https://doi.org/10.33271/nvngu/2026-1/076

O. D. Nikolayev[*1],
orcid.org/0000-0003-0163-0891,
Yu. O. Zhulay[2],
orcid.org/0000-0001-7477-2028,
A. Yu. Lysenko[3],
orcid.org/0009-0000-3816-8392

1 – Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine, Dnipro, Ukraine
2 – Institute of Transport Systems and Technologies of National Academy of Sciences of Ukraine, Dnipro, Ukraine
3 – LLC "IMPORT TRADE COMPANY", Kyiv, Ukraine
[*] Corresponding author e-mail: nikolaev.o.d@nas.gov.ua

CURRENT STATE OF TECHNOLOGICAL PROCESSES FOR HIGH-PERFORMANCE CLEANING OF FOULED HEAT EXCHANGERS: PROSPECTS AND RESEARCH DIRECTIONS

Plate and shell-and-tube heat exchangers are widely used in the chemical and food industries, as well as in nuclear and thermal power generation. Physical and chemical phenomena such as sedimentation, crystallization, chemical reactions, corrosion, and biofouling, which occur during heat exchange processes, reduce heat transfer rates. They form solid deposits, and foul the internal tubes of heat exchangers, which is an extremely critical factor for industrial production and can lead to unprecedented financial losses.

Purpose. To determine the most promising directions for developing methods for cleaning shell-and-tube heat exchangers for nuclear, thermal power plants, and other industrial applications based on determining the current state of technological processes for high-performance cleaning of contaminated heat exchangers.

Methodology. Theoretical and experimental data are studied, obtained during the development of methods for cleaning the internal surfaces of heat exchangers, and presented in various scientific and technical sources of information.

Findings. The results are presented by comparing the nature of technological processes and the effectiveness of methods for cleaning the internal surfaces of heat exchangers, as well as assessing the influence of certain coatings on increasing the service life of internal pipelines.

Originality. The conducted analysis of methods for cleaning the internal surfaces of heat exchangers, as well as the impact of coatings on extending the service life of internal pipelines, allowed us to:

- identify progressive technologies for cleaning contaminated heat exchangers used in the energy sector and various industries;
- establish methods for determining the effectiveness of new and proven technologies, such as ultrasonic vibrations of the cleaning fluid;
- summarize assessments of the impact of various treatments (chemical and vibrational) on the quality of cleaning heat exchanger tubes.

Practical value. A comparative analysis of the effectiveness of potential research approaches to improving heat exchanger cleaning methods will enable the selection of the most promising ones for solving practical problems in improving cleaning technologies for specific heat exchanger designs.

Keywords: *shell-and-tube heat exchanger, pipeline surface cleaning, heat transfer rate, cavitation oscillations*

Introduction. The increasing capacity of power generation systems is driving the search for new ways to improve the efficiency of their heat exchangers. Heat exchangers are also widely used in the chemical and food industries.

Most heat exchangers in development are plate [1] and shell-and-tube heat exchangers [2]. Improving energy efficiency and energy conservation are key areas of development in the modern energy sector [3]. Plate and shell-and-tube heat exchangers are designed to address energy conversion and energy conservation issues, particularly in modern thermal and nuclear power plant systems.

Shell-and-tube heat exchangers (Fig. 1 shows their operating principle) have a more robust design compared to plate heat exchangers, which is necessary to ensure the reliable operation of large power generation systems. Shell-and-tube heat exchangers provide higher throughput and operate optimally at large temperature differences and are preferred over plate heat exchangers.

Shell-and-tube heat exchangers for nuclear power plants naturally have specific design features. They are capable of withstanding higher specific heat fluxes than heat exchangers used in conventional power plant processes.

Nuclear power plant heat exchangers, whose tubes carry radioactive and corrosive media, are made of relatively expensive stainless steel. To conserve steel, heating surfaces and heat exchanger shells are designed with minimal thickness, avoiding excessive safety margins while still ensuring the necessary reliability for long-term operation [4].

However, it is known that various physical and chemical processes occur in shell-and-tube heat exchangers in power generation systems, such as sedimentation, crystallization [4], chemical reactions, corrosion, and biofouling. The combination of these processes leads to fouling of the internal surfaces of the pipelines. Fouling of the internal surfaces of the heat exchangers reduces the rate of heat transfer. Over long periods of operation, this can become extremely critical to operational performance, forming hard deposits and clogging internal tubes. A decrease in heat transfer rate leads to significant technical problems in the heat exchanger's operational process. Fouling causes significant losses in power generation due to the deterioration of the power generation system's efficiency. These losses in power generation can lead to unplanned or planned system shutdowns due to fouling, which ultimately result in significant financial losses.

In the chemical industry, the main problems with heat exchangers include pipeline wall fouling, leaks, and increased energy consumption. All of these issues directly impact heat exchanger efficiency and, consequently, the performance of downstream equipment. It has been noted [5] that many of these issues are interrelated. For example, many heat exchanger leaks are caused by technical issues in the fluid flow distribution units. If the unsteady flow through the heat exchanger is uneven, high turbulent flow velocities can cause an additional problem: vibration. This uncontrolled vibration can, in some cases, exacerbate the erosive effects in heat exchangers, which then leads to frequent, uncontrolled leaks, creating problematic maintenance and associated unnecessary financial costs.

In the agro-industrial and water supply sectors, fouling of the hot walls of process heat exchangers is also common. Eliminating fouling requires frequent cleaning cycles to ensure hygienic requirements [6]. However, the use of frequent, drastic, and expensive cleaning measures to avoid any risk of heat exchanger fouling leads to excessive use of rinse water and caustic chemicals (sodium hydroxide and hydrochloric acid solutions). This reduces the environmental performance of process equipment and increases the risk of subsequent surface fouling and biofilm formation, which also carries the risk of causing significant environmental damage to the plant.

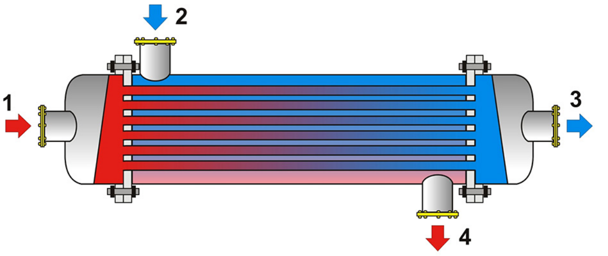

Fig. 1. Schematic diagram of a shell-and-tube heat exchanger:

1 and 3 are the inlet and outlet channels of the cooled liquid; 2 and 4 are the inlet and outlet channels of the cooling liquid

The purpose of this article is to:

- determine the current state and analyze the effectiveness of various technological processes for the high-performance cleaning of contaminated heat exchangers;
- systematize potential research areas for improving modern heat exchanger cleaning methods, including the use of high-frequency turbulent flows of cleaning fluids in combination with chemical methods for treating the internal surfaces of pipelines.

Systems for diagnosing the degree of fouling of the surface of heat exchanger pipelines as an integral part of progressive cleaning technologies. Currently, heat exchanger diagnostic systems (in particular, those for determining the critical degradation time and the need for heat exchanger cleaning) are not established for modern heat exchanger designs. Their operating principles and the equipment used can vary significantly for different heat exchange processes.

For example, Algorithmica Technologies GmbH has developed a method that predicts the operating time of a shell-and-tube heat exchanger before it reaches critical degradation. Such critical degradation in a heat exchanger system cannot be tolerated, requiring major repairs or cleaning of the shell-and-tube heat exchanger [4]. After conducting sample measurements, the method determines the time dependence of heat transfer degradation and calculates the estimated operating time before heat exchanger cleaning becomes absolutely necessary.

In this context, the method developed by Hexxcell Studio™ is of interest. This method enables advanced monitoring, preliminary analytical processing of results, and mandatory maintenance of industrial heat transfer systems.

At the same time, quantitative assessment of heat exchanger fouling can be performed using experimental methods, and in some cases, numerical methods are also used.

The most common experimental methods are based on measurements of the following parameters:

- pressure drop;
- mass flow rate of liquids and determination of heat transfer parameters [7–9];
- as well as hydrodynamic monitoring and acoustic analysis methods.

According to [4], the most important advantages of existing online fouling monitoring methods are the reliability, relevance, and ease of interpretation of the information contained in the indicator (local fouling, representing the local thickness of the hot wall layer, or global fouling, representing the fouling state throughout the heat exchanger), as well as the time required to determine the degree and causes of fouling.

The article [7] presents a non-destructive ultrasonic testing technology. The non-destructive ultrasonic testing method (using coded waves and associated signal processing) was used to monitor the evolution of a deposit layer on a solid wall over time during a cleaning process. The feasibility of the method was tested by applying a wax sample of controlled thickness to the surface to simulate the initial state of contamination, and then "starting" the cleaning cycle. Experimental results showed that the non-destructive testing technology proposed by the authors is quite sensitive to changes in the degree of contamination, and the correlation coefficient curves are consistent with video data of the cleaning kinetics.

Modern technologies for cleaning contaminated heat exchangers. This section presents some technological directions for cleaning heat exchangers, based on technologies that are either already used in industry and require development, or promising ones that require further theoretical and experimental development and implementation.

Ultrasonic cleaning technologies for heat exchangers. Heat exchangers can be cleaned using in-situ ultrasonic heat exchanger cleaning technology [10, 11]. Cleaning contaminated shell-and-tube heat exchangers requires shutting down the entire process. Experience shows [12] that solutions implemented on a shut-down shell-and-tube heat exchanger ultimately yield fairly reliable cleaning results.

The TECH SONIC'S Cleaning technology [13] is successfully used in Canada and the USA. This technology requires removing the tube bundle of a shell-and-tube heat exchanger from the process unit and placing it in an external ultrasonic cleaning system. The tube bundle is completely immersed in a cleaning fluid in a special tank. The tube bundle and cleaning fluid are exposed to ultrasound. According to the developer, existing contaminants are removed quite reliably in practice.

In practice, a cleaning method is also used that involves inserting a removable ultrasonic transducer into the shell of a shell-and-tube heat exchanger. The liquid medium is excited by an ultrasonic source to generate cavitation acoustic waves. The position of the ultrasonic transducer within the tube inside the heat exchanger is adjusted. Preferably, the cleaning equipment should include a control system for the ultrasonic transducer excitation and position, as well as a liquid fouling sensor.

Cleaning technologies for heavily contaminated internal tubes of shell and tube heat exchangers using drilling holes. Due to the low efficiency of cleaning technologies in the presence of solid contaminants and blockages, as well as other negative phenomena, drilling holes in contaminated heat exchanger pipes is often chosen as a solution.

During the development of this technology, many concerns were raised about using this method for cleaning internal pipes due to the potential for damage. With the Radler Tube Cleaning (RTC) process [14] being used, this negative effect can be completely avoided. During cleaning, a drill inserted into the pipe is held away from the internal surfaces by a guide ring, while water exits the guide ring under 2 bar pressure, carrying away loosened contaminants. Water and contaminants flow between the guide ring and the internal surface of the pipe in the direction opposite to the drill's movement [15].

Friction between the surface of the internal pipe and the guide ring creates a very clean surface for the internal pipes. In practice, the high quality of cleaning achieved using the RTC method leads to an increase in the service life between repairs. However, residual deposits on the inner tube surfaces lead to rapid fouling and increased blockage. Using the RTC method significantly reduces environmental impact and operator workload.

However, since this drilling process can only be used to remove hard deposits and blockages in straight tubes, pipe elbows connecting tubes or the hoods (chambers) of shell-and-tube heat exchangers must be cleaned using other cleaning processes.

Chemical cleaning technologies for heat exchangers. The operation of heat exchange equipment is often associated with the formation of scale deposits due to the crystallization of calcium and magnesium salts. Effective scale removal remains a complex scientific and technical challenge. In the work [16], the results of the study are presented showing that "10 % sulfamic acid dissolves up to 46 % of the deposit in the tube of the KhVO PP-1 heat exchanger, while the average corrosion rate of the metal of the heat exchanger tubes is 0.861 10-7 kg/m^2 s. Deposits from the tubes of the KhVO PP-1 heat exchanger were also subjected to dissolution by hydrochloric acid". In order to improve the anti-corrosion properties, the authors of the given work developed their own method of inhibiting hydrochloric acid. It consists of introducing a nitrogen-containing corrosion inhibitor (thiourea) into 20 % hydrochloric acid. According to the results of laboratory tests it was established that 20 % hydrochloric acid with the addition of thiourea completely dissolves the deposit. In this work also the negative influence of zinc (present in brass) on the protective properties of the corrosion inhibitors urotropine and thiourea is noted. Effectively creating protective effects on pure metals (iron, copper) and alloys containing zinc, these inhibitors do not prevent the dissolution of zinc from the alloy upon contact with acids and the subsequent dissolution of the base metal itself.

In [16], the optimal protective effect of a corrosion inhibitor of 55.2 % was established. It was obtained on a copper plate immersed in a 5 % hydrochloric acid solution with the addition of 100 mg/l of AZ 8104 inhibitor.

Chemical methods of descaling include the cleaning method [17], which consists of dissolving scale inside heating devices. The resulting descaling concentrate contains phosphoric acid (V) and components that inhibit corrosion, antifoaming agents, and antimicrobial agents (formaldehyde, ammonium chloride, copper sulfate, and zinc sulfate). As a result of scale dissolution, wastewater is formed, which can be fully used as raw material for the production of phosphate fertilizers. As a result, both the resulting preparation and its use are completely waste-free.

Technologies for hydrodynamic cleaning of heat exchangers under high pressure when dismantling is necessary. Given the various fluid flows, flow rates, and prevailing temperatures that occur in heat exchangers under operating conditions, heat exchanger cleaning technologies can utilize vibration in the internal tubes and the use of cleaning balls during operation [2].

One method for cleaning shell-and-tube heat exchangers without dismantling them is to flush the tubes internally and externally with cleaning fluids [18]. These cleaning fluids utilize cleaning technology based on biochemical or chemical processes [19], as well as physical laws and the processes that implement them [5].

Most cleaning service providers utilize high-pressure cleaning technology to clean fouled shell-and-tube heat exchangers [19]. The external surfaces of tube bundles are generally successfully cleaned using high-pressure cleaning technology. However, if the internal tubes of heat exchangers contain hard deposits and fouling, cleaning by using high-pressure hydraulic cleaning technology becomes a challenge. High-pressure cleaning technology typically uses water or, in some cases, chemical additives dissolved in water. Other methods use dry ice or special cleaning granules [20]. These methods also require a long time to achieve acceptable cleaning results.

Intensification of hydrodynamic cleaning of heat exchangers. The development of cavitation-pulse technologies using hydrodynamic processes implemented with a cavitation fluid pressure pulse generator and the creation of a surface cleaning technology for various industrial devices based on this approach by the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine (under the direction of Academician V. V. Pilipenko [21]) have found application in the space and metallurgical industries of Ukraine. The possibilities for using such pulsating liquid flows at the outlet of a cavitation generator have been explored and new approaches have been developed for the development of new, high-performance, environmentally friendly technological processes for cleaning the surfaces of various devices in metallurgy, mining, and other industries. A schematic axonometric view of a cavitation generator is shown in Fig. 2.

The cavitation generator *2* is the key element of the device. It converts a steady fluid flow into a discrete, pulsed, high-power fluid flow. The generator's flow path is designed as a converging-expanding channel, similar to a Venturi tube, with a special geometry [22, 23]. The inlet hydraulic channel *1* of the cavitation generator serves to equalize the fluid flow velocity field at the generator entrance and is designed as a pipe with a specific length-to-diameter ratio.

The outlet hydraulic channel *3* is a section of pipe with geometric dimensions that, at a given generator operating mode, ensure pressure oscillation ranges two or more times greater than the static pressure at the generator inlet, with minimal vibrational energy loss at the cavitation generator outlet.

The cavitation generator is secured with tie bolts *4* via flange connections between the inlet *1* and outlet *3* hydraulic channels. The inlet and flow channels of the cavitation generator also provide places for installing pressure gauges *5*, as well as a pressure pulsation sensor – *6*.

The Institute of Mechanical Engineering of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine also conducted research into the cavitation flow patterns of a high-pressure pulsed hydroabrasive jet and the conditions for its formation. The results of these theoretical and experimental studies [21] enabled the development and practical implementation of promising technologies and installations for cavitation-pulse hydroabrasive machining (KIGAU) of various surfaces, particularly the metal surfaces of rocket structures. The KIGAU circuit and technical solutions are based on more than 25 inventions.

The above-mentioned scientific and technical achievements were utilized by Import Trade Company and the Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine [22]. An experimental prototype of a device for intensifying the cleaning process for the surfaces of a shell-and-tube heat exchanger, incorporating a cavitation generator, was created.

The equipment installation diagram for testing the new technology for hydropulse cleaning of the inner surface of a tubular heat exchanger collector using a cavitation generator is shown in Fig. 3.

The process unit consisted of the following main components:

1 – pump unit;

2 – cavitation generator, a Venturi tube with special geometric parameters;

3 – hydraulic outlet channel;

4 – tubular heat exchanger manifold;

5 – pressure gauges;

6 – pressure pulsation sensor;

7 – adjustable throttle;

8 – drain line.

The technological capabilities of installing the equipment according to this scheme made it possible to test the cavitation generator to determine its dynamic parameters (the amplitude of self-oscillating pressure ΔP and their frequency f versus the backpressure P_2) and the initial and final cleaning times of the tubular collector, as well as the effectiveness of the new technology using periodically stalled cavitation flow modes of the cleaning fluid.

A study of the cavitation generator's dynamic parameters – the amplitude of self-oscillating pressure ΔP and their frequency f – confirmed the presence of a pulsed oscillatory process. Thus, during hydropulse cleaning of the inner surface of the VVP 219 × 4000 × 1.0-RG heat exchanger tubes at steady-state inlet pressures of $P_1 = 5.2$ kg/cm^2 and backpressure $P_2 \approx 1.6$ kg/cm^2 – the amplitude of self-oscillating pressure ΔP was approximately three times greater than the pressure at the generator inlet. This is clearly confirmed by the oscillogram (recorded by the pulsation sensor *6* in Fig. 3) of the dynamic process of changing the pressure over time in the flow channel of the cavitation generator, shown in Fig. 4.

Using vibration acceleration measurements during hydropulse cleaning, the dominant (fundamental) modes of natural mechanical vibrations of the heat exchanger structure were determined. It was determined

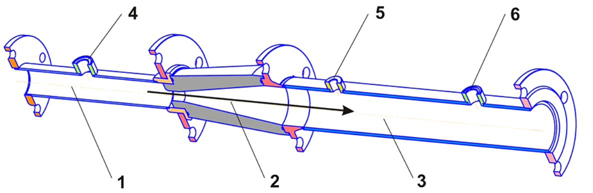

Fig. 2. Schematic representation of a 3-D projection of a cavitation generator

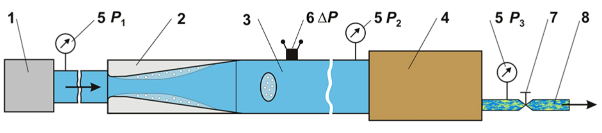

Fig. 3. Flow chart for testing hydropulse cleaning of the inner surface of a tubular heat exchanger collector

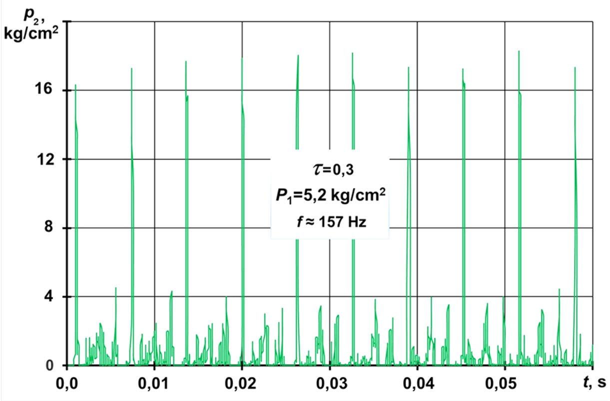

Fig. 4. The process of change in time t of the experimental dependence of pressure p_2 in the flow part of the output hydraulic channel

that during testing, secondary vibration modes with a frequency of approximately 157 Hz were superimposed on the fundamental vibration modes of the structure. These modes were caused by the repeated collapse of the cavitation cavity and the dynamic interaction of the mechanical part of the structure with the fluid in the flow path of the cavitation generator and the hydraulic outlet channel. This vibrational action on the surface deposits of the heat exchanger tubes, with frequencies close to resonant frequencies, promotes the development of a network of microcracks in the existing surface deposits. This leads to delamination and disruption of the deposits, as well as the effective removal of detached particles from the cleaning zone by the pulsating flow of cleaning fluid.

Figs. 5 and 6 show photographs of the internal surfaces of the heat exchanger tubes before cleaning them using the hydropulse method.

The average thickness of the growths on the inner surfaces of the tubes (mainly with a chemical composition of calcium, iron and sulfur oxides) ranged from 1 to 3 mm.

As can be seen in Fig. 6, the coolant inlet channel was additionally clogged with sludge deposits, chlorides, sulfates, and other aggressive compounds that promote latent corrosion. Such fouling of the internal and external surfaces of the heat exchanger tubes significantly reduces its efficiency. The results of cleaning the same heat exchanger tube bundle using hydropulse are shown in Fig. 7.

The results of hydropulse cleaning of the internal (*a*) and external (*b*) tube surfaces using a heat exchanger cleaning solution under industrial conditions showed that high cleaning quality was achieved, reaching practically Sa3 according to ISO 8501. The use of the developed heat exchanger cleaning technology did not require the heat exchanger itself.

The use of a cavitation generator in hydropulse cleaning technologies for heat exchanger working surfaces leads to increased cleaning speed and quality while reducing specific energy consumption by up to 30 %.

Fig. 5. Photograph of the internal surfaces of the heat exchanger tube bundle before cleaning

Fig. 6. Photograph of the external surfaces between the tube bundles of the heat exchanger before their cleaning

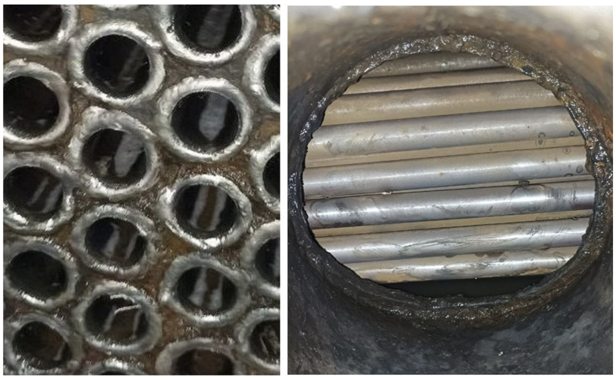

Fig. 7. Photographs of the inner (a) and outer (b) top of the heat exchanger tube bundle after cleaning by the hydro-impulse method

Development of technologies for increasing the efficiency of heat exchange devices at the design stage in order to ensure a reduced rate of fouling during operation. It is advisable to develop cleaning technologies during the design stage of heat exchangers, taking into account the potential for surface fouling during operation. In this case, the design must employ methods to mitigate the impact of factors that lead to possible fouling during operation, as well as to maintain the heat transfer area under potential fouling conditions.

The use of special technical solutions to reduce the tendency to fouling. During the design of heat exchangers, many important factors are considered [24] to minimize the occurrence and accumulation of fouling. Specifically, these may include:

a) redistributing the greater flow rate of the fouling fluid to the tube side;

b) designing the heat exchanger to optimize the fluid flow rate in various sections of the heat exchanger;

c) ensuring easy access for cleaning the heat exchanger;

d) creating a system to control fluid flow conditions and the condition of the tube wall, preventing the temperature at which unwanted salt deposition begins to occur.

The use of coatings with special films. The use of amorphous carbon coatings, also known as diamond-like carbon (DLC), in heat exchangers has demonstrated significant fouling reduction. However, their successful application, particularly in shell-and-tube heat exchangers, has not yet been widely adopted. Researchers at the Upper Austrian University of Applied Sciences (Wels, Austria) are advancing the industrial application of DLC using the RUBIG Group's PACVD reactor technology [25].

The article [26] presents experience in testing the welding of DLC-coated tubes and components for a shell-and-tube heat exchanger (internal diameter 600 mm, length 5,000 mm, 200 tubes with an external diameter of 25 mm). It was determined that the achieved weld quality was quite satisfactory. The coatings exhibited minor ablative defects near the weld zone. It has been shown that devices of this size can be used with DLC coatings with an efficiency of 80–90 %, capable of withstanding high pressures and temperatures up to 450 °C. With improvements in the quality of DLC-coated tube production, the authors plan to achieve a coating efficiency of 99 % in the future.

The authors summarize the current state of research and future work on the application of DLC coatings to heat exchangers as follows. Currently, industrial use of DLC [27] is primarily found in plate heat exchangers, as coating flat surfaces has already proven itself to be effective. Applying the coating inside deep cavities is generally difficult, so long tubes, typically used in shell-and-tube heat exchangers, cannot be coated internally on an industrial scale.

In cases where the base material can withstand sufficient corrosion resistance without coating, full protection with a DLC layer is not necessary. For example, if weld areas are not coated, there may be a limited anti-fouling effect of around 10 %, but the major benefit in terms of heat transfer will still occur.

The potential of 3D printing heat exchanger designs to optimize heat transfer and reduce heat exchanger fouling. In addition to traditional heat exchanger manufacturing methods (such as casting, cavity machining, and molding), additive manufacturing is of significant interest in achieving heat exchanger fouling reduction goals [28]. Additive manufacturing is also known as 3D printing.

Designing unique heat exchanger designs and implementing additive manufacturing offers many advantages over traditional shell-and-tube heat exchanger manufacturing methods.

The main advantages of using additive manufacturing include:

- a greater degree of freedom in developing new design solutions and heat exchanger structures (3D printing has currently become the most powerful technology for rapid design, prototyping, and manufacturing [29]);
- 3D printing appears to enable the creation of more complex and integrated structures, in which the heat exchange surface area can be optimally increased, significantly improving heat transfer performance;
- custom design (using fins and meshes) can be optimized to meet specific heat transfer requirements;
- the ability to easily print replaceable parts [30].

Complex geometry and internal design are among the key advantages of 3D printing technology. These features enable the creation of complex and customized designs that are difficult or impossible to achieve using traditional manufacturing methods.

In particular, a case study of temperature-sensitive composite structures (TPMS) is described in the literature [31], where Cheng et al. designed a heat exchanger based on minimal surfaces. The flow passed along a TPMS with dimensions of 2.54 × 2.54 × 20.32 mm with a structure porosity of $\varepsilon = 20–80$ %. In another study, Khalil, et al. [32] first numerically and then experimentally investigated forced convection during heat transfer using a triple periodic minimum surface TPMS structure, i. e., diamond-shaped (*D*) or gyroidal (*G*), with a size of 10 mm and a porosity of 80 %. It was found that the gyroidal plate structure has the lowest thermal resistance and the highest heat transfer coefficient due to its largest surface area. This work opens new perspectives for the design of 3D printed structures. Thus, the new capabilities of 3D printing for developing complex heat exchanger geometries have revolutionized heat transfer. These heat exchanger designs offer increased efficiency and the ability to customize their operating parameters over a wide range.

The implementation of these more efficient heat exchanger designs can lead to more efficient processes in power plant heat exchangers, reducing operating costs for electricity generation.

Conclusions. Based on advances in research into various technological processes for the highly effective cleaning of fouled heat exchangers, a number of conclusions have been drawn regarding the current state of development of methods and devices for diagnosing, removing, and ensuring the stable operation of industrial heat exchangers. It has been established that a number of technological processes and their heat exchange equipment require targeted development, both for improvement and for a revolutionary revision of their design principles. Specifically, the following research areas are promising:

- the development and implementation of systems for diagnosing the degree of fouling in shell-and-tube heat exchangers, both for determining the start time of the heat exchanger cleaning process and for optimizing heat transfer control, can significantly improve the quality of technological processes in existing power generation systems and various industries;
- ultrasonic cleaning of heat exchangers ultimately yields fairly reliable results and can be used in advanced cleaning systems;

- due to the low efficiency of existing cleaning technologies in the presence of solid contaminants and blockages, drilling holes in contaminated heat exchanger pipelines is also a promising solution (however, the drilling process can only be used to remove hard crusts and blockages in straight pipes);

- work on heat exchanger cleaning technologies using chemical action on contaminated surfaces is promising, although, depending on the scope of their industrial application, there are a number of materials science issues that need to be addressed when implementing these technologies;

- the use of cleaning solutions, vibration in internal pipes, and the use of wash balls during operation are also promising in heat exchanger cleaning technologies;

- use of a cavitation generator in the technological process of cleaning the surfaces of a tubular heat exchanger. An analysis of the results of an experimental study on the use of a cavitation generator in the cleaning process of tubular heat exchanger surfaces revealed that the cavitation generator is a promising device for increasing the efficiency of heat exchanger surface cleaning. Under repeated alternating pressure pulses and additional vibration, the stress-strain state of deposits on the cleaned surface takes on a fatigue nature, and with the development of a network of microcracks, deposit destruction occurs. Cleaning tubular heat exchanger surfaces using a cavitation generator leads to increased cleaning speed and quality while reducing specific energy consumption by up to 30 %;

- the use of specialized technical solutions, such as optimizing the flow and velocity of contaminated liquid in the heat exchanger and creating a wall temperature control system in certain pipe sections, can minimize the occurrence and accumulation of contaminants;

- application of coatings with special films to the surfaces of the heat exchanger structure can also contribute to a significant reduction in the degree of fouling of heat exchangers under operating conditions;

- 3D printing can be a significant factor in optimizing and ensuring stable heat transfer in industrial applications. This technology enables the creation of complex designs and the production of heat exchange systems with customized shapes and sizes, tailored to specific production needs that are difficult to achieve using traditional methods. As a result, the extent of heat exchanger fouling can be significantly reduced, and the performance of the heat transfer process itself can be significantly improved.

References.

1. Elmardi, O., & Khayal, S. (2018). Fundamentals of heat exchangers. *International journal of research in computer applications and robotics, 6*(12), 1-11. https://doi.org/10.13140/RG.2.2.12166.42563
2. Wegener, E. (2013). *Planning a heat exchanger – a holistic task solution up to the repair of a tube bundle heat exchanger*. Weinheim: Wiley-VCH. ISBN: 978-3-527-33304-2.
3. Patel, A. (2023). Heat Exchangers in Industrial Applications: Efficiency and Optimization Strategies. *International journal of engineering research & technology (IJERT), 12*(09), (September 2023), 1-9. https://doi.org/10.17577/IJERTV12IS090003
4. Kastner, H. (2021). *Featured Story – Field report: cleaning of shell & tube heat exchangers*. Heat Exchanger World Publisher. Retrieved from https://heat-exchanger-world.com/featured-story-field-report-cleaning-of-shell-tube-heat-exchangers/
5. Mrinal Das (2023). *Fouling: A major challenge for heat exchangers in chemical process industries*. Heat Exchanger World Publisher. Retrieved from https://heat-exchanger-world.com/fouling-a-major-challenge-for-heat-exchangers-in-chemical-process-industries/
6. Alvarez, N., Daufin, G., & Gésan-Guiziou, G. (2010). Recommendations for rationalizing cleaning-in-place in the dairy industry: Case study of an ultra-high temperature heat exchanger. *International Journal of Dairy Science, 93*(2), 808-821. https://doi.org/10.3168/jds.2009-2760
7. Chen, B., Callens, D., Campistron, P., Moulin, E., Debreyne, P., & Delaplace, G. (2019). Monitoring cleaning cycles of fouled ducts using ultrasonic coda wave interferometry (CWI). *Ultrasonics, 96*, 253-260. https://doi.org/10.1016/j.ultras.2018.12.011
8. Mustafa, S., Taha, M., Zatout, A., Sedahmed G., & El-Gayar, D. (2021). Mass transfer at the outer surface of a spiral tube heat exchanger in a stirred tank reactor and possible applications. *Chemical Engineering Research and Design, 165*, 426-434. https://doi.org/10.1016/j.cherd.2020.11.023
9. Gonzalez, D., Tjandraatmadja, G., Barry, K., Vanderzalm, J., Kaksonen, A., Dillon, P., Puzon, G., ..., & Low, J. (2016). Biofouling potential and material reactivity in a simulated water distribution network supplied with stormwater recycled via managed aquifer recharge. *Water Research, 105*(15), 110-118. https://doi.org/10.1016/j.watres.2016.08.066
10. Yan, J., Wright, W. M. D., O'Mahony, A. J., Roos, Y., Cuijpers, E., & van Ruth, S. M. (2019). A sound approach: Exploring a rapid and non-destructive ultrasonic pulse echo system for vegetable oils characterization. *Food Research International, 125*, 108552. https://doi.org/10.1016/j.foodres.2019.108552
11. Legaya, M., Le Persond, S., Gondrexona, N., Boldod, P., & Bontemps, A. (2012). Performances of two heat exchangers assisted by ultrasound. *Applied Thermal Engineering, 37*, 60-66. https://doi.org/10.1016/j.applthermaleng.2011.12.051
12. Klaren, D. G., & de Boer, E. F. (2012). Self-Cleaning Fluidized Bed Heat Exchangers for Severely Fouling Liquids and their Impact on Process Design. In J. Mitrovic (Ed.). *Heat Exchangers – Basic Design Applications*. Retrieved from http://www.intechopen.com/books/heatexchangers-basics-design-applications
13. Kieser, B., Goode, A., & Philion, R. (2019). *From practice-to-theory-to-practice: advances in the cleaning of heat exchangers using ultrasound*. Retrieved from https://www.researchgate.net/profile/Byron-Kieser-2/publication/336220952
14. Rädler, G. (2022). *Wärmetauscher instand halten: So durchbrechen Sie den Energie-Teufelskreis. Anlagenbau: Wärmetauscher instand halten: So durchbrechen Sie den Energie-Teufelskreis* [Maintaining heat exchangers: How to break the energy vicious circle. Plant engineering: Maintaining heat exchangers: How to break the energy vicious circle]. Retrieved from https://www.process.vogel.de/waermetauscher-instand-halten-so-durchbrechen-sie-den-energie-teufelskreis-a-bf5b5386bd64ba5ceaaaa9df2b5d0ab4/
15. Kastner, H. J. (2018). *Saving added shell and tube heat exchangers with economical effort and little ecological consequences*. ISBN 978-3-7011-8085-1.
16. Tayekenova, A. T., Akurpekova, A. K., & Tastemirova, A. T. (2023). Cleaning the heat exchanger pipes from salt deposit. *Practice of Anticorrosive Protection, 28*(1), 29-42. https://doi.org/10.31615/j.corros.prot.2023.107.1-4
17. Olczak, P., Kowalski, Z., Kulczycka, J., & Agnieszka, M. (2020). Eco-innovative method of cleaning heat exchangers from boiler scale. *Management and Production Engineering Review, 11*(1), 23-30. https://doi.org/10.24425/mper.2020.132940
18. James, L. (September 24, 2024). *Hydroblasting: Techniques, Applications, Benefits, Hazards & Controls*. Retrieved from https://hsenation.com/blog/hydroblasting-techniques-applications-benefits-hazards-controls/#what-is-hydroblasting
19. Chauke, N., Munonde, T., & Mketo, N. (2025). A critical review of the anti-biofouling properties of biogenic-based silver nanoparticles (AgNPs) embedded on polymer membranes for wastewater treatment. *Journal of Industrial and Engineering Chemistry, 149*(25), 209-232. https://doi.org/10.1016/j.jiec.2025.02.012
20. Kohli, R. (2019). Applications of Solid Carbon Dioxide (Dry Ice) Pellet Blasting for Removal of Surface Contaminants. *Developments in Surface Contamination and Cleaning: Applications of Cleaning Techniques, 11*, 117-169. https://doi.org/10.1016/B978-0-12-815577-6.00004-9
21. Pylypenko, O. V., & Dovgotko, N. I. (2015). Viktor Vasilyevich Pilipenko is an outstanding scientist in the field of mechanics. *Technical mechanics, 4*, 3-22.
22. *CPR – heat exchanger cleaning technology* (2025). Retrieved from https://imp-trade.com/cpr-en
23. Nikolayev, O., Zhulay, Yu., Kvasha, Yu, & Dzoz, N. (2020). Eval-

uation of the vibration accelerations of drill bit for the well rotative-vibration drilling using the cavitation hydrovibrator. *International Journal of Mining and Mineral Engineering, 11*(2), 102-120. https://doi.org/10.1504/ijmme.2020.108643

24. Kapustenko, P., JiE Kleme, J., & Arsenyeva, O. (2023). Plate heat exchangers fouling mitigation effects in heating of water solutions: a review. *Renewable and Sustainable Energy Reviews, 179*, 113283. https://doi.org/10.1016/j.rser.2023.113283

25. Nicoletti, C., Delfin, F., & Forsich, C. (2023). Barrier Properties Improvement of Biopolymers by Means of Bipolar Pulsed DC PACVD Coatings. *66th Society of Vacuum Coaters Annual Technical Conference*. https://doi.org/10.14332/svc23.proc.0044

26. Liu, Z., Hongtao Wang, H., Wang, Y., Tian, L., Li, H., Liu, W., He, P., Liu, H., & Li, R. (2023). Comparative study on the annealing of cold-sprayed boron nitride nanosheet/copper coating using spark plasma sintering and atmosphere furnace. *Surface and Coatings Technology, 453*, 129041. https://doi.org/10.1016/j.surfcoat.2022.129041

27. Augustin, W., & Bialuch, I. (2016). *Verbesserung des Fouling – und Reinigungs-verhaltens wärmeübertragender Flächen durch optimierte Oberflächenbeschichtung (Fortsetzungsantrag)*. [Improvement of fouling and cleaning behavior of heat transfer surfaces through optimized surface coating (continuation application)]. Retrieved from https://www.efds.org/wp-content/uploads/2016/05/IGF-06-01-Schlussbericht.pdf

28. Anwajler, B. (2024). Potential of 3D Printing for Heat Exchanger Heat Transfer Optimization – Sustainability Perspective. *Inventions, 9*(3), 60. https://doi.org/10.3390/inventions9030060

29. Peruchi da Silva, R. P., Muneeshwaran, M., Krishnan, E. N., Li, X., Nawaz, K., & Kim, H. J. (2025). Advances in high-pressure and high-temperature heat exchangers: Innovations via additive manufacturing and their applications. *Thermal Science and Engineering Progress, 65*, 2025. https://doi.org/10.1016/j.tsep.2025.103844

30. Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production, 137*, 1573-1587. https://doi.org/10.1016/j.jclepro.2016.04.150

31. Cheng, Z., Li, X., Xu, R., & Jiang, P. (2021). Investigations on porous media customized by triply periodic minimal surface: Heat transfer correlations and strength performance. *International Communications in Heat and Mass Transfer, 129*, 105713. https://doi.org/10.1016/j.icheatmasstransfer.2021.105713

32. Khalil, M., Hassan Ali, M. I., Khan, K. A., & Abu Al-Rub, R. (2022). Forced convection heat transfer in heat sinks with topologies based on triply periodic minimal surfaces. *Case Studies in Thermal Engineering, 38*, 102313.

Сучасний стан технологічних процесів очистки теплообмінників: перспективи й напрями досліджень

О. Д. Ніколаєв[*1], *Ю. О. Жулай*[2], *А. Ю. Лисенко*[3]

1 – Інститут технічної механіки Національної академії наук України і Державного космічного агентства України, м. Дніпро, Україна
2 – Інститут транспортних систем і технологій Національної академії наук України, м. Дніпро, Україна
3 – ТОВ «Компанія Імпорт Трейд», м. Київ, Україна
*Автор-кореспондент e-mail: nikolaev.o.d@nas.gov.ua

Пластинчасті й кожухотрубчасті теплообмінники широко використовуються в хімічній, харчовій промисловості, а також в атомній і тепловій енергетиці. Фізичні й хімічні процеси, такі як седиментація, кристалізація, хімічні реакції, корозія, біонаростання, що мають місце в теплообмінниках, знижують швидкість теплопередачі. Утворення твердих відкладень і засмічення їхніх внутрішніх трубок є надзвичайно критичним фактором для промислового виробництва, що може призводити до безпрецедентних фінансових збитків.

Мета. Визначення найбільш перспективних напрямів розробки методів очищення кожухотрубних теплообмінників для атомних, теплових електростанцій та інших промислових застосувань на основі визначення сучасного стану технологічних процесів із високопродуктивного очищення забруднених теплообмінників.

Методика. Заснована на вивченні теоретичних і експериментальних даних, отриманих при розробці методів очищення внутрішніх поверхонь теплообмінників, і представлених у джерелах науково-технічної інформації.

Результати. Представлені за допомогою порівняння сутності технологічних процесів та ефективності методів очищення внутрішніх поверхонь теплообмінників, а також оцінок впливу деяких покриттів для збільшення термінів експлуатації внутрішніх трубопроводів.

Наукова новизна. Проведений аналіз методів очищення внутрішніх поверхонь теплообмінників, а також впливу покриттів для збільшення строків експлуатації внутрішніх трубопроводів, дозволив:

- виявити прогресивні технології очищення забруднених теплообмінників, що використовуються в енергетиці й різних галузях промисловості;
- установити методи визначення ефективності нових і тих, що вже зарекомендували себе технологій, наприклад, ультразвукових коливань рідини, що очищає;
- узагальнити оцінки ступеня впливу різних процесів (хімічних і вібраційних) на якість очищення поверхні труб теплообмінників.

Практична значимість. Порівняльний аналіз ефективності потенційних наукових напрямів по вдосконаленню методів очищення теплообмінників дозволяє вибрати найбільш перспективні з них для рішення практичних завдань зі вдосконалення технологій очищення конкретних конструкцій теплообмінників.

Ключові слова: *кожухотрубчастий теплообмінник, очищення поверхні трубопроводів, швидкість теплопередачі, кавітаційні коливання*

The manuscript was submitted 24.08.25.