research include studying the interaction of torsion shafts with other elements of the transmission system and the impact of various operating conditions, such as temperature fluctuations or high humidity, on their performance. In addition, the interaction of torsion shafts with external factors, such as impacts or explosions, should be analysed to develop technologies for increased durability and safety in extreme conditions.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Averin, D., & Borovytskyi, V. (2023). Multi-beam optical sensor for measuring drone coordinates. *Bulletin of Cherkasy State Technological University*, 1, 5-12. doi: 10.24025/2306-4412.1.2023.267070.

[2] Bankar, H., Shinde, V., & Baskar, P. (2013). Material optimization and weight reduction of drive shaft using composite material. *IOSR Journal of Mechanical and Civil Engineering*, 10(1), 39-46.

[3] Bilalis, E.P., Keramidis, M.S., & Tsouvalis, N.G. (2022). Structural design optimization of composite materials drive shafts. *Marine Structures*, 84, article number 103194. doi: 10.1016/j.marstruc.2022.103194.

[4] Chovnyuk, Y.V., Diachenko, L.A., Ivanov, Y.O., Dichek, N.P., & Orel, O.V. (2022). Optimisation of dynamic loads of rope systems of lifting mechanisms of bridge cranes during cargo handling. *Scientific Herald of Uzhhorod University. Series Physics*, 51, 59-73. doi: 10.54919/2415-8038.2022.51.59-73.

[5] Feyye, L.E., Edo, S.M., & Badasa, T.D. (2021). Optimization of driveshaft material for light commercial vehicle (automobile). *Natural Volatiles & Essential Oils*, 8(5), 10368-10382.

[6] Hajiyev, M., & Damirov, M. (2023). Stress-strain state and bearing capacity of compressed reinforced concrete elements of annular section. *Architectural Studies*, 9(2), 35-46. doi: 10.56318/as/2.2023.35.

[7] Hrubel, M., Manziak, A., Lanets, O., Khoma, V., & Andriienko, A. (2023). Mobility simulation modelling of wheeled military vehicles under off-road traffic conditions. *Military-Technical Collection*, 28, 10-17. doi: 10.33577/2312-4458.28.2023.10-17.

[8] Huda, Z. (2021). Torsion in shafts. In *Mechanical behavior of materials: Fundamentals, analysis, and calculations* (pp. 189-198). Cham: Springer. doi: 10.1007/978-3-030-84927-6_10.

[9] Kaššay, P., Grega, R., Urbanský, M., Krajňák, J., Kačír, M., & Žuľová, L. (2023). Novel design of variable stiffness pneumatic flexible shaft coupling: Determining the mathematical-physical model and potential benefits. *Machines*, 12(1), article number 28. doi: 10.3390/machines12010028.

[10] Koch, A., Brauer, J., & Falkenstein, J. (2023). Detection of torque security problems based on the torsion of side shafts in electrified vehicles. *World Electric Vehicle Journal*, 14(6), article number 151. doi: 10.3390/wevj14060151.

[11] Krainyk, L., Hrubel, M., & Kokhan, V. (2022). The design development of medium tactical vehicles. *Collection of Scientific Works of the Kharkiv National University of the Air Force*, 4(74), 7-12. doi: 10.30748/zhups.2022.74.01.

[12] Kushwah, S., Parekh, S., & Mangrola, M. (2021). Optimization of coil spring by finite element analysis method of automobile suspension system using different materials. *Materials Today: Proceedings*, 42(2), 827-831. doi: 10.1016/j.matpr.2020.11.415.

[13] Kyrychenko, I.H., Chernikov, O.V., Rogovyi, A.S., Ragulin, V.M., Reznikov, O.O., & Taburov, O.S. (2021). Study of lifting platforms using three-dimensional computer-aided modeling. *Bulletin of Kharkiv National Automobile and Road University*, 95, 143-148. doi: 10.30977/BUL.2219-5548.2021.95.0.143.

[14] Liang, M., Wang, S., & Ma, J. (2022). Modeling and simulation of torsional resistance of hollow shaft with small diameter based on ABAQUS. *Journal of Physics: Conference Series*, 2403, article number 012044. doi: 10.1088/1742-6596/2403/1/012044.

[15] Light armoured vehicles for the Armed Forces are undergoing the final stage of national trials. (2019). Retrieved from https://specmachinery.com.ua/news/military/4229-lehki-bronemashyny-dlia-zsu-prokhodiat-zavershalnyi-etap-natsionalnykh-vyprobuvan.

[16] Manziak, M., Krainyk, L., & Hrubel, M. (2021). Trends in the development of structures of suspensions of military vehicles. *Weapon Systems and Military Equipment*, 1(65), 27-35. doi: 10.30748/soivt.2021.65.04.

[17] Nuraliyev, M., Dundar, M.A., Akyildiz, H.K., & Sahin, D.E. (2023). A novel approach for the determination of optimal diameter of shaft with keyway: Analytical and numerical study. *Mechanics Based Design of Structures and Machines*. Retrieved from doi: 10.1080/15397734.2023.2259968.

[18] Nussupbek, Z.T., Bekenov, T.N., Sattinova, Z.K., Beisenbi, M.A., & Tassybekov, Z.T. (2023). Substantiation of methods for calculation of traction forces redistribution indicators on modular front and rear wheels of the vehicle (4X4). *Transportation Engineering*, 13, article number 100193. doi: 10.1016/j.treng.2023.100193.

[19] Osakue, D.E., Anetor, D.L., & Odetunde, D.C. (2015). Fatigue shaft design verification for bending and torsion. *International Journal of Engineering Innovation and Research*, 4(1), 197-206.

[20] Pavlikov, A., Kochkarev, D., & Harkava, O. (2019). Calculation of reinforced concrete members strength by new concept. In *Proceedings of the fib Symposium 2019: Concrete – Innovations in Materials, Design and Structures* (pp. 820-827). Krakow: International Federation for Structural Concrete.

[21] Polyak, I., Borysov, O., & Matsayenko, A. (2023). Modeling of the springed part of a mobile vehicle. *Systems and Technologies of Communication, Informatization and Cyber Security*, 3, 66-73. doi: 10.58254/viti.3.2023.08.66.

[22] Sklyarov, M.V., & Shapovalov, O.I. (2021). Mathematical simulation of movement on a deformed supporting surface with change of tire pressure in wheel tires of a multi-purpose armored vehicle in the example of KrAZ "Hurricane". *Collection of Scientific Works of the National Academy of the National Guard of Ukraine*, 1(37), 78-88.

[23] Skorokhod, A.Z., Sviridova, I.S., & Korzhik, V.N. (1995). The effect of mechanical pretreatment of polyethylene terephthalate powder on the structural and mechanical properties of coatings made from it. *Mechanics of Composite Materials*, 30(4), 328-334. doi: 10.1007/BF00634755.

[24] Tkachuk, M., Zavorotnii, A., Zinchenko, O., Grabovskiy, A., Tkachuk, M., Pinchuk, N., Shevchenko, A., & Tsendra, G. (2022). Development of approaches, methods and models of research of durability and longevity of torsion billows of the suspension system the light armored vehicle. *Bulletin of the National Technical University "KhPI". Series: Mechanical Engineering and CAD*, 2, 80-93. doi: 10.20998/2079-0775.2022.2.09.

[25] Venczel, M., Veress, Á., & Peredy, Z. (2022). Past and future practical solutions for torsional vibration damping in vehicle industry. *Periodica Polytechnica Transportation Engineering*, 50(4), 318-329. doi: 10.3311/PPtr.19194.

[26] Wang, J., Yao, Z., Hassan, M.F., & Zhao, Y. (2022). Modeling and dynamics simulation of spur gear system incorporating the effect of lubrication condition and input shaft crack. *Engineering Computations*, 39(5), 1669-1700. doi: 10.1108/EC-03-2021-0183.

[27] Wieczorek, A.N., Konieczny, Ł., Burdzik, R., Wojnar, G., Filipowicz, K., & Kuczaj, M. (2022). A complex vibration analysis of a drive system equipped with an innovative prototype of a flexible torsion clutch as an element of pre-implementation testing. *Sensors*, 22(6), article number 2183. doi: 10.3390/s22062183.

[28] Zeng, W., Mao, L., Huang, D., Wang, C., & Chen, Q. (2023). Simulation analysis and lightweight design of automotive transmission shafts based on Optistruct. *Journal of Physics: Conference Series*, 2660, article number 012039. doi: 10.1088/1742-6596/2660/1/012039.

[29] Zhu, Z., Tang, X., Chen, C., Peng, F., Yan, R., Zhou, L., Li, Z., & Wu, J. (2022). High precision and efficiency robotic milling of complex parts: Challenges, approaches and trends. *Chinese Journal of Aeronautics*, 35(2), 22-46. doi: 10.1016/j.cja.2020.12.030.

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Аналіз та оптимізація торсіонних валів в контексті поліпшення міцності та довговічності легкої броньованої машини

Анотація. У контексті постійного розвитку бронетехніки та зростання вимог до міцності та ефективності броньованих машин, вивчення та удосконалення торсіонних валів стає актуальним для забезпечення високої тривалості служби та оптимального функціонування. Метою даного дослідження є проведення аналізу торсіонних валів легких броньованих машин для ідентифікації можливих напрямків оптимізації з підвищенням міцності та довговічності цих елементів транспортного засобу. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. У результаті дослідження було здійснено комплексний аналіз та оптимізацію торсіонних валів для легких броньованих машин з метою підвищення їхньої міцності та довговічності. Вибір високоміцного матеріалу та урахування ваги сприяли зниженню ваги транспортного засобу, підвищуючи його ефективність. Геометричне проектування включало застосування передових технік для оптимізації форми вала, а аналіз напружень та деформацій дозволив визначити оптимальні параметри. Використання комп’ютерного моделювання та симуляції спростило аналіз поведінки вала під навантаженням. Застосування коефіцієнтів безпеки та врахування імпактних навантажень під час експлуатації сприяло підвищенню надійності та довговічності конструкції. Використання новітніх матеріалів та технологій виготовлення дозволило досягти оптимальних параметрів трансмісійного елемента. Тестування прототипів в реальних умовах підтвердило їхню ефективність та міцність. Оптимізація маси та розподілу ваги була спрямована на покращення стійкості броньованої машини, з урахуванням вимог конкретного застосування та виробника. Отримані результати вказують на потенціал вдосконалення конструкції торсіонних валів для підвищення продуктивності та стійкості легких броньованих машин. Це дослідження приносить важливий внесок у науку, оскільки виявлені оптимізації та покращення в конструкції торсіонних валів легких броньованих машин сприяють не лише збільшенню їхньої міцності та витривалості, але й раціональному використанню ресурсів та підвищенню загальної продуктивності транспортного засобу

Ключові слова: геометрія; композитні матеріали; підвіска; плавність руху; напруженість; деформації

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Technical solutions to prevent blackouts in order to provide the population with electricity: The case of Ukraine

Abstract. Due to the deteriorating condition of the power grids and the increasing number of power outages, research on technical solutions to prevent blackouts in the Ukrainian energy system is becoming an extremely relevant and necessary task. This study aims to analyse technical solutions aimed at increasing the resilience of Ukraine's energy system to prevent blackouts and ensure reliable electricity supply to the population. The methods used include the analytical method, classification method, functional method, statistical method, synthesis method, and others. The study analysed modern technical solutions to improve the resilience of the Ukrainian energy system. The study included a detailed analysis of innovative approaches to modernizing the energy infrastructure. The primary objective was to study and evaluate modern technologies for designing new power lines with improved transmission characteristics. The study emphasized the importance of expanding automation systems to effectively monitor and control the state of the power grid. The study

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also identified the importance of using energy storage, developing renewable energy sources and improving electricity consumption forecasting systems. Flexible load management measures and improved cybersecurity systems were identified as critical. It is noted that the implementation of the project to provide electricity to the conditional area will be a key step in improving the lives of the local population and providing the necessary conditions for the development of the area's infrastructure and economy. In addition, the operation of generators for electricity supply will help to reduce the feeling of lack of electricity among residents and ensure reliability in the use of electricity for all sectors of the district's economy. The overall conclusion is that the implementation of such technical solutions will significantly increase the resilience of Ukraine's energy system. The results obtained make it possible to effectively avoid blackouts and ensure a sustainable electricity supply to the population. This allows energy companies, government agencies and other stakeholders to optimize energy resource management and make informed decisions to ensure the sustainable and efficient operation of Ukraine's energy system in the face of a possible blackout risk

Keywords: power grids; infrastructure modernization; power automation system; renewable energy sources; flexible load management

INTRODUCTION

Against the backdrop of the war between Russia and Ukraine, the study of technical solutions to prevent blackouts and ensure the resilience of energy systems is becoming particularly important. The war reinforces the need to improve technical means for effective management and protection of power grids in the face of possible increased risk and challenges arising from martial law. Increased burden on power grids and possible attacks on infrastructure may pose serious challenges to Ukraine's energy security. Ensuring the stability and reliability of energy systems is becoming a strategic task to ensure the normal functioning of the economy and the living standards of the population in times of war. The study of technical aspects, such as protection against cyber threats, enhancing cybersecurity and emergency response, is becoming an important element of the strategy to ensure energy security in the face of a military threat.

The research is aimed at developing and implementing effective technical solutions to prevent blackouts in the power supply system, in particular, in the conditions specific to Ukraine. Ensuring a sustainable and reliable energy infrastructure is an important task, as blackouts can have serious consequences for society, the economy and vital infrastructure. The study aims to improve monitoring systems, demand management, renewable energy sources, backup power supply and other technical aspects to minimize the risks and consequences of energy accidents.

V. Shchelkunov *et al.* (2023) emphasize the critical need to introduce new technical solutions to increase the resilience of the Ukrainian energy system. The authors insist on the importance of modernizing infrastructure and applying innovative methods of automation and control. As noted, the study does not consider the impact of energy systems on environmental aspects and the possibility of improving energy efficiency, considering environmental requirements. V. Vashchenko & I. Korduba (2023) note that the efficiency of energy supply is of particular importance in the context of increasing load on the power grid and unpredictability of electricity consumption, which can lead to serious problems. It is important to note that the researcher did not consider the relationship between flexible load management and emissions reduction, which may prove to be key in measuring environmental impact.

In their work, P.P. Myrutenko & L.K. Listovshchik (2022) note that the use of energy storage and the promotion of renewable sources are key elements of a strategy to increase the resilience of the energy system. However, it should be noted that the study does not consider the possibilities of using hybrid energy systems to maximize the use of renewable sources and increase the resilience of energy infrastructure. Researchers S.M. Stezhko & V.M. Fitsa (2021) note the importance of implementing flexible load management and improvements in energy systems to ensure resilience and protect against potential cyber threats. However, it should be noted that the researcher's attention is not focused on specific cyber defence technologies and strategies, which may have an impact on the effectiveness of measures to counter cyber threats.

In the work by A.V. Polukhin *et al.* (2023), special attention is paid to the analysis of current technical solutions and their impact on increasing the resilience of the Ukrainian energy system. However, it is important to note that the study does not pay due attention to the dynamics of changes in electricity consumption and their possible impact on the stability of energy systems in the future. In the study by R. Hryshchenko (2022), the author raises an important issue of effective forecasting of electricity consumption, which is a key element in improving forecasting systems and optimizing resource use. It is worth noting that the study does not go into greater depth on the importance of introducing intelligent forecasting systems that consider socio-economic factors and changes in consumption.

The purpose of this study is to analyse technical solutions that can increase the resilience of Ukraine's energy system and prevent power outages.

MATERIALS AND METHODS

The analytical method helped to thoroughly analyse technical solutions aimed at improving the resilience of Ukraine's energy systems. The use of this method allowed for a detailed consideration of the effectiveness and possible limitations of each technical solution, which became the basis for further conclusions and recommendations for improving the energy infrastructure. The statistical method was used to study trends and patterns in the functioning of the energy system, which allowed for reliable forecasts of possible variations in electricity production and consumption. This method has proven to be an effective tool for formulating energy management strategies and identifying the best ways to improve system efficiency.

Using the functional method, the key functional components of the energy system and their interactions were identified. This method allowed understanding important aspects of the internal interaction of the system components, which is critical for optimizing the operation and ensuring the highest efficiency of energy processes. The results of the functional method serve as the basis for further recommendations to improve the system's operation.

The deduction method helped to study the cause-and-effect relationships between different elements of the energy system and identify the main factors that affect its sustainability. This method helped to identify the key aspects that determine the efficiency and reliability of the system. Based on the findings, sound strategies can be developed to further improve and optimize the energy infrastructure.

By applying the synthesis method, integrated concepts for improving the energy system were created. This method allowed combining various technical solutions and strategies into a single harmonious system aimed at increasing sustainability and efficiency. The synthesis method helped to find optimal combinations of technical solutions that can be implemented to achieve the goal of ensuring the stability of energy systems. The results of the synthesis identify practical steps for implementing innovations and optimizing system performance.

The classification method helped to structure various technical solutions and components of the energy system, identify their main characteristics and group them by common features. This method helped to systemize information and make the variety of available technical solutions clear. The classification method has become an important tool for selecting the optimal system components, which contributes to the goal of increasing the resilience and reliability of the energy infrastructure.

The induction method, in the context of this study, was used to investigate the collected facts and data to identify general trends and patterns in energy systems. This method helped to identify the internal relationships and dynamics of the system, considering various influences and factors. This method allowed considering the specific conditions and context of the Ukrainian energy system in order to develop balanced recommendations and strategies to improve its performance and reliability.

The synthesis method combined the findings and conclusions to provide an overall picture of the energy system. This method allowed abstracting from the details and identifying the main trends and key relationships, which is important for understanding the overall dynamics of energy processes. Summarizing the findings helped to identify strategic areas for further research and action to improve the efficiency and stability of the energy system.

RESULTS

The energy crisis in Ukraine is the result of a variety of factors. The crisis is driven by the difficult situation in the energy market, including insufficient infrastructure development, malfunctioning of the electricity supply system, and institutional weaknesses in the management of the energy sector. Not only socio-economic factors contributed to the energy crisis, but also political, institutional, environmental, and regional aspects. The threats in this context are the war on the part of Russia and the occupation of Donetsk, Luhansk, Kherson and Zaporizhzhia regions, where the main thermal coal production is located, which is used to generate electricity for thermal power plants (TPPs). Other challenges include the monopolization of the electricity market, high depreciation of power plants, the constant decommissioning of unprofitable coal mines, low penetration of alternative electricity sources, ongoing ambiguity over Energy Community reforms, reduced dependence on external supplies, institutional imbalances in the energy market, and others. As a result of these threats, a situation has arisen where energy demand has exceeded supply, which necessitates the creation of mechanisms to ensure Ukraine's energy security (Kulcsár *et al.*, 2021).

To ensure the stability of electricity supply, measures are taken to protect power grids from possible enemy attacks. Attacks can take many forms: physical (including bombings, shelling, and sabotage), cyber (such as hacking, viruses, and hacker attacks), and electromagnetic (high voltage or frequency pulses). A variety of strategies can be implemented to successfully defend against various attacks (Karako & Dahlgren, 2022). Physical protection includes strengthening the structures and materials of equipment and power transmission lines, installing barriers and fences, as well as using video surveillance and alarm systems, and organizing security and patrols.

Protection against cyber threats includes the use of encryption, authentication, and access control to information systems and networks. Equally important is the installation of antivirus and anti-spyware software, regular updates of software and operating systems, as well as data backup and the creation of alternative communication channels. Electromagnetic protection includes the use of means of filtering, stabilizing, and controlling the voltage and frequency of electrical energy. It is also essential to install protective devices against overloads, short circuits, and overvoltage, as well as to use shielded cables and equipment.

Ensuring the resilience of power supply in the face of a full-scale invasion and restoring years of experience in critical situations (the process of restoring and applying the experience of operating systems or technologies accumulated over many years in conditions of critical situations or emergencies) involves the use of a set of measures. For example, the creation of additional sources of electricity, such as diesel generators, batteries, and renewable energy sources, which can be switched on when the main sources fail. An important element is the use of automation, control, and protection systems for power grids that can respond quickly to changes in electricity parameters and the network situation, such as relay protection, automatic backup, and remote control. Also, important is the development of small distribution generating systems, such as microgrids, mini-hydroelectric power plants and solar panels, which can operate independently or in parallel with centralized grids, contributing to decentralization. This set of measures is aimed at guaranteeing the reliability, quality, and efficiency of electricity supply during wartime, as well as increasing the resilience of electricity grids to extreme impacts.

In addition to quality and reliability aspects, there is another important factor in the electricity supply sector – efficiency, which is determined by the ratio of the costs of electricity generation, transmission, and distribution to its efficient use (Butt *et al.*, 2021). The efficiency of electricity supply is determined by the choice of optimal schemes and designs of system elements, as well as the rational distribution of loads in accordance with different reliability categories. In addition, the efficiency of electricity supply is closely related to the reduction of electricity losses during transmission and distribution, as well as to the improvement of energy efficiency of consumers.

When considering the structure of electricity generation in the United Energetic System of Ukraine (UES), it is important to note that nuclear power plants (NPPs) account for more than half of the total, exceeding 50% (Fig. 1).

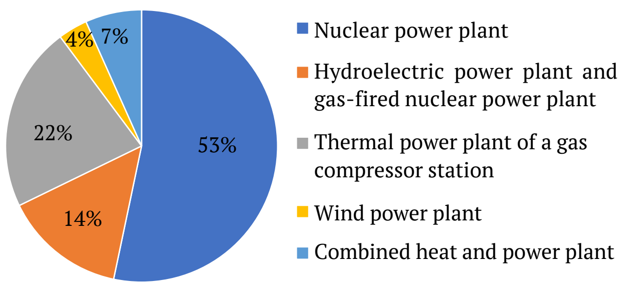

Figure 1. Ratio of electricity generation in UES of Ukraine during maximum load
Source: compiled by the authors based on M.P. Pablo-Romero *et al.* (2021)

The ratio of electricity generation in the UES of Ukraine during peak load determines an important aspect of the country's energy system. During this period, it is possible to note which energy sources provide the largest contribution to electricity generation. This information is important for planning and managing energy resources, allowing to optimize the use of different sources and ensure stable operation of the system during peak load. Analysing this ratio is an important step in improving generation strategies and ensuring the efficiency of Ukraine's energy system. The distribution of electricity consumption in Ukraine is shown in Figure 2.

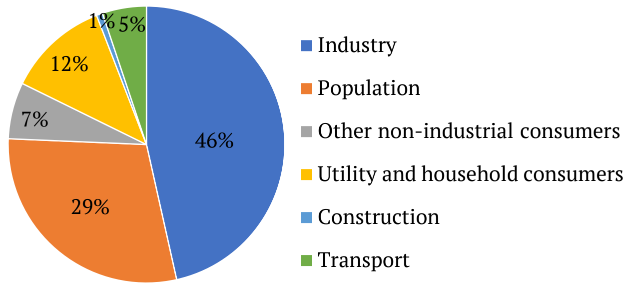

Figure 2. Distribution of electricity among different groups of consumers in Ukraine, except for temporarily occupied territories
Source: compiled by the authors based on A. Szeberényi & F. Bakó (2023)

The distribution of electricity among different consumer groups in Ukraine, excluding the temporarily occupied territories, is a key aspect of analysing the country's energy system. This structure determines how different sectors of the economy and the population use electricity and can indicate the needs and requirements of different industries. It is advisable to take this distribution into account when developing strategies to ensure the sustainability and reliability of energy supply, as different segments may have different requirements for power, quality, and reliability of electricity consumption. Such an analysis also helps to identify potential areas for improving and optimizing energy infrastructure, considering the needs of different sectors of the economy and the population.

It is worth considering a notional district with a population of 100,000 people that was left without electricity supply. The area of the district is 100 km². The total electricity demand for the district's population is about 10 MW. This electricity demand includes different areas of consumption, including housing, transport, trade, and public facilities. Residential use, which includes lighting, heating and household appliances, accounts for 7 MW. Transport infrastructure requires 1 MW of electricity, trade uses 1 MW, and public facilities require another 1 MW. In total, these sectors have a combined need for 10 MW of electricity. The total cost of purchasing and operating the generators to provide electricity to the district is estimated at approximately UAH 100 million. This financial amount includes an amount of UAH 50 million for the purchase of generators and an additional UAH 50 million to be spent on the purchase of fuel for the continuous operation of these generators.

Various technical solutions can be used to ensure the district's electricity supply. The most reliable solution is to install generators at critical infrastructure facilities. This option ensures uninterrupted power supply for vital facilities, but is costly due to the need to purchase and operate numerous generators. Installing generators at critical infrastructure facilities is the best solution in terms of reliability. However, this solution is also the most expensive. The distributed power generation option involves installing generators at every home or business. This approach is less reliable; as other generators may be overloaded if one of them fails. However, it is more cost-effective because it requires fewer generators. Distributed power generation is a less reliable solution, but it is also cheaper. This option may be acceptable for areas with limited financial resources.

The combined approach includes both the installation of generators at critical infrastructure facilities and distributed power generation. This option is the most optimal, as it ensures reliable power supply at relatively low costs. The combined option is the most optimal in terms of reliability and costs. This option may be acceptable for most areas. Within the combined option, different technical solutions can be used to provide electricity supply in different areas (Fig. 3). For the residential sector, solar power plants are an effective solution, providing clean and affordable energy. However, gas generators can be used for uninterrupted power supply at night.

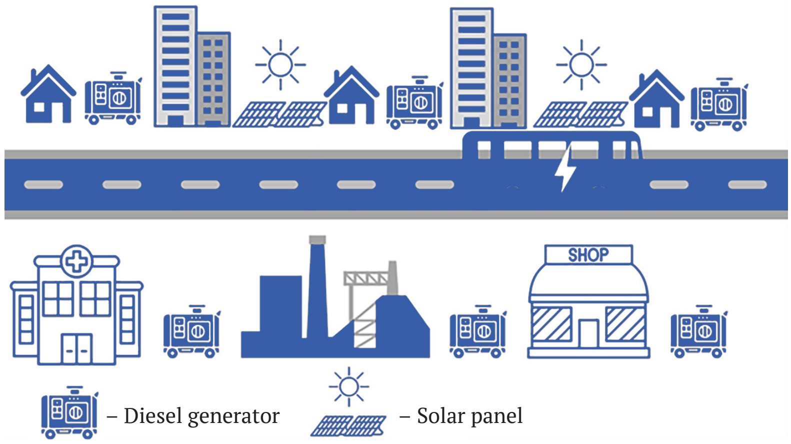

Figure 3. Scheme of an electro-dependent district during a power outage
Source: compiled by the authors

It is recommended to use electric buses for transport, which are more environmentally friendly than traditional diesel buses. However, due to the limited range of electric buses, charging stations can be used to ensure uninterrupted power supply at night. Diesel generators are recommended for use in retail and public facilities. Diesel fuel is more affordable, which can make diesel generators a cost-effective solution for providing power to these facilities. Implementation of the technical solutions described above could help ensure reliable power supply for the population of Ukraine even in the event of a power grid failure. These solutions will require significant investment, but they can bring significant social and economic benefits.

The current challenges in the energy sector require appropriate technical solutions and strategies, including infrastructure expansion and modernization. One of the key areas of this process is to increase the capacity of transmission lines. The installation of new transmission lines and the modernization of existing ones are critical elements for increasing the capacity and resilience of energy systems (Ghiasi *et al.*, 2023). New technologies and materials are enabling transmission lines to be built with high efficiency, ensuring optimal transmission of electricity over long distances without losses. In addition, the development of automation and control systems is a necessary step in the evolution of energy infrastructure. The introduction of modern automation systems allows grid operators to instantly interact with system components, monitor the status of grid elements in real time and respond effectively to any deviations or emergencies. This approach to infrastructure expansion and modernization not only improves the efficiency and resilience of the energy system, but also enables the integration of renewable energy sources, which contributes to sustainable development and reduces emissions. These measures set the right course for building a future energy landscape that meets the current and future needs of society.

The introduction of battery storage is an important step in improving grid resilience and reliability. These storages can effectively compensate for electricity losses, smooth out demand peaks and provide energy reserves in the event of accidents or grid failures. They allow for the accumulation of excess energy generated during periods of low consumption and its use during peak times, which is key to ensuring the resilience and efficiency of the system. The development of renewable energy sources, such as solar and wind power, is a strategic step towards sustainable development (Østergaard *et al.*, 2022). Increasing the share of renewable energy sources allows for decentralized electricity production, reduced dependence on traditional sources, and lower greenhouse gas emissions. In addition, it contributes to the creation of a sustainable energy system capable of addressing the challenges of climate change and ensuring a stable electricity supply in all conditions.

In general, increasing the efficiency of electricity supply through the use of energy storage and renewable sources is a key step towards a sustainable, efficient and environmentally friendly energy future. The development and implementation of energy efficiency systems includes the use of advanced technologies and energy saving systems in industry, businesses, and households. The use of energy-efficient technologies can significantly reduce energy consumption, ensuring optimal use of resources and thus reducing the negative impact on the environment.

The use of "flexible" control technologies allows for the regulation of electricity consumption depending on the needs of the system (Ma *et al.*, 2022). This means that the load can be adapted to changes in energy demand, reducing the risk of overloading and ensuring efficient energy use. Flexible control also makes it possible to use renewable energy sources in the most optimal way, helping to balance production and consumption. Load management and energy efficiency not only ensure the stability of energy systems, but are also strategic steps towards a sustainable, efficient, and environmentally friendly energy sector. This is an investment in the future, where modern technologies and innovative approaches define the path to an energy system that meets the current challenges and needs of society.

In today's world, where electricity is an integral part of life, improving forecasting systems is becoming a strategic task to ensure the sustainability and reliability of energy systems. It is important to improve electricity consumption forecasting systems. The use of modern algorithms and technologies allows accurately predicting peak loads and optimizing the operation of power supply systems. This is especially important in the context of growing demand and various factors that can affect the energy system. Accurate forecasts allow system operators to fine-tune the production and distribution of electricity, avoid congestion and ensure efficient use of resources. Improved forecasting systems are also a key element for the integration of renewable energy sources (Erdiwansyah *et al.*, 2021). With accurate forecasting of weather conditions and renewable energy production, systems can effectively account for fluctuations in production and align it with consumption. This enables optimal use of renewable sources and contributes to system resilience.

With rapid technological developments, improving forecasting systems is a strategic step in building the future of energy. Accurate and efficient forecasts not only ensure the sustainability of systems, but also lay the foundation for the development of intelligent energy systems that can meet the challenges of today and contribute to sustainable development. In the era of digital transformation and the growing number of connected systems, resilience to cyber threats is becoming an integral part of ensuring the security of energy networks. A key aspect is protection against cyber threats, which involves the development and implementation of effective cybersecurity measures. Energy infrastructure is becoming an attractive target for cybercriminals, and it is therefore important to develop and implement strategies and technologies that effectively protect systems from attacks and intrusions. This may include improving authentication systems, encrypting data, and even implementing artificial intelligence to detect and remediate threats in real time.

The knowledge and skills of cybersecurity personnel can be a key factor in preventing and detecting attacks (Zwilling *et al.*, 2022). Regular training, simulations and updates to security procedures can significantly increase the resilience of systems. Resilience to cyber threats is becoming a top priority in a world where technology is evolving rapidly and threats are becoming more sophisticated and complex. Protecting energy infrastructure from cyberattacks is not only a security measure, but also a guarantee of the stability of energy systems and protection against the negative impact of external factors.

Successful implementation of the above technical solutions opens up the prospect of ensuring the resilience of the power grid in Ukraine and effective prevention of possible blackouts. This will help to create a more reliable and resilient energy infrastructure, reducing the risks of situations that could lead to major power outages. Given the growing burden on the power grid and the threat of blackouts, the successful implementation of these solutions is key to ensuring uninterrupted and stable power supply for the population and various sectors of the economy. This step will help improve energy security and meet the requirements of the modern energy landscape.

DISCUSSION

Energy security is a critical aspect of any country's life, especially in times of geopolitical conflict and war. Ukraine, being at the centre of energy tensions due to the war with Russia, is studying and implementing technical solutions to prevent blackouts and ensure the resilience of the power grid. One of the key challenges for Ukraine is the need to increase the resilience of the energy system in the context of the escalating war. An important part of this process is the development and modernization of infrastructure. The installation of new power lines and the modernization of existing ones play a key role in increasing the capacity and resilience of the system.

Consideration and implementation of the latest automation and control technologies is another perspective. The use of systems that allow operators to monitor the grid in real time and respond effectively to deviations in power consumption can significantly improve the response to potential threats. Increasing the efficiency of electricity supply also requires the introduction of energy storage. Battery storage can compensate for power losses and ensure grid resilience. The development of renewable energy sources, such as solar and wind power plants, is also a key element of the energy security strategy (Sadykov *et al.*, 2023). However, all these technical solutions must be combined with cybersecurity considerations. In the face of cyber threats, it is important not only to develop the resilience of physical infrastructure elements, but also to implement effective cyber defence measures to prevent attacks on information systems and energy infrastructure management.

Ukraine has extensive experience of working in wartime, and studying its approaches to technical solutions can serve as an example for other countries that also face similar challenges in ensuring the resilience and security of their energy systems. According to the research by S.V. Kalantar *et al.* (2021), the study of consumer behavioural potential plays an important role in developing effective solutions to prevent a power outage crisis. Understanding and analysing electricity consumption patterns can identify consumer patterns and help develop strategies to optimize energy consumption. Applying artificial intelligence and data analytics technologies to study electricity consumption habits can provide valuable insights into how to effectively manage load and generation. The development and use of solar energy is also an important aspect in preventing an energy supply crisis. Increasing the capacity of solar power plants can make the energy system more resilient and less dependent on traditional sources. The use of solar technologies will not only reduce the responsibility for CO_2 emissions, but also ensure stability in energy supply, even in the event of a crisis (Rausch & Suchanek, 2021). These findings are in line with the theses presented in the previous section. The combination of behavioural potential analysis and active development of solar technologies can contribute to a more resilient and sustainable energy system, providing the necessary reserves and energy sources for unforeseen circumstances.

Referring to the definition of N. Sharma *et al.* (2021), large-scale power outages are a serious problem that can have a significant impact on society and the economy. One of the main reasons for such outages is the obsolescence of energy systems and infrastructure, which is not always able to withstand the load during rapid changes or emergencies. Technical failures, malfunctions in network equipment and insufficient preventive measures also contribute to the occurrence of major outages (Panov & Tymchuk, 2023). To prevent such situations, it is important to consider recommendations for modernizing energy systems. This may include infrastructure improvements, the use of new technologies such as monitoring and remote control systems, and increased maintenance activities. However, there are a number of challenges to improving energy resilience, such as the financial costs of modernization, difficulties in implementing new technologies, and coordination between different energy sector actors (Selvakumar *et al.*, 2023). It is worth noting that addressing the problem of large-scale power outages will require a comprehensive approach, combining technical innovations, modernization strategies and sound decisions to increase the resilience of energy systems.

Researchers D. Majchrzak *et al.* (2021) determined that the preparedness of the crisis management system in Poland plays a key role in addressing long-term and large-scale problems related to electricity shortages and possible power outages. This preparedness is determined by the effectiveness and coordination of measures aimed at ensuring the resilience of the energy system in times of great difficulty. An important aspect is the development of crisis management strategies that include large-scale power outages. This includes not only technical aspects, but also evacuation plans, ensuring the living environment for the population and maintaining critical infrastructures. Emergency response systems must be ready to take immediate action to prevent a humanitarian crisis and ensure the safety of citizens. In addition, the effectiveness of the crisis management system is determined by the level of interaction between different branches of government, local authorities, energy companies and other stakeholders (Ostudimov & Kaminska, 2023). It is important to have communication and information exchange mechanisms in place to respond quickly to any challenges that may arise as a result of a long-term electricity shortage. These results confirm the above study, as the Polish crisis management system should also consider supporting measures to increase the efficiency and flexibility of the energy infrastructure, such as the development of energy storage and the use of renewable energy sources. Taking these aspects into account, a more resilient and crisis-ready electricity supply system in Ukraine could be created.

G. Mutani *et al.* (2021) have shown through their work that the creation of energy communities is a strategic step to ensure territorial resilience and minimize the risks of power outages. One of the key advantages of energy communities is their ability to introduce innovative technologies and effectively coordinate the operation of the electricity supply system at the local level. This creates opportunities for load sharing and the use of local renewable energy sources. The measure of blackout risk is becoming an important tool for energy communities to define response strategies and plan for negative scenarios. Measuring this risk involves analysing factors such as the technical condition of the grid, the dynamics of electricity demand, the degree of renewable energy use, and the interaction with neighbouring power systems (Zhuravel *et al.*, 2023). This view can be agreed with, as the development of an effective load monitoring and forecasting system can be critical to reducing the risk of blackouts. These measures are aimed at ensuring the elasticity of power supply management to respond to changes in consumption, in particular, in blackouts and emergencies. Implementing smart solutions at the local level can help optimize system performance and ensure the sustainability of the electricity infrastructure, especially in the face of emergencies.

As noted by R. Bajo-Buenestado (2021), the power outages have a significant impact on household electrification, especially in countries where access to energy may be limited. In Kenya, for example, the electricity supply system has been challenged by numerous outages due to technical failures, inadequate infrastructure, and unstable power generation. Power outages in Kenya can have serious socio-economic impacts on households. Many homes and businesses may have limited access to lighting, communications, and electrical appliances, affecting the convenience and efficiency of their operations. This is especially true in rural areas, where a large proportion of the population may be dependent on electricity for agricultural activities. Analysing the results and conclusions obtained, we can assume that the results proposed by the authors in the analysed papers may be appropriate not only under normal conditions, but also in the context of emergency outages and blackouts. Adaptation to such challenges will require the implementation of technical and infrastructural solutions, such as the development of stable power supply systems, the use of alternative energy sources and effective crisis management strategies.

Researchers N. Fabra *et al.* (2022) identified that developing resilience strategies in electricity markets is important to ensure efficient and reliable electricity supply. Lessons that can be learnt from electricity markets can help develop effective strategies to ensure the resilience and reliability of energy systems. An important element is to understand the impact of market mechanisms on the resilience of electricity supply. For example, the introduction of electricity trading systems can create incentives for the development of new technologies and increase competition in the market. However, at the same time, it is necessary to avoid the "too much flexibility" effect, where a high dependence on market mechanisms can be vulnerable to extreme situations.

Considering the issue of blackouts and blackouts, it can be noted that the implementation of a resilience strategy in electricity markets requires a comprehensive approach that considers technical, economic, and environmental aspects. At the same time, it is important to assume that the results of the analysed work are applicable in situations of emergency outages, not just in normal conditions. Learning from the experience of other markets can be a valuable tool for developing effective strategies aimed at sustainable and resilient energy systems.

CONCLUSIONS

Infrastructure development and modernization is an important step in ensuring the resilience of the electricity supply system. Installing new transmission lines and improving the efficiency of existing structures is crucial to increase the capacity and reliability of the grid. Given the consideration of an off-grid scenario and the different consumption sectors, a combined approach is recommended to ensure reliable and cost-effective power supply, including the installation of generators at critical infrastructure and distributed power generation. The introduction of systems that allow operators to monitor the grid in real time and respond effectively to potential threats can significantly improve system resilience.

One of the key tasks was to research and evaluate the latest technologies for the installation of new power lines with improved transmission characteristics. The importance of expanding automation systems to effectively monitor and control the state of the power grid was noted. Increasing the efficiency of electricity supply in Ukraine is also driven by the development of energy storage and the use of renewable energy sources. Battery storage and renewable energy sources play a key role in ensuring grid stability and compensating for electricity losses. It is impossible to ignore the issue of cybersecurity in the context of technical solutions. The use of effective cyber defence measures to protect energy infrastructure from attacks and intrusions is an integral part of the strategy.

Ukraine, in the midst of a difficult military conflict, is studying and implementing these technical solutions to provide electricity to its population and maintain the stability of the energy system. The country's experience can serve as an important source of information for other countries facing similar challenges and create the basis for further development and improvement of technical aspects of energy security. Implementation of these technical solutions in Ukraine can significantly increase the resilience of the energy system, ensuring the efficiency and reliability of electricity supply. Optimization and modernization of infrastructure, use of innovative technologies and implementation of cybersecurity measures are key steps for Ukraine's modern energy sector.

In the future, for a more complete understanding and successful implementation of technical solutions to prevent blackouts in Ukraine, it is important to study in detail the interaction between these technological solutions, assess their cost and cost-effectiveness, and analyse potential challenges and limitations in their implementation in the Ukrainian context.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Bajo-Buenestado, R. (2021). The effect of blackouts on household electrification status: evidence from Kenya. *Energy Economics*, 94, article number 105067. doi: 10.1016/j.eneco.2020.105067.

[2] Butt, O.M., Zulqarnain, M., & Butt, T.M. (2021). Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal*, 12(1), 687-695. doi: 10.1016/j.asej.2020.05.004.

[3] Erdiwansyah, Mahidin, Husin, H., Nasaruddin, Zaki, M., & Muhibbuddin. (2021). A critical review of the integration of renewable energy sources with various technologies. *Protection and Control of Modern Power Systems*, 6, article number 3. doi: 10.1186/s41601-021-00181-3.

[4] Fabra, N., Motta, M., & Peitz, M. (2022). Learning from electricity markets: How to design a resilience strategy. *Energy Policy*, 168, article number 113116. doi: 10.1016/j.enpol.2022.113116.

[5] Ghiasi, M., Niknam, T., Wang, Z., Mehrandezh, M., Dehghani, M., & Ghadimi, N. (2023). A comprehensive review of cyber-attacks and defense mechanisms for improving security in smart grid energy systems: Past, present and future. *Electric Power Systems Research*, 215, article number 108975. doi: 10.1016/j.epsr.2022.108975.

[6] Hryshchenko, R. (2022). Forecasting electrical energy consumption of electrical complexes of the city electrical network. *International Science Journal of Engineering & Agriculture*, 1(3), 152-160. doi: 10.46299/j.isjea.20220103.13.

[7] Kalantar, S.V., Saifoddin, A.A., Hajinezhad, A., & Ahmadi, M.H. (2021). A solution to prevent a blackout crisis: Determining the behavioral potential and capacity of solar power. *International Journal of Photoenergy*, 2021, article number 2092842. doi: 10.1155/2021/2092842.

[8] Karako, T., & Dahlgren, M. (2022). *Complex air defense: Countering the hypersonic missile threat*. Retrieved from https://globalsentinelng.com/complex-air-defense-countering-the-hypersonic-missile-threat/?utm_source=rss&utm_medium=rss&utm_campaign=complex-air-defense-countering-the-hypersonic-missile-threat.

[9] Kulcsár, B., Mankovits, T., & Ailer, P.G. (2021). The renewable energy production capability of settlements to meet local electricity and transport energy demands. *Sustainability*, 13(7), article number 3636. doi: 10.3390/su13073636.

[10] Ma, K., Hu, X., Yue, Z., Wang, Y., Yang, J., Zhao, H., & Liu, Z. (2022). Voltage regulation with electric taxi based on dynamic game strategy. *IEEE Transactions on Vehicular Technology*, 71(3), 2413-2426. doi: 10.1109/tvt.2022.3141954.

[11] Majchrzak, D., Michalski, K., & Reginia-Zacharski, J. (2021). Readiness of the Polish crisis management system to respond to long-term, large-scale power shortages and failures (blackouts). *Energies*, 14(24), article number 8286. doi: 10.3390/en14248286.

[12] Mutani, G., Santantonio, S., Brunetta, G., Caldarice, O., & Demichela, M. (2021). An energy community for territorial resilience: Measurement of the risk of an energy supply blackout. *Energy and Buildings*, 240, article number 110906. doi: 10.1016/j.enbuild.2021.110906.

[13] Myrutenko, P.P., & Listovshchik, L.K. (2022). Energy accumulators. Main types and perspectives of use. *Energy: Economics, Technologies, Ecology*, 4, 107-116. doi: 10.20535/1813-5420.4.2022.273433.

[14] Østergaard, P.A., Duic, N., Noorollahi, Y., & Kalogirou, S. (2022). Renewable energy for sustainable development. *Renewable Energy*, 199, 1145-1152. doi: 10.1016/j.renene.2022.09.065.

[15] Ostudimov, B., & Kaminska, N. (2023). Energy security principles: Legal nature, classification and modernisation. *Scientific Journal of the National Academy of Internal Affairs*, 28(1), 55-67. doi: 10.56215/naia-herald/1.2023.55.

[16] Pablo-Romero, M.P., Sánchez-Braza, A., & Galyan, A. (2021). Renewable energy use for electricity generation in transition economies: Evolution, targets and promotion policies. *Renewable and Sustainable Energy Reviews*, 138, article number 110481. doi: 10.1016/j.rser.2020.110481.

[17] Panov, A., & Tymchuk, S. (2023). Model for regulating electricity quality indicators in 0.4-10 kv distribution networks. *Bulletin of Cherkasy State Technological University*, 2, 13-23. doi: 10.24025/2306-4412.2.2023.275897.

[18] Polukhin, A.V., Mykhaylova, L.M., Semenyshina, I.V., & Chernyavskyi, A.V. (2023). Anti-crisis regulation of the economy in 2023: To the issue of implementing the energy security strategy of Ukraine. *Academic Visions*, 17.

[19] Rausch, P., & Suchanek, M. (2021). Socioeconomic factors influencing the prosumer's investment decision on solar power. *Energies*, 14(21), article number 7154. doi: 10.3390/en14217154.

[20] Sadykov, M., Almanbetov, A., Ryskulov, I., Barpybaev, T., & Kurbanbaev, A. (2023). Autonomous hybrid power plants based on renewable and traditional sources of electricity. *Polityka Energetyczna*, 26(4), 149-164. doi: 10.33223/epj/169742.

[21] Selvakumar, R.D., Wu, J., Afgan, I., Ding, Y., & Alkaabi, A.K. (2023). Melting performance enhancement in a thermal energy storage unit using active vortex generation by electric field. *Journal of Energy Storage*, 67, article number 107593. doi: 10.1016/j.est.2023.107593.

[22] Sharma, N., Acharya, A., Jacob, I., Yamujala, S., Gupta, V., & Bhakar, R. (2021). Major blackouts of the decade: Underlying causes, recommendations and arising challenges. In *2021 9th IEEE International Conference on Power Systems (ICPS)* (pp. 1-6). Kharagpur: Institute of Electrical and Electronics Engineers. doi: 10.1109/ICPS52420.2021.9670166.

[23] Shchelkunov, V., Andrianov, O., Zalizniuk, V., Zhukova, I., Balakan, G., Dudar, O., & Shuster, M. (2023). Practical aspects of increasing the stability of the energy system, its ability to balance the load under exceptional conditions or with frequency regulation. *Science and Technology Today*, 5(19), 72-96. doi: 10.52058/2786-6025-2023-5(19)-72-96.

[24] Stezhko, S.M., & Fitsa, V.M. (2021). Cyber security as an important factor in ensuring the vital activity of the domestic energy industry. *Information and Law*, 4(39), 113-120. doi: 10.37750/2616-6798.2021.4(39).248828.

[25] Szeberényi, A., & Bakó, F. (2023). Electricity market dynamics and regional interdependence in the face of pandemic restrictions and the Russian-Ukrainian conflict. *Energies*, 16(18), article number 6515. doi: 10.3390/en16186515.

[26] Vashchenko, V., & Korduba, I. (2023). Problems of safe operation of Zaporizhzhia NPP in the conditions of war in Ukraine. *Environmental Safety and Nature Management*, 47(3), 29-38. doi: 10.32347/2411-4049.2023.3.29-38.

[27] Zhuravel, Y., Artemenko, O., Lytvyn, N., Yara, O., & Uliutina, O. (2023). International experience in the use of alternative energy sources (within the European Union). *Law. Human. Environment*, 14(3), 46-59. doi: 10.31548/law/3.2023.46.

[28] Zwilling, M., Klien, G., Lesjak, D., Wiechetek, Ł., Cetin, F., & Basim, H.N. (2022). Cyber security awareness, knowledge and behavior: A comparative study. *Journal of Computer Information Systems*, 62(1), 82-97. doi: 10.1080/08874417.2020.1712269.

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Технічні рішення щодо запобігання блекауту задля забезпечення населення електроенергією: кейс України

Анотація. У зв’язку з погіршенням стану електромереж та збільшенням кількості відмов у постачанні електроенергії, проведення досліджень щодо технічних рішень для запобігання блекаутам українською енергетичною системою стає вкрай актуальним та необхідним завданням. Це дослідження має на меті аналіз технічних рішень, спрямованих на підвищення стійкості енергетичної системи України для запобігання блекаутам та забезпечення надійного електропостачання населенню. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. У ході дослідження було проведено аналіз сучасних технічних рішень для підвищення стійкості української енергетичної системи. У рамках дослідження було здійснено докладний аналіз інноваційних підходів до модернізації енергетичної інфраструктури. Першочерговою задачею було вивчення та оцінка сучасних технологій проєктування нових ліній електропередачі з покращеними характеристиками передачі електроенергії. Підкреслено важливість розширення систем автоматизації для ефективного моніторингу та керування станом енергетичної мережі. Дослідження також визначило важливість використання сховищ енергії, розвитку відновлювальних джерел та удосконалення систем прогнозування споживання електроенергії. Заходи з гнучкого керування навантаженням та покращення систем кібербезпеки були визначені як критичні. Зазначено, що реалізація проєкту забезпечення електропостачання умовного району буде ключовим кроком у покращенні життя місцевого населення та забезпеченні необхідних умов для розвитку інфраструктури та економіки району. Крім того, експлуатація генераторів для електропостачання допоможе зменшити відчуття відсутності електроенергії серед мешканців та забезпечить надійність у використанні електричної енергії для всіх секторів господарства району. Загальним висновком є те, що впровадження таких технічних рішень дозволить значно підвищити стійкість енергетичної системи України. Отримані результати дозволяють ефективно уникати блекаутів та забезпечувати стале електропостачання населенню. Це дозволяє енергетичним компаніям, урядовим органам та іншим зацікавленим сторонам оптимізувати управління енергетичними ресурсами та приймати обґрунтовані рішення для забезпечення сталої та ефективної роботи енергетичної системи України в умовах можливого ризику блекаутів

Ключові слова: електромережі; модернізація інфраструктури; система автоматизації електроенергії; відновлювані джерела; гнучке керування навантаженням

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Possibilities of landfills and solid waste sites for energy production in Ukraine

Abstract. Dynamic changes in the energy sector towards the priority of renewable energy are stimulated by the political decisions in the European integrated environment aimed at achieving climate neutrality within the framework of the European Green Deal. The study aims to provide an in-depth investigation of the potential of landfills and solid waste sites for energy production in Ukraine. The study was conducted using general scientific methods, in particular, analysis and synthesis, abstraction, and comparison. The study examined the issues of developing the bioenergy potential of solid waste sites in Ukraine, including organisational, regulatory, technological, financial and investment aspects. The position of various operations for bioenergy waste processing in the solid waste management system, in particular, anaerobic digestion and solid fuel production, was identified, and an analysis of several thermal waste processing technologies was carried out. Among the features and characteristic requirements for the biogas production process using anaerobic methodology, the aspects of technological availability and economic feasibility are highlighted. The study examines the experience of production and use of organic Refuse Derived Fuel and Solid Recovered Fuel produced from solid waste sites, proving the need to optimise the regulatory support for biogas production at solid waste sites storage sites in the national legislative field. The article emphasises the possibility of practical use of Refuse Derived Fuel and Solid Recovered Fuel, in a partial format, to offset the shortage of fossil fuels in Ukraine and actively implement the concept of a sustainable green course for rational waste management. The results obtained can be used to improve the optimisation of strategic programmes for solid waste management in terms of their bioenergy potential

Keywords: renewable fuel resources; calorific value; biogas; morphological composition; biomass; sustainable development

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INTRODUCTION

The priority of developing the biogas and biomass potential is intensified by the introduction of the principles of circular production processes and climate neutrality against the background of general European integration processes. Solid waste sites (SWS) have a significant bioenergy potential due to their specific morphological composition. The overall morphological composition of municipal waste in Ukraine is made up of food waste (30-45%), paper and cardboard (5-15%), secondary polymers (8-17%), glass (9-14%), and other waste (Davydov and Chebanenko, 2023). Among the key priorities of biofuels derived from SWS, particular emphasis should be placed on the potential for a significant contribution to electricity production and reduction of energy dependence, and the possibility of replacing traditional fuels in heat and power generation and transport.

The relevance and urgency of the need to study the bioenergy potential of SWS is determined by the irrationality of the traditional approach to municipal waste processing in Ukraine, which involves the joint disposal of components dumped in landfills, landfills and unauthorised locations. A particular danger is posed by the prevalence of biogenic fractions in the morphological composition of household waste, which is a source of potential pollution of the water and soil environment, as well as the air, and an increased level of fire hazard due to the presence of biogas (Chupa & Adamenko, 2023). If the optimal management and technological concept of waste management based on recycling is implemented, opportunities for the effective transformation of biogenic waste into a sustainable source of energy needs are opened.

The interdisciplinary concept of the problem under study has created the need for a preliminary study of a significant volume of scientific sources from various fields of knowledge. Modern studies highlight the basic concepts of the potential of using landfills and landfills for energy production and consider the risks and challenges related to their practical implementation. L. Haponych *et al.* (2022) study the algorithm of technology for the production and use of organic fuels such as Solid Recovered Fuel (SRF) and Derived Fuel (RDF) produced from SWS. Scientists see the advantage of the method of producing RDF/SRF from SWS fractions as the conversion of waste into renewable fuel that can be accumulated, stored, transported and used in the energy sector. The researchers believe that this concept can partially meet the shortage of organic fuels while complying with EU waste management requirements.

Yu. Holik *et al.* (2023) study the environmental aspects of using the potential of solid waste as a source of biogas, in particular, in terms of the complication of the situation due to martial law. The researchers note that Ukraine is experiencing a shortage of primary energy resources and is highly dependent on external supplies. They also note that significant volumes of waste pose a real danger to the environment, which is a complex problem that needs to be addressed urgently. At the same time, V.M. Marchenko *et al.* (2022) study the peculiarities of fuel characteristics in approximation with the emission of pollutants in the process of thermal utilisation of biomass. The scientists note that the volume and efficiency of thermal waste treatment are determined by the state environmental policy, the availability of sufficient natural energy sources, and the ability of the facilities to ensure that the technological process meets environmental standards. In continuation, O.A. Trehub (2022) thoroughly investigates the economic feasibility of introducing modern recycling and biofuel production technologies. The author emphasises that the definition of "landfill" biogas as a pollutant rather than a potentially efficient fuel dominates in the Ukrainian waste legislation. According to O.A. Trehub (2022), such a significant inconsistency requires immediate elimination as part of the adaptation to Directive 1999/31/EU on landfill.

Modern studies addressed the criteria for developing and assessing the possibilities of effective SWS processing to maximise their potential as a source of alternative energy, which is positioned as a current trend in the global integrated environment. In particular, S. Kobzar *et al.* (2021) substantiate the priority vectors of transformation of the use of biogas potential, considering the global concept of growing interest in biofuel production at waste storage sites. O.O. Romaniuk & V.S. Yarovenko (2020) focus on the complexities of implementing biogas production and use systems. The researchers argue that the efficiency of thermal waste treatment plants depends on the structure of SWS, with the fractions with the highest bioenergy potential characterised by the least controllability of combustion product indicators. According to the authors, the maximum efficiency can be achieved under conditions of continuous receipt of large volumes of waste.

Despite the relevance of the issue of using landfills and landfills for energy production by scientists, the issues of developing the bioenergy potential of solid waste in the national space remain poorly understood. The study aims to provide an extended investigation of the potential of landfills and landfill sites for energy production in Ukraine through innovative technological approaches.

MATERIALS AND METHODS

The study was carried out using several general scientific methods. The systemic approach, as well as the accepted concepts of complexity and dialectic, were chosen as the basis of the methodological and theoretical framework. The systemic concept created the prerequisites for an effective analysis of the phenomenon under study as a systemic phenomenon in the entirety of interconnections. The analytical method was used to identify opportunities and trends in the development of the subject of research. Using the analytical and synthetic methods, the essence and strategic directions of unlocking the potential of using landfills and landfills for energy production in Ukraine were identified. The article also identifies the characteristic features of the functionality of the influencing elements on the dynamics of the development of biofuel production opportunities in places of solid waste storage within the current socio-economic realities.

The identification of basic categorical concepts was carried out employing abstraction. It was used to form the concept of integrity and the structural and consequential nature of the processes of the solid waste recycling system. Using this method, the characteristic properties and relations of the research object were separated, focusing on the most valuable ones. As a logical continuation of abstraction, the method of generalisation was applied, which involves approximating the characteristic range of potential opportunities for solid waste recycling, summarising the dynamics of scientific thought from a general judgement to a specific vision of the possibilities of using the identified potential. The method of specification was used to identify the effectiveness and feasibility of implementing SWS energy transformation technologies, select the best solutions to maintain optimal environmental conditions and mitigate environmental risks in the case of using waste storage sites for biogas production.

Induction was used to study the facts that characterise the properties of SWS, which led to the generalised characteristics of biofuels produced from SWS. Along with induction, the deductive method was used to identify the specifics of biofuel production in the process of waste recycling for Ukrainian realities. A comparison method was used to compare the performance indicators of individual methods of obtaining renewable energy from waste, as well as their environmental impact. The formalisation method was used to identify the priority aspects of optimising the waste management system to tap the potential of using landfills and landfill sites for energy production in Ukraine. To track and analyse the actual state of solid waste management, we used statistics from official sources, namely the State Statistics Service of Ukraine (2024) on the morphological composition of waste and the state of implementation of productive waste processing operations. Data on the energy use of SWS were obtained through the Bioenergy Association of Ukraine.

RESULTS

The production of biogas from solid waste is one of the most promising areas, as Ukraine generates approximately 10 million tonnes of waste annually (State Statistics Service of Ukraine, 2024). The intensification of the involvement of the bioenergy potential of SWS use is driven by the national strategy for climate change prevention and environmental security stabilisation, which positions the vector development of energy towards the involvement of renewable sources as promising (Order of the..., 2021). The waste management hierarchy operating in Ukraine provides for the main strategic vectors of waste prevention, reuse and recycling, as well as regeneration through energy production. For bioenergy, the object of research, development and practical use is the bioorganic component of SWS. Energy operations, by their very nature, do not fall within the definition of recycling, as they are a one-time use of raw materials without variability in their prospective recovery. Anaerobic decomposition of the bio-organic component of SWS is considered an exception. This approach allows to produce biogas to meet energy needs, as well as organic fertiliser for agronomy.

In general, two modes of anaerobic digestion are basic, with a temperature range 28-40°C (mesophilic) and 41-55°C (thermophilic). In the case of the mesophilic mode, the processes are slower and with lower biogas production, but despite these disadvantages, mesophilic reactors are used more often due to low energy costs (Kolienko *et al.*, 2023). The anaerobic digestion process algorithm includes a certain order of processes, which include acid genesis, hydrolysis, methanogenesis and acetogenesis, with the specifics of the process depending on the nature of the interaction of microorganisms that can participate in each stage of digestion (Atelge *et al.*, 2020). In the case of single-stage batch reactors, the entire volume of waste is loaded at the same time, so all stages of the process algorithm can be carried out sequentially in one location.

Figure 1 shows that the basic functional component of the proposed plant is a methane digester, which directly implements the process of biomass decomposition using methanogenic bacteria, provided that the required temperature for anaerobic digestion is met.

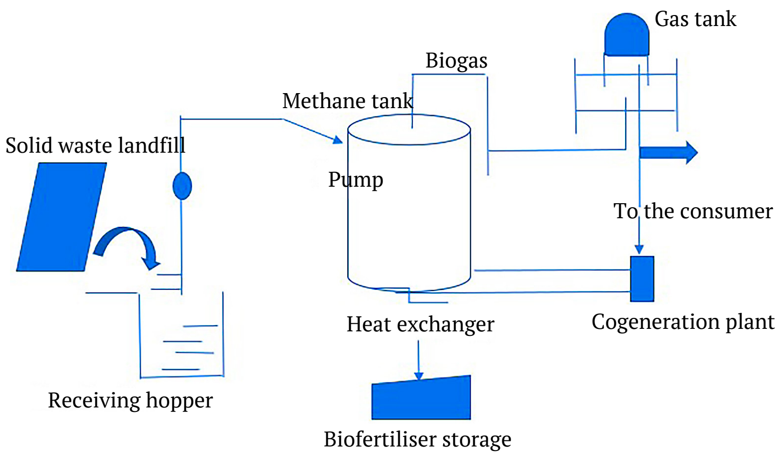

Figure 1. Anaerobic SWS treatment process in a single-stage reactor
Source: compiled by the authors based on M.R. Atelge *et al*. (2020), V.M. Marchenko *et al*. (2022)

It is worth characterising each stage of the anaerobic digestion process to identify potential productivity and, therefore, to search for promising optimisation. Hydrolysis is the process of transformation of biogenic fractions into individual components involved in the functional activity of acidogenic bacteria (Ghosh *et al.*, 2020; Zupančič *et al.*, 2022). The acetogenesis stage involves the conversion of the resulting substances into acetate compounds, which is accompanied by the release of hydrogen. The resulting hydrogen forms a synthetic functional bond – an interspecies hydrogen delegation. At the same time, excessive partial pressure is considered extremely harmful to acetogenic microorganisms (Atelge *et al.*, 2020).

Methanogenesis is the final stage of the anaerobic digestion algorithm, where methanogenic microorganisms consume available variations of intermediates to produce methane. It is worth noting that methanogens require more time for regeneration than other microorganisms in the overall anaerobic digestion process. The difference is, on average, 5-16 days (Ghosh *et al.*, 2020). The completion of the methanogenesis process in batch reactors is identified by the stop of biogas production. At the same time, the degree of sludge digestion is determined based on information on the content of volatile solids and their ability to completely dewater (Zupančič *et al.*, 2022).

In the case of the multi-stage method, the fermentation process is differentiated into several reactors or chambers in one fermenter. Considering the need for different environmental conditions for microorganisms at different stages of the process, this method allows for greater process efficiency, although it requires more significant financial costs. Multistage methods are more appropriate in case of mandatory substrate hygiene, the need to increase the degree of hydrolysis with a small volume of the fermentation chamber, in case of difficulty in implementing the mixing process at maximum fermenter loading. Thus, the recommended optimal approach to ensuring the process of digestion of the organic fraction of SWS is the mesophilic digestion mode, single-stage digestion and wet fermentation, with continuous operation of the digester.

The energy generated from the thermal treatment of SWS has a significant potential for transformation into electricity and heat. The concept of Waste-to-Energy (WtoE) includes the production of biogas, as well as SRF and RDF fuels (Nwokolo *et al.*, 2020; Arias *et al.*, 2021). The approach proposed by WtoE technology is currently positioned as the main effective vector for saving fossil energy resources and minimising greenhouse gas emissions. Today, the most popular basic technological solutions for the extraction of a high-calorie specific SWS fraction that is appropriate for RDF are mechanical and biological treatment (MBT) of waste and dry stabilisation (Maroušek *et al.*, 2020). MBT is based on the convergence of mechanical and biological methods, with the separated recyclable materials being processed. The fractions of waste that are biodegradable are sent to composting and anaerobic digestion processes, while the rest is used to produce solid fuels RDF or SRF.

In the case of the dry stabilisation process, the selected SWS is subject to biological treatment, during which it is dried and stabilised by composting. As a result, a fuel with a high calorific value is produced. Thus, RDF is identified as an organic fuel obtained by separating recyclable materials from waste. Equipment based on pyrolysis processes for SWS processing consists of certain elements (detectors, separators, crushers, dryers, vibrating screens). The process of processing SWS directly into RDF fuel follows a certain universal algorithm (Fig. 2).

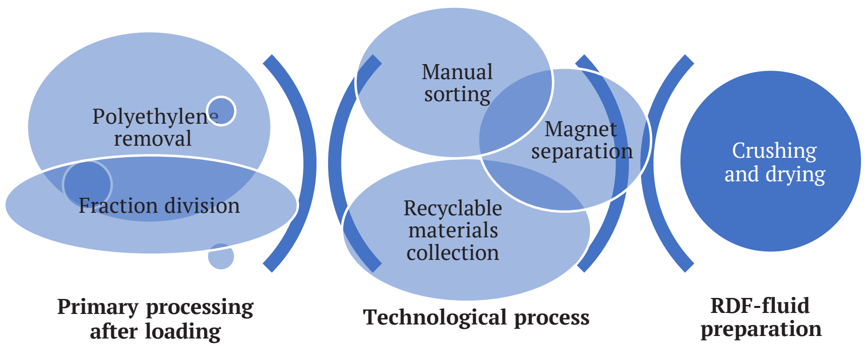

Figure 2. A general algorithm for processing solid waste into RDF fuel
Source: compiled by the authors based on S. Kobzar *et al.* (2021), N. Nwokolo *et al.* (2020)

Analysing the algorithm shown in Figure 2, an important point is the fact that this type of equipment is advantageous due to the variability of parameter adjustment for a specific type of raw material, maximum process automation and remote control, and high productivity. The RDF production process begins with the loading of household waste into a conveyor hopper, which is stripped of its plastic packaging through an automated process, followed by its separation into fractions and transport to the manual sorting and magnetic separation stage. At this stage, metal components, stones and glass are removed. Subsequently, crushers are used to crush the waste in stages, followed by drying it in a special drum. The hammer crusher crushes the raw material to a fraction of no more than 5-10 mm (Arias *et al.*, 2021).

Pyrolysis equipment for SWS processing has an attractive payback period. RDF fuel is positioned in the energy market as an inexpensive source of thermal energy. Additional benefits of the RDF production process include reduced funding for solid waste disposal and the possibility of extracting glass and metal fractions. An incinerator is a modern facility with the functionality of processing various wastes based on thermal treatment, with mandatory subsequent maximum purification of combustion products. For incineration, certain types of thermal treatment of SWS are used, including incineration, pyrolysis and gasification (Nwokolo *et al.*, 2020). Technologies for the production and practical use of RDF/SRF fuels are most popular in developed European countries – the UK, Germany, Italy, and Austria. The annual demand for RDF/SRF in these countries reaches 55-67 million tonnes (Maroušek *et al.*, 2020). According to experts, Ukraine has a significant potential for RDF/SRF production, so the latter is considered an affordable and economically viable source of renewable energy (Marchenko *et al.*, 2022; Davydov & Chebanenko, 2023).

The implementation of the WtoE concept in practical projects is characterised by significant financial costs, so the potential of solid waste to energy in the national field will only be unlocked if the process of waste disposal is costlier than its recycling. There is a need for significant changes in the legal and regulatory framework for Ukraine's obligations in this area. According to the national strategy, the rate of solid waste disposal through thermal recycling should reach 10% by 2030, through the construction of thermal recycling facilities (Romaniuk & Yarovenko, 2020). Ukraine should take advantage of the practical experience of developed countries, where the main advantage of this approach is the transformation of waste into marketable products. Thus, the biogenic component of SWS is seen as an effective feedstock for biogas production and a component of solid fuels such as SRF and RDF. The outlined concept finds active support at the level of the state management paradigm and can be intensified by attracting available international support tools during the post-war recovery period.

The phenomenon of a certain struggle for priority between biogas and multicomponent solid fuels is based on the fact that anaerobic waste processing can be carried out in both wet and dry environments, so that biogas is produced from identical biogenic fractions of SWS through recycling, and solid fuels are produced through recovery operations (Pak & Pak, 2017). The hierarchy of the waste management system prioritises recycling, i.e. biogas production using anaerobic digestion, over waste incineration. However, it is necessary to consider the practical difficulty of maintaining the desired strategic line due to the influence of the commercial component (Order of the..., 2021; Zupančič *et al.*, 2022). In the process of searching for variations in energy transformation towards sustainable energy generation solutions, the possibilities of effective development of the potential of sustainable biomass are seen as relevant. The production of biogas and biomethane through anaerobic digestion is seen as an optimal alternative to the current paradigm of solid waste management. Aerobic and anaerobic ways of using landfills and landfills for energy production are technologically more accessible and cost-effective than thermal utilisation of pre-treated (RDF, SRF) of SWS.

In a globally integrated environment, the resolution to maximise the efficiency of reducing methane emissions from landfills through its controlled collection and utilisation is a priority. In addition, the successful implementation of energy recovery projects minimises greenhouse gas and air pollutant emissions, which positively affects environmental quality and reduces potential risks to public health (Abdibattayeva *et al.*, 2021). Such projects significantly reduce dependence on certain types of energy, contributing to savings, the creation of new jobs and the overall regional development of economic processes. Significant opportunities for expanding the use of landfill bioenergy potential are identified. At the same time, the priority of selecting a particular method of biogas utilisation is formed under the influence of determining factors, such as individual conditions of economic activity at the landfill and the availability of a solvent consumer of energy produced from biogas. In most developed countries, this process is stimulated by the state through regulatory and legislative regulation. The cost-effectiveness of biogas production and use projects demonstrates the feasibility and profitability of the proposed concept of solid waste management, which is intensified by the presence of an industrial gas consumer near the waste storage site.

Currently, about 6,000 landfills and landfills covering an area of more than 9,000 ha have been identified in Ukraine (State Statistics Service of Ukraine, 2024). At the same time, only 19 landfills are equipped with a biogas extraction system. Thus, the biogas resource of solid waste disposal sites is not used on a national scale in today's realities. The absence of developed infrastructure for energy transformation of waste in the Ukrainian national space creates optimal preconditions for the implementation of an effective and viable system of solid waste management. The proposed concept will help to expand the capabilities of recycling technologies, which will allow full use of landfills and landfills for energy production in Ukraine. This approach will maximise the expected positive effects in terms of environmental optimisation, energy imbalance and agricultural-technical intensification.

DISCUSSION

Research on the possibilities of using the potential of organised solid waste storage sites for renewable energy production is reflected in the results of numerous scientific studies by modern researchers, which reveal several characteristic features of the field under study in diametric positions, which stimulate the intensification of improving approaches to studying the potential of bioenergy in the concept of strategic development of Ukraine.

M. Govarthanan *et al*. (2022) focus on the individual qualities of renewable fuels, which are seen as potentially possible based on WtoE solutions. The authors argue that the directions of development of technological possibilities for the use of landfills and landfills for energy production are formed using optimal design of regional development and economic efficiency for business, which is synergistic with the findings of this study.

Contemporary researchers K.R. Chew *et al.* (2021) consider the large-scale use of RDF and SRF to be one of the positive factors influencing the air protection system against excessive pollution and reducing carbon emissions. The researchers claim that, compared to the environmental burden of traditional solid waste disposal, the introduction of thermal treatment methods for pre-treated waste has environmental benefits. The statement is valid only in terms of the catastrophic consequences of spontaneous waste disposal, as the relative advantages of thermal treatment of pre-treated waste do not offset the destructive impact of these processes on environmental parameters, which becomes apparent against the background of more advanced waste management methods that exclude interference with the system of morphological and functional concepts of the environment (Rausch & Suchanek, 2021).

The conclusions of Q. Haar (2023) identify the management support of the solid waste management paradigm as a basic prerequisite for energy transformation within the framework of a green development course. The scientist shows that the concept of waste management is characterised by the dynamics of functionality against the background of the global trend of greening, being identified as a hub of potential concepts within the general vector of the modern ecosystem approach towards sustainable development. The scientist emphasises that efficient and cost-effective growth in biogas production and utilisation is possible only in the case of successful convergence of regulatory support, management support and investment intensification. Comparing the results of the researcher with the conclusions of the current study, the priority task of the state administrative paradigm in the field of waste management policy implementation, within the framework of the post-war regeneration paradigm, is the active implementation of innovative technologies for thermal utilisation of municipal solid waste components.

F. Aliaghaei *et al.* (2020) emphasise the priority role of sustainable biomass and biogas in the green energy transformation, while, according to scientists, waste incineration is less competitive. The separation of the biogenic flow from the total volume of solid waste for biogas production is important to ensure that the destructive trends of the national energy crisis are levelled. According to scientists, this approach meets global requirements for decarbonising energy generation.

A separate strategic vector for the optimal use of the bioenergy potential of SWS is the production of biogas directly at waste disposal sites (Danylyshyn & Koval, 2023). This is supported by the research by S. Gerassimidou *et al.* (2020). This approach is significantly inferior in the functional aspect to the organised process of anaerobic digestion of waste fractions, but, according to these researchers, it is possible to produce almost three times more methane under artificially created conditions, removing up to 70% of biogas from the landfill body. The scientists insist that their proposed method of biogas production has certain disadvantages, including the financial burden of building a special complex biogas collection system. Nevertheless, the scientists argue that the installation of innovative biogas collection systems at solid waste sites with their subsequent utilisation is not only technically feasible but also a cost-effective and environmentally sound solution. The results of the study by the researchers are synergistic with the conclusions of the current study in terms of the priority of the renewable energy concept using the potential of SWS.

J.S. Chae *et al.* (2020) note that the phenomenon of biogas uncontrollably generated in places of large-scale accumulation and disposal of municipal waste in urban agglomerations should be considered in two concepts of impact: negative – as an environmental hazard of a substance, and positive – as a renewable fuel. The researchers analyse the algorithmic structure of a typical scheme of controlled biogas production, expanding the traditional vision of the technological target potential and justifying the need to intensify investment in this area. The authors strongly believe that renewable nature is the main component of a sustainable approach to the management paradigm in the field under study, which allows ensuring the sustainability of ecosystems that can function effectively without requiring significant investment.

A. Calbry-Muzyka *et al.* (2022) provide a list of the main prerequisites for the priority reorganisation of the municipal solid waste management system in the concept of stimulating biogas production. While assessing the practical effectiveness of waste management system optimisation in several developed countries, scientists have found that local requirements, obstacles and advantages are the priority factors influencing the implementation of optimisation measures. Considering the specifics of the current study, it is necessary to formulate an individual strategy for the development of the waste management system in the context of Ukrainian realities. This approach will allow stabilising and development of the sustainability and competitiveness of national economic processes (Piskun *et al.*, 2024).

A. Sobczak *et al.* (2022) combine the effectiveness of technologically competent waste management with the principles of sustainable development. The scientists argue that the bioenergy approach balances the balance in the socio-economic space and promotes the rational use of resource potential and the overall optimisation of the environment. In addition, scientists draw attention to the need to implement the principles of sustainable development in the waste management sector, highlighting the related issues of financing, investment and availability of qualified personnel. Considering the results of scientific research in the context of the specifics of the current study, it should be noted that promising opportunities to involve international cooperation mechanisms in post-war reconstruction will allow for to resolution of the issue of targeted investments and subsidies for the introduction of modern technologies for the use of landfills and landfills for energy production in Ukraine.

Active motivation and economic tools to stimulate the use of innovative bioenergy projects at the national and regional levels are currently positioned as the main effective means of optimising the situation in the industry. The proposed strategy of solid waste management allows us to expect optimisation of the socio-economic and environmental microclimate in society, an increase in the financial efficiency of projects, and an overall improvement of the social environment of urban agglomerations. The effectiveness of the practical testing of the outlined concept directly depends on the level of formation of the management paradigm in the industry, the establishment of strict standards and measures of responsibility for their violation, and the motivation of process participants in the effectiveness of measures. The prognostic perspective is to expand the functionality of the urban agglomerations' solid waste management system as a component of a successful management paradigm in the energy sector of post-war Ukraine. This concept involves intensifying the indicators of the economic feasibility of innovations and the successful implementation of green energy development projects.

CONCLUSIONS

The current study provided a detailed analysis of the possibilities of using the potential of landfills and landfills for energy production in the national Ukrainian space. In the process of studying the problems of developing the bioenergy potential of solid waste in Ukraine, the importance of various operations for bioenergy waste processing in the solid waste management system was highlighted. The analysis of several technologies for thermal waste processing has made it possible to identify the characteristic features and requirements for the biogas production process using an anaerobic methodology, in particular, technological prerequisites, organisational and economic aspects, and the specifics of the innovative concept.

In the course of the research, based on the study of practical experience in the production and use of organic fuels RDF and SRF produced from SWS, the priority of the potential for biogas and biomethane production through anaerobic digestion was argued, which is considered to be the best alternative to the existing waste management paradigm. The results of the study show that aerobic and anaerobic ways of using landfills and landfills for energy production are more technologically accessible and cost-effective than thermal utilisation of pre-treated (RDF, SRF) SWS. There is a need to optimise the regulatory framework for biogas production in specialised SWS storage facilities in the national legislative field. The production and practical use of RDF and SRF can partially offset the shortage of fossil fuels in Ukraine. In addition, innovative technological capabilities will satisfy the accepted integrated requirements for sustainable waste management.

Bioorganic components of SWS are positioned as a valuable renewable energy resource, the rational management of which contributes to strengthening energy independence and solving global climate problems. The functional paradigm of SWS management in Ukraine requires a gradual transition towards the introduction of economically and environmentally efficient waste management methods, among which the priority is given to the technology of anaerobic digestion of SWS components. The study established the need to understand the risk of redistributing the functionality of processing bioorganic components of SWS in favour of thermal treatment processes of waste as RDF and SRF, which will slow down the integration of anaerobic biogas production.

The direction of promising research in this area is the establishment of special criteria in the national legal field for the positioning of waste decomposed in the anaerobic environment as such that has undergone the recycling process, which will create preconditions for the integration of innovative opportunities to regulate household waste management. In the process, it is advisable to use the results of practical testing of the successful experience of other countries, involving a range of innovative approaches and methods of waste management based on regeneration and sustainable development.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Abdibattayeva, M., Bissenov, K., Zhubandykova, Z., Orynbassar, R., Tastanova, L., & Almatova, B. (2021). Purification of oil-containing waste using solar energy. *Environmental and Climate Technologies*, 25(1), 161-175. doi: 10.2478/rtuect-2021-0011.

[2] Aliaghaei, F., Pazoki, M., Farsad, F., & Tajfar, I. (2020). Evaluating of refuse derived fuel (RDF) production from municipal solid waste (case study: Qazvin Province). *Environmental Energy and Economic Research*, 4(2), 97-109. doi: 10.22097/EEER.2020.187286.1088.

[3] Arias, D.E., Veluchamy, C., Habash, M.B., & Gilroyed, B.H. (2021). Biogas production, waste stabilization efficiency, and hygienization potential of a mesophilic anaerobic plug flow reactor processing swine manure and corn stover. *Journal of Environmental Management*, 284, article number 112027. doi: 10.1016/j.jenvman.2021.112027.

[4] Atelge, M.R., Krisa, D., Kumar, G., Eskicioglu, C., Nguyen, D.D., Chang, S.W., Atabani, A.E., Al-Muhtaseb, A.H., & Unalan, S. (2020). Biogas production from organic waste: Recent progress and perspectives. *Waste and Biomass Valorization*, 11, 1019-1040. doi: 10.1007/s12649-018-00546-0.

[5] Calbry-Muzyka, A., Madi, H., Rüsch-Pfund, F., Gandiglio, M., & Biollaz, S. (2022). Biogas composition from agricultural sources and organic fraction of municipal solid waste. *Renewable Energy*, 181, 1000-1007. doi: 10.1016/j.renene.2021.09.100.

[6] Chae, J.S., Kim, S.W., & In Ohm, T. (2020). Combustion characteristics of solid refuse fuels from different waste sources. *Journal of Renewable Materials*, 8(7), 789-799. doi: 10.32604/jrm.2020.010023.

[7] Chew, K.R., Leong, H.Y., Khoo, K.S., Vo, D.V.N., Anjum, H., Chang, C.K., & Show, P.L. (2021). Effects of anaerobic digestion of food waste on biogas production and environmental impacts: A review. *Environmental Chemistry Letters*, 19(4), 2921-2939. doi: 10.1007/s10311-021-01220-z.

[8] Chupa, V., & Adamenko, Ya. (2023). Study of ash level and content of chemical elements in ash of different types of household solid waste and solid fuel pellets. *Ecological Safety and Balanced Use of Resources*, 14(1), 92-98. doi: 10.31471/2415-3184-2023-1(27)-92-98.

[9] Danylyshyn, V., & Koval, M. (2023). Analysis of biogas production and prospects for the development of biogas technologies in Ukraine. *Ukrainian Black Sea Region Agrarian Science*, 27(3), 90-102. doi: 10.56407/bs.agrarian/3.2023.90.

[10] Davydov, V., & Chebanenko, M. (2023). The main problems in the utilisation of municipal solid waste. In *Proceedings of the III International Scientific and Practical Conference "Theoretical and Practical Aspects of Modern Scientific Research"* (pp. 104-109). Seoul: ΛΌΓΟΣ. doi: 10.36074/logos-24.11.2023.31.

[11] Gerassimidou, S., Velis, C.A., Williams, P.T., & Komilis, D. (2020). Characterisation and composition identification of waste-derived fuels obtained from municipal solid waste using thermogravimetry: A review. *Waste Management & Research*, 38(9), 942-965. doi: 10.1177/0734242X20941085.

[12] Ghosh, P., Shah, G., Sahota, S., Singh, L., & Vijay, V.K. (2020). Biogas production from waste: Technical overview, progress, and challenges. In *Bioreactors* (pp. 89-104). London: Elsevier. doi: 10.1016/B978-0-12-821264-6.00007-3.

[13] Govarthanan, M., Manikandan, S., Subbaiya, R., Krishnan, R.Y., Srinivasan, S., Karmegam, N., & Kim, W. (2022). Emerging trends and nanotechnology advances for sustainable biogas production from lignocellulosic waste biomass: A critical review. *Fuel*, 312, article number 122928. doi: 10.1016/j.fuel.2021.122928.

[14] Haar, Q. (2023). *Refuse Derived Fuels (RDF) and Solid Recovered Fuels (SRF) A case study of characteristics and opportuniti*es. Retrieved from https://hdl.handle.net/11250/3092828.

[15] Haponych, L., Topal, O., Golenko, I., & Kobzar, S. (2022). Estimation of potential of RDF production based on found technological and morfological properties of munisipal solid wastes of Ukraine. *Scientific Papers of the National University of Food Technologies*, 28(3), 44-59.

[16] Holik, Yu., Krot, O., & Serha, T. (2023). Household solid waste as a reserve energy potential of the city. In *Ecology. Environment. Energy Saving* (pp. 37-47). Poltava: National University "Yuri Kondratyuk Poltava Polytechnic".

[17] Kobzar, S., Topal, O., Haponych, L., & Golenko, I. (2021). Investigation of the co-firing of natural gas and RDF in a model combustion chamber. *Bulletin of Igor Sikorsky Kyiv Polytechnic Institute. Series "Chemical Engineering, Ecology and Resource Saving"*, 20(4), 67-73. doi: 10.20535/2617-9741.4.2021.248946.

[18] Kolienko, A., Shelimanova, O., & Biletskyi, D. (2023). Factors of using waste as fuel in thermal energy systems of. *Energy and Automation*, 6, 98-107. doi: 10.31548/energiya6(70).2023.098.

[19] Marchenko, V.M., Kavtysh, O.P., & Makalyuk, I.V. (2022). Energy potential of waste in the EU and Ukraine. In *Materials of the XVIII International Scientific and Practical Conference "Modern Problems of Management"* (pp. 54-56). Kyiv: Igor Sikorsky Kyiv Polytechnic Institute.

[20] Maroušek, J., Strunecký, O., Kolář, L., Vochozka, M., Kopecký, M., Maroušková, A., & Cera, E. (2020). Advances in nutrient management make it possible to accelerate biogas production and thus improve the economy of food waste processing. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. doi: 10.1080/15567036.2020.1776796.

[21] Nwokolo, N., Mukumba, P., Obileke, K., & Enebe, M. (2020). Waste to energy: A focus on the impact of substrate type in biogas production. *Processes*, 8(10), article number 1224. doi: 10.3390/pr8101224.

[22] Order of the Cabinet of Ministers of Ukraine No. 1363-r "On Approval of the Strategy of Environmental Safety and Adaptation to Climate Change for the Period up to 2030". (2021). Retrieved from https://zakon.rada.gov.ua/laws/show/1363-2021-%D1%80#Text.

[23] Pak, Y.N., & Pak, D.Y. (2017). Solid fuel quality control by the pulsed neutron-gamma method. *Solid Fuel Chemistry*, 51(3), 183-187. doi: 10.3103/S0361521917030089.

[24] Piskun, V., Zolotarov, A., Ponomarova, M., Zolotarova, S., & Yevsiiukov, O. (2024). Utilisation of livestock by-products for resource-saving biogas production in industrial pork production. *Scientific Horizons*, 27(1), 117-126. doi: 10.48077/scihor1.2024.117.

[25] Rausch, P., & Suchanek, M. (2021). Socioeconomic factors influencing the prosumer's investment decision on solar power. *Energies*, 14(21), article number 7154. doi: 10.3390/en14217154.

[26] Romaniuk, O.O., & Yarovenko, V.S. (2020). Thermochemical methods of energy production from waste. In *Proceedings of the III International Scientific and Practical Conference "Energy Saving and Industrial Safety: Challenges and Prospects"* (pp. 316-322). Kyiv: Osnova.

[27] Sobczak, A., Chomać-Pierzecka, E., Kokiel, A., Różycka, M., Stasiak, J., & Soboń, D. (2022). Economic conditions of using biodegradable waste for biogas production, using the example of Poland and Germany. *Energies*, 15(14), article number 5239. doi: 10.3390/en15145239.
[28] State Statistics Service of Ukraine. (2024). *Economic statistics/Environment*. Retrieved from https://ukrstat.gov.ua/operativ/menu/menu_u/ns.htm.
[29] Trehub, O.A. (2022). Development of bioenergy potential of household waste in the conditions of post-war recovery: Economic and legal dimension. *Economics and Law*, 3(66), 47-59. doi: 10.15407/econlaw.2022.03.047.
[30] Zupančič, M., Možic, V., Može, M., Cimerman, F., & Golobič, I. (2022). Current status and review of waste-to-biogas conversion for selected European countries and worldwide. *Sustainability*, 14(3), article number 1823. doi: 10.3390/su14031823.

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Можливості використання звалищ та полігонів твердих побутових відходів для виробництва енергії в Україні

Анотація. Динамічні зміни у енергетиці в напрямку пріоритетності відновлюваної енергетики інтенсифікується спрямованістю політичних рішень у євроінтегрованому середовищі на досягнення кліматичної нейтральності у межах реалізації Європейського зеленого курсу. Мета статті полягає у поглибленому дослідженні потенціалу звалищ та полігонів твердих побутових відходів для виробництва енергії в Україні. Реалізація дослідження проводилась із залученням загальних наукових методів, зокрема, аналізу та синтезу, абстрагування, порівняння. Вивчено проблематику освоєння біоенергетичного потенціалу твердих побутових відходів в Україні, у тому числі, організаційний, нормативно-правовий, технологічний та фінансово-інвестиційний аспекти. Проведена ідентифікація позиції різнопланових операцій щодо біоенергетичної переробки відходів у системі поводження з твердими побутовими відходами, зокрема, анаеробного знезараження та виробництва твердого палива, реалізована аналітика низки технологій термічної переробки відходів. Серед особливостей та характерних вимог щодо процесу виробництва біогазу з застосуванням анаеробної методики виділені аспекти технологічної доступності та економічної доцільності. У дослідженні розглядається досвід виробництва і використання органічного палива з відходів (RDF) та твердого відновлюваного палива (SRF), що виробляються з твердих побутових відходів, доведена необхідність оптимізації нормативного забезпечення виробництва біогазу у місцях складування твердих побутових відходів у національному законодавчому полі. Акцентовано спроможність практичного використання органічного палива з відходів (RDF) та твердого відновлюваного палива (SRF), у частковому форматі, нівелювати дефіцит викопних видів палива в Україні та активно втілювати концепцію сталого зеленого курсу щодо раціонального поводження з відходами. Отримані результати можуть бути застосовані при вдосконаленні оптимізаційних стратегічних програм управління твердими побутовими відходами у аспектах їх біоенергетичного потенціалу

Ключові слова: відновлювані паливні ресурси; теплота згоряння; біогаз; морфологічний склад; біомаса; стійкий розвиток

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Experimental study of the time of pressure rise and fall in the sprayer pipe

Abstract. A wide variety of meteorological factors, soil and climatic conditions, the saturation of fields with many types of weeds, a significant set of cultivated plants and many other factors necessitate the implementation of innovative technological schemes for the use of pesticides, which will reduce the pesticide load as much as possible and determine the safe environmental effect of preparations. Experimental studies were carried out to determine the time of pressure rise and fall in the sprayer pipe and to establish the corresponding functional dependencies. The automatic adjustment system of the application rate was set to change the pressure when the green simulation surface hit 0.5 MPa, and the yellow surface hit 0.2 MPa. Sensor impact on a surface of different colours was simulated. At the same time, the pressure in the system changed. The pressure in the sprayer pipe of trailer sprayer OP-2000-2 was measured using a WIKAI EN837-1 pressure gauge and the readings were recorded with a Panasonic NV-GS75 digital video camera mounted on a Continent TRIPOD A2 stand. As a result of calculating the experimental data, it was found that the arithmetic mean of pressure reduction from 0.5 to 0.2 MPa is 1.94 s. And the arithmetic mean for four experiments, a pressure reduction of 0.05 MPa is 0.32 s. When calculating the experimental data of the pressure rise, it was found that the arithmetic mean of the pressure rise from 0.2 to 0.5 MPa is 2.37 s. And the average value for four experiments, the pressure rise by 0.05 MPa is 0.395 s. After approximation of experimental data obtained during single-factor experiments, when the pressure *P* and the corresponding

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time values *t* change, the corresponding polynomial functions describing the characteristic $t = f(P)$ when operating a sprayer with automatic application rate control were obtained. The results obtained would allow calculating the time of delay or advance opening of the spray torch when working with variable standards for target plans, in order to avoid non-compliance with the application rate with the specified values

Keywords: polynomial functions; boom; field sprayer; plant protection; application rate; spray swath

INTRODUCTION

Agricultural production is a complex process that requires thoughtful and rational use of natural and climatic conditions, soil resources, and the biological potential of plants. To achieve optimal yields and ensure the sustainability of crop production, it is important to effectively control factors that may threaten the crop. In this context, the control of weeds, pests, and diseases that can attack crops plays a key role. These threats can spread to a variety of plant species, creating significant difficulties for agricultural producers.

Due to the wide variety of meteorological conditions and soil characteristics, and the presence of various types of weeds in the fields, production faces various challenges. This is where the introduction of advanced technological methods for the use of pesticides becomes important. This includes the use of advanced integrated plant protection techniques that help reduce the pesticide burden on the environment. This approach allows for effective control of pests and diseases, while maintaining safety for nature and agroecosystems. Consequently, the introduction of advanced technological solutions in the field of plant protection becomes a strategically important stage for ensuring the sustainability and efficiency of agricultural production.

Many researchers have studied technological processes and working bodies for chemical plant protection. M. Hulin *et al.* (2021), M. Djouhri *et al.* (2023) investigated models of the drift of sprayed pesticides, the processes of scattering, evaporation of droplets, their deposition to the ground and interception by air flow, and atmospheric stability and turbulence modes. The researchers considered drift patterns of sprayed pesticides by analysing the processes of scattering, evaporation of droplets, precipitation to the ground, and interception by air flow. In addition, they analysed atmospheric stability and turbulence regimes, which contributed to a deeper understanding of the dynamics and effects of sprayed pesticides in the environment.

B. Xiahou *et al.* (2020) conducted modelling and experimental studies of the characteristics of droplet flow and their deposition in the air flow field. They focused on carefully analysing the impact of these factors on the distribution of pesticides and developing strategies to optimise the use of plant protection products to ensure efficiency and environmental safety.

C. Dereumeaux *et al.* (2020), I.W.P. Paulson *et al.* (2022) studied in detail the experimental characteristics of the aerodynamic footprint of a high-clearance sprayer when changing the operating parameters. This helped to establish optimal conditions for ensuring the efficiency of cutting and minimising the negative impact on the environment. The study also revealed important relationships between spray parameters and the distribution of pesticides in the atmosphere, contributing to the development of recommendations for improving the efficiency and sustainability of sprayers in agriculture.

According to the findings by R.N. Martins *et al.* (2021), the effect of sprayer types and sprayer pipe pressure on the characteristics of sprayed droplets was determined. These results provide important information for understanding the impact of these factors on droplet size, distribution, and behaviour, which are key aspects of effective pesticide use in agriculture. In addition, this study contributed to the development of recommendations for optimising the operating parameters of sprayers, which can lead to an improvement in the quality of spraying and minimise the loss of pesticides as a result of uncontrolled dispersion of particles into the atmosphere. Consideration of these factors is an important step in the practical implementation of environmentally effective spraying strategies.

H.V. Mercaldi *et al.* (2017), J. Wawrzosek & S. Parafiniuk (2022) considered the use of a permutation algorithm to suboptimise the location of spent nozzles on the sprayer boom. The use of this algorithm allows optimising the location of the nozzles, considering various parameters, such as the width of the droplet flight, their concentration, and uniformity of distribution. This approach may prove important for improving the efficiency of sprayers by promoting more accurate and cost-effective distribution of pesticides. The results will help to identify optimal nozzle configurations, contributing to the improvement of spray technologies and reducing the impact on the environment.

The analysis of the papers by prominent researchers showed that no studies of the time of pressure rise and fall in the sprayer pipe have been carried out. Therefore, the purpose of the experimental study was to determine the time of pressure rise and fall in the sprayer pipe and establish the corresponding functional dependencies.

MATERIALS AND METHODS

The research was carried out at the National University of Life and Environmental Sciences of Ukraine at the Department of Agricultural Machinery and System Engineering named after Academician P.M. Vasylenko in 2021-2023. Since it is impossible to record the time of pressure rise and fall in the sprayer pipe using a stopwatch and eyesight, it was decided to record the pressure gauge readings using a Panasonic NV-GS75 digital video camera (Japan), which allows 25 frames per second. Experimental OP-2000-2 trailer sprayer (Ukraine) (Fig. 1) transported to the test site. A driveshaft was attached to the sprayer pump and connected to the power take-off shaft (PTO) of the MTW-82 tractor (Belarus). The tractor's PTO speed was set at 540 rpm.

Collector pressure was monitored using a WIKAI EN837-1 pressure gauge (WIKA Group, USA) in accordance with DSTU 7224:2011 (2011). Since the sprayers operated at a pressure of 0.2 to 0.5 MPa, the test was performed at a pressure of 0.2 to 0.5 MPa. The Panasonic NV-GS75 digital video camera was mounted on a Continent TRIPOD A2 (Continent, China) stand. The height of the video camera installation was 1.5 metres above the ground, and 1 metre from the WIKAI EN837-1 pressure gauge. The video camera was set to a shutter speed of 1/500 of a second, an aperture of D=8 to ensure the greatest clarity of shooting, and a 5x optical zoom (Fig. 2). The automatic application rate control system was set to change the pressure when the green simulation surface hits by 0.5 MPa and the yellow by 0.2 MPa. They simulated the sensor hitting a surface of different colours. At the same time, the pressure in the system changed. The survey was carried out in four-fold repetition, to raise and lower the pressure.

Figure 1. Conducting experiments on a prototype trailer sprayer OP-2000-2

Source: photo by authors

Figure 2. Recording the readings of the WIKAI EN837-1 pressure gauge when raising and lowering the pressure in the pipe

Source: photo by authors

After the research, the camera was connected using a FireWire connector to a PC based on the Athlon 2800+ processor (China). The video was processed using Motion DV STUDIO 5.3 E (Fig. 3), where the time for the pressure to drop and rise from 0.2 to 0.5 MPa was calculated.

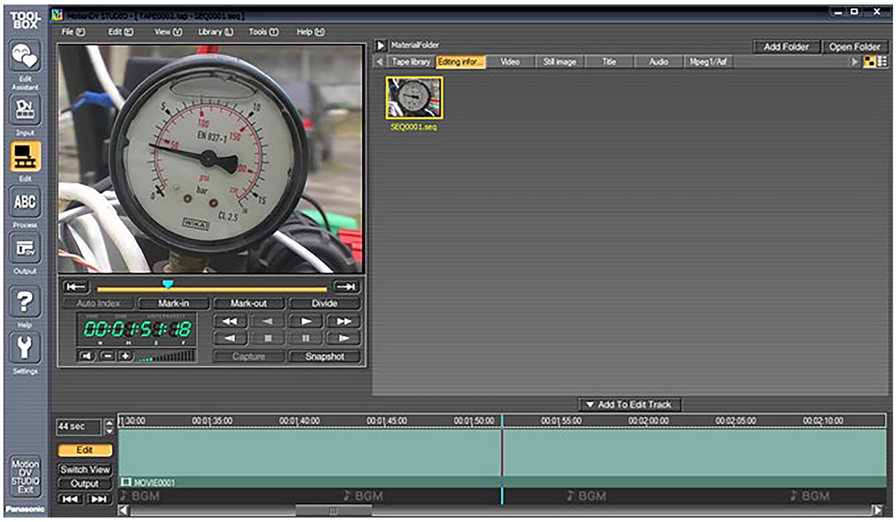

Figure 3. Video data analysis in Motion DV STUDIO 5.3E

Source: photo by authors

The research data were processed using the method of statistical processing of empirical data and evaluated by the arithmetic mean of the time of pressure rise and fall in the sprayer pipe, the standard deviation, and the coefficient of variation. Calculations were performed using the following equations (1)-(4):

- the arithmetic mean of the time of pressure rise and fall in the sprayer pipe (Bugutsky, 1999):

$$\bar{x} = \frac{\sum x_i}{N}, \quad (1)$$

where x – time, s; N – number of experiments,

- mean square deviation (variance):

$$\sigma^2 = \frac{\sum (x_i - \bar{x})^2}{N-1}, \quad (2)$$

- mean square deviation (standard):

$$\sigma = \sqrt{\sigma^2}, \quad (3)$$

- coefficient of variation based on the standard deviation:

$$V = \frac{\sigma}{\bar{x}} \cdot 100\%. \quad (4)$$

Experiments to determine the time of pressure rise and fall in the sprayer pipe were carried out in four repetitions. Calculations were performed using Microsoft Office Excel 2007 software suite.

RESULTS AND DISCUSSION

The results of calculating the standard deviation (variance), standard deviation (standard) and coefficient of variation are presented in Table 1 (calculations were performed using equations 1-4)

Table 1. Results of experimental studies of pressure reduction

No. of experiment	Average pressure reduction value t, s, by 0.05 MPa	Variance	Mean square deviation	Variation coefficient
1	0.27	0.01	0.11	39.87
2	0.29	0.01	0.12	41.06
3	0.44	0.06	0.25	57.21
4	0.29	0.01	0.12	41.06

Source: compiled by the authors

As a result of calculating the experimental data, it was found that the average value of the pressure drop from 0.5 to 0.2 MPa is 1.94 s. And the average value for four experiments, a pressure drop of 0.05 MPa is 0.32 seconds. Results of pressure drop by 5 to 2 atm (in increments of 1 atm) are shown in Figure 4.

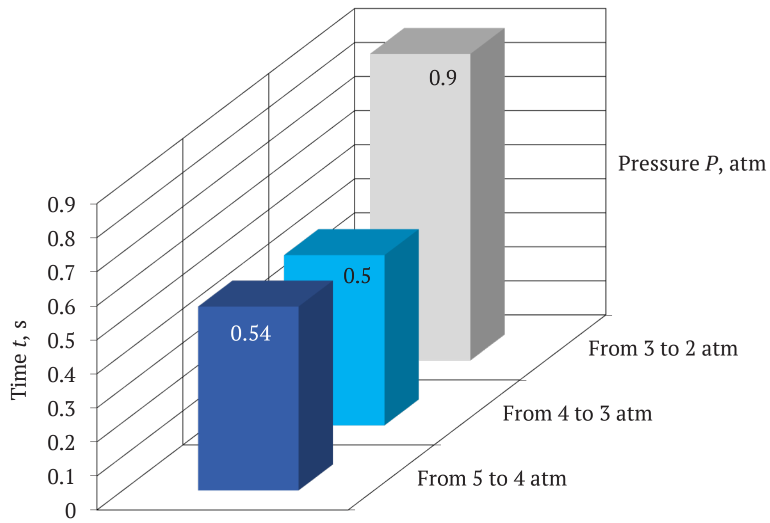

Figure 4. Diagram of the time t required to reduce the pressure in the sprayer pipe by 1 atm
Source: compiled by the authors

As a result of approximation of experimental values obtained during a single-factor experiment with pressure changes P and the corresponding calculated time values t, it is established that the best corresponding functional dependencies are described by a polynomial function. Therefore, the functional dependence describing the characteristic $t = f(P)$ (Fig. 5) when the sprayer with automatic application rate control is as follows:

$$P = 0.4017 \cdot t^2 - 2.4051 \cdot t + 5.1017, \quad (5)$$

where P – pressure in the sprayer pipe, atm; t – time, s.

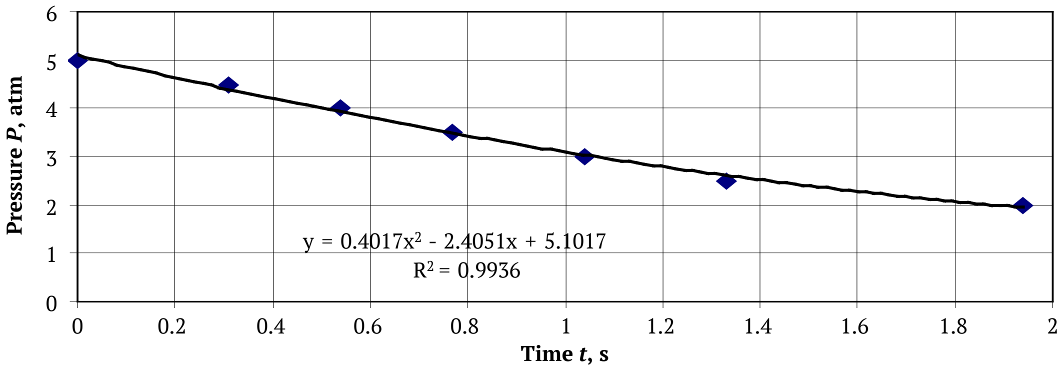

Figure 5. Dependence of pressure in the sprayer pipe *P* on time *t*

Source: compiled by the authors

Coefficient of determination of this dependence $R^2 = 0.9936$. Equation (5) is appropriate, given that the probability is 0.99 for the calculated value of the Fisher's criterion $F_{calc.} = 156$ is much larger than the table value of Fisher's criterion $F_{table} = 12.25$. Based on the findings of J.F. Reyes *et al.* (2015), it can be argued that equation (5) is significant and its coefficients cannot be ignored. The materiality of the coefficient of determination was estimated using the Student's t-test. The coefficient of determination of this dependence is significant because the probability of $R = 0.99$, $t_{calc.} = 508$ is much higher than $t_{table} = 3.50$ (Bugutsky, 1999).

The arithmetic mean of the pressure rise from 0.2 to 0.5 MPa, by 0.1 and 0.05 MPa was determined by the equation (1). The results of calculations of the standard deviation (variance), standard deviation (standard) and coefficient of variation are presented in Table 2 (calculations were performed using equations 1-4).

Table 2. Results of experimental studies of pressure rise

No. of experiment	Average value of pressure rise t, s, by 0.05 MPa	Variance	Mean square deviation	Variation coefficient
1	0.31	0.02	0.14	46.42
2	0.26	0.03	0.17	64.36
3	0.65	0.004	0.07	10.00
4	0.36	0.03	0.18	50.18

Source: compiled by the authors

As a result of calculating the experimental data, it was found that the average time of pressure rise from 0.2 to 0.5 MPa is 2.37 s. And the average value for four experiments, the pressure rise by 0.05 MPa is 0.395 s. As a result of approximation of the experimental values of pressure rise from 0.2 to 0.5 MPa obtained during a one-factor experiment with a change in pressure *P* and the corresponding calculated values of time t, it was found that the functional dependencies described by the polynomial function are the most appropriate. Therefore, a functional dependency describing a characteristic $t = f(P)$ (Fig. 6) when using sprayer with automatic adjustment of the application rate, has the following form:

$$P = 0.2024 \cdot t^2 + 0.8171 \cdot t + 1.9864, \quad (6)$$

where *P* – pressure in the sprayer pipe, atm; *t* – time, s.

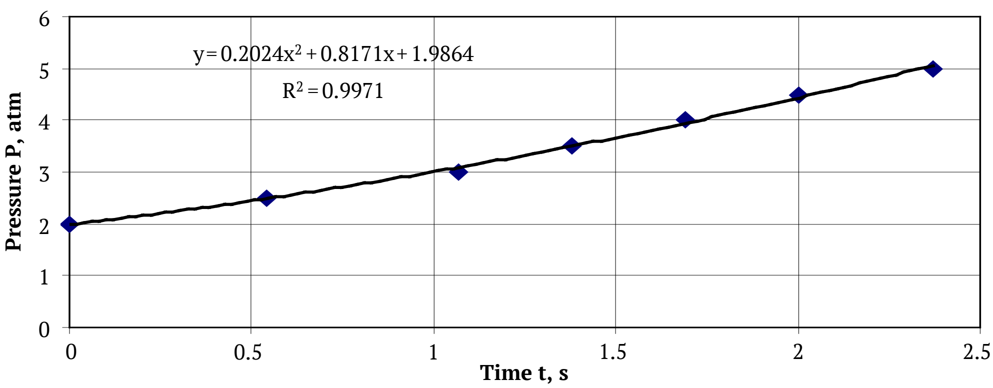

Figure 6. Dependence of the pressure in the sprayer pipe *P* on time *t*

Source: compiled by the authors

Coefficient of determination of this dependence is $R^2 = 0.9971$. Equation (6) is appropriate because, with a probability of 0.99, the calculated value of the Fisher's criterion $F_{calc.} = 172$ is much larger than the table value of Fisher's criterion $F_{table} = 12.25$. Based on the findings of J.F. Reyes (2015), it can be argued that equation (6) is significant and its coefficients cannot be ignored. The materiality of the coefficient of determination was evaluated according to the Student's t-test. The coefficient of determination of this dependence is correspondingly significant because if the probability $p = 0.99$, $t_{calc.} = 607$, which is much larger than $t_{table} = 3.50$ (Bugutsky, 1999). J.V. Fabula *et al.* (2020) investigated the effect of pipe pressure uniformity and droplet size when using pulse-width modulation spray technology. D. Nuyttens *et al.* (2017) investigated the drift of working fluid droplets by different application methods using a drift test bench and compared it with other evaluation methods.

Similar studies have been conducted by D.G. Voytyuk (2015), where the researcher reviewed and analysed machine protection devices, describing their characteristics, technological schemes, settings, and methods of use. The study has provided important insights into understanding the diversity and functionality of protective devices, including their adaptation to different conditions and types of cultivated fields, and highlighted not only the technical aspects of plant protection machines, but also considered their technological purpose and optimal settings for effective use. The review included an analysis of various technological schemes used in such machines, and determined their suitability for various types of agricultural land. Special attention is paid to the adaptation of protective devices to different conditions and types of cultivated fields. This is important to ensure optimal efficiency in a diverse agricultural landscape. The results of the study helped not only to improve existing plant protection machines, but also to develop recommendations for the selection and effective use of such technical means, depending on specific business conditions.

A. Sharda *et al.* (2011) investigated the norm of working fluid from a single series of sprayers when using water-sensitive paper maps. This approach helps to determine in detail the distribution of liquid on the surface and evaluate the efficiency of sprayers. The study considered the interaction of the liquid with the surface based on the characteristics of each sprayer. The results obtained have a positive impact on improving the accuracy and efficiency of sprayers in agriculture, and on the rational use of working fluids. O.I. Melezhik (2010) improved the dispersion of pesticide spraying, and developed a new type of centrifugal sprayer. This approach helps to determine in detail the distribution of liquid on the surface and evaluate the efficiency of sprayers. The study considered the interaction of the liquid with the surface based on the characteristics of each sprayer. The results obtained have a positive impact on improving the accuracy and efficiency of sprayers in agriculture, and on the rational use of working fluids.

V.M. Polischuk (2005) substantiated the parameters of the pneumohydraulic system for dosing and supplying working fluid in sprayers. He investigated the optimal characteristics of this system to maximise the accuracy and efficiency of spraying, reduce fluid loss, and optimise the flow rate of working material. Based on the findings, it can be stated that the developed parameters of the pneumohydraulic dosing system are of great importance for improving the control of the spraying process. This approach helps not only to increase the efficiency of sprayers, but also to reduce the negative impact on the environment through more accurate dosing of the working fluid. J.D. Luck *et al.* (2011), A.B. Dorneles *et al.* (2018) investigated the flow characteristics, spray pattern, and droplet spectra of an actively controlled nozzle with a variable opening at constant carrier pressure. Their results helped to identify optimal operating modes of the nozzle, ensuring maximum spray efficiency and saving working material. This study occupies an important place in understanding the technical aspects of the operation of actively controlled injectors and indicates the prospects for their use in modern spray systems. The analytical approach to investigating the characteristics of injectors contributes to the development and improvement of spraying technologies, which affects the quality and efficiency of using working fluids in agriculture.

O. Baranovskyi & V. Polischuk (2001), O. Baranovskyi *et al.* (2010) studied a jet pump for direct delivery of pesticides to the sprayer discharge line and analysed the metering systems of boom sprayers. They analysed the dosing systems of boom sprayers aimed at improving the accuracy and efficiency of the distribution of working fluids during spraying.

Research on this aspect of spraying technology is important for agriculture, as it aims to develop and improve systems that ensure efficient delivery of pesticides to the field. The results obtained can affect the rational use of working fluids, increase productivity, and reduce material losses during spraying. These results should be considered when developing and implementing modern spraying technologies in order to optimise the use of pesticides and ensure sustainable production in agriculture.

CONCLUSIONS

As a result of calculating the experimental data, it was found that the arithmetic mean of pressure reduction from 0.5 to 0.2 MPa is 1.94 s, and the arithmetic mean for four experiments, a pressure drop of 0.05 MPa, is 0.32 s. As a result of approximation of experimental values obtained during a single-factor experiment with pressure reduction P and the corresponding calculated time values t, it is established that the best corresponding functional dependencies are described by a polynomial function. Therefore, a functional dependency describing a characteristic $t = f(P)$ when the pressure drops, has the following form: $P = 0.4017\ t^2 + 2.4051\ t + 5.1017$. When calculating the experimental data of the pressure rise, it was found that the arithmetic mean of the pressure rise from 0.2 to 0.5 MPa is 2.37 s. And the average value for four experiments, the pressure rise of 0.05 MPa is 0.395 s. As a result of the approximation of the experimental values of the pressure rise from 0.2 to 0.5 MPa obtained during a single-factor experiment with a change in pressure P and the corresponding calculated values of time t, it was found that the polynomial function describes the best corresponding functional dependences. Therefore, a functional dependency describing a characteristic $t = f(P)$ when the pressure rises, is $P = 0.2024\ t^2 + 0.8171\ t + 1.9864$. These experiments in the future would allow calculating the time of delay or advance of opening the spray swath when working with variable standards on target plans.

Further research can be aimed at experimentally studying the time of pressure rise and fall in the sprayer pipe. A detailed analysis of these parameters is key to optimising the operation of sprayers and improving the efficiency of pesticide use in agriculture. The study of the pressure rise time in the pipe will help determine the optimal parameters for a quick and efficient start-up of the spraying system. Pressure reduction is a critical factor in ensuring the accuracy of the working fluid distribution, so a detailed study of this process can lead to improvements in the design and functionality of sprayers. Optimisation of these parameters can improve spray efficiency, reduce working fluid loss, and affect the consistency and accuracy of the process. Such studies will be an important contribution to the improvement of modern spraying technologies in agricultural production.

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CONFLICT OF INTEREST

None.

References

[1] Baranovskyi, O., & Polischuk, V. (2001). Analysis of metering systems for boom sprayers. *Bulletin of the State Academy of Agrarian Sciences of Ukraine,* 2, 141-146.

[2] Baranovskyi, O.S., Pyatachenko, V.I., & Sergeeva, O.V. (2010). Investigation of a jet pump for direct supply of pesticides to the sprayer discharge communication. *Mechanization and Electrification of Agriculture*, 94, 206-215.

[3] Bugutsky, O.A. (Eds.). (1999). *Statistics*. Kyiv: Complex Vita LLC.

[4] Dereumeaux, C., Fillol, C., Quenel, P., Denys, S. (2020). Pesticide exposures for residents living close to agricultural lands: A review. *Environment International*, 134, article number 105210. doi: 10.1016/j.envint.2019.105210.

[5] Djouhri, M., Loubet, B., Bedos, C., Dages, C., Douzals, J.-P., & Voltz, M. (2023). ADDI-Spraydrift: A comprehensive model of pesticide spray drift with an assessment in vineyards. *Biosystems Engineering*, 231, 57-77. doi: 10.1016/j.biosystemseng.2023.05.008.

[6] Dorneles, A.B., Bottega, E.L., Oliveira, Z.B., Knies, A.E., Silva, C.M., & Souza, I.J. (2018). Using different spray tips to control diseases in wheat. *Ciencia e Natura*, 40, 11-17. doi: 10.5902/2179460X35494.

[7] DSTU 7224:2011. (2011). *Metrology. Pressure gauges, manovacuum gauges, vacuum gauges, pressure meters, traction pressure meters, weights with pneumatic output signals. Verification (calibration) methods*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=67905.

[8] Fabula, J.V., Sharda, A., Flippo, D., Ciampitti, I., & Kang, Q. (2020). Boom pressure and droplet size uniformity of a pulse width modulation (PWM) spray technology. *ASABE*. doi: 10.13031/aim.202001041.

[9] Hulin, M., *et al.* (2021). Monitoring of pesticides in ambient air: Prioritization of substances. *Science of the Total Environment*, 753, article number 141722. doi: 10.1016/j.scitotenv.2020.141722.

[10] Luck, J.D., Pitla, S.K., Zandonadi, R.S., Sama, M.P., & Shearer, S.A. (2011). Estimating off-rate pesticide application errors resulting from agricultural sprayer turning movements. *Precision Agriculture*, 12(4), 534-545. doi: 10.1007/s11119-010-9199-9.

[11] Martins, R.N., Moraes, H.M.F., de Freitas, M.A.M., da Costa Lima, A., & Furtado Junior, M.R. (2021). Effect of nozzle type and pressure on spray droplet characteristics. *Idesia*, 39(1), 101-107. doi: 10.4067/S0718-34292021000100101.

[12] Melezhik, O.I. (2010). *Improvement of dispersion for pesticide spraying*. (PhD thesis, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine).

[13] Mercaldi, H.V., Peñaloza, E.A.G., Mariano, R.A., Oliveira, V.A., & Cruvinel, P.E. (2017). Flow and pressure regulation for agricultural sprayers using solenoid valves. *Escola de IFAC PapersOnLine*, 50(1), 6607-6612. doi: 10.1016/j.ifacol.2017.08.693.

[14] Nuyttens, D., Zwertvaegher, I.K.A., & Dekeyser, D. (2017). Spray drift assessment of different application techniques using a drift test bench and comparison with other assessment methods. *Biosystems Engineering*, 154, 14-24. doi: 10.1016/j.biosystemseng.2016.09.013.

[15] Paulson, I.W.P., Gerspacher, J., Gagnon, B.J., Landry, H., Sumner, D., & Bergstrom, D.J. (2022). Experimental characterization of the aerodynamic wake of a high-clearance sprayer with changing operating parameters. *Journal of the ASABE*, 65(3), 665-679. doi: 10.13031/JA.14941.

[16] Polischuk, V.M. (2005). *Substantiation of parameters of the pneumohydraulic system of dosing and supply of working fluid in sprayers*. (PhD thesis, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine).
[17] Reyes, J.F., Esquivel, W., Cifuentes, D., & Ortega, R. (2015). Field testing of an automatic control system for variable rate fertilizer application. *Computers and Electronics in Agriculture*, 113, 260-265.
[18] Sharda, A., Fulton, J.P., McDonald, T.P., & Brodbeck, C.J. (2011). Real-time nozzle flow uniformity when using automatic section control on agricultural sprayers. *Computers and Electronics in Agriculture*, 79(2), 169-179. doi: 10.1016/j.compag.2011.09.006.
[19] Voytyuk, D.G. (Ed.). (2015). *Agricultural machinery*. Kyiv: Agroosvita.
[20] Wawrzosek, J., & Parafiniuk, S. (2022). The use of the permutation algorithm for suboptimising the position of used nozzles on the field sprayer boom. *Applied Sciences*, 12(9), article number 4359. doi: 10.3390/app12094359.
[21] Xiahou, B., Sun, D., Song, S., Xue, X., & Dai, Q. (2020). Simulation and experimental research on droplet flow characteristics and deposition in airflow field. *International Journal of Agricultural and Biological Engineering*, 13(6), 16-24. doi: 10.25165/j.ijabe.20201306.5455.

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Експериментальне дослідження часу підняття та зниження тиску в колекторі обприскувача

Анотація. Велике різноманіття метеорологічних факторів, ґрунтово-кліматичних умов, насиченість полів багатьма видами бур'янів, значний набір культурних рослин і багато інших факторів обумовлюють необхідність втілення інноваційних технологічних схем використання отрутохімікатів, це дозволить максимально зменшити пестицидне навантаження та зумовить безпечну екологічну дію препаратів. Експериментальні дослідження були проведені з метою визначення часу підняття та зниження тиску в колекторі обприскувача та встановлення відповідних функціональних залежностей. Систему автоматичного регулювання норми внесення було налаштовано на зміну тиску при потраплянні зеленої імітаційної поверхні на 0,5 МПа, а жовтої на 0,2 МПа. Імітовано потрапляння сенсора на поверхню різного кольору. При цьому змінювався тиск в системі. Тиск в колекторі обприскувача ОП-2000-2 вимірювався за допомогою манометра WIKAI EN837-1 та фільмовано показання цифровою відеокамерою Panasonic NV-GS75 встановленою на штатив Continent TRIPOD A2. В результаті обрахунку експериментальних даних встановлено, що середнє арифметичне значення зниження тиску від 0.5 до 0.2 МПа становить 1.94 с. А середнє арифметичне значення по чотирьом дослідам, зниження тиску на 0.05 МПа становить 0.32 с. При обрахунку експериментальних даних підняття тиску встановлено, що середнє арифметичне значення підняття тиску від 0.2 до 0.5 МПа становить 2.37 с. А середнє значення по чотирьом дослідам, підняття тиску на 0.05 МПа становить 0.395 с. Після апроксимації експериментальних даних, отриманих при проведенні одно факторних експериментів, при зміні тиску P і відповідних значень часу t, отримані відповідні поліноміальні функції, що описують характеристику $t = f(P)$ при роботі обприскувача з автоматичним регулюванням норми внесення. Отримані результати в майбутньому дають можливість розрахувати час затримки або випередження розкриття факелу розпилювача при роботі з змінними нормами по картам завдань, для уникнення невідповідності нормі внесення заданим значенням

Ключові слова: поліноміальні функції; штанга; польовий обприскувач; захист рослин; норма внесення; факел розпилу

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Achievements and problems in studying the mechanism of thermal potential transfer regulation between liquids

Abstract. The relevance of the study is determined by its focus on one of the key problems of the Ukrainian economy, namely the problem of energy resources, which is a necessary step in the development of resource management and planning strategies in the context of modern challenges and instability in the energy market. The purpose of the study is to determine the hydrodynamic and mass-heat transfer characteristics of the process of mixing liquids with different thermal potentials, and to investigate the influence of design factors on the intensity and efficiency of the flow jet. Experimental methods were used to specify the hydrodynamic and mass-heat transfer parameters of the liquid mixing process, and modelling was used to analyse the influence of design factors and develop a scientifically based methodology for calculating new device designs. An approach is obtained that allows solving two problems simultaneously: to decrease energy costs through their rational operation and to reduce environmental pollution, avoiding harmful emissions that

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occur during fuel combustion. The functional scheme of the test stand is described, the research methodology is presented, and statistical modelling of the influence of parameters on the length of the liquid jet is carried out. Studies of the energy efficiency of the initial stage of the interaction of thermal potentials during the generation of a liquid jet in a recuperative heat exchanger of mixed action to ensure storage conditions and potential movement in front of the nozzle are presented. A mathematical model for describing the length of a continuous water jet when flowing out of the nozzle is proposed and an analysis of the laminar flow of liquid from the nozzle is performed. The length of the continuous water jet when flowing out of the nozzle is determined and the technical capabilities of the process are identified. The efficiency of installing the tip in front of the nozzle for creating turbulent mixing and the method of controlling the water supply during the mixing of thermal potentials are determined. To control the water supply process, a step-by-step method has been developed that allows gradually increasing or decreasing the length of a continuous water jet through the nozzle. The results of the study provide an opportunity to optimise heat exchangers and mixing machines to increase their efficiency and productivity

Keywords: nozzle; continuous jet; experiment; jet feed length; jet feed length control

INTRODUCTION

The energy resources of each country have historically been a key systemic factor in the economic structure. Nowadays, there is a physical limitation, which leads to a gradual decrease in these resources and, accordingly, to an increase in their value on the world market. The availability and use of energy-efficient technologies define long-term trends that can model the energy landscape over several decades, influencing the energy strategy of different countries and global energy trends. An important moment in this context was the energy crisis of 1973 (Rosen, 2002), which defined a new course in energy policy and acted as a catalyst for change. This crisis has played an important role in shaping approaches to energy consumption, improving energy efficiency, and developing alternative energy sources. As a result, new strategies and approaches to energy security and sustainable development have emerged and are emerging.

One of the strategic areas for achieving this goal is to optimise the use of heat and power resources in an in-depth analysis of the energy potential of the system. For this purpose, mathematical modelling methods can be used, considering the parameters of thermal systems, thermodynamic characteristics, and dynamics of energy flows. G. Lohar *et al.* (2019) noted that the implementation of optimisation is based on consideration of the influence of various factors on the thermal efficiency of the system. This includes analysis of thermal resistance, heat transfer efficiency, and other physical and technical aspects that determine energy losses in the system. Implementation of the results of research and optimisation of heat and power systems may include the development of new technologies, improvement of existing heating networks, and rational distribution of energy in the system. According to O.M. Yanchuk & O.V. Marchuk (2020) liquid flows are widely used in various technological processes, this is especially important when creating their uniform thermal potential and developing dispersed systems. The interaction of these flows occurs due to the interaction of flows through the design parameters of equipment or factors of tangential liquid supply to the system.

Results of experimental studies by P. Martin Díaz (2022) indicate that high-speed fluid flows significantly affect flow characteristics, in particular jet expansion, injection processes, heat-mass transfer, and diffusion. I. Stadnyk *et al.* (2020) noted that even small changes in the flow rate of the jet can lead to significant changes in the width of the jet itself. It is important to note that exposure to a low liquid flow rate leads to an increase in the width of the jet core while reducing the speed of the central part of the flow. However, the weak characteristics of the interaction of liquids limit the application of this phenomenon in studies aimed at optimising the energy potential.

The interaction of flows is the result of the interaction of flows through the design parameters of equipment or factors of its tangential supply to the system. Ya. Mykhaylovskyi *et al.* (2021) argue that experimental studies show that high-speed fluid flows have a significant impact on the flow field: jet expansion, injection processes, heat-mass transfer, and diffusion. The influence of a low jet outflow rate leads to an increase in the width with a decrease in the flow core velocity, which limits the use of temperature potential stabilisation in studies.

Existing advanced new methods in which the initiative of dosing and mixing in the system is already provided. Findings of A. Mehralizadeh *et al.* (2021) showed better process control, shorter reaction time, and better product quality and process time. In addition, in this process, due to dose variation in several stages, interaction management will be easier. Therefore, with the increasing use of various factors in the interaction of liquid mixtures to save energy potential at the present stage, they have become more important because of their characteristics. Mixing flows can create new systems that have new properties at standard thermal potential formations and be economical.

The use of suspended bed mixing in contact heat exchangers to obtain a homogeneous temperature of substances in the food and pharmaceutical industry requires constant modernisation of the hardware design. To reduce the size of the equipment, one method is to increase the relative velocity of the continuous and dispersed phases, as indicated by A. Mehralizadeh *et al.* (2020). This is achieved by using vortex and highly turbulent flows in suspended layer devices. An increase in productivity (phase load) for devices with this type of flow movement leads to a smaller increase in their dimensions and energy costs to ensure the uniformity of the temperature system. This raises an important task of upgrading existing equipment to use two-phase flows in these processes.

The purpose of the study is to consider the process of controlling the flow of mixing liquids with different values of thermal potential through experimental and theoretical studies when creating a scientifically based methodology for calculating them, depending on variable factors.

Therefore, it is necessary to solve the following tasks: 1) to conduct theoretical and experimental studies to determine the rate of outflow of a continuous water jet by a nozzle from variable factors affecting the process of its control during heat transfer; 2) to present a mathematical model for determining the change in temperature flows when they are mixed; 3) to develop a methodology for controlling the process of the length of a continuous water jet in front of turbulent dispersion devices.

MATERIALS AND METHODS

The research was conducted in the laboratory of the Ternopil Ivan Puluj National Technical University and at the Ternopil confectionery factory "Tera". According to the objectives of experimental research, the test stand of 2021 was upgraded to investigate the interaction of liquid flow with elements of dynamic devices. The initial design was based on the discrete pulsed injection of liquid components when they were mixed in the specially developed mixing machine. The upgraded test stand had more advanced capabilities for studying the energy potential involving temperature gradients.

Figure 1 shows the functional diagram of the test stand. The elements of the test stand are grouped as follows:

- equipment – a model of modular dynamic contact recuperative mixing heat exchanger, a nozzle for accelerating the flow of liquid, a turbulent mixing nozzle tip;
- devices – a nozzle device, a container for further recovery of heat flows of liquid.

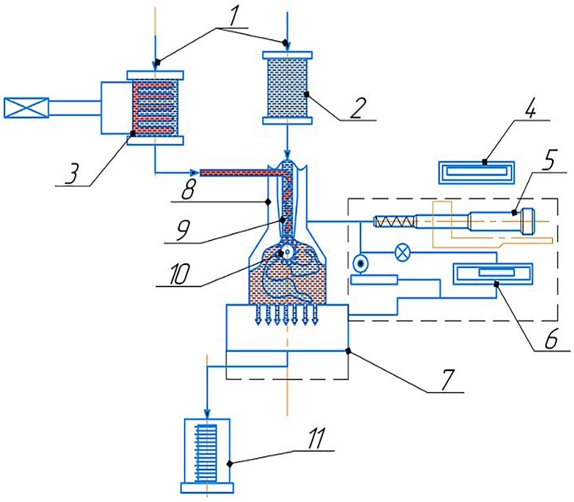

Figure 1. Functional diagram of the test stand

Note: 1 – water supply pipelines; 2 – rotameter Winsen F1012; 3 – water heater with voltage regulator RNO-250/25; 4 – Arduino MEGA 2560; 5 – measuring device G1/4; 6 – Arduino MEGA 2560; 7 – heat exchanger capacity for heat recovery; 8 – water supply pipe with pre-mixing; 9 – nozzle; 10 – turbulent nozzle tip; 11 – tank of homogeneous warm water

Source: compiled by the authors

The test stand works as follows: Water from two pipelines 1 with different temperatures (or air) is supplied with the pressure that is created in the pipeline to the nozzle channel 9. If necessary, the channel was connected to the nozzle and the turbulent nozzle tip 10 to create a turbulent movement of the water jet and its high-quality mixing. Next, the water droplet mixture of thermal potential was fed into the modular lattice device, which captures dispersed particles, while creating pressure on the surface of the grid 7. The liquid was discharged from the grid in the form of trapped water film droplets through its drainage channels to the main part of the heat exchanger. In the main part, the water was finally reheated for recuperative heating. A measuring system has been developed to determine the process parameters.

Devices. A water heater with a voltage regulator RNO-250/25 (Ukraine) and a pressure sensor G1/4 with an analogue converter (Switzerland) were used to obtain the data of the measured values during the study on the test stand. Its range is 0-3 MPa with an operating constant voltage of 5 V and a relative measurement error of 0.01; rotameter Winsen F1012 (China) with a measurement range of 0.02-1.5 dm^3/min and the relative measurement error of 1.5% and the G1/4 measuring device. Arduino MEGA 2560 system (Italy) with software, connected to a PC via a USB cable, was used to collect data from the sensors. The saved data was viewed and processed using MS Excel® software suite.

Statistical mathematical modelling. Experimental studies have been carried out to determine the rate of outflow of a continuous water jet by a nozzle from variable factors using a fractional factorial experiment of type 2^{3-1}. The factors are coded to translate natural factors into dimensionless values in the construction of a standard orthogonal plan-matrix of the experiment. The encoded data is shown in Table 1.

Table 1. Levels of change in factors

Factor levels	Working pressure P, MPa		Outlet nozzle diameter, mm		Nozzle tilt angle, α	
	x_1	$\ln x_1$	x_2	$\ln x_2$	x_3	$\ln x_3$
upper (+1)	0.2	-1.6094	32	3.47	40	3.68
zero (0)	0.1		28.5		25	-
lower (-1)	0.09	-2.4079	25	3.23	10	2.28

Source: compiled by the authors

The dependence was used to transform variables of independent factors x_1 into dimensionless

$$x_1 = 2(\ln x_1 - \ln x_{1min})/\ln x_{1max} - \ln x_{1min} + 1. \quad (1)$$

Expression of code variables:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3. \quad (2)$$

To ensure the reliability and reproducibility of findings, the number of replications (r) was assumed to be 2. To consider the influence of random factors on the result of the experiment and reasonably use the methods of mathematical statistics, an element of randomness was introduced. Maintaining the number of repeated experiments equal to 2 and introducing random factors helped to create conditions for a reasonable analysis of the results of the experiment and determine their reproducibility in different situations. A random order of experiments was established in time, i.e., randomisation. For this purpose, random number tables were used.

The specified sequence of experiments – 2, 3, 1, 2, 4, 1, 3, 4 – indicated that each experiment number (level) was repeated twice, which corresponds to the set number of repetitions ($r = 2$). This allowed for parallel studies to assess the reproducibility of the process and statistical assessments. In this case, the mathematical model can be represented as:

$$y = 3.97 + 0.21x_1 + 0.08x_2 + 0.018x_3. \quad (3)$$

Based on the use of dependency (1), obtained:

$$x_1 = 4.02\,ln \cdot P - 1.62x_1, \quad (4)$$
$$x_2 = 8.34\,ln \cdot d - 27.62, \quad (5)$$
$$x_3 = 1.44\,ln \cdot \alpha - 1.64. \quad (6)$$

Next, the reproducibility of the experiments was checked using the Cochrane criterion. The scattering variance was determined, where S^2_{maxpi} – the highest value of the scattering variance. To bring the equation with coded factors to the form with natural variables, the data on the transition from natural values of factors to coded dimensionless ones were used using dependence (1). The length of a continuous jet L in CM was determined by the dependence:

$$y = 3.97 + 0.21(4.02\,lnP - 1,62) + 0.08(8.34\,ln - - 27.62) + 0,018(1.44n\alpha - 1.64), \quad (7)$$

then: $lnL = lne^{1.68} + lnP^{0.18} + lnd^{0.87}ln\alpha^{0.03}$.

After potentiation,

$$L = 5.41P^{0.18}d^{0.87}\alpha^{0.03}. \quad (8)$$

RESULTS AND DISCUSSION

In the limited space of the proposed initial temperature mixing of liquids, the nature of the movement of the free convective flow depends on a number of parameters:

- temperature condition of surfaces;
- directions of heat supply;
- shape and size of the space in which substance moves.

Characteristic types of fluid circulation in a confined space are shown in Figure 2.

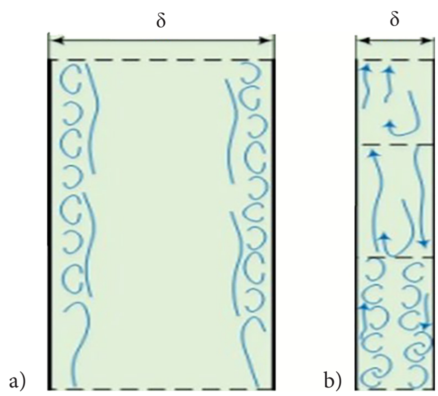

Figure 2. Types of fluid circulation in a confined space
Note: a – in wide channels, b – in narrow channels; δ – distance between the channel walls
Source: compiled by the authors

In vertical channels, the nature of circulation depended on the distance δ between the channel walls as follows: in wide channels (Fig. 2a) upstream and downstream flows move without interference and do not affect each other; in narrow channels (Fig. 2b) upstream and downstream flows create mutual interference, resulting in circulation circuits whose dimensions depend on the temperature difference and channel width. Due to the complexity of processes that occur in a limited enclosed space, it is impossible to determine the coefficient based on the characteristics of circulation. Therefore, the coefficient of equivalent thermal conductivity is used in practice (Nochnichenko & Yakhno, 2020):

$$\lambda_{eq} = \varepsilon_k \lambda, \quad (9)$$

where: ε_k – correction factor that considers free convection (depends on the number $Re = \Pr Gr$); λ – thermal conductivity of the medium (liquid). For $Re > 3^{10}$, the correction factor is equal to: $\varepsilon_k = 0.18\,Re^{0.25}$. The characteristic linear size is taken as the interlayer thickness δ, and the average liquid temperature $t = 0.5(t_1 + t_2)$. For a flat channel, the heat flux density will be determined by the equation: $q = \lambda_{eq}(t_1 + t_2)/\delta$.

Modelling of a laminar flow jet. The conditions of mixing two liquids with different thermal potentials when they are fed into the nozzle were considered, according to the developed stand (Fig. 1). The source analysis described above established the main regularities of liquid flow with different temperatures and considered its behaviour in the cylindrical part of the pipe and at the outlet of the nozzle opening. This connection helped to consider the pre-mixing of two liquids and determine the possible length of the jet flowing out of the nozzle. The non-scattered jet length is kinetic and thermal energy for further use in scattering nozzle tips when creating a turbulent flow regime.

It was assumed that a mixed jet of liquids with an initial temperature T_0 and speed w_0 and with temperature T_n flows out of a circular hole with a radius r_0 in the space in front of the nozzle tip, friction on the interfacial surface was ignored. Under these conditions, the radial component of the temperature gradient is greater than the axial component. The radial velocity variable is not taken into account.

1.Computer modelling. The programme visualised the movement of liquids before and after the nozzle (Fig. 3).

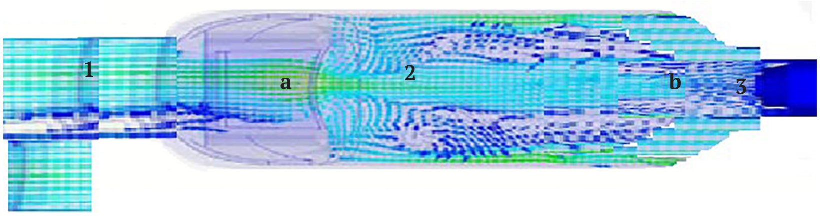

Figure 3. Generation of isotherm flow in a free water jet

Note: 1 – initial mixing area, 2 – flow of two liquids, 3 – flow at the outlet of the nozzle; a – free flow of water, b – a turbulent spot of the water jet

Source: compiled by the authors

From the obtained data, it follows that the maximum heat transfer corresponds to a laminar turbulent transition (LTT) in a long pipe. For this mode, it is established that LTT is implemented in accordance with the discontinuity scenario, that is, when areas with laminar flow alternate with areas with turbulent flow (turbulent spots – torqueing) (Kutsenko *et al.*, 2020). This process is illustrated in Figure 3 on the example of propagation a free flow of water (d = 3 mm, Re = 2,850). Visualisation was performed using the Hilbert method (Nochnichenko & Yakhno, 2020). According to Figure 3a at the initial site of the jet is an extended laminar region, at the end of which there is a rather sharp transition to turbulence. In Figure 3b there is a turbulent spot about 10-12 pipe diameters long at the beginning of the jet. In the near field of the jet, an intermittent nature of instantaneous speed changes over time can be observed, which is associated with the presence of turbulent spots.

The change in heat transfer isolines can be determined based on the specified data. The transition from laminar flow to turbulent flow affects the distribution of heat transfer along the pipeline. These changes in the flow mode (from laminar to turbulent) cause changes in the distribution of heat transfer along the long pipeline. According to the obtained data, the change in heat transfer isolines reflects the process of laminar-turbulent transition.

An unbounded volume whose dimensions are so large that a thermal disturbance (e.g. caused by a temperature difference) in this volume does not affect all its boundaries. This means that temperature anomalies do not extend over long distances, and the system can be considered unlimited. The laminar mode of flow and movement of the coolant occurs layer by layer without crossing mass currents. The liquid flow is divided into thin layers, each of which moves parallel to the other. In a turbulent flow mode, chaotic and confusing movements of a liquid or gas occur. Here, the current is no longer divided into separate layers, and a large number of vortices and turbulence occur. Convection along a vertical pipe is considered. The laminar flow mode is established in the boundary layer, but over time this laminar layer goes into a transient mode and, at a certain distance from the input section, becomes turbulent. The thickness of the laminar layer increases in the direction of movement.

Figure 3a shows that heat transfer isolines can be more concentrated in the initial section of the jet. At the end of this region, there is a sharp transition to a turbulent flow, which can lead to the expansion of isolines. In Figure 3b, near the beginning of the jet, a turbulent spot can be detected where the change in heat transfer insulators can be significant. In the near field of the jet, due to the intermittent nature of instantaneous velocity changes, there are turbulent spots, which also affect the distribution of heat transfer isolines. This highlights the effect of changes in the flow mode on the distribution of heat transfer and uses a scientific approach to explain these phenomena.

Figure 4 shows experimental data on the average value of the heat transfer coefficient at the stagnation point. As can be seen from the Figure 4, for leakage from the nozzle, there is a monotonous dependence of the average value of the heat transfer coefficient α_0 from the Reynolds number of the jet in the range of its values Re = 200-20,000.

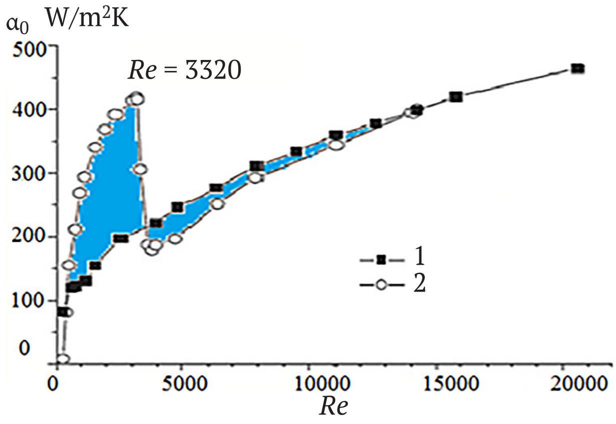

Figure 4. Dependence of the heat transfer coefficient on the Reynolds number

Note: 1 – nozzle, 2 – pipe

Source: compiled by the authors

The behaviour of α_0 is significantly different for leakage from a pipe. There are three characteristic zones: in the first zone (Re < 3,300), an increase in α_0 was observed, in the second zone (Re = 3,300-3,500), a marked decrease in α_0 was observed, and in the third zone (Re > 3,500), the parameter α_0 increased again. Thus, in the region of low Reynolds numbers (Re < 4,000), a non-monotonic change in the average value of the heat transfer coefficient α_0 was detected at Re = 3,320, which is 12%, and for the third zone (Re > 3,500), a monotonous decrease in velocity is observed.

Rational use of production resources becomes a key factor for optimising the efficiency and competitiveness of enterprises. The implementation of this principle significantly affects various aspects of the activity, in particular, reducing costs and increasing the profitability of production. Optimisation of processes and implementation of modern technologies reduces production costs, while effective resource management contributes to their economical use (Stadnyk *et al.*, 2020). This is important for enterprises in a competitive environment, where production efficiency is a key success factor and an important component of a successful enterprise development strategy in a changing economic environment.

Researchers are tasked with developing new energy-saving and, in particular, energy-efficient technologies related to the creation of high-performance and intensively operating devices. The actual task is to develop multifunctional devices of combined action, in which it is possible to perform several processes simultaneously. In such devices, the efficiency of using the working volume should be 2-3 times higher than in existing analogues (Shullie, 2020). Many branches of the food industry use heterogeneous processes and heat transfer that occur in the "gas-liquid-liquid-solid" system. These processes play a special role among others, since their speed is determined by the patterns of mass and heat transfer between the interacting phases. Hydrodynamics and heat-mass transfer serve as the theoretical basis for these processes and the creation of methods for engineering and optimisation calculations of equipment. Considering the relationship and interdependence between the hydrodynamic and heat-mass transfer characteristics of the interacting phases, the study by A. Kovalyov *et al.* (2018) considers the stage-by-stage use of the thermal potential of industrial furnaces.

There is little information about the mechanisms of motion, structure, hydrodynamics, and heat-mass transfer in a suspended vortex layer when mixing liquids to obtain their uniform temperature. A. Mehralizadeh *et al.* (2021) revealed the mixing of liquids in mixers of various designs to obtain temperature uniformity. Such data could be used as the basis for the methodology of engineering calculation of equipment of this type, in particular, contact recuperative heat exchangers. Scientific studies of hydrodynamics and mass-heat transfer in devices with one-and two-phase flows have become more intensive. These studies indicate the feasibility of highly turbulent flows during heat transfer. Investigation of the mechanisms of vortex formation and interaction in a liquid depending on various parameters, such as the size and shape of suspended particles, the influence of rheological properties of a liquid on the structure and movement of vortex layers.

When developing mathematical models of hydrodynamics for describing fluid motion in vortex suspended layers, V.M. Atamanyuk (2019) studied the influence of various parameters (velocity, concentration of suspended particles) on the nature of hydrodynamic processes. Heat-mass transfer in vortex flows contributed to the development of heat transfer models for various conditions and configurations of mixing contact vortex heat exchangers. To develop methods of engineering calculation, the efficiency of vortex flows is used, considering hydrodynamic and heat-mass transfer processes.

Research by V.V. Mykytenko (2004) highlights aspects of accessibility and implementation of energy-saving technologies. The document states that the development and implementation of energy-saving technologies have a decisive impact on long-term trends in energy consumption. Improvements in technology can lead to a significant reduction in energy costs in various industries, which affects overall energy demand. According to J.C. Wu (2018), migration of energy consumption centres and the development of new industrial enterprises can lead to changes in the structure of energy consumption. This may include an increase in energy demand as a result of the growth of new industries and the settlement of consumers. Given these factors, there is a need for a global approach to the use of energy resources.

Investigation of advantages and possibilities of using highly turbulent flows in various types of equipment (heat transfer, granulation, separation) by O.F. Luhovskyi *et al.* (2011) helped to establish their optimal design and operating conditions. Their data in these areas not only help to understand the features of hydrodynamics and heat-mass transfer in suspended vortex layers, but can also lead to the creation of new technologies and designs that will improve the efficiency of liquid mixing processes.

I. Stadnyk *et al.* (2019) highlight important aspects of implementing technologies in production in the context of minimising energy losses, avoiding problems, automating and optimising the entire technological process, and considers some key aspects that may be important for achieving these goals. The introduction of automation systems for controlling technological processes based on the use of modern technologies, such as sensorics, machine learning and artificial intelligence is revealed. The use of robots for handling, transferring materials, and other operations to reduce energy and material costs, reduce human intervention, and increase productivity. This includes the use of monitoring and control systems that allow real-time determination of process parameters and modular technologies that can be easily modified and updated. These approaches are aimed at creating efficient and environmentally friendly production processes that consider product quality, production efficiency, and compliance with modern standards of sustainable development.

The liquid flow spray method is widely used in the food industry for forced decomposition of liquid jets to form droplet structures. It is important that the resulting droplets are monodisperse, that is, they have the same size and temperature distribution. This is achieved with the help of specially designed technical devices, vibrations in achieving monodispersity of particles, which is important for high-quality products. This method using centrifugal or static vibration devices is promising in modern heat transfer and meets high standards of quality and production efficiency.

Theoretical aspects of hydrodynamics, heat transfer and mass transfer are considered in the study by I. Beljakova *et al.* (2020). The study of systems of differential equations that describe the heat-mass transfer between a thermal agent is considered on the analysis of the laws of conservation of heat and mass in the context of the filtration drying process, which helps to understand how energy and matter are stored and transferred in the system. The basic equations of heat-mass transfer can be used to describe the heat and mass transfer between water heat transfer agents. Based on the above-mentioned theoretical foundations, it is possible to better understand and optimise the process of heat and mass transfer.

Therefore, one of the potential areas of development in this context is the use of heat flow recovery. By considering this aspect, it is possible to increase energy efficiency and reduce losses, which helps ensure a more environmentally sustainable and rational approach (Kudelya & Dubovskyi, 2020).

Thus, the **e**ffectiveness of water flow control directly depends on the serviceability of the valves. Even a small leak can lead to significant resource losses. Moreover, faulty fittings not only ensure constant water leakage, but also increase the risk of damage to the water supply system.

The use of dispersing nozzles for water taps and faucets can significantly affect the optimisation of water consumption. These devices, which inject a significant amount of air into the water jet, can achieve savings of up to 30% (Luhovsky & Lyashok, 2014). Their application is an important step towards sustainable use of water resources. Mixing air with water, provided by dispersing nozzles, contributes not only to the preservation of water, but also provides a comfortable water supply. Technological innovations also include automatic measurement and control systems that improve the accuracy of flow control and optimise water efficiency.

The results of the analysis of the study by Yu. Maiboroda (2020) are related to technical means of heat transfer. They establish the absence of data on the characteristics of the nozzles in the development of uniformity of the temperature field of mixed liquids. The creation of a water jet depends on the pressure of the liquid, the diameter of the nozzle, the angle of inclination, and the height of placement above the surface of the liquid in the heat exchanger housing. In the process of heat transfer recovery, it is necessary to direct a continuous jet into the heat exchanger assembly by changing the pressure, nozzle diameter, inclination angle, etc. To solve this problem from the standpoint of process management, the task is to conduct experimental research and develop an empirical mathematical model based on the results obtained. This model should consider the influence of various factors on the length of a continuous jet.

The studies by M.I. Gorbiychuk *et al.* (2021) indicate that the working pressure of 0.6 MPa creates a continuous water jet length of 61-68 m. The analysis of the current state of continuous water jet supply length controls has shown that they are not available today. Therefore, the solution to the problem involves conducting theoretical and experimental studies to determine the influence of parameters on a continuous water jet. Establishing the variable factors affecting the process of controlling the formation of a homogeneous jet of heat flow of a liquid should substantiate the idea of a new recuperative heat exchanger of combined action.

Mathematical modelling. The general form of the thermal conductivity equation for a continuous medium in polar coordinates has the form:

$$\frac{\partial\theta}{\partial t} = \alpha\left(\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right) + \frac{1}{r^2}\cdot\frac{\partial^2\theta}{\partial\phi^2}\right), \tag{10}$$

where: θ – excess temperature of the liquid; t – time; α – coefficient of thermal conductivity; r – radius. This equation is a partial differential equation of thermal conductivity that describes the temperature regime of a liquid jet. It has a form of a simplified equation for a liquid jet with mixed temperatures. However, in order to provide a concrete solution, additional conditions, such as initial conditions or boundary conditions, describing the physical context of the fluid movement, need to be known. Usually, velocity w is defined as the ratio of a change in coordinate to a change in time: $v = dx/d\tau$.

The expression $dx = w \cdot x \cdot d\tau$ is accepted, which indicates that the velocity is defined as the product of the velocity w times the coordinate x multiplied by the time element $d\tau$. Ignoring the change in velocity w_x in the direction of the radius, it can be assumed that the velocity w_x it is a constant parameter, i.e., $w_x = w_0$, and it does not change with the radius. This allows simplifying the equation of thermal conductivity, especially considering that the change in velocity along the radius is not included. This can greatly facilitate the analysis and solution of the equation. Thus, the equation of thermal conductivity with respect to the coordinate X with the condition $wx = w_0 w$, can be expressed as:

$$\frac{\partial\theta}{\partial x} = \alpha\left(\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial\theta}{\partial r}\right), \quad (11)$$

where x – coordinate (if it is a space, such as a radius).

The coefficient of thermal conductivity varies along the length of the jet, i.e. $a = a(L)$. If a depends on L, that is $a = a(L)$, then the derivative da/dx represents the rate of change of a relative to L, a dL – length element. Thus, based on the differentiation of a function by another function, $d\tau a$ can be expressed as $\frac{da}{dx}dL$, representing the change in the coefficient of thermal conductivity over an elementary length segment. This allows considering the change in the coefficient of thermal conductivity relative to the dependence of the coordinate L in the analysis along the jet. The initial equation of thermal conductivity with the dependence of the coefficient of thermal conductivity can now be written as follows:

$$\frac{\partial\theta}{\partial x} = \alpha(L)\left(\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial\theta}{\partial r}\right), \quad (12)$$

under the conditions $w_x = w_0$ and $a = a(L)$. For a dimensionless form, dimensionless variables are introduced into the thermal conductivity equation. Typically, dimensionless coordinates and dimensionless time are entered. Dimensionless variables are denoted as follows: $\eta = \epsilon/L$, where L – characteristic jet length. Dimensionless time is also introduced where a_0 – initial value of the thermal conductivity coefficient. Then the dimensionless temperature is indicated:

$$\theta^* = \frac{\theta-\theta_0}{\theta_1-\theta_0}, \quad (13)$$

where θ_0 – temperature of the initial liquid, θ_1 – initial temperature of the liquid. With these definitions in mind, the thermal conductivity equation can be rewritten in a dimensionless form:

$$\frac{\partial\theta^*}{\partial\mathcal{T}^*} = \frac{1}{\eta}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\theta^*}{\partial\eta}\right) + \frac{1}{\eta^2}\cdot\frac{\partial^2\theta^*}{\partial\phi^2}, \quad (14)$$

where ϕ – dimensionless time.

This dimensionless equation can be useful in analysing heat transfer along a liquid jet. The use of the Bessel function of the first (J_0) and the second (Y_0) order of the zero-order kind, will allow expressing a dimensionless equation in some variable form. Considering the dependence of the coefficient of thermal conductivity on the coordinate $\mathcal{T}^*$, as $a = a(\mathcal{T}^*)$, the Bessel function is also used as part of the solution. The solution of such an equation may include other conditions or definitions that depend on the specific physical situation or boundary conditions of the problem. The use of Bessel functions is usually associated with problems where it is important to consider cylindrical symmetry.

Considering the boundary case when ϵ (or η) coincides to 0, and the Bessel function of the second kind Y_0 increases to infinity, this indicates the need to adjust the coefficient at Y_0 so as to avoid infinity of temperature on the jet axis. When considering equation (2), where $\eta = \frac{\epsilon}{L}$ and $\tau^* = \frac{a_0\tau}{L^2}$, θ^* is defined as:

$$\theta^* = \frac{\theta-\theta_0}{\theta_1-\theta_0}.$$

This equation is complex with a number of symbols and differentiable functions. To solve this problem, it is necessary to apply the rules of differentiation step by step and solve for the given variables. Next, it is necessary to consider each member of the equation: $\frac{\partial\theta^*}{\partial\mathcal{T}^*}$ – partial derivative of θ^* by $\mathcal{T}^*$, $\frac{1}{\eta}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\theta^*}{\partial\eta}\right)$ – the second term depends on η,where $\eta = \varepsilon/L$, $\frac{1}{\eta^2}\cdot\frac{\partial^2\theta^*}{\partial\phi^2}$ – the third term contains $\frac{\partial^2\theta^*}{\partial\phi^2}$.

To solve this equation, a specific type of function is considered θ^* and the equation is solved taking into account the specified parts. Providing a function $\theta^* = \theta - \theta_0/\theta_1 - \theta_0$, it can be used to express the necessary derivatives and substitute them into a given equation. Next, there are derivatives for T^*, N and ϕ: $\frac{\partial\theta^*}{\partial\mathcal{T}^*}$, $\frac{1}{\eta}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\theta^*}{\partial\eta}\right)$, $\frac{1}{\eta^2}\cdot\frac{\partial^2\theta^*}{\partial\phi^2}$. The obtained derivatives are then substituted into the given equation (14):

$$\frac{\partial\theta^*}{\partial\mathcal{T}^*} = \frac{(\theta_1-\theta_0)\frac{\partial\theta}{\partial\mathcal{T}^*}}{(\theta-\theta_0)^2}, \quad (15)$$

$$\frac{1}{\eta}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\theta^*}{\partial\eta}\right) = \frac{1}{\eta}\cdot\frac{1}{\theta_1-\theta_0}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial}{\partial\eta}\right)(\theta-\theta_0), \quad (16)$$

$$\frac{1}{\eta^2}\cdot\frac{\partial^2\theta^*}{\partial\phi^2} = \frac{1}{\eta^2}\cdot\frac{(\theta_1-\theta_0)^2}{(\theta-\theta_0)^3}\frac{\partial^2\theta}{\partial\phi^2}. \quad (17)$$

Accordingly, this equation is simplified and solved to obtain the expression for θ relative to $\mathcal{T}^*$, η, and ϕ. After the introduction of the Bessel function of the first kind J_0 and Bessel functions of the second kind Y_0, the expression of the dimensionless equation of thermal conductivity can be represented in a new form:

$$\frac{(\theta1-\theta0)\frac{\partial\theta}{\partial\mathcal{T}^*}}{(\theta-\theta0)^2} = \frac{1}{\eta}\cdot\frac{1}{(\theta1-\theta0)}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial}{\partial\eta}\right)(\theta-\theta0) + \\ + \frac{1}{\eta^2}\cdot\frac{(\theta1-\theta0)^2}{(\theta-\theta0)^3}\frac{\partial^2\theta}{\partial\phi^2}. \quad (18)$$

Value $(\theta_1 - \theta_0)$ is removed, and both sides are divided by $1/\eta$:

$$\frac{\partial\theta}{\partial\mathcal{T}^*} = \frac{\partial}{\partial\eta}\left(\eta\frac{\partial}{\partial\eta}\right)(\theta-\theta_0) + \frac{1}{\eta}\cdot\frac{\partial^2\theta}{\partial\phi^2}.$$

It is assumed that $\eta = \varepsilon/L$. For simplicity, both sides can be divided into ε:

$$\frac{1}{\varepsilon}\frac{\partial\theta}{\partial\mathcal{T}^*}=\frac{1}{\varepsilon}\frac{\partial}{\partial\eta}\left(\eta\frac{\partial}{\partial\eta}\right)(\theta-\theta_0)+\frac{1}{\varepsilon}\frac{1}{\eta}\cdot\frac{\partial^2\theta}{\partial\phi^2}. \quad (19)$$

Both parts are discussed below. The first part is the derivative with respect to , what can be integrated with respect to $\mathcal{T}^*$. This is considered as a form of the derivative of the function $f(\theta, \eta, \phi)$ by $\mathcal{T}^*$. The second part can be expressed as a differential equation of the form:

$$\frac{\partial^2 f}{\partial\eta^2}+\frac{1}{\eta}\cdot\frac{\partial f}{\partial\eta}+\frac{1}{\eta^2}\cdot\frac{\partial^2\theta}{\partial\phi^2}. \quad (20)$$

This equation can be solved depending on the specific conditions and values. Having specific task conditions that determine the type of function f and the initial / boundary conditions, then it will be possible to solve this equation and find the expression for θ relative to $\mathcal{T}^*$, η and ϕ.

The differential equation that is obtained has a form:

$$\frac{\partial^2\theta}{\partial\eta^2}+\frac{1}{\eta}\cdot\frac{\partial\theta}{\partial\eta}+\frac{1}{\eta^2}\cdot\frac{\partial^2\theta}{\partial\phi^2}=\frac{\varepsilon}{L}\cdot\frac{\partial\theta}{\partial\mathcal{T}^*}. \quad (21)$$

If there are additional boundary conditions, for example, the value of a function or its derivatives for certain values η, ϕ, then these conditions must be considered when solving the equation. This may require the use of numerical methods or analytical methods, depending on the specific conditions and form of the equation. Some other conditions or parameters may affect the solution.

Use of the Bessel function. The solution of the temperature field in a liquid jet can be represented as a series using Bessel functions. If we assume that $A_3=0$ in the Bessel function, then the second-order Bessel function Y_0 is not included in the solution. Therefore, a number of the following type is considered:

$$\theta^*(\eta,\tau*)=\sum_{n=1}^{\infty}An(\tau*)J_0(\lambda_n\eta), \quad (22)$$

where λ_n – roots of the equation $J_0(\lambda_n)=0$, a $A_n(\tau^*)$ – coefficients that depend on time. This form of the series is one of the possible ones, and it uses the Bessel function of the first kind J_0. This form of the series looks like a Fourier series for the function θ^* of η and τ^*, where J_0 – Bessel function of the first kind; λ_n – roots of the equation $J_0(\lambda_n)=0$; $A_n(\tau^*)$ – coefficients that may depend on time $\mathcal{T}^*$. This series can be used to decompose a function θ^* as an infinite sum. Each term in this series has the form $A_n(\tau^*)$, $J_0(\lambda n\eta)$. Bessel functions are used to represent various types of quantities, such as temperature distribution, etc.

To solve the equation, it is necessary to use the properties of Bessel functions and consider the conditions of the problem for determining the coefficients $A_n(\tau^*)$. There is an indefinite number of terms in a series (from $n=1$ to infinity), and these coefficients should be determined according to the problem. Usually, for such problems, orthogonal properties of Bessel functions and normalisation methods are used to determine the coefficients of a series. This includes integral transformations, solving systems of differential equations, or using boundary conditions. The use of orthogonal properties of Bessel functions and normalisation methods for determining coefficients $A_n(\tau^*)$ in the Fourier series for the function θ^* is considered, which has a form $\theta^*(\eta,\mathcal{T}^*)=\sum_{n=1}^{\infty}A_n(\mathcal{T}^*)J_0(\lambda_n\eta)$. Orthogonality of Bessel functions of the first kind J_0 used as an integral $\int_0^L\theta\,(\lambda m\eta)J_0(\lambda_n\,\eta)\eta d\eta=\delta mn\frac{L^2}{2}$, where δ_{mn} – a Kronecker symbol that is equal to 1 if $m=n$, and 0 in other cases. Now this orthogonality can be used to find the coefficients $A_n(\mathcal{T}^*)$. Both sides of the equation are multiplied by $J_0(\lambda m\eta)\eta$ and integrated from 0 to L:

$$\int_0^L\theta\,(\,\eta.\mathcal{T}^*)J_0(\lambda_m\,\eta)\,\eta d\eta=$$
$$=\sum_{n=1}^{\infty}An(\mathcal{T}^*)\int_0^L J_0(\lambda_n\eta)\cdot J_0(\lambda_m\eta)\,\eta d\eta. \quad (23)$$

According to the orthogonality of Bessel functions, the right-hand side becomes: $\sum_{n=1}^{\infty}\frac{\mathrm{An}(\mathcal{T}^*)\delta_{\mathrm{mn}}\mathrm{L}^2}{2}=A_m\,(\mathcal{T}^*)\frac{\mathrm{L}^2}{2}$. Now it remains to express $A_n(\mathcal{T}^*)$ as an integral of the expression $\theta^*(\eta,\mathcal{T}^*)J_0(\lambda n\eta)\eta$ from 0 to L:

$$Am(\mathcal{T}^*)\,\frac{L^2}{2}=\int_0^L\theta^*\,(\eta,\mathcal{T}^*)J0(\lambda m\eta)\eta d\eta\eta. \quad (24)$$

This integral equation (18) can help find the coefficients $A_n(\mathcal{T}^*)$ in the problem. It is necessary to use boundary conditions or other properties of the problem to determine the specific form and values of these coefficients. In addition, there is a time dependence $a(\tau)$, which can be entered into the equation for the coefficients $A_n(\mathcal{T}^*)$, considering the relevant conditions of the task. It is necessary to provide that the exact type of solution may depend on the specific conditions of the problem and additional details of the model. Certain specific data from the conducted experiments allow making calculations and analysis. To continue, when applying the theory of heat transfer, the dimensionless heat conduction equation can be used to define certain dimensionless numbers, such as the Biot and Nusselt numbers. A characteristic temperature difference $\Delta T=T\lambda$ - $T0$ can be determined, where $T\lambda$ – temperature of the jet at the nozzle outlet. The defined Biot number (Bi) indicates the ratio of internal thermal conductivity to external convection: $Bi=\mathrm{a}R_0/\lambda$ where a – heat transfer coefficient; λ – coefficient of thermal conductivity of the liquid.

Example of analysis. Dimensionless numbers based on the parameters must be found. It was found whether it is possible to obtain certain conclusions about heat transfer from the nozzle. Preset parameters: nozzle diameter: $d=6$ mm = 0.006 m; water velocity at the nozzle outlet – $w_0=0.115$ m/s (minimum value); Reynolds numbers: $Re=w_0/dv=0.115\times0.006/v$ (minimum value). The Casey and Prandtl numbers 5.5 are also provided. Now, using the specified values, dimensionless numbers can be calculated. The Biot and Nusselt numbers for this calculation are very small, which may indicate that the convection heat transfer from the water nozzle may be insignificant compared to the internal thermal conductivity.

With dimensionless numbers, it is important to continue analysing heat transfer based on their values. For example, the effect of these numbers on the temperature profile of the jet and other parameters can be considered.

They can also be compared with critical values or consider the influence of other factors. Therefore, further consideration of the effect of the Biot and Nusselt numbers on the jet temperature profile is considered from the dimensionless thermal conductivity equation introduced earlier (14).

There are two important dimensionless quantities: the Biot number (*Bi*) and the Nusselt number (*Nu*), which describe the relationship between convection heat transfer and internal thermal conductivity. Next, their impact was determined. If *Bi* is very small (close to zero), this indicates that convection heat transfer is dominant, and heat transfer occurs quickly compared to internal heat conduction. If *Bi* is large, then internal heat transfer dominates, and convection has less effect on the temperature profile. Large values of *Nu* indicate a large influence of convection on heat transfer, while small ones may indicate the importance of internal thermal conductivity. Given a laminar water jet characterised by smooth fluid movement, internal thermal conductivity and convection usually work simultaneously and are important for heat transfer. Heat is transferred through the inner layer of the liquid (thermal conductivity), and through the movement of the liquid mass (convection). Figure 5 shows data for comparing experimental and calculated heat transfer during local braking of the outgoing jet from the pipe and nozzle.

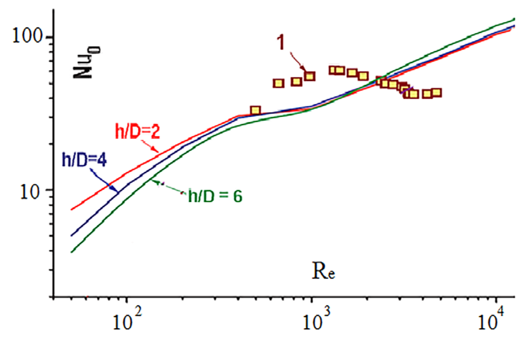

Figure 5. Heat transfer during local braking of the flowing jet

Note: 1 – pipe jet, 2 – nozzle jet

Source: compiled by the authors

Studies have shown that local heat transfer in the outgoing jet depends not only on similarity criteria (*Re*, *Pr*, *h/d*, *Nu*), but also on the characteristics of the method of forming the jet when it flows out of the nozzle, pipe and hole. There is also consistency in the calculation for laminar and turbulent flow modes. Especially in the area of laminar-turbulent transition, which will allow considering heat transfer in more detail. The Nusselt number (*Nu*), describing the degree of convective heat transfer based on the correlation for the heat flow from the cylinder or nozzle (Sherwood number) for the output heat flow from the cylinder has the expression:

$$Nu = 0.3 + 0.62 \cdot Re0.5 \cdot$$
$$\cdot Pr1/3/(1 + 0.4 \cdot Pr2/3)1/4(1 + (Re/282000)5/8)4/5, \quad (25)$$

where $Re = w0d/\nu$ – Reynolds number, $Pr = \nu/\alpha$ – Prandtl number.

With this in mind, numerical calculations can be performed for specific values of the Biot and Nusselt numbers, or general conclusions can be drawn about the effect of these numbers on the jet temperature profile. In a turbulent jet, there may be a displacement of the thermal front or thermal layers, since turbulent vortices and currents can cause nonlinear effects. In addition, vortices can occur in a turbulent jet that separate the "hot" and "cold" layers of liquid, which can affect the efficiency of convective heat transfer. Thus, in both modes, both local heat transfer through the inner layer and convection can be observed, which is determined by the mass of the moving liquid.

Given the turbulent flow, simplified correlations for heat flow can be used. One such correlation for turbulent flow through a cylindrical body (such as a nozzle) is the Duque-Hunt correlation (Baldino *et al.*, 2014):

$$N_{uD} = 0.3 + 0.62 \cdot Re0.5 \cdot$$
$$\cdot Pr1/3/(1 + 0.4 \cdot Pr2/3)1/4\ (1 + (Re/282000)5/8)4/5, \quad (26)$$

where N_{uD} – Nusselt number for cylinder (nozzle), *Re* – Reynolds number, *Pr* – Prendtl number. This correlation is calculated for the turbulent flow regime, that is, for large values of the Reynolds number, since the jet under study belongs to high velocities. Knowing N_{uD}, determined by the heat transfer coefficient a using the equation:

$$a = \lambda \cdot N_{uD}/R_o, \quad (27)$$

where λ – coefficient of thermal conductivity of the liquid. Therefore, for specific conditions, it is necessary to determine the value of the Reynolds number and the Prandtl number for a turbulent flow, and then calculate the heat transfer coefficient a and then use it to analyse the thermal profile of the water jet. Longitudinal component of speed w_x does not change either in cross-section or length of the jet and is equal to the initial outflow velocity w_0. In reality, the nozzle has a finite length and the flow undergoes partial stabilisation. At the nozzle outlet, the dynamic boundary conditions change, which should lead to a change in the distribution of the jet over the jet cross-section. In addition, at low outflow velocities, the acceleration of the jet under the influence of gravity can have an impact.

From the standpoint of the latest research on the motion of liquids, there is no single mechanism for the decay of jets. It all depends on various factors, such as the volume of liquid and other various parameters. The paper by M.I. Gorbiychuk *et al.* (2021) described variants of liquid jet decay due to capillary instability under various conditions. An example is forced capillary decay of a jet or Kelvin-Helmholtz instability. The decay of liquid jets and the occurrence of instabilities in these situations are completely different. In the first case, the main cause is the influence of capillary forces, while in the second case, the gradient of the fluid velocity in the jet plays a key role. The latter mechanism becomes dominant at high jet speeds, especially if there is a gap in speed between the jet itself and its environment.

The decay of liquid jets under the action of capillary forces in the stability of the system depends on an increase or decrease in the potential energy of the system, which is not minimal for such a geometric configuration, as noted by A. Lugovskoy & A. Lyashok (2019). This is defined as an instability problem, and the cylindrical shape of a liquid jet cannot exist in nature without breaking down into smaller spherical volumes. This decay into spherical volumes (a process known as Reynolds instability) is typical of liquid systems and arises from the system's desire to reduce its potential energy. This can lead to the development of droplets or other more stable forms. Their disintegration does not require strong external influence.

The study by V. Suvolapov *et al.* (2020) explains that the phenomenon of instability of a liquid cylindrical body is caused by the surface tension force (the potential energy of a liquid cylinder and droplets). It is determined by the surface energy (capillary forces) formed in the presence of a phase interface. Their action leads to intensive development of capillary waves. Therefore, there is a local reduction in the jet diameters relative to the initial value with a corresponding displacement of the liquid to form a jet expansion. Accordingly, it alternates between compression and swelling. Areas of reduced diameter are gradually stretched in length and torn to form droplets.

There is another theory of jet instability, which was expressed by I. Nochnichenko & O. Yakhno (2020). In their opinion, surface elastic vibrations of jets can occur, but they will always have a fading character along the jet. Therefore, the decay of the jet can only occur in the place where such fluctuations occur. The sequence of alternating constrictions and expansions along the jet is explained not by elastic vibrations, but by Laplace forces, which have a constant direction. Fluid from the place of narrowing necessarily flows to the places of expansion, and this process is irreversible, since Laplace forces act in one direction. Thus, a narrowing that occurs at a certain intersection will only contract, while an expansion will only expand. Each narrowing will necessarily affect the formation of a series of extensions by squeezing the liquid there, and each expansion, in turn, will cause a narrowing due to a symmetrical distribution of forces. A sequential chain of constrictions and extensions is formed along the jet.

Therefore, the nature of the influence of the flow rate on the heat transfer coefficient during the interaction of liquids in the sprayed layer depends on the difference in the heat flow value. G. Kosmadakis (2019) noted that with a small heat flow, the heat transfer coefficient is completely determined by flow conditions and practically independent of q. Free-flow heat transfer occurs due to the difference in the density of heated and cold layers. In this case, the intensity of heat transfer depends on the parameters of the channel in space relative to gravity. In addition, the nature of free convection is affected by the conditions in which the flow occurs: in an unlimited space or in a limited volume. This is a typical situation for free convection, when a thermal disturbance causes a liquid or gas to move, and the flow mode can change depending on the conditions and parameters of the system.

In papers by A.P. Vragov (2003) and A.P. Vragov *et al.* (2008) reported that in the initial sections of the channel, the flow structure corresponds to the phase separation model proposed by Lockhart and Martinelli. This model treats the liquid as two separate phases separated by a clear interface. Features of this model are shown in how they affect the phase distribution in the liquid jet. In this model, a characteristic phase distribution profile is defined at the initial channel segments, which may vary depending on specific parameters and flow conditions. In particular, the interaction of liquids along the interface is important, which can be determined by the design parameters of the equipment. The importance of the model in the analysis and explanation of flow dynamics at the initial stages is highlighted since it considers the features of phase interaction and jet structure. Consideration of these aspects is important in the context of understanding thermal mass transfer, diffusion, and other physical phenomena in flow systems. Therefore, the Lockhart-Martinelli model helps to reveal more deeply the features of the operation of fluid flows at the initial stages of their movement through the channel.

CONCLUSIONS

As a result of the experiments, the length of the continuous water jet that can be produced by the nozzle was determined depending on various factors. These studies allowed the authors to more accurately determine the technical capabilities of this process and develop a way to control the water supply during the mixing of thermal potentials. A mathematical model was developed that describes the length of a continuous jet of water coming out of the nozzle and, accordingly, the adequacy of this model is checked using the Fisher's optimisation criterion To control the water supply process in accordance with the required distance to the centre of the nozzle, a step-by-step method has been developed. This method allows gradually increasing or decreasing the length of a continuous jet of water through the nozzle.

Temperature changes in the heat exchangers depend on several factors, including the specific heat transfer conditions, the characteristics of the system, and the devices used to generate the heat flow. Some of the key factors that can influence temperature changes include:

- thermal conditions: temperature of the medium with which the heat transfer takes place and the temperature of the walls that carry out the heat transfer;
- heat transfer characteristics: heat transfer area and type of heat transfer (convection, condensation, evaporation, etc.);
- physical properties of the working medium: heat capacity and thermal conductivity of the working medium;
- characteristics of heat flow generating devices: heat output of devices and types of heat generators (heat pumps, heating elements, solar collectors, etc.);

- flow mode: laminar or turbulent flow mode;
- geometry of the heat exchanger: shape and dimensions of the nozzle and equipment.

These factors interact with each other, and their impact can be complex and contextual. When designing and operating heat exchangers, it is important to consider all these aspects to achieve optimal efficiency and meet the specific requirements of the system.

Further research could be devoted to the use of innovative materials with the ability to effectively regulate thermal potential to improve the efficiency of heat exchangers and reduce energy consumption, or to the development of more accurate mathematical models and simulation methods for analysing the dynamics of heat transfer in liquids to predict and control this process in real time.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Atamanyuk, V.M., & Humnytskyi, Y.M. (2019). *Scientific basis of filtration drying of dispersed materials*. Lviv: Lviv Polytechnic Publishing House.

[2] Baldino, N., Gabriele, D., Lupi, F., de Cindio, B., & Cicerelli, L. (2014). Modeling of baking behavior of semi-sweet short dough biscuits. *Innovative Food Science & Emerging Technologies*, 25, 40-52. doi: 10.1016/j.ifset.2013.12.022.

[3] Beljakova, I.V., Vakulenko, O.O., & Deket, I.M. (2020). Energy efficiency in industry as a factor of reducing cost products. In *Materials of the 19th international scientific and technical conference of young scientists and students. Actual tasks of modern technologies* (pp. 90-91). Ternopil: Ivan Puluj Ternopil National Technical University.

[4] Gorbiychuk, M.I., Kogutyak, M.I., & Garasimov, V.M. (2021). Mathematical model of a heater with an intermediate heat carrier. *Quality Control Methods and Devices*, 2(47), 5-13. doi: 10.31471/1993-9981-2021-2(47)-83-95.

[5] Kosmadakis, G. (2019). Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. *Applied Thermal Engineering*, 156, 287-298. doi: 10.1016/j.applthermaleng.2019.04.082.

[6] Kovalyov, A., Shutyuk, V., & Karwacki, A. (2013). Physical and mathematical models of baking process of dough pieces in oven units. *Scientific Works of National University of Food Technologies*, 24(1), 144-153.

[7] Kudelya, K., & Dubovskyi, S. (2020). Energy and exergy approaches to the problem of rational energy use Sustainable Energy. *Technologies and Assessments*, 2, 7-16. doi: 10.20535/1813-5420.2.2020.220705.

[8] Kutsenko, O.S., Tovazhnyansky, V.I., Perevertailenko, O.Yu., Kapustenko, P.O., Vedh, V.Ye., & Yuzbashyan, A.P. (2020). Research of thermal inertial characteristics of a plate heat exchanger in a building heating control system based on an independent connection system. *Integrated Technologies and Energy Saving*, 4, 11-22. doi: 10.20998/2078-5364.2020.4.02.

[9] Lohar, G., Tambe, P., & Jogi, B. (2019). Influence of dual compatibilizer and carbon black on mechanical and thermal properties of PP/ABS blends and their composites. *Composite Interfaces*, 27(12), 1101-1136. doi: 10.1080/09276440.2020.1726137.

[10] Luhovskiy, A., & Lyashok, A. (2014). Physical analogue of the process of ultrasonic liquid nebulization in a thin layer. *Mechanical Engineering of the National Technical University of Ukraine "Kyiv Polytechnic Institute"*, 1, 99-105.

[11] Luhovskyi, O.F., Lyashok, A.V., & Pyzhikov, Yu.O. (2011). Method and devices for obtaining a liquid aerosol. *Bulletin of the National Technical University of Ukraine "Kyiv Polytechnic Institute". Mechanical Engineering Series*, 61(1), 107-113.

[12] Maiboroda, Yu. (2022). Advantages and prospects for the development of plate scraper heat exchangers in the production of spreads and mixtures with milk fat. *Food Resources*, 10(19), 81-87.

[13] Martin Díaz, P. (2022). *Influence of mixing and heat transfer in process scale-up*. (Independent thesis Advanced level, Luleå University of Technology, Luleå, Sweden).

[14] Mehralizadeh, A., Derakhshanfard, F., & Ghazi Tabatabaei, Z. (2020). Studying the influence of the mixing speed of the polymer blend of general-purpose polystyrene and acrylonitrile-butadiene styrene with the applications of artificial neural networks Iranian *Journal of Chemical Engineering*, 17(4), 21-32. doi: 10.22034/ijche.2020.130358.

[15] Mehralizadeh, A., Derakhshanfard, F., & Ghazi Tabatabei, Z. (2021). Applications of multi-layer perceptron artificial neural networks for polymerization of expandable polystyrene by multi-stage dosing Initiator. *Iranian Journal of Chemistry & Chemical Engineering*, 41(3), 890-901. doi: 10.30492/ijcce.2021.125618.4106.

[16] Mykhaylovskyi, Ya.E. (Ed.). (2021). *Heat and mass transfer processes and equipment of chemical and oil and gas processing plants in "gas (steam) – liquid" systems*. Sumy: Sumy State University.

[17] Mykytenko, V.V. (2004). *Energy efficiency of industrial production*. Kyiv: United University of Economics.

[18] Nochnichenko, I., & Yakhno, O. (2020). Information and energy approach to solving problems of hydrodynamics and mechatronics in energy transfer processes. *Mechanics and Advanced Technologies*, 88(1), 38-48. doi: 10.20535/2521-1943.2020.88.195505.

[19] Rosen, V.P. (Ed.). (2002). *Regulatory and legal issues of energy saving*. Kyiv: National Technical University of Ukraine "Institute of Energy Conservation and Energy Management".

[20] Shullie, Iu. (2020). Energy efficiency of industrial enterprises. In *XLIX Scientific and technical conference of the Faculty of Electrical Power Engineering and Electromechanics of VNTU* (pp. 45-48). Vinnytsia: Vinnytsia National Technical University.

[21] Stadnyk, I., Pankiv, Y., Vasyliv, V., & Kos, T. (2020). Dynamics of inter-phase interaction of components during mixing. *Food Resources*, 8(15), 174-184.

[22] Stadnyk, I.Ya., Pankiv, Ju., Havrylko, R., & Karpyk, H. (2019). Researching of the concentration distribution of soluble layers when mixed in the weight condition. *Potravinarstvo Slovak Journal of Food Sciences,* 13(1), 581-592. doi: 10.5219/1129.

[23] Suvolapov, V., Novitskiy, A., Khmelevski, V., & Bustruy, O. (2020). Investigation of the heat transfer process in internal combustion engine cylinders. *Central Ukrainian Scientific Bulletin. Technical Sciences*, 3(34), 266-274. doi: 10.32515/2664-262X.2020.3(34).266-274.

[24] Vragov, A.P. (2003). *Hydromechanical processes and equipment of chemical and oil refining industries*. Sumy: Alan-Ex.

[25] Vragov, A.P., Mykhaylovskyi, Ya.E., & Yakushko, S.I. (2008). *Materials for calculations of processes and equipment of chemical and gas-oil processing industries: study guide*. Sumy: Sumy State University.

[26] Wu, J.C. (2018). *Elements of vorticity aerodynamics*. Berlin: Springer.

[27] Yanchuk, O.M., & Marchuk, O.V. (2020) *Physical chemistry. Chemical and statistical thermo-dynamics*. Lutsk: IE V.P. Ivanyuk.

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Досягнення і проблеми у вивченні механізму регулювання передачі теплового потенціалу між рідинами

Анотація. Актуальність дослідження визначається його фокусом на одній з ключових проблем економіки України, а саме проблемі енергоносіїв, що є необхідним кроком у розвитку стратегій управління та планування ресурсів в контексті сучасних викликів та нестабільності на енергетичному ринку. Метою дослідження є визначення гідродинамічних та масотеплообмінних характеристик процесу змішування рідин з різним тепловим потенціалом, а також вивчення впливу конструктивних факторів на інтенсивність і ефективність струменя потоку. Використано експериментальні методи для визначення гідродинамічних та масотеплообмінних параметрів процесу змішування рідин, а також моделювання для аналізу впливу конструктивних факторів та розробки науково обґрунтованої методики розрахунку нових конструкцій апаратів. Отримано підхід, який дозволяє вирішити дві проблеми одночасно: зменшити витрати на енергоносії шляхом їхньої раціональної експлуатації та зменшити забруднення навколишнього середовища, уникнувши шкідливих викидів, які виникають під час згорання палива. Подано опис функціональної схеми експериментального стенду, наведено методику проведення дослідження та проведено статистичне моделювання впливу параметрів на довжину струменя рідини. Наведено дослідження енергоефективності початкової стадії взаємодії теплових потенціалів при утворенні струменя рідини в рекуперативному теплообміннику змішаної дії для забезпечення умов зберігання та переміщення потенціалу перед насадкою. Запропоновано математичну модель опису довжини суцільного струменя води при витіканні із сопла та проведено аналіз ламінарної течії рідини із сопла. Встановлено довжину суцільного струменя води при витіканні із сопла та визначено технічні можливості процесу. Визначено ефективність встановлення сопла перед насадкою для створення турбулентного змішування та спосіб управління подачею води під час змішування теплових потенціалів. Для управління процесом подачі води розроблено покроковий метод, що дозволяє поетапно збільшувати або зменшувати довжину суцільного струменя води через сопло. Результати дослідження надають можливість оптимізації теплообмінних апаратів та змішувальних машин для підвищення їхньої ефективності та продуктивності

Ключові слова: сопло; суцільний струмінь; експеримент; довжина подачі струменя; керування довжиною подачі струменя

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