Machinery & Energetics
Vol. 15, No. 4. 2024

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

UDC 66.021.4
Doi: 10.31548/machinery/4.2024.82

Viktor Zavodyannyi*
PhD in Physical and Mathematical Sciences, Associate Professor
Kherson State Agrarian and Economic University
25031, 5/2 Universytetskyi Ave., Kropyvnytskyi, Ukraine
https://orcid.org/0000-0002-8224-8215

Mykola Voloshyn
PhD in Technical Sciences, Associate Professor
Kherson State Agrarian and Economic University
25031, 5/2 Universytetskyi Ave., Kropyvnytskyi, Ukraine
https://orcid.org/0000-0003-0467-1963

Volodymyr Kravchenko
PhD in Technical Sciences, Associate Professor
Kherson State Agrarian and Economic University
25031, 5/2 Universytetskyi Ave., Kropyvnytskyi, Ukraine
https://orcid.org/0000-0003-2245-7194

Valentina Zubenko
PhD in Technical Sciences, Associate Professor
Kherson State Agrarian and Economic University
25031, 5/2 Universytetskyi Ave., Kropyvnytskyi, Ukraine
https://orcid.org/0000-0002-8401-755X

Roman Zhesan
PhD in Technical Sciences, Associate Professor
Central Ukrainian National Technical University
25006, 8 Universytetskyi Ave., Kropyvnytskyi, Ukraine
https://orcid.org/0000-0002-9212-7361

Experimental study of heat exchangers and mixing machines operation optimisation methods

Abstract. The study aimed to optimise the operation of heat exchangers and mixing machines to improve the efficiency of production processes. An experimental approach with models that describe the processes of heat transfer, hydraulic resistance and mixture homogeneity was used to determine the optimal equipment parameters. The study showed that optimisation of the operation of heat exchangers can lead to a significant increase in energy efficiency and a reduction in operating costs. The best results were achieved at a coolant temperature of 90°C and a pressure of 5 bar, which resulted in a maximum heat transfer of 350,000 W. The study determined that reducing the hydraulic resistance to the optimum level can reduce energy costs for pumping coolant by 15%. The study also showed that to achieve maximum homogeneity of the mixture in mixing machines, the optimal rotation speed is 400 rpm. This resulted in a mixture homogeneity index of 16. The study determined that the temperature of the components fed into the mixing machines has a significant impact

Article's History: Received: 04.07.2024; Revised: 11.10.2024; Accepted: 27.11.2024.

Suggested Citation:
Zavodyannyi, V., Voloshyn, M., Kravchenko, V., Zubenko, V., & Zhesa, R. (2024). Experimental study of heat exchangers and mixing machines operation optimisation methods. *Machinery & Energetics,* 15(4), 82-93. doi: 10.31548/machinery/4.2024.82.

*Corresponding author

on the final product quality. For example, the optimum temperature for certain components had reduced mixing time by 10%, which had contributed to an increase in overall productivity. The integration of automatic control systems, such as the automatic control system, allowed for real-time monitoring and adjustment of equipment parameters, which further increased the efficiency of production processes. In addition, the study determined that comprehensive optimisation of the parameters of the devices' operation allows for an increase in the duration of their life cycle, reducing the frequency of maintenance by 20%. Optimisation of the operation of heat exchangers and mixing machines significantly increases production efficiency and the quality of final products, contributing to cost reduction and increasing equipment reliability

Keywords: materials; temperature; pressure; optimum parameters; efficiency improvement

INTRODUCTION

In modern environment, improving the efficiency of production processes is critical to the competitiveness of enterprises. High energy and resource costs, as well as increasing demands on product quality, are forcing industrial enterprises to seek new approaches to optimising equipment performance. Heat exchangers and mixing machines are key elements in many production processes, so their efficient operation directly affects the productivity and efficiency of the enterprise. However, there is a lack of research that would comprehensively analyse these processes concerning modern technologies and automatic control systems.

The main problem addressed in this study is the optimisation of the operating parameters of heat exchangers and mixing machines. These units often operate in conditions that are far from optimal, resulting in increased energy consumption, reduced product quality and reduced equipment life. There is a need to develop scientifically based recommendations for the effective management of heat exchange and mixing processes, considering the specifics of modern production and the capabilities of automated control systems.

According to the study, artificial intelligence (AI) is proposed as a universal approach for designing and optimising heat exchangers. J. Krzywanski (2022) noted that a combination of genetic algorithms and artificial neural networks can accurately predict the thermal performance of a falling film evaporator. C. Abeykoon (2020) confirmed that Computational Fluid Dynamics (CFD) modelling can be promising for the design and optimisation of heat exchangers and allows the testing of numerous design options without the need for physical prototypes.

M.H. Mohammadi *et al*. (2020) found that low baffles provided the highest heat transfer, but they also caused a significant pressure drop, which limits their effectiveness. A porosity of 0.2 showed better results for heat transfer, but the high-pressure drop makes it not an optimal option. The analysis showed that baffles have the greatest impact on heat transfer and pressure drop, while porosity has the least impact. Using a genetic algorithm, the optimal parameters were calculated to maximise heat transfer with a minimum pressure drop.

D. Gürses *et al*. (2023) presented the Multi-Strategy Boosted Prairie Dog Optimisation Algorithm for optimising three types of heat exchangers (shell-and-tube, fin-and-tube, and plate-and-fin) with a focus on minimising installation and maintenance costs. The Multi-Strategy Boosted Prairie Dog Optimisation Algorithm outperformed other algorithms in terms of efficiency and is proposed for use in real-world engineering problems.

Researches C. Elsido *et al*. (2021) presented a multi-period optimisation method for utility systems, Rankine cycles, and heat exchangers with different operating modes. The results demonstrated a significant improvement in cost-effectiveness compared to single-period projects. A.H. Pordanjani *et al*. (2020) analysed scraping surface heat exchangers and noted that increasing the rotor speed or mass flow rate increases the heat transfer coefficient while decreasing the heat flow reduces the heat transfer coefficient and increases the outlet temperature. The sensitivity analysis revealed that the outlet temperature is most dependent on the mass flow rate. Optimisation using the Non-Dominated Sorting Genetic Algorithm-II yielded 35 non-dominated solutions to balance the maximum heat transfer coefficient and minimum temperature.

Scientists J.M. Zamora *et al*. (2020) analysed the optimisation of utility placement in heat exchange networks. The results showed that the proposed methodology improved network designs with alternative topologies that reduced the total annual costs. Four examples have confirmed the effectiveness of this approach. M. Ghalandari *et al*. (2021) showed that intelligent machine learning methods effectively predict heat exchanger performance, ensuring accuracy and speed of calculations. The results highlight the importance of algorithm architecture, input data, and system complexity. Key conclusions on the successful application of these methods are presented and recommendations for improving the accuracy of modelling in future studies were provided.

The authors of the studies did not address several important aspects that required additional attention. D. Gürses *et al*. (2023) and C. Elsido *et al*. (2021) addressed economic optimisation but did not investigate the long-term impact of equipment maintenance and wear and tear on operating costs. More research is needed to assess changes in heat exchanger efficiency over a long period of operation. Environmental aspects were understudied in studies such as C. Abeykoon (2020). The impact of materials and energy consumption of equipment on the environment was not investigated. Life cycle analysis of equipment could help create more sustainable solutions.

M.H. Mohammadi *et al*. (2020) did not consider the interaction of different operating conditions, such as changes in pressure, temperature, and flow rate. This limited the understanding of system behaviour in more complex operating conditions. C. Abeykoon (2020), while considering CFD modelling, did not investigate the dynamic changes in parameters during system operation. It is not clear how short-term fluctuations affect the long-term performance of heat exchangers. The authors did not pay enough attention to the use of new materials with high thermal conductivity and corrosion resistance, such as nanomaterials, which could improve efficiency. M. Ghalandari *et al*. (2021) did not consider the integration of smart methods with real industrial control systems, which could improve efficiency. Most studies, such as the one by J.M. Zamora *et al*. (2020), focused on large enterprises but did not address the needs of small and medium-sized industries.

This study aimed to optimise the operation of heat exchangers and mixing machines to improve the efficiency of production processes. The main objectives of the study were to analyse existing methods for optimising the operation of heat exchangers and mixing machines, develop experimental models describing the processes of heat transfer, hydraulic resistance and mixture homogeneity, and conduct a series of experiments to determine the optimal parameters of heat exchangers.

MATERIALS AND METHODS

At the first stage of the study, existing methods and approaches to optimising the operation of heat exchangers and mixing machines were collected and analysed. The study primarily addressed heat transfer processes, hydraulic resistance and mixture homogeneity, as these factors directly affect the efficiency of the equipment. The information was collected from scientific articles, technical documents and reports of companies using similar equipment.

The analysis identified the most promising approaches and justified the choice of parameters for further experiments. The next step was the development of mathematical and physical models describing the processes of heat transfer, hydraulic resistance and mixture homogeneity. The models were built based on accepted physical laws, such as the Fourier heat transfer law and the Navier-Stokes equation for describing fluid motion. For this purpose, modelling software packages were used to accurately reflect the behaviour of heat exchangers and mixing machines under various conditions. Particular attention was paid to modelling hydraulic resistance, as reducing this indicator is one of the key factors for improving the energy efficiency of equipment.

The study included a series of experiments. First, the heat exchangers were tested at different temperatures and coolant pressures. The main goal was to determine the optimal parameters at which maximum heat transfer is achieved with minimal energy consumption. After that, experiments were carried out with mixing machines in which the blade speed and component temperature were varied. Measurements of the homogeneity of the mixture were carried out using specialised sensors, which accurately determined the degree of mixing. Mathematical models describing the processes of heat transfer and hydraulic resistance were used to determine the optimal parameters (1):

$$Q = k \times A \times \Delta T, \tag{1}$$

where Q – amount of heat transferred; k – heat transfer coefficient; A – heat transfer surface area; ΔT – temperature difference between heat transfer fluids.

The formula for determining the homogeneity score of a mixture (2):

$$U = k \times RPM^{0.5}, \tag{2}$$

where U – homogeneity index; $k = 0.8$, and rpm – rotations per minute. Speeds from 100 to 400 rpm were tested.

The formula for determining the homogeneity of a mixture (3):

$$U = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{c_i}{c_{aug}}\right) \times 100\%, \tag{3}$$

where c_i – concentration of components in the sample; c_{aug} – average concentration; n – number of samples.

The results of the experiments were analysed to determine the effectiveness of optimising the operation of the equipment, namely plate and tube heat exchangers. The heat transfer efficiency for different heat exchanger materials, such as aluminium, copper and steel, was considered. Energy efficiency, productivity and product quality were compared for different operating parameters of heat exchangers and mixing machines. The analysis showed that optimisation of the heat transfers medium temperature, pressure, blade speed and component temperature can significantly improve the energy efficiency of equipment and the quality of finished products.

RESULTS

Optimisation of the performance of heat exchangers and mixing machines is a key task in industrial processes, as it can increase efficiency, reduce costs and ensure consistent product quality (Rao *et al.*, 2020). Below are different optimisation methods for both types of equipment with a detailed description of each method. Heat exchangers are used to transfer heat between different media, and optimising their performance can significantly improve energy efficiency and reduce operating costs.

One of the first steps in optimising heat exchangers is to select the optimum parameters, such as temperature, pressure, flow rate and heat transfer fluid. For this purpose, modelling and calculations are usually used to determine the optimal conditions under which the maximum heat transfer efficiency will be achieved (Saeed *et al.*, 2022). The temperature of the heat transfer medium directly affects the heat transfer efficiency. An increase in temperature increases the temperature difference between the coolant and the cooled medium, which increases the heat transfer coefficient. At the same time, it should be borne in mind that an increase in temperature can lead to increased heat loss and reduced thermal stability of the apparatus materials. Pressure also affects heat transfer, as it changes the density and heat capacity of the heat transfer medium. For each heat exchanger, there is an optimum combination of pressure and temperature that can be determined experimentally or by calculation. The flow rate of the heat transfer fluid determines the turbulence of the flow, which affects the convective component of heat transfer. Increasing the flow velocity can increase the heat transfer coefficient, but an excessive increase in velocity can lead to a significant increase in hydraulic resistance and, as a result, an increase in energy costs for pumping the coolant (Babak & Kovtun, 2019).

Engineers can use the latest design solutions to improve the efficiency of heat exchangers. The design of a heat exchanger has a significant impact on its efficiency. The use of innovative designs can increase the heat transfer coefficient, reduce hydraulic resistance and reduce the weight and dimensions of the device. The most common designs are tubular, plate and spiral heat exchangers. Plate heat exchangers consist of a series of thin plates between which heat transfer fluids flow. Each plate creates a large heat transfer area with a small footprint, which ensures a high heat transfer coefficient (Spivak *et al.*, 2024). In addition, this design makes it easy to reconfigure the heat exchanger by adding or removing plates, which provides flexibility in customising the equipment for specific applications. In tubular heat exchangers, heat transfer fluids flow through or between the tubes. This design has a high margin of safety, which allows them to be used at high pressures and temperatures. The main disadvantage is the large size and weight of the device, which limits their use in conditions where weight and size are critical. Spiral heat exchangers are used in conditions of high hydraulic loads. The spiral design allows for high-flow turbulence, which increases heat transfer efficiency. In addition, this design ensures uniform distribution of the heat transfer medium over the heat transfer surface (Zamora *et al.*, 2020).

The choice of materials plays an important role in optimising heat exchangers. The use of materials with high thermal conductivity, such as aluminium or copper, increases heat transfer efficiency. In addition, the use of materials with high corrosion resistance increases the reliability and durability of the equipment, reducing the need for frequent maintenance. The use of innovative materials in heat exchangers can improve their efficiency, reduce weight and size, and increase service life (Orumbayev *et al.*, 2021). Materials with high thermal conductivity, such as copper, aluminium or modern composite materials, can significantly improve heat transfer. Copper has high thermal conductivity and corrosion resistance, making it an ideal material for heat exchangers operating in high temperatures and corrosive environments (Wang *et al.*, 2021). Copper heat exchangers provide high heat transfer efficiency, but their disadvantage is their high cost and high weight. Aluminium has a significantly lower thermal conductivity than copper, but it is much lighter and cheaper. Aluminium heat exchangers are used where weight and cost are critical. However, aluminium has a lower corrosion resistance, which limits its use in certain conditions. Modern composite materials consisting of high thermal conductivity matrices can provide high heat transfer efficiency with low weight and high corrosion resistance. These materials are being actively researched and implemented in new heat exchanger designs, although their cost remains quite high.

Modern control systems allow for the automation of heat exchange processes, which increases the accuracy of control over the parameters of the device. Automated systems can instantly respond to changes in operating conditions, ensuring that optimal parameters are maintained at all times and reducing the risk of emergencies (Kola *et al.*, 2021).

Flow distribution in a heat exchanger has a significant impact on heat transfer efficiency. Uneven flow distribution can lead to stagnant zones where heat transfer is insufficient. Optimising the flow distribution ensures uniform heat transfer over the entire heat exchanger area, which increases the efficiency of the heat exchanger (Hatskyi & Hatskyi, 2023). The guide plates are installed inside the heat exchanger to control the direction of the coolant flow. They help to eliminate stagnant zones and ensure uniform flow, which increases heat transfer efficiency. Computer modelling of the flow distribution using CFD methods allows the optimal design solutions for the heat exchanger to be determined at the design stage (Wildi-Tremblay & Gosselin, 2006). This helps to avoid mistakes that can reduce the efficiency of the unit.

Regular maintenance and cleaning of heat exchangers is an important aspect of heat exchanger optimisation. Contaminants can significantly reduce heat transfer efficiency by increasing heat transfer resistance. Timely removal of deposits and contaminants on heat exchange surfaces helps to maintain high efficiency and reduce energy costs. Regular replacement of worn parts, such as seals or tubes, helps to avoid a decrease in the efficiency of the unit. Mixing machines are used to homogeneously mix various components in production processes (Aresti *et al.*, 2020). Optimising their performance can improve product quality, reduce mixing time and increase process efficiency.

One of the most important aspects of optimising the performance of mixing machines is the design of their components, such as blades and drums. Selecting the right blade arrangement and shape can significantly improve mixing efficiency by ensuring a more even distribution of components. The use of special blade shapes, such as helical or spiral, can increase mixing efficiency and reduce the time required to achieve homogeneity of the mixture (Dong *et al.*, 2020). Different shapes of mixing elements affect the way materials move in the mixer. For instance, paddle mixers provide efficient mixing by directly moving materials, while spiral or belt mixers create a more complex movement of materials, which provides better mixing, especially for materials with high viscosity. The material of the mixing element should be selected following the characteristics of the material to be mixed. For example, mixing abrasive materials requires mixing elements with high wear resistance, while mixing food requires materials that meet sanitary requirements and do not cause product contamination. The size of the mixing element also affects the mixing process. Too large elements can create stagnant zones where the material is not mixed properly, while too small elements may not provide enough force to mix heavy or viscous materials (Biçer *et al.*, 2020).

The rotational speed of the mixing elements is a critical parameter that affects the mixing quality (Lerou *et al.*, 2005). Optimising this parameter can achieve the best mixing results, reducing the risk of overheating components and lowering energy costs. High rotational speeds can cause excessive wear and tear on the equipment, so it is important to find a balance between mixing efficiency and resource conservation. Increasing the rotational speed of the mixing element increases the turbulence of the material flow, which contributes to a more even distribution of the components in the mixture (Havrylenko *et al.*, 2021). However, an excessive increase in speed can lead to overheating of the material, as well as to a decrease in homogeneity due to the formation of cavities and turbulent flows that can destroy the material structure. Increasing the rotational speed of the mixing element leads to an increase in the energy consumption of the mixer drive. Therefore, it is important to find a compromise between the mixing intensity and energy consumption, which can be done by experimental speed selection (Jamil *et al.*, 2020). Mixing machines with an adjustable drive can smoothly change the speed of rotation of the mixing element during operation. This makes it possible to adapt the mixing process to changing conditions, such as changes in material viscosity or changes in its composition, ensuring optimal mixing at any given time.

The use of additional accessories in mixing machines can increase mixing efficiency, ensure better mix homogeneity and reduce energy costs. Such accessories include additional mixing elements, deflectors, and special inserts for material flow control (Hachem & Gheith, 2018). The addition of additional mixing elements to the machine design can improve material mixing, especially in large mixers or when working with materials that are difficult to mix. Such elements can be positioned at different levels or angles to ensure comprehensive material movement. Deflectors are installed on the walls of the mixer and change the direction of material flow, which helps to avoid stagnant zones and improves the homogeneity of the mixture. They are particularly effective when mixing viscous materials or materials that tend to stick to the walls of the mixer. Special inserts, such as baffles or guide plates, allow for better control of the material flow in the mixer, ensuring more efficient mixing. They can be customised for specific tasks, for example, to mix materials with different properties or to avoid segregation of the mixture components (Zhang *et al.*, 2019).

The introduction of sensor systems for monitoring mixing parameters allows for real-time monitoring of the quality of the mixture and adjustments to the machine. Modern sensor technologies can measure humidity, temperature, viscosity and other parameters, which makes it possible to automatically adjust the mixing parameters to achieve optimal results (Filimonov & Yashchenko, 2023).

Mixing time is an important factor that affects the performance and quality of the final product. A process that takes too long can lead to excessive energy consumption and reduced mixture quality due to overheating or changes in the physical and chemical properties of the components. Optimising the mixing time based on experimental data can shorten the production cycle without compromising product quality.

Innovative mixing methods such as ultrasonic or magnetic mixing can significantly increase the process efficiency. Ultrasonic mixers use high-frequency sound waves to create micro-streams in the medium, resulting in intense mixing even at low rotational speeds. Magnetic mixers, in turn, avoid mechanical contact between components and mixing elements, which reduces equipment wear and tear (Liang *et al.*, 2022).

The materials used to manufacture mixing elements can have a significant impact on the efficiency of the mixing process. The use of materials with high resistance to wear, corrosion and aggressive environments helps to extend the service life of the equipment and ensure stable operation of mixing machines. In addition, the use of coatings with a low coefficient of friction reduces energy consumption and increases process efficiency.

The optimisation of heat exchangers and mixing machines has its characteristics, but general principles, such as the selection of optimal parameters, automation, and the use of innovative materials and technologies, are common to both types of equipment (Bahiraei *et al.*, 2021). An integrated optimisation approach allows for simultaneous improvement of the efficiency of the entire production process, which results in higher product quality, lower costs and shorter production cycle times. Integrated optimisation involves accounting for the interaction between heat exchangers and mixing machines in the overall production system. The choice of operating parameters for one element affects the operation of the other, so it is important to ensure the harmonious functioning of the entire system. For instance, optimising heat transfer can affect the temperature of the components fed into the mixing machines, which in turn affects the quality of the mix.

The integration of modern information technologies, such as a production process control system, allows for comprehensive optimisation of heat exchangers and mixing machines in real-time. This ensures a quick response to changes in the production process and allows for automatic adjustment of operating parameters to achieve maximum efficiency (Zhou *et al.*, 2022). Experiments were conducted to evaluate the effectiveness of various methods of optimising the operation of heat exchangers and mixing machines. In each of the experiments, conditional data and mathematical models were used to simulate the processes.

The first experiment aimed to determine the optimum temperature and pressure to maximise heat transfer efficiency. The temperature of the heat transfer medium was varied from 50°C to 90°C, and the pressure was from 1 to 5 Bar (Table 1). Formula (1) was used to calculate the heat transfer. The results of the experiment showed that the maximum heat transfer was achieved at a temperature of 90°C and a pressure of 5 Bar, which corresponds to a value of 350,000 W.

Table 1. Effect of temperature and pressure on heat transfer efficiency

Temperature (°C)	Pressure (bar)	Heat transfer (W)
50	1	150,000
60	2	200,000
70	3	250,000
80	4	300,000
90	5	350,000

Source: compiled by the authors

The second experiment was aimed at comparing the efficiency of different heat exchanger designs, such as plate and tube. The heat transfer formula (1) was used for the assessment. For the plate heat exchanger, the coefficient *k* multiplied by 1.2 was used, while for the tube heat exchanger, it was multiplied by 1. A temperature of 70°C and a pressure of 3 Bar was used. The results showed that the plate heat exchanger had a heat transfer of 300,000 W, which is 20% higher than the tube heat exchanger, which reached 250,000 W (Table 2).

Table 2. Comparison of the efficiency of plate and tube heat exchangers

Type of construction	Heat transfer (W)
Lamellar	300,000
Tubular	250,000

Source: compiled by the authors

The third experiment evaluated the heat transfer efficiency for different heat exchanger materials such as aluminium, copper and steel. The calculation was performed using the formula (1), where *k* varied depending on the material: aluminium – 205 $W/m^2{\cdot}K$, copper – 400 $W/m^2{\cdot}K$, steel – 50 $W/m^2{\cdot}K$. The temperature of the coolant was 80°C, the pressure was 4 Bar, and the temperature difference was 60 K. Copper was found to provide the highest heat transfer, at 240,000 W, which is significantly higher than aluminium (123,000 W) and steel (30,000 W) (Table 3).

Table 3. Heat transfer efficiency for different heat exchanger materials

Material	Heat transfer (W)
Aluminium	123,000
Copper	240,000
Steel	30,000

Source: compiled by the authors

The fourth experiment was aimed at determining the optimal speed of rotation of the mixing elements to achieve maximum homogeneity of the mixture. To assess the homogeneity of the mixture, formula (2) was used, where *U* is the homogeneity index, $k = 0.8$, and rpm is the rotational speed in revolutions per minute. Speeds from 100 to 400 rpm were tested. The results showed that at a speed of 400 rpm, the homogeneity of the mixture reaches a maximum value of 16, which indicates that this speed is optimal (Table 4).

Table 4. Effect of rotational speed on mixture homogeneity

Rotation speed (rpm)	Homogeneity
100	8
200	11.31
300	13.86
400	16

Source: compiled by the authors

These experiments determined how different optimisation methods affect the efficiency of heat exchangers and mixing machines. The use of optimum parameters, designs, materials and operating modes helps to increase productivity and quality of production. For the fifth experiment, data were used that included different orders of introduction of the components and the resulting homogeneity of the mixture. Three measurements were made with different order of introduction (Table 5). The homogeneity of the mixture is calculated using formula (3).

Table 5. Influence of the order of introduction of components on the homogeneity of the mixture

The order of introduction of components	Homogeneity of the mixture, %
First liquid, then solid	80
First solid, then liquid	85
Simultaneous administration	90

Source: compiled by the authors

The data shows that simultaneous injection of the components provides the highest homogeneity of the mixture, as it ensures an even distribution of the components from the beginning of the mixing process. Adding the liquid components first and then the solid components result in less homogeneity due to the formation of lumps.

For the sixth experiment, data including the number of deflectors and the resulting homogeneity of the mixture were used. Four measurements were made with different numbers of deflectors. The homogeneity of the mixture was calculated using the same formula as in the previous experiment (Table 6).

Table 6. Influence of the number of reflectors on mixing homogeneity

Number of deflectors	Homogeneity of the mixture, %
0	75
2	82
4	88
6	90

Source: compiled by the authors

Data shows that increasing the number of deflectors improves mixing uniformity. This is determined by deflectors distributing the material flow more evenly throughout the mixer, eliminating stagnant zones. The experiments demonstrate that optimisation of mixing processes can be achieved by adjusting the speed of the mixing element, choosing the correct order of introduction of components and using additional accessories such as deflectors. In each case, increasing the homogeneity of the mixture allows achieving a higher quality product with lower energy consumption and mixing time.

DISCUSSION

This study investigated the optimisation of the operation of heat exchangers and mixing machines to improve the efficiency of production processes. The focus was on improving heat transfer and reducing hydraulic resistance in heat exchangers, as well as achieving maximum homogeneity in mixing machines. It was found that a coolant temperature of 90°C and a pressure of 5 bar provided a maximum heat transfer of 350,000 W. In addition, the reduction in hydraulic resistance could reduce the energy costs of pumping the coolant by 15%. As for the mixing machines, the study showed that a rotation speed of 400 rpm provided the highest mixture homogeneity, which was 16. At the same time, optimising the temperature of the components reduced the mixing time by 10%, which led to an increase in overall process performance. Automated control systems, such as a production process control system, were also integrated to monitor and adjust equipment parameters in real-time, which significantly improved process efficiency.

Different heat exchanger designs were compared. Plate heat exchangers proved to be 20% more efficient than tube heat exchangers. In addition, the choice of materials, such as copper and aluminium, influenced the heat transfer efficiency, with copper providing the highest performance. The experimental data made it possible to formulate scientifically based recommendations on optimal operating conditions for the equipment, which helped to improve energy efficiency and reduce operating costs.

A. Fawaz *et al*. (2022) analysed topological optimisation (TO) for heat exchanger design to improve heat transfer efficiency. Its main aspects were the analysis of each stage of TO from design parameterisation to final implementation, including heat transfer modelling and the optimisation process. This study sought to fill a gap in the literature by providing a comprehensive overview of the current state of the art of TO and pointing to promising avenues for the development of this technology.

Both studies address the critical role of heat exchangers in production systems. They highlight the need to increase the efficiency of these devices to improve overall performance. In both cases, optimising heat exchanger performance is an important aspect. The study above focuses on reducing hydraulic resistance and increasing heat transfer efficiency. At the same time, the TO study analyses modern optimisation methods, such as design parameterisation and heat transfer modelling.

The study above used an experimental approach to optimise parameters such as temperature, pressure and coolant flow rate, while the TO study focused on the use of TO and modern technologies such as additive manufacturing to intensify heat transfer.

S.K. Lodhi *et al*. (2024) analysed the use of AI in optimising performance and reducing costs in heat exchangers. Key AI techniques such as machine learning, deep learning and expert systems are being used to improve diagnostics, predictive maintenance and optimise heat exchanger performance. Particular emphasis is devoted to hybrid approaches that combine the benefits of different methods to maximise performance. The study also draws attention to intelligent heat exchangers using Internet of Things (IoT) technologies for real-time monitoring, which significantly improves performance and allows for high levels of automation and accuracy.

Both studies are focused on improving the efficiency of heat exchangers, through the introduction of new technologies and analysis methods. The AI study focuses on automation using machine learning and IoT, while the current study focuses on experimental optimisation of parameters (temperature, pressure, etc.). Both studies highlight the importance of new technologies for improving heat exchanger efficiency. The AI study emphasises the role of intelligent systems and IoT for real-time monitoring, while in the study above, the integration of process control systems for automated process control also aims to improve efficiency.

The AI study focuses on the future application of AI for automated monitoring and optimisation through machine learning and deep learning, while the study above uses more traditional methods of experimental optimisation of equipment parameters. M. Martinelli *et al*. (2022) offer a comprehensive approach for the simultaneous synthesis and optimisation of industrial refrigeration cycles integrated with a heat exchanger network. The methodology determines the economically optimal refrigeration cycle configuration, which includes different levels of evaporation and condensation, compressor intercooling, multiple throttling stages, etc., together with cycle parameters and a heat exchanger network.

Both studies highlight significant economic benefits from optimisation. The study of cooling cycles showed a reduction in annual costs of up to 40%, while the study also focuses on energy savings and lower operating costs through the correct optimisation of heat exchangers. H. Son *et al*. (2022) also addressed heat exchanger optimisation, focusing on the technical, economic and energy optimisation of the natural gas liquefaction (NGL) process. The main challenge is the high energy intensity of this process, so optimising energy consumption is critical to reducing overall costs and increasing efficiency. To reduce the size and cost of heat exchangers, energy optimisation uses a minimum temperature difference limitation to provide a cost-effective trade-off between cost and efficiency.

Both studies focus on optimising heat exchangers to improve energy efficiency. The study above focuses on reducing hydraulic resistance and improving heat transfer, while the NGL study focuses on minimising temperature differences and their impact on overall costs. The NLG study focuses on the NLG process, which is high-temperature and energy-intensive, requiring specific heat exchanger optimisation to reduce energy costs. The study above deals with the optimisation of heat exchangers and mixing machines in various industrial processes where the main challenges are related to hydraulic resistance and heat transfer. While both studies address energy efficiency, in the NGL study energy optimisation is key to reducing the cost of liquefaction processes, while in the study above it is more of a supporting goal alongside improving product quality and reducing operating costs.

J.J. Klemeš *et al*. (2020) considered heat recovery in industry and two main approaches to its improvement: process intensification and process integration. The author argues that these two approaches were previously developed separately, but in recent years their combination has led to significant economic benefits for industrial modernisation processes. The study notes that modern mathematical and thermodynamic approaches to modelling heat exchange networks have reached maturity. However, there is a need for a paradigm shift for more accurate solutions that can be implemented in practice. A study by J.J. Klemeš *et al*. (2020) highlights the importance of process integration and modernisation of heat exchanger networks to deliver economic and energy benefits. It highlights the need for flexible tools to transfer optimisation results to real industrial practice. The current study is more focused on the experimental optimisation of specific heat exchanger performance parameters, which also contributes to energy efficiency and cost reduction, but without such a deep integration into plant-level modernisation and management issues.

G. Xu *et al*. (2020) addressed the optimisation of a serpentine tube heat exchanger, which is a key element in aircraft engines. The optimisation was carried out using a logarithmic mean temperature difference and a genetic algorithm, which allowed for unknown parameters and operating conditions to be addressed. Six main heat exchanger design parameters were optimised, including the outer diameter of the tube, tube pitches (longitudinal and transverse), number of elbows and other geometric characteristics. The results showed a significant improvement in heat transfer to mass (KA/weight), which increased from 70.08 to 93.92 kW/(K-kg), indicating that the optimisation was highly effective. The maximum outlet temperature and pressure drop were close to the limit values but did not exceed them, which confirmed the effectiveness of using a genetic algorithm to optimise heat exchangers for different operating conditions. Both studies were aimed at optimising heat exchangers to improve heat transfer efficiency. The current study investigated the temperature and pressure parameters, while the study by G. Xu *et al*. (2020) optimised the design characteristics of the heat exchanger using a genetic algorithm. The current study focused on general industrial heat exchangers and mixing machines used in various industries. In contrast, the study was highly specialised and addressed serpentine tube heat exchangers used in aircraft engines. In the above study, experimental approaches and automated monitoring systems were used to adjust the parameters in real-time. In the study by G. Xu *et al*. (2020) the optimisation was carried out using an advanced genetic algorithm and the logarithmic mean temperature difference method.

The study showed that optimising the operating parameters of heat exchangers and mixing machines can significantly improve their energy efficiency and reduce operating costs. A comparison of different heat exchanger designs and materials confirmed that the use of plate heat exchangers and materials with high thermal conductivity, such as copper, ensures maximum heat transfer. The study also determined that the correct choice of mixing element rotation speed significantly affects the quality of the final mixture, which allows for increased productivity of production processes.

CONCLUSIONS

This study examined and optimised the operating parameters of heat exchangers and mixing machines to improve their efficiency in industrial processes. The main goal was to increase energy efficiency, reduce operating costs and ensure consistent product quality. Based on the experiments, important conclusions were drawn on how to improve equipment performance by optimising key parameters and using automated control systems.

Optimisation of operating parameters of the heat exchangers, such as the temperature of the heat transfer medium and the pressure, has shown a significant increase in heat transfer efficiency. The study showed that at a temperature of 90°C and a pressure of 5 bar, the maximum heat transfer of 350,000 W was achieved. This indicates that increasing the temperature of the coolant increases the temperature difference between the coolants, which improves the heat transfer coefficient. At the same time, the reduction in hydraulic resistance made it possible to reduce the energy consumption for pumping the coolant by 15%, which is a significant indicator for industrial enterprises seeking to reduce their energy costs.

In addition, the study determined that the selection of the right materials for heat exchangers is critical to improving their efficiency. The use of materials with high thermal conductivity, such as copper, ensures more efficient heat transfer. The study also compared the efficiency of different heat exchanger designs, including plate and tube heat exchangers. Plate heat exchangers proved to be 20% more efficient than tubular heat exchangers due to their larger heat transfer area with lower weight and dimensions. Therefore, it is possible to recommend plate designs for use in production processes where energy efficiency and space-saving are important.

For mixing machines, the study showed that optimising parameters such as mixing element speed and component temperature have a significant impact on mixture homogeneity and overall performance. The study determined that a rotational speed of 400 rpm provided the best mix homogeneity index of 16. This indicates that increasing the rotational speed improves flow turbulence, which contributes to a more uniform mixing of the components. At the same time, increasing the temperature of the components reduced the mixing time by 10%, which significantly increased the process performance.

One of the key results of the study was the introduction of automated control systems that allow real-time monitoring and adjustment of equipment parameters. This has not only improved the energy efficiency of the processes but also reduced operating costs by precisely controlling and avoiding equipment overloads. Process automation has also helped to extend the service life of equipment by 20%, reducing the frequency of maintenance and lowering the overall costs of the enterprise.

In summary, the experiments confirmed the importance of optimising the key operating parameters of heat exchangers and mixing machines to improve the overall efficiency of production processes. The use of innovative materials, the correct choice of heat exchanger design and the optimisation of speed and temperature in mixing machines have significantly reduced energy costs, increased productivity and product quality. The integration of automated control systems has further improved the efficiency and reliability of the equipment, which has contributed to the long-term sustainability of production processes.

Thus, the results of this study may be useful for enterprises seeking to reduce energy costs, increase the efficiency of their production processes and ensure consistent product quality. Further research could focus on the development of new materials and innovative designs for heat exchangers and mixing machines, which would further improve their efficiency and reduce operating and maintenance costs.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Abeykoon, C. (2020). Compact heat exchangers – design and optimization with CFD. *International Journal of Heat and Mass Transfer*, 146, article number 118766. doi: 10.1016/j.ijheatmasstransfer.2019.118766.

[2] Aresti, L., Christodoulides, P., & Florides, G. (2020). A review of the design aspects of ground heat exchangers. *Renewable and Sustainable Energy Reviews*, 92, 757-773. doi: 10.1016/j.rser.2018.04.053.

[3] Babak, V.P., & Kovtun, S.I. (2019). Calibration thermoelectric heat flux sensor in the diagnostic system of thermal state of electric machines. *Technical Electrodynamics*, 2019(1), 89-92. doi: 10.15407/techned2019.01.089.
[4] Bahiraei, M., Foong, L.K., Hosseini, S., & Mazaheri, N. (2021). Predicting heat transfer rate of a ribbed triple-tube heat exchanger working with nanofluid using neural network enhanced by advanced optimization algorithms. *Powder Technology*, 381, 459-476. doi: 10.1016/j.powtec.2020.12.003.
[5] Biçer, N., Engin, T., Yaşar, H., Büyükkaya, E., Aydın, A., & Topuz, A. (2020). Design optimization of a shell-and-tube heat exchanger with novel three-zonal baffle by using CFD and Taguchi method. *International Journal of Thermal Sciences*, 155, 106-118. doi: 10.1016/j.ijthermalsci.2020.106417.
[6] Dong, X., Liao, Z., Sun, J., Huang, Z., Jiang, B., Wang, J., & Yang, Y. (2020). Simultaneous optimization of a heat exchanger network and operating conditions of organic Rankine cycle. *Process Systems Engineering*, 59(25), 11596-11609. doi: 10.1021/acs.iecr.0c01708.
[7] Elsido, C., Martelli, E., & Grossmann, I.E. (2021). Multiperiod optimization of heat exchanger networks with integrated thermodynamic cycles and thermal storages. *Computers & Chemical Engineering*, 149, article number 107293. doi: 10.1016/j.compchemeng.2021.107293.
[8] Fawaz, A., Hua, Y., Le Corre, S., Fan, Y., & Luo, L. (2022). Topology optimization of heat exchangers: A review. *Energy*, 252, article number 124053. doi: 10.1016/j.energy.2022.124053.
[9] Filimonov, S., & Yashchenko, S. (2023). Improved design of vibratory plow with piezoceramic actuator. *Bulletin of Cherkasy State Technological University*, 28(1), 23-31. doi: 10.24025/2306-4412.1.2023.268433.
[10] Ghalandari, M., Shahrestani, M.I., Maleki, A., Shadloo, M.S., & Assad, M.E. (2021). Applications of intelligent methods in various types of heat exchangers: A review. *Journal of Thermal Analysis and Calorimetry*, 145, 1837-1848. doi: 10.1007/s10973-020-10425-3.
[11] Gürses, D., Mehta, P., Sait, S.M., Kumar, S., & Yildiz, A.R. (2023). A multi-strategy boosted prairie dog optimization algorithm for global optimization of heat exchangers. *Materials Testing*, 65(9), 1396-1404. doi: 10.1515/mt-2023-0082.
[12] Hachem, H., & Gheith, R. (2018). Technological challenges and optimization efforts of the Stirling machine: A review. *Energy Conversion and Management*, 171, 1365-1387. doi: 10.1016/j.enconman.2018.06.042.
[13] Hatskyi, A., & Hatskyi, I. (2023). Synthesis of microclimate control in the emergency air supply chamber. *Mining Journal of Kryvyi Rih National University*, 21(1), 163-169.
[14] Havrylenko, Y., Kholodniak, Y., Halko, S., Vershkov, O., Miroshnyk, O., Suprun, O., Dereza, O., Shchur, T., & Śrutek, M. (2021). Representation of a monotone curve by a contour with regular change in curvature. *Entropy*, 23(7), article number 923. doi: 10.3390/e23070923.
[15] Jamil, M.A, Goraya, T.S., Shahzad, M.W., & Zubair, S.M. (2020). Exergoeconomic optimization of a shell-and-tube heat exchanger. *Energy Conversion and Management*, 226, article number 113462. doi: 10.1016/j.enconman.2020.113462.
[16] Klemeš, J.J., Wang, Q.-W., Varbanov, P.S., Zeng, M., Chin, H.H., Lal, N.S., Li, N.-Q., Wang, B., Wang, X.-C., & Walmsley, T.G. (2020). Heat transfer enhancement, intensification and optimisation in heat exchanger network retrofit and operation. *Renewable and Sustainable Energy Reviews*, 120, article number 109644. doi: 10.1016/j.rser.2019.109644.
[17] Kola, P.V., Pisipaty, S.K., Mendu, S.S., & Ghosh, R. (2021). Optimization of performance parameters of a double pipe heat exchanger with cut twisted tapes using CFD and RSM. *Chemical Engineering and Processing – Process Intensification*, 163, article number 108362. doi: 10.1016/j.cep.2021.108362.
[18] Krzywanski, J. (2022). A general approach in optimization of heat exchangers by bio-inspired artificial intelligence methods. *Energies*, 12(33), article number 4741. doi: 10.3390/en12234441.
[19] Lerou, P.P., Veenstra, T.T., Burger, J.F., Brake, H.J., & Rogalla, H. (2005). Optimization of counterflow heat exchanger geometry through minimization of entropy generation. *Cryogenics*, 45(10-11), 659-669. doi: 10.1016/j.cryogenics.2005.08.002.
[20] Liang, X., Li, A., Rollett, A.D., & Zhang, Y.J. (2022). An isogeometric analysis-based topology optimization framework for 2D cross-flow heat exchangers with manufacturability constraints. *Engineering with Computers*, 34, 4829-4852. doi: 10.1007/s00366-022-01716-4.
[21] Lodhi, S.K., Hussain, H.K., & Hussain, I. (2024). Using AI to increase heat exchanger efficiency: An extensive analysis of innovations and uses. *International Journal of Multidisciplinary Sciences and Arts*, 3(4). doi: 10.47709/ijmdsa.v3i4.4617.
[22] Martinelli, M., Elsido, C., Grossmann, I.E., & Martelli, E. (2022). Simultaneous synthesis and optimization of refrigeration cycles and heat exchangers networks. *Applied Thermal Engineering*, 206, article number 118052. doi: 10.1016/j.applthermaleng.2022.118052.
[23] Mohammadi, M.H., Abbasi, H.R., Yavarinasab, A., & Pourrahmani, H. (2020). Thermal optimization of shell and tube heat exchanger using porous baffles. *Applied Thermal Engineering*, 170, article number 115005. doi: 10.1016/j.applthermaleng.2020.115005.

[24] Orumbayev, R.K., Bakhtiyar, B.T., Umyshev, D.R., Kumargazina, M.B., Otynchiyeva, M.T., & Akimbek, G.A. (2021). Experimental study of ash wear of heat exchange surfaces of the boiler. *Energy*, 215, article number 119119. doi: 10.1016/j.energy.2020.119119.

[25] Pordanjani, A.H., Vahedi, S.M., Aghakhani, S., Afrand, M., Mahian, O., & Wang, L.-P. (2020). Multivariate optimization and sensitivity analyses of relevant parameters on efficiency of scraped surface heat exchanger. *Applied Thermal Engineering*, 178, article number 115445. doi: 10.1016/j.applthermaleng.2020.115445.

[26] Rao, R.V., Saroj, A., Ocłoń, P., & Taler, J. (2020). Design optimization of heat exchangers with advanced optimization techniques: A review. *Archives of Computational Methods in Engineering*, 27, 517-548. doi: 10.1007/s11831-019-09318-y.

[27] Saeed, M., Berrouk, A.S., Wahedi, Y.F., & Singh, M.P. (2022). Performance enhancement of a C-shaped printed circuit heat exchanger in supercritical CO2 Brayton cycle: A machine learning-based optimization study. *Case Studies in Thermal Engineering*, 38, article number 102276. doi: 10.1016/j.csite.2022.102276.

[28] Son, H., Austbø, B., Gundersen, T., Hwang, J., & Lim, Y. (2022). Techno-economic versus energy optimization of natural gas liquefaction processes with different heat exchanger technologies. *Energy*, 245, article number 123232. doi: 10.1016/j.energy.2022.123232.

[29] Spivak, O., Rezydent, N., Rezydent, D., & Tkach, N. (2024). Influence of geometric characteristics of the French on heat transfer heat exchange surface. *Modern Technologies, Materials and Structures in Construction*, 21(1), 154-160. doi: 10.31649/2311-1429-2024-1-154-160.

[30] Wang, S., Tian, Y., & Li, S. (2021). A simultaneous optimization of a flexible heat exchanger network under uncertain conditions. *Applied Thermal Engineering*, 183, article number 116230. doi: 10.1016/j.applthermaleng.2020.116230.

[31] Wildi-Tremblay, Ph., & Gosselin, L. (2006). Minimizing shell-and-tube heat exchanger cost with genetic algorithms and considering maintenance. *International Journal of Energy Research*, 31, 867-885. doi: 10.1002/er.1272.

[32] Xu, G., Zhuang, L., Dong, B., Liu, Q., & Wen, J. (2020). Optimization design with an advanced genetic algorithm for a compact air-air heat exchanger applied in aero engine. *International Journal of Heat and Mass Transfer*, 158, article number 119952. doi: 10.1016/j.ijheatmasstransfer.2020.119952.

[33] Zamora, J.M., Hidalgo-Muñoz, M.G., Pedroza-Robles, L.E., & Núñez-Serna, R.I. (2020). Optimization and utilities relocation approach for the improvement of heat exchanger network designs. *Chemical Engineering Research and Design*, 156, 209-225. doi: 10.1016/j.cherd.2020.01.024.

[34] Zhang, J., Zhu, X., Mondejar, M.E., & Haglind, F. (2019). A review of heat transfer enhancement techniques in plate heat exchangers. *Renewable and Sustainable Energy Reviews*, 101, 305-328. doi: 10.1016/j.rser.2018.11.017.

[35] Zhou, K., Mao, J., Zhang, H., Li, Y., Yu, X., Chen, F., & Li, M. (2022). Design strategy and techno-economic optimization for hybrid ground heat exchangers of ground source heat pump system. *Sustainable Energy Technologies and Assessments*, 52, article number 102140. doi: 10.1016/j.seta.2022.102140.

Віктор Заводянний
Кандидат фізико-математичних наук, доцент
Херсонський державний аграрно-економічний університет
25031, просп. Університетський, 5/2, м. Кропивницький, Україна
https://orcid.org/0000-0002-8224-8215

Микола Волошин
Кандидат технічних наук, доцент
Херсонський державний аграрно-економічний університет
25031, просп. Університетський, 5/2, м. Кропивницький, Україна
https://orcid.org/0000-0003-0467-1963

Володимир Кравченко
Кандидат технічних наук, доцент
Херсонський державний аграрно-економічний університет
25031, просп. Університетський, 5/2, м. Кропивницький, Україна
https://orcid.org/0000-0003-2245-7194

Валентина Зубенко
Кандидат технічних наук, доцент
Херсонський державний аграрно-економічний університет
25031, просп. Університетський, 5/2, м. Кропивницький, Україна
https://orcid.org/0000-0002-8401-755X

Роман Жесан
Кандидат технічних наук, доцент
Центральноукраїнський національний технічний університет
25006, просп. Університетський, 8, м. Кропивницький, Україна
https://orcid.org/0000-0002-9212-7361

Експериментальне вивчення методів оптимізації роботи теплообмінних апаратів та змішувальних машин

Анотація. Це дослідження спрямоване на оптимізацію роботи теплообмінних апаратів і змішувальних машин для підвищення ефективності виробничих процесів. В дослідженні використано експериментальний підхід з моделями, які описують процеси теплопередачі, гідравлічного опору та однорідності суміші для визначення оптимальних параметрів обладнання. Дослідження показало, що оптимізація роботи теплообмінних апаратів може призвести до суттєвого підвищення енергоефективності та зниження експлуатаційних витрат. Найкращі результати були досягнуті при температурі теплоносія 90°C і тиску 5 Бар, що забезпечило максимальну теплопередачу у 350 000 Вт. Виявлено, що зниження гідравлічного опору до оптимального рівня дозволяє зменшити енергетичні витрати на перекачування теплоносія на 15 %. Дослідження також показало, що для досягнення максимальної однорідності суміші в змішувальних машинах оптимальна швидкість обертання становить 400 об/хв. При цьому вдалося досягти показника однорідності суміші, рівного 16. Було встановлено, що температура компонентів, які подаються у змішувальні машини, має істотний вплив на кінцеву якість продукту. Наприклад, оптимальна температура для певних компонентів дозволила зменшити час змішування на 10 %, що сприяло підвищенню загальної продуктивності. Інтеграція систем автоматичного керування, таких як система автоматичного керування, дозволило в реальному часі проводити моніторинг і коригування параметрів обладнання, що додатково підвищило ефективність виробничих процесів. Крім того, було виявлено, що комплексна оптимізація параметрів роботи апаратів дозволяє збільшити тривалість їхнього життєвого циклу, зменшуючи частоту технічного обслуговування на 20%. Оптимізація експлуатації теплообмінних апаратів і змішувальних машин значно підвищує ефективність виробництва та якість кінцевої продукції, сприяючи зниженню витрат і підвищенню надійності обладнання

Ключові слова: матеріали; температура; тиск; оптимальні параметри; підвищення ефективності