Machinery & Energetics
Vol. 15, No. 1. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 621.646
DOI: 10.31548/machinery/1.2024.104

Andriy Derkach
PhD in Technical Sciences
Ternopil Ivan Puluj National Technical University
46001, 56 Ruska Str., Ternopil, Ukraine
https://orcid.org/0000-0002-0395-362x

Igor Stadnyk*
Doctor of Technical Sciences, Professor
Ternopil Ivan Puluj National Technical University
46001, 56 Ruska Str., Ternopil, Ukraine
https://orcid.org/0000-0003-4126-3256

Volodymyr Piddubnyi
Doctor of Technical Sciences, Professor
Kyiv National University of Trade and Economics
02156, 19 Kyoto Str., Kyiv, Ukraine
https://orcid.org/0000-0002-1497-7133

Andrii Chahaida
PhD in Technical Sciences, Associate Professor
Zhytomyr Polytechnic State University
10005, 103 Chudnivska Str., Zhytomyr, Ukraine
https://orcid.org/0000-0003-1826-9545

Iurii Radchenko
Independent Researcher
Darmi Fabarm Company
25039, 31 Averolda Str., Travagliato, Italy
https://orcid.org/0009-0001-7435-0738

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

Article's History: Received: 23.10.2023; Revised: 30.01.2024; Accepted: 28.02.2024.

Suggested Citation:
Derkach, A., Stadnyk, I., Piddubnyi, V., Chahaida, A., & Radchenko, Iu. (2024). Achievements and problems in studying the mechanism of thermal potential transfer regulation between liquids. *Machinery & Energetics,* 15(1), 104-117. doi: 10.31548/machinery/1.2024.104.

*Corresponding author

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.

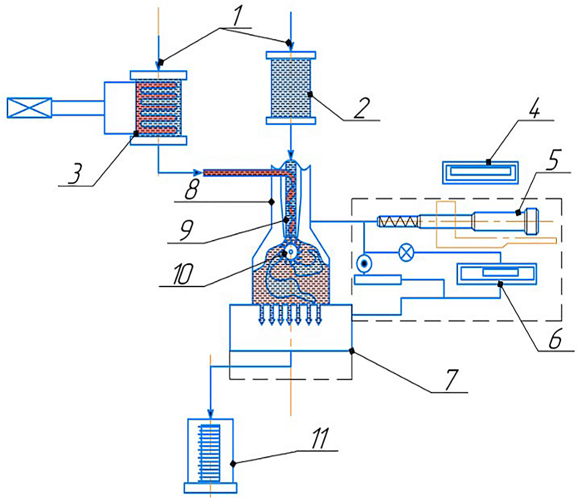

Figure 1. Functional diagram of the test stand

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:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3. \quad (2)$$

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:

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

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.

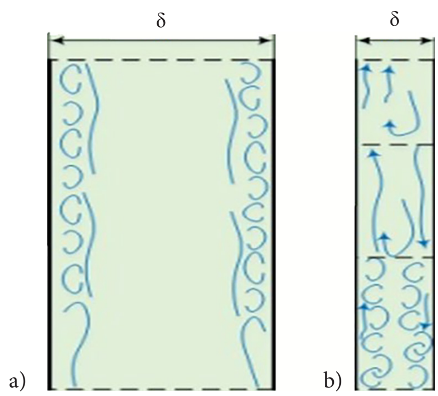

Figure 2. Types of fluid circulation in a confined space
Note: a – in wide channels, b – in narrow channels; δ – distance between the channel walls
Source: compiled by the authors

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).

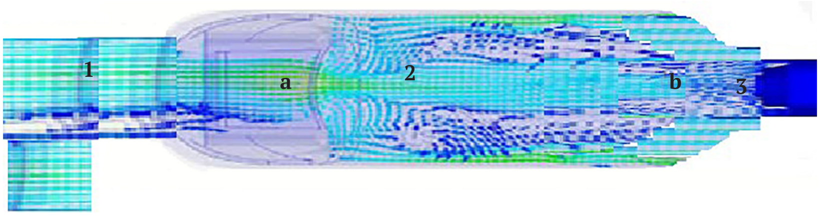

Figure 3. Generation of isotherm flow in a free water jet

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.

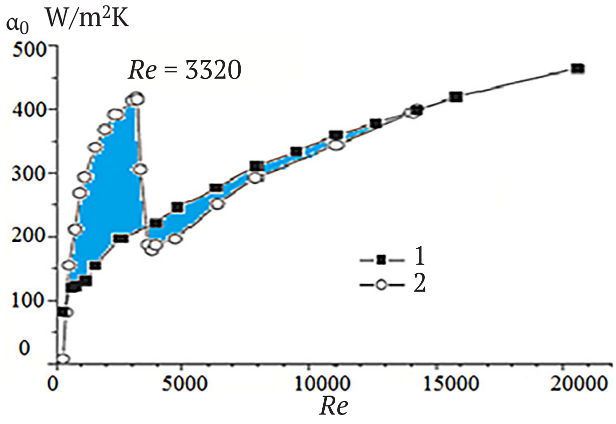

Figure 4. Dependence of the heat transfer coefficient on the Reynolds number

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:

$$\frac{\partial\theta}{\partial t} = \alpha\left(\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right) + \frac{1}{r^2}\cdot\frac{\partial^2\theta}{\partial\phi^2}\right), \qquad (10)$$

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 $dx = \mathrm{w} \cdot x \cdot d\tau$ 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:

$$\frac{\partial\theta}{\partial x} = \alpha\left(\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial\theta}{\partial r}\right), \tag{11}$$

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:

$$\frac{\partial\theta}{\partial x} = \alpha(L)\left(\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial\theta}{\partial r}\right), \tag{12}$$

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:

$$\theta^* = \frac{\theta-\theta_0}{\theta_1-\theta_0}, \tag{13}$$

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:

$$\frac{\partial\theta^*}{\partial\mathcal{T}^*} = \frac{1}{\eta}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\theta^*}{\partial\eta}\right) + \frac{1}{\eta^2}\cdot\frac{\partial^2\theta^*}{\partial\phi^2}, \tag{14}$$

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):

$$\frac{\partial\theta^*}{\partial\mathcal{T}^*} = \frac{(\theta_1-\theta_0)\frac{\partial\theta}{\partial\mathcal{T}^*}}{(\theta-\theta_0)^2}, \tag{15}$$

$$\frac{1}{\eta}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\theta^*}{\partial\eta}\right) = \frac{1}{\eta}\cdot\frac{1}{\theta_1-\theta_0}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial}{\partial\eta}\right)(\theta-\theta_0), \tag{16}$$

$$\frac{1}{\eta^2}\cdot\frac{\partial^2\theta^*}{\partial\phi^2} = \frac{1}{\eta^2}\cdot\frac{(\theta_1-\theta_0)^2}{(\theta-\theta_0)^3}\frac{\partial^2\theta}{\partial\phi^2}. \tag{17}$$

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:

$$\frac{(\theta1-\theta0)\frac{\partial\theta}{\partial\mathcal{T}^*}}{(\theta-\theta0)^2} = \frac{1}{\eta}\cdot\frac{1}{(\theta1-\theta0)}\cdot\frac{\partial}{\partial\eta}\left(\eta\frac{\partial}{\partial\eta}\right)(\theta-\theta0) + \\ + \frac{1}{\eta^2}\cdot\frac{(\theta1-\theta0)^2}{(\theta-\theta0)^3}\frac{\partial^2\theta}{\partial\phi^2}. \tag{18}$$

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: $\sum_{n=1}^{\infty}\frac{An(\mathcal{T}^*)\delta_{mn}L^2}{2}=A_m\,(\mathcal{T}^*)\frac{L^2}{2}$. 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: $Bi=aR_0/\lambda$ 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: $Re = w_0/dv = 0.115{\times}0.006/v$ (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.

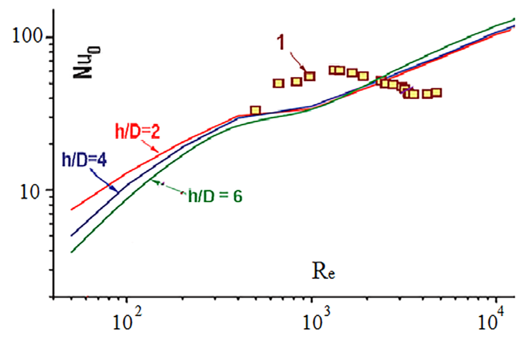

Figure 5. Heat transfer during local braking of the flowing jet

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.

ACKNOWLEDGEMENTS

None.

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.

Андрій Васильович Деркач
Кандидат технічних наук
Тернопільський національний технічний університет імені Івана Пулюя
46001, вул. Руська, 56, м. Тернопіль, Україна
https://orcid.org/0000-0002-0395-362x

Ігор Ярославович Стадник
Доктор технічних наук, професор
Тернопільський національний технічний університет імені Івана Пулюя
46001, вул. Руська, 56, м. Тернопіль, Україна
https://orcid.org/0000-0003-4126-3256

Володимир Антонович Піддубний
Доктор технічних наук, професор
Державний торговельно-економічний університет
02000, вул. Кіото, 19, м. Київ, Україна
https://orcid.org/0000-0002-1497-7133

Андрій Олегович Чагайда
Кандидат технічних наук, доцент
Державний університет «Житомирська політехніка»
10005, вул. Чуднівська, 103, м. Житомир, Україна
https://orcid.org/0000-0003-1826-9545

Юрій Ігорович Радченко
Незалежний дослідник
Компанія «Дармі Фабарм»
25039, вул. Аверольда, 31, м. Травальято, Італія
https://orcid.org/0000-0002-4499-0910

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