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# ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

# OPTIMIZATION OF THE EFFICIENCY OF MARINE HEAT EXCHANGERS

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|---|---|
| Specialty: | 3319.01— « Shipping techniques » |
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# GENERAL CHARACTERISTICS OF THE WORK

**Relevance of the topic and the degree of development.** Marine Heat Exchangers (MHE) are devices that facilitate heat transfer from one medium (the heat-donating fluid) to another (the heat-receiving fluid). The operational conditions of these exchangers depend on several factors, including the type of fluids used, their temperature, pressure, flow rates, and the specific design of the heat exchanger. Given these factors, the thermal efficiency of MHEs is a key performance indicator that determines how effectively heat is transferred between the media.

The main challenges in the design and operation of marine MHEs include corrosion and scale formation on the inner surfaces of tubes, as well as the optimal design and arrangement of baffles in the tube bundle. Various solutions have been proposed to address these issues. Notably, corrosion and scale buildup can deteriorate the technological performance of MHEs by 40–50%, causing significant difficulties in heating or cooling the working fluids. Additionally, a major drawback of existing MHE designs with different types of transverse baffles is the inefficient heat exchange on the tube surfaces within the tube bundle and the substantial energy losses in the shell-side flow.

The optimization of technological processes, the design of transverse baffles, and the thermal strength of the tube bundle represent significant scientific and technical challenges. These issues form the core research focus of this dissertation.

**Object and subject of research:** The object of study in this dissertation is the use of heat exchanger tubes of various diameters and wall thicknesses, the application of threading on the outer surface, and the coating of the inner surface with a silicate layer. An experimental tube-in-tube heat exchanger setup was designed and assembled. Taking into account the technological parameters of the working fluids in marine heat exchangers, this setup fully replicates the operation of a heat exchanger under laboratory conditions.

**The purpose and objective of the study.** The objective of the dissertation is to improve the efficiency of the heat exchange process and optimize the design of the transverse baffle in the shell-side space of the tube bundle in a marine heat exchanger (MHE). It is evident that seawater, flowing along the inner surface of the tube in the required stationary mode over time, ensures the distribution of heat transfer, thermal conductivity, and temperature field along the entire length of the tube up to the outlet, as well as complete heat exchange with the heated or cooled fluids between the tubes of the tube bundle in the MHE.

In accordance with the need to optimize the structural and technological parameters of the thermal process in the tube bundle of the MHE, the main research tasks of this work are:

1. Optimization of structural parameters, geometric shapes, and the placement of the transverse baffle in the tube bundle of the MHE.
2. Optimization of corrosion formation, scale buildup, and heat exchange processes in the heat exchanger tubes of the tube bundle.
3. Investigation of thermal strength and vibration in a bundle composed of internally silicate-coated tubes and externally threaded tubes with triangular transverse baffles.
4. Implementation of research results and economic efficiency assessment of a bundle composed of internally silicate-coated tubes and externally threaded tubes with triangular transverse baffles in the MHE.

To achieve these objectives, an experimental setup was developed, along with a triangular baffle design for a tube bundle with externally threaded tubes and internally silicate-coated surfaces, in accordance with high technological standards.

**Research methods:** Modern methods for optimizing the structural dimensions and technological parameters of heat exchangers have been applied in the dissertation. A study was conducted to determine the optimal geometric shape and placement of the triangular baffle structure within the apparatus. An experimental setup was developed to investigate the optimization of heat exchange processes in the tube bundle of a marine heat exchanger (MHE). The research results include studies on vibration methods, thermal strength, and adhesive strength of the silicate coating on the tube bundle of the heat exchanger. The reliability of the theoretical and experimental results has been confirmed in laboratory and industrial conditions at thermal power plants (TPPs) and marine heat exchangers (MHEs).

The research findings can be applied in enterprises related to heat supply, shipbuilding, oil refining, and thermal power stations (TPPs).

**The main provisions submitted for defense:**

1.Comparison of the efficiency of heat exchanger designs with segmental and helical baffles.

2.Comparison of the efficiency of heat exchanger designs with segmental and triangular baffles and externally threaded tubes.

3.Comparison of the efficiency of heat exchanger designs with helical and triangular baffles and triangular threaded tubes.

4.Optimization of corrosion processes in silicate coatings on externally threaded tubes.

5.Optimization of scale deposition on the inner surface of silicate-coated, externally threaded heat exchanger tubes.

6.Optimization of heat transfer and thermal conductivity in the heat exchanger tubes of the MHE tube bundle.

7.Optimization of the heat transfer coefficient parameters in silicate coatings on externally threaded tubes.

8.Vibration analysis of externally threaded tubes with triangular baffles in the tube bundle of the heat exchanger.

9.Thermal and adhesive strength of externally threaded tubes with silicate coatings in the tube bundle.

10. Implementation results of heat exchanger tubes with triangular baffles in marine power plants.

11.Preliminary economic effect of implementing externally threaded tubes with internal silicate coatings in MHEs.

**Scientific novelty of the work.** The optimization of the structural parameters, geometric shape, and placement of the transverse baffle in the tube bundle of marine heat exchangers (MHE) has been conducted. A triangular cross-section transverse baffle design for the tube bundle of MHEs has been proposed. It has been established that triangular transverse baffles, compared to segmental and helical baffles, enhance heat exchange efficiency within the tube bundle while also leading to significant hydraulic losses in the shell-side flow of the heat exchanger. The threading of the outer surface of heat exchanger tubes has been presented, with three types of threaded tubes considered: rectangular, triangular, and symmetrical trapezoidal. It has been found that increasing the outer contact surface of the tube allows the cooling fluid to cover a larger area, enhancing heat transfer and ensuring greater contact between the liquid and the tube wall.

The optimization of operational parameters for the technological processes within the tube bundle has been presented. The optimization of corrosion resistance, scale formation, heat transfer, and thermal conductivity of silicate coatings on heat exchanger tubes has been achieved.

Indicators of efficiency and practical application of the optimized tube bundle design for MHEs have been provided. A vibrational analysis and stress assessment of threaded silicate-coated tubes have been conducted, along with an economic evaluation and the potential for implementing tube bundles with external threading and internal silicate coatings with triangular baffles.

**Practical and theoretical value of the research.** Taking into account the developed theoretical and experimental studies, an experimental apparatus was manufactured from external threaded and internal silicate coatings of pipes with triangular baffles. Industrial tasks were set to obtain reliable results. A marine heat exchange apparatus from external threaded and internal silicate coatings of tubes with triangular baffles is presented for industrial implementation on vessels.

**Testing and Implementation of Research Results.** The scientific developments and technical solutions presented in this dissertation are recommended for wide application in heat exchangers used in the ships of the Caspian Shipping Company of the Republic of Azerbaijan. The materials of the dissertation have been reported, discussed, and approved at:

- Materials of the first international scientific and practical conference «Problems of sustainable development of the marine industry», November 3-5, 2021, Kherson, Ukraine.

- Proceedings of international and scientific conference on “prospects of innovative development of technical and natural sciences” , November 25-26, 2021, Baku, Azerbaijan.

-“ Proceedings of international scientific and technical conference "modern problems and development outlooks of power engineering" (November 17-18, 2022, Baku, Azerbaijan).

- "Scientific Seminar of the Department of Applied Mechanics at Azerbaijan State Maritime Academy, May 12, 2022.

- II-International scientific and practical conference “Science in modern society” July 18-19, Beijing, China 2023.

-“Republic Scientific Conference of Energy Specialties”, November 17–18. ASMA-Baku-2023.

-“ Scientific herald the Academy of the Ministry of Emergency Situations. Baku-September-2023.

-“Problems of energy and sources saving” International conference– Uzbekistan.Tashkent - 2024.

-“ 27th National Scientific Conference of Doctoral Students and Young Researchers (NASCO XXVII), December 10–11, 2024.

**Name of the organization where the dissertation was conducted.** The dissertation was carried out at the Azerbaijan State Maritime Academy and the Zykh Ship Repair and Construction Plant of the Caspian Shipping Company.

**Personal Contribution of the Candidate.** The optimization of structural parameters, geometric shape, and placement of the transverse baffle in the tube bundle of the heat exchanger, as well as the obtained results, were performed exclusively by the author. The experimental research, analysis of experimental results, calculation of economic efficiency, presentation at scientific conferences, and the preparation of scientific articles based on the obtained results were also carried out by the author.

**Structure and Volume of the Dissertation.** The dissertation consists of an introduction, four chapters, conclusions and recommendations, a list of references (115 sources), and additional appendices. The structure of the dissertation includes: title page: (348 characters), table of contents (1,897 characters), introduction (13,107 characters), Chapter I- (36,083 characters), Chapter II- (43,140 characters), Chapter III- (46,083 characters), Chapter IV- (67,911 characters), main conclusions: (3,596 characters), list of references: (18,294 characters), appendices: (15,200 characters), the total volume of the dissertation consists of 200,406 characters (excluding images, tables, appendices, and references). The work is presented on 187 pages of computer-typed text and contains 39 figures, 18 tables, and 16 graphs.

**Publications on the topic of the research.** The main results of the dissertation were obtained by the author and have been fully published in 8 articles (2 single-authored, 2 indexed in international databases) and 6 conference materials (2 presented abroad). Additionally, a patent application has received a positive decision for issuance in the Republic of Azerbaijan.

## MAIN CONTENT OF THE WORK

**The introduction** substantiates the relevance of the research topic, defines the objective, tasks, object, subject, and research methods, and outlines the main provisions to be defended, scientific novelty, practical value, and implementation of results. Additionally, it presents the testing of the research findings, the structure and volume of the dissertation, and publications related to the dissertation topic.

**In the first chapter**, a literature review on the optimization of the thermal efficiency of marine heat exchangers is conducted. The operating conditions of marine heat exchangers (MHEs) are analyzed in relation to heat transfer processes and hydraulic characteristics, depending on the structural parameters of the tube bundle. The results demonstrating the enhancement of thermal efficiency in MHEs are presented.

It has been established that heat transfer and hydraulic processes occurring in the shell-side flow mainly depend on the design and arrangement of the transverse baffle in the tube bundle of the heat exchanger. The heat transfer performance of the tube bundle is significantly influenced by the design, geometric dimensions, and positioning of the transverse baffle.

The thermal efficiency of marine heat exchangers is a key performance indicator, determining how effectively heat is transferred from one medium to another.

It is proposed to use the thermal efficiency of the apparatus as a basis for comparison, which can be evaluated as follows:

$$TE = \frac{\delta t}{\Delta t} = f\left(\frac{KF}{\varepsilon_{\min}};\frac{\varepsilon_{\min}}{\varepsilon_{\max}}\right) \tag{1}$$

where $\delta t$ — temperature change of the coolant with a smaller water equivalent, ºC; $K$ — heat transfer coefficient, $W / m^2 \cdot K$; $F$ — heat exchange surface area, $m^2$; $\Delta t$ — temperature difference in the heat exchanger.

When designing heat exchangers and using charts for evaluating thermal efficiency $\Delta t$ under different coolant flow schemes, errors are allowed. The calculations can be tedious and cumbersome, as the designer has to perform many successive approximations [34][1].

In most cases, the deposition of scale and corrosion products is most intense on the internal surface of the heat exchanger tubes, resulting from contact with seawater, which operates in a wide range of temperatures, pressures, and velocities. Experimental studies have shown that the rates of corrosion processes occurring on the heat transfer surface depend on heat transfer conditions. However, when solving technical problems related to the selection of materials for the apparatus and optimizing their operational modes, it is essential to know the corrosion rate of the metal tubes in specific heat exchange conditions. It is important to understand the trend of changes in this value influenced by factors that reflect the operating conditions of the apparatus.

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[1] .Ладанов К. И. Обобщенные методы теплового расчета кожух-трубных теплообменников-рекуператоров/ К. И. Ладонов // Альтернативная энергетика и экология. — 2013. — № 15 (137). — С. 17–28.

Sometimes, the rate of growth of such deposits of corrosion products and scale reaches 1.0-3.0 mm/year, which significantly reduces the heat transfer coefficient and decreases the cross-sectional area of the tubes, thereby reducing the flow of circulating water. Both of these factors disrupt the normal operating conditions of heat exchange equipment [20][2], [36][3].

The baffle, as one of the key components of the heat exchanger (STX), strongly influences the fluid parameters related to the assessment of efficiency in the inter-tube space. To improve the state of the baffle, as one of the main components (STX), it greatly impacts fluid parameters associated with the efficiency assessment in the inter-tube space.

The crossflow is characterized by greater turbulence and higher heat extraction for the same heat transfer surface area compared to parallel flow and laminar flow regimes. Cross-sectional baffles, despite the application of all advanced methods to improve hydraulic characteristics (KTA) with a segmental baffle, still have drawbacks, such as clogging in stagnant zones, vibration caused by flow through the tube bundle, and high pressure drop in the inter-tube space.

In accordance with the need to change the technological parameters of the tube bundle of marine heat exchangers, the main research focus is the optimization of the structural parameters, geometrical shape, and placement of the transverse baffle in the tube bundles of marine heat exchangers [39][4].

**In the second chapter**, a study is conducted on the optimization of the structural parameters of the tube bundle in the heat exchanger.

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[2] Ибрагимов Н.Ю. Исследование накипи образования и коррозионно-механического изнашивания эмалированных покрытий труб тепло-энергетических установок //Промышленная энергетика, 2005, №12, с. 33-35.

[3].Макаров В. В. Анализ тепловой эффективности судовых теплообменных аппаратов / В. В. Макаров, А. Р. Алтаев // Энергомашиностроение. — 2006. — № 1. — С. 48–50.

[4] Светлов Ю.В. Интенсификация гидромеханических и тепловых процессов в аппаратах теплоснабжения / Ю.В. Светлов. – М.: Энерго атомиздат, 2003. – 304 с.

Various types of construction and characteristics of the transverse baffle in the tube bundle of the apparatus are presented. Optimization and comparative characteristics of the structural parameters, geometrical shape, and placement of the transverse baffle in the tube bundle of the heat exchanger are discussed.

The drawback of using STHE with segmental transverse baffles is the inefficient heat exchange on the tube surfaces and the occurrence of significant hydraulic losses in the inter-tube space of the tube bundle. Stagnation zones form behind the segmental baffles for the cooled viscous fluid, which leads to poor heat exchange and the intense formation of scale deposits and corrosion products. To address the aforementioned issues, Luch and Nemansky proposed a helical flow in 1999 as an alternative to the zigzag flow in heat exchangers with segmental baffles. However, flow leakage in this zone, formed by adjacent baffles, can lead to a short circuit effect and reverse flow, which significantly impacts the reduction of heat exchange in the inter-tube space.

Unlike these drawbacks, as a novelty, a new design of a shell-and-tube heat exchanger with a combined triangular-helical baffle is proposed in Figure 1, and the performance evaluation criteria (PEC) is compared with all other types of baffles in Figure 2.

Figure 3 shows the dependence of the efficiency evaluation coefficient (EEC) on the mass flow rate m for three different designs: TB-SHTX, SB-SHTX and HSTB-STHX.

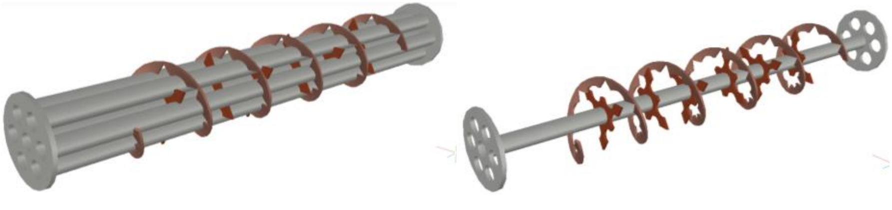

**Figure 1. The tube bundle for a shell-and-tube heat exchanger with a hybrid triangular-helical baffle (HTHB-STHX)**

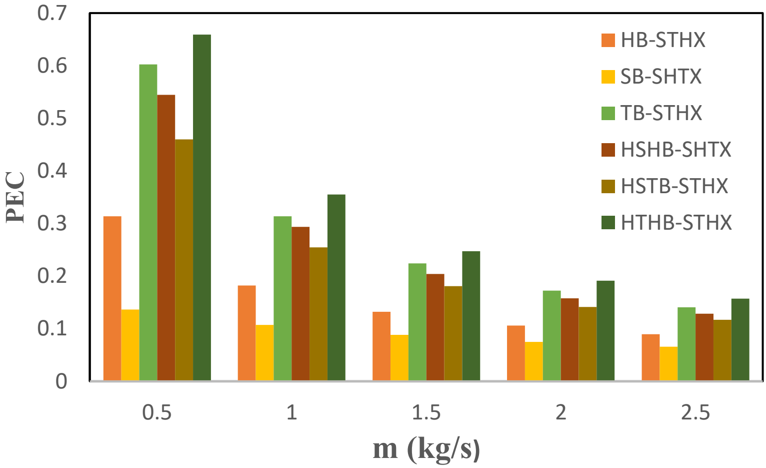

**Figure 2. Values of the PEC for different types of STHX with mass flow rates**

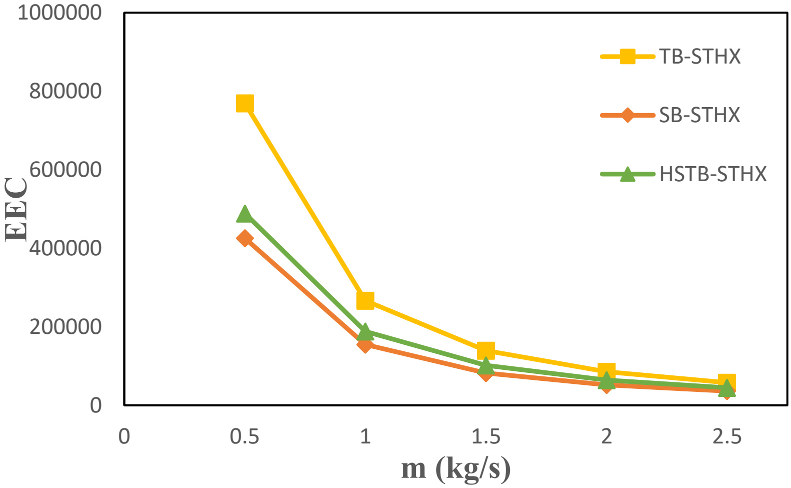

**Figure 3. Comparison of efficiency evaluation coefficient from mass flow rate for TB-SHTX, SB-SHTX and HSTB-STHX**

At low mass flow rates (m=0.5 kg/s), the lowest value of the efficiency evaluation coefficient is demonstrated by, HSTB-STHX has a 20–25% higher efficiency rating than SB-STHX. TB-STHX shows maximum efficiency, exceeding SB-STHX by 40–50%. The efficiency evaluation coefficient (EEC) is determined by [71][5].

$$EEC = \frac{Q_1 / Q_0}{P_1 / P_0} \tag{2}$$

where $P$ and $Q$ are the values of power consumption and heat transfer rate in the device under study, respectively; subscripts 1 and 0 represent the new model (HSTB-STHX) and the base model (SB-STHX).

The proposed triangular design stands out by ensuring uniform temperature distribution for cooling (or heating) and reducing hydraulic losses while minimizing the surface area of the heat exchanger’s tube bundle.

The triangular baffle design in the shell-side flow significantly enhances the thermal efficiency of the tube bundle's surface and improves the techno-economic performance of marine heat exchangers operating with seawater.

Figure 4 illustrates the flow streamlines for a heat exchanger with a triangular baffle (TB-STHX). The proposed new shell-and-tube heat exchanger is equipped with triangular baffles, which redirect the flow of the working fluid inside the shell. These baffles cause multiple flow direction changes, increasing turbulence and enhancing heat transfer between the working fluids.

The fluid enters through the inlet nozzle at the top of the shell, where its initial distribution occurs. In this zone, higher velocity regions (green areas) indicate concentrated flow before passing through the first baffle. Inside the shell, the flow passes through multiple baffles, creating alternating zones of acceleration and deceleration of the fluid.

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[5] Dong QW, Wang YQ, Liu MS (2008) Numerical and experimental investigation of shell-side characteristics for ROD baffle heat exchanger. Appl Therm Eng 28(7):651–66

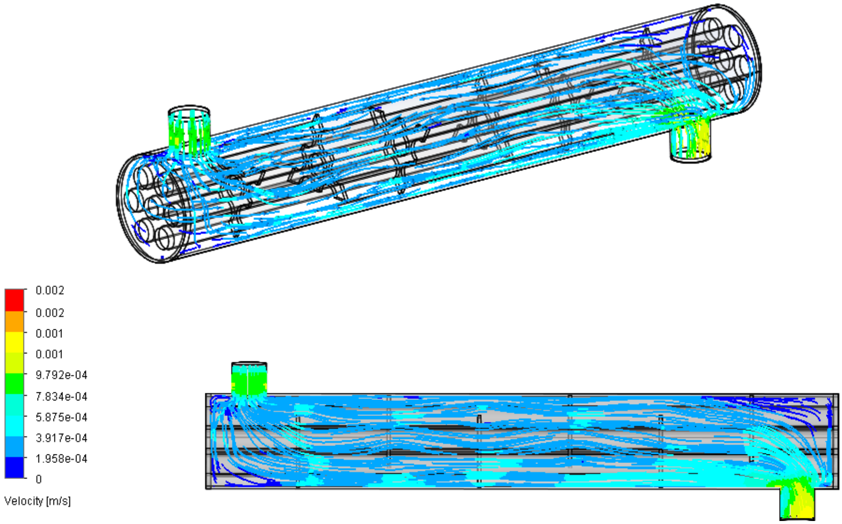

**Figure 4. Flow paths in a shell and tube heat exchanger with triangular baffles (TB-STHX).**

Acceleration zones (green and yellow regions) occur in narrow passages between the baffles, where the fluid is forced to change direction.

Deceleration zones (blue regions) are found in more open spaces, where the flow is less intense.

The fluid exits through the outlet nozzle at the bottom of the device, where velocity redistribution occurs, making the flow more uniform before leaving the system. The color scale in the image shows the distribution of flow velocities in m/s. Maximum velocities (~0.002 m/s, red and yellow colors) are recorded in narrow channels between the baffles, where local acceleration of the flow occurs. Medium velocities (~0.001 m/s, green and light blue colors) are observed in active flow zones. Minimum velocities (~0–0.0002 m/s, blue areas) are characteristic of stagnant flow zones, where there is a significant decrease in fluid movement intensity.

The use of triangular baffles effectively distributes the flow within the shell side of the heat exchanger, increasing turbulence and reducing the likelihood of stagnant zones.

There is a significant redistribution of velocities in the inlet and outlet areas, which is important to consider when designing the structure to minimize hydrodynamic losses.

Low-velocity zones (blue areas) may indicate potential deposition areas or deterioration of heat transfer, requiring further analysis for structural optimization.

Thus, the presented simulation results confirm that the use of triangular baffles contributes to increased heat exchange efficiency due to enhanced turbulence in the flow.

Optimizing the baffle design can help improve velocity distribution and minimize hydrodynamic losses.

According to the obtained results, in all three directions, the flow passes uniformly over the wetted surfaces of the tubes, ensuring improved heat transfer in this proposed new design.

The temperature distribution in the shell-side of the shell-and-tube heat exchanger (STHX) depends on many factors, such as the design of the apparatus, operating mode, properties of the heat transfer fluids, and their flow rates.

In the shell-side, the temperature changes along the length of the heat exchanger.

If the heat transfer fluid in the shell-side space is being heated, its temperature will increase from inlet to outlet.

If the heat transfer fluid is being cooled, its temperature will decrease from inlet to outlet.

Temperature distribution also depends on flow velocity, heat capacity, and thermal conductivity of the heat transfer fluid.

Based on the obtained data, after simulation, a detailed comparison of different STHX configurations can be conducted to determine which one is the most efficient in terms of temperature distribution and heat exchange. Each configuration will be examined separately and compared with one another.

Figure 5 presents the temperature distribution for STHX with different types of baffles in the temperature range from 300 to 450 K.

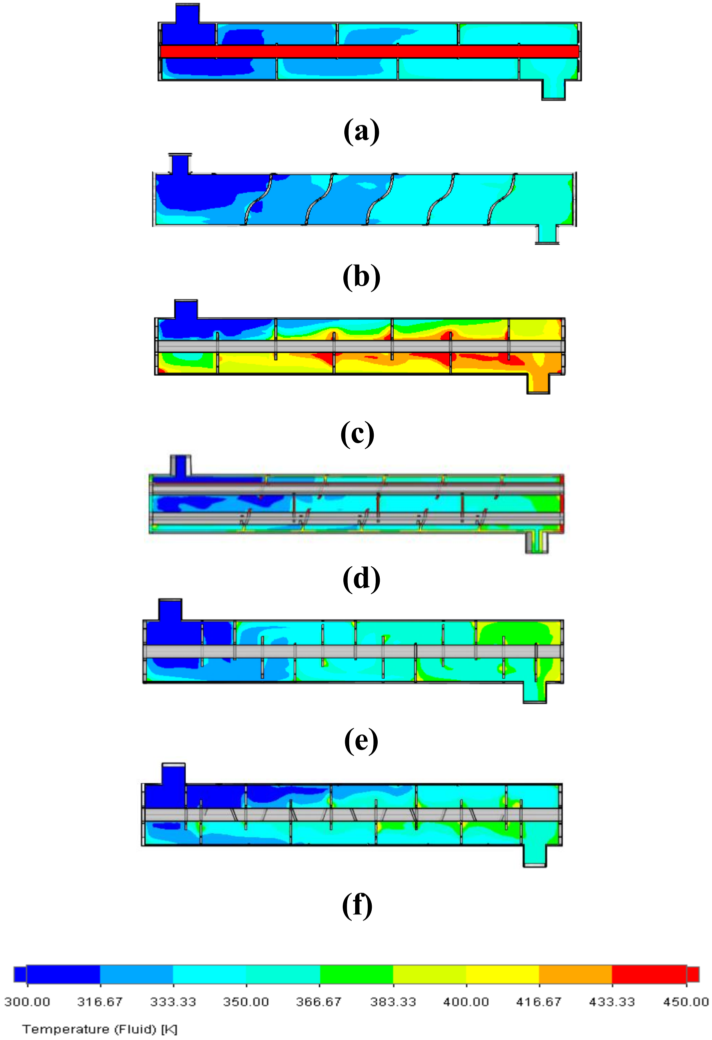

**Figure 5. Temperature distribution in the shell side for different types of STHX;**

a) segmental baffles (SB-SHTX), b) helical baffles (HB-STHX); c) triangular baffles (TB-STHX); d) hybrid segmental-helical baffles (HSHB-STHX); e) hybrid segmental-triangular baffles (HSTB-STHX); f) hybrid triangular-helical baffles (HTHB-STHX)

Segmental baffles (SB-STHX) (Figure 5a) provide good flow distribution and uniform heat transfer. However, they may create zones with reduced turbulence, which can decrease heat transfer efficiency in certain areas.

The highest heat exchange efficiency is observed in hybrid baffles: triangular-helical (HTHB-STHX) (Figure 5e) and segmental-helical (HSHB-STHX) (Figure 5g). They ensure uniform temperature distribution and intense flow movement, which enhances turbulence and improves heat transfer.

Helical baffles (HB-STHX) (Figure 5b) also demonstrate high efficiency but may cause increased hydraulic losses.

Segmental and triangular baffles (TB-STHX) provide uniform temperature distribution but are less effective in generating turbulence. For maximum heat transfer efficiency, it is recommended to use hybrid baffles: triangular-helical (HTHB-STHX) or segmental-helical (HSHB-STHX).

If structural simplicity and minimal hydraulic losses are a priority, segmental or triangular baffles can be considered.

Further research may focus on optimizing hybrid baffles to reduce pressure drops and simplify design.

**Chapter three** presents the optimization of operational parameters in the technological processes of the tube bundle in the STHX. Corrosion and scale formation protection for metallic components, primarily heat exchanger tubes, is one of the most significant scientific and technical challenges. The service life of bundle of heat exchanger tubes made from MNZh-5-1 alloy, when cooled by Caspian Sea water, can be estimated at 2–3 years, with a maximum failure rate of 30% to 50% of the tubes during this period.

One of the most versatile solutions is a silicate coating. A silicate coating is a firmly bonded inorganic glass-like layer on metal. It exhibits high resistance to erosion wear and corrosion. Silicate coating can be effectively used to improve the hydraulic characteristics of tubes, enhance heat transfer, reduce hydraulic resistance, and prevent deposits on the inner walls of small-diameter heat exchanger tubes.

An experimental setup was developed to study corrosion processes, scale formation, and thermal processes on the inner surfaces of silicate coatings and metallic heat exchanger tubes.

Figure 6 shows that the experimental setup consists of the following elements: 1 – condensation tube, 2 – sight glass, 3 – heat exchanger housing, 4 – silicate-threaded heat exchanger tube, 5 – outlet pipe for diesel oil, 6 – gland connection, 7 – rubber and plastic gaskets, 8 – round nut, 9 – seawater outlet, 10 – seawater inlet, 11 – diesel oil inlet pipe, 12 – tube sheet mounting.

The most common contaminants include sodium chlorides and sulfates, which generally reduce the durability of protective tube coatings, leading to an increased corrosion rate of the tube coatings. The study was conducted at pH values ranging from 2 to 10, with a fluid velocity of $v$ = 0.2–1.2 m/s, which corresponds to typical conditions in thermal power plants (TPPs) and ship energy units (SEUs).

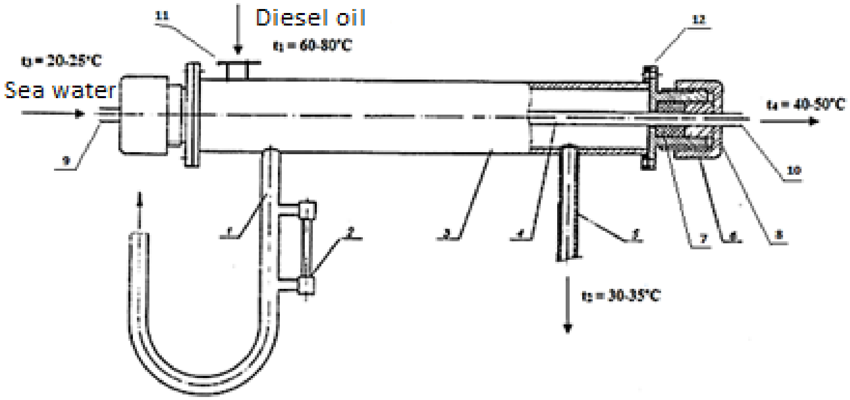

**Figure 6. Experimental setup for studying corrosion and thermal processes of heat exchange tube**

The following grades of silicate coatings, commonly used in TPPs and SEUs, were selected for experimental research: SEP-13V, SEP-AB-1, SEP-S-52-1, and SEP-S-89. To determine the rate of scale and corrosion product formation on the silicate coating, known volumetric and gravimetric methods were used. The calculation was performed using the formula:

$$S_i = \frac{V_{2i} - V_{1i}}{L_i} \qquad (3)$$

Where $V_{2i}, V_{1i}$ - internal volumes of tubes before and after testing; $L_i$ - length of pipe sections; $i = 1, 2$—index corresponding to vitrified and metal pipe samples.

$$K = (m_2 - m_1) / F \cdot \tau, \ \left(g / m^2 h\right) \qquad (4)$$

where $m_1$, $m_2$ $(g)$– respectively, the mass of silicate coatings of tubes before and after long-term testing; $F$ – $(m^2)$ inner surface of the silicate tube coating; τ – duration of tests (5–45 days).

The test samples used in the experiments were tubes with a length of L = 1.0–1.5 m, with the following diameters and wall thicknesses: 22 mm (2.0 mm wall thickness), 25 mm (2.5 mm wall thickness), 32 mm (4.0 mm wall thickness), and 57 mm (3.5 mm wall thickness). The velocity of seawater V during the experiments ranged from 0.2 to 2.0 m/s, and the temperature difference of the water ΔT varied between 15 and 35°C. Figures 7 and 8 present the results of studies on the rate of corrosion processes and scale formation depending on the velocity of seawater.

Experimental studies have shown that during prolonged operation of the heat exchanger, only minor scale deposits are observed on the surface of the silicate-coated tubes, with a thickness ranging from 0.14 to 0.42 mm. In contrast, a dense layer of scale with a thickness of 1.24 to 1.98 mm forms on the metallic surfaces of the tubes. The near absence of deposits on the glass-coated surfaces of the tubes is explained by the high smoothness of the coating surface and its resistance to the aggressiveness of substances dissolved in seawater.

The amount of scale formed is so minimal that it is washed away by the flow of seawater.

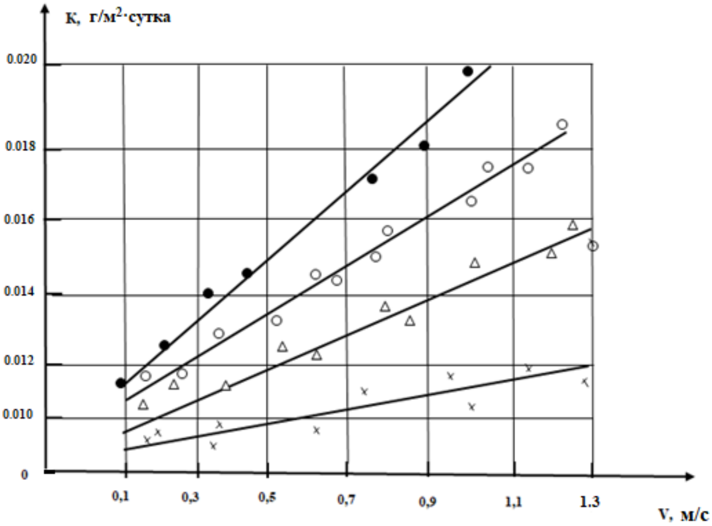

**Figure 7. Dependence of the corrosion rate of silicate pipe coatings on the velocity of sea water designation:**
× – SEP-13V; o –SEP- S89; Δ – SEP-S-52-1; ● – SEP-AB-1

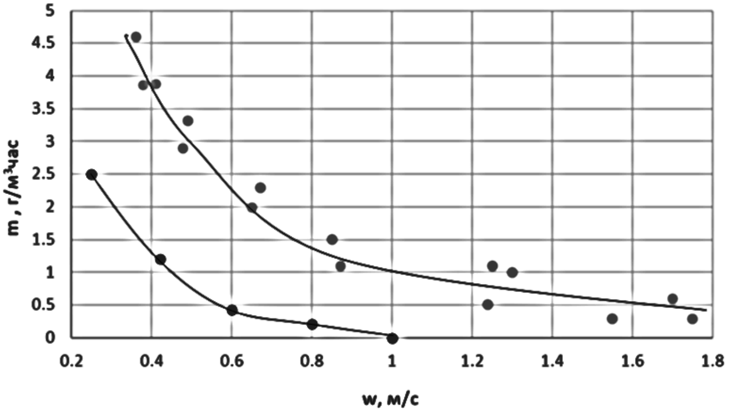

**Figure 8. Scale formation depending on the speed of sea water.**
1-scale of copper tubes, 2-silicate coating of the tube

To increase the external surface area of the tube bundle in the heat exchanger, cylindrical threads are cut with triangular, rectangular, and trapezoidal symmetric profiles across the entire surface of all the tubes in the heat exchanger.

The external surface area of a tube with a triangular thread is determined by:

$$F_{\max} = 2\pi d_2 \frac{d_2 - d_1}{\cos\beta} n \tag{5}$$

Where β is the thread lead angle, i.e., the angle formed between the tangent to the thread line at a point on the mean diameter of the thread and a plane perpendicular to the axis of the threaded pipe, $d_2$ is the outer diameter, and $d_1$ is the inner diameter of the threaded pipe.

Similarly, the optimal surfaces of rectangular and trapezoidal threaded heat exchanger tubes can be determined. The ratio of the heat exchange surface area with and without threading is as follows:

For a triangular-threaded tube 1.5 times, For a rectangular-threaded tube 2.0 times and for a trapezoidal-threaded tube 2.75 times compared to the smooth surface of heat exchanger tubes.

The study of heat transfer optimization is associated with determining the heat transfer coefficients of silicate-coated and metallic heat exchanger tubes as follows: [76][6]

For metal tube:

$$K_1 = \frac{1}{\frac{1}{d_н \cdot \alpha_1} + \frac{1}{2\lambda_м} \ln \frac{d_н}{d} + \frac{1}{d \cdot \alpha_2}} \tag{6}$$

For silicate tube:

$$K_2 = \frac{1}{\frac{1}{d_н \cdot \alpha_1} + \frac{1}{2\lambda_м} \ln \frac{d_н}{d} + \frac{1}{2\lambda_с} \ln \frac{d}{d_в} + \frac{1}{d_в \cdot \alpha_3}} \tag{7}$$

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[6] E.N. Ibrahimli. Strength of Silicate-Enamel Coating of Heat Exchanger Pipe. Herald of the Azerbaijan Engineering Academy 2023, vol. 15, no. 4, pp. 21-25.

where $\alpha_1, \alpha_2, \alpha_3$ - the heat transfer coefficients correspond to the following: from the heat carrier to the outer surface of the metal tubes, from the inner surface of the metallic tube to the outer surface of the glass coating, from the inner surface of the glass coating to the seawater in glass-coated heat exchanger tubes; $d_в, d_н, d$ - the inner diameter of the glass coating, the outer and inner diameters of the metal pipe, respectively; $\lambda_м, \lambda_с$ - thermal conductivity coefficients of metal and glass tube coatings.

To optimize the parameters of the heat transfer coefficient, using the expression for the linear heat transfer coefficient in the presence of a silicate coating of the heat exchange tube, we differentiate it $(d_в)$ and $(d_н)$ separately and equate it to zero in order to find the extremum. Differentiating expression (7) by the internal diameter of the silicate coating, we have. [79][7]

$$\frac{dK_2}{dd_b} = \frac{1}{\frac{1}{d_н \cdot \alpha_1} + \frac{1}{2\lambda_м}\ln\frac{d_н}{d} + \frac{1}{2\lambda_с}\ln\frac{d}{d_в} + \frac{1}{d_в \cdot \alpha_3}} = 0 \qquad (8)$$

We will obtain:

$$\frac{\frac{1}{2\lambda_с d_в} - \frac{1}{d_в{}^2 \cdot \alpha_3}}{\frac{1}{d_н \cdot \alpha_1} + \frac{1}{2\lambda_м}\ln\frac{d_н}{d} + \frac{1}{2\lambda_с}\ln\frac{d}{d_в} + \frac{1}{d_в \alpha_3}} = 0 \qquad (9)$$

Here:

$$\frac{1}{2\lambda_с d_в} - \frac{1}{d_в^2 \alpha_3} = 0 \qquad (10)$$

The solution of equation $(10)$ gives the maximum value of heat transfer of the inner surface of the tube coating in the following form:

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[7] Ibragimov N.Yu. Heat Resistance and Strength of the Silicate Coating of Pipe //Chemical and Petroleum Engineering, vol.52, Nas.1-2 may, 2016 P.126-129.

$$\alpha_3^{\max} = \frac{\lambda_c^{max}}{d_в^{onm}} \qquad (11)$$

where - $\lambda_c^{\max}$ maximum value of the thermal conductivity coefficient of the tube, $d_в^{onm}$ - optimal value of the internal diameter of the pipe coating.

Also, differentiating expression (8) by the outer diameter of the metal tube, we have: [34][8]

$$\frac{\dfrac{1}{2\lambda_м d_н} - \dfrac{1}{d_н^{\,2}\cdot\alpha_3}}{\dfrac{1}{d_н\cdot\alpha_1} + \dfrac{1}{2\lambda_м}\ln\dfrac{d_н}{d} + \dfrac{1}{2\lambda_c}\ln\dfrac{d}{d_в} + \dfrac{1}{d_в\alpha_3}} = 0 \qquad (12)$$

From here we finally have the following form

$$\alpha_1^{\max} = \frac{\lambda_м^{max}}{d_н^{onm}} \qquad (13)$$

By solving equation (13) one can determine the maximum value of heat transfer of the outer surface of a metal tube.

Here - $\lambda_м^{max}$ maximum value of the thermal conductivity coefficient of the tube, $d_н^{onm}$ - optimal value of the outer diameter of a metal tube.

In connection with the smooth surface of the experiments, the influence of operational factors on the heat transfer coefficient during the deposition of salts on the internal surfaces of smooth silicate tube coatings was investigated. Table 1 shows the results of the study of heat transfer of silicate coatings and metal heat exchange tubes.

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[8] Луданов К. И. Обобщенные методы теплового расчета кожухотрубных теплообменников-рекуператоров / К. И. Луданов // Альтернативная энергетика и экология. — 2013. — № 6-с.13-16

**Table 1**

**Heat transfer coefficient in silicate coatings and metal tubes with dimensions of Ø22x2.0 mm, industrial coating grade SEP-S-89**

| Temperature , $^0$C | Speed of movement , m/s | | Heat transfer coefficient | |
|---|---|---|---|---|
| | Cooling water | Cooled oil | Tube coatings, W/m$^2$ $^0$C | Metal tube, W/m$^2$ $^0$C |
| 12 | 0,40 | 0,05 | 1210 | 1260 |
| 14 | 0,45 | 0,10 | 1321 | 1365 |
| 17 | 0,50 | 0,15 | 1380 | 1420 |
| 19 | 0,55 | 0,20 | 1456 | 1470 |
| 21 | 0,60 | 0,25 | 1484 | 1520 |
| 23 | 0,65 | 0,30 | 1491 | 1530 |

The greater the flow velocity of seawater, the more likely it is that sediments will be subject to periodic removal as a result of the shear force of viscoelastic seawater.

**The fourth chapter** discusses the optimization of the efficiency of implementing heat exchanger tubes with external threading and internal silicate coatings, using triangular baffles in the tube bundle of the apparatus. The results of the vibration process of segmental, helical, and triangular baffles in the tube bundle with externally threaded and internally silicate-coated heat exchanger tubes are presented. The main factor influencing tube vibration is the flow rate of the liquid passing through the shell-side space. An increase in fluid flow rate, while maintaining the same tube bundle design, leads to an increase in flow velocity. Consequently, the amplitude of tube oscillations rises.

Table 2 presents the vibration parameters of the tube bundle in the heat exchanger apparatus.

The vibration parameters indicate that vibrations may occur in heat exchanger bundles due to high flow velocities of the heat transfer fluid. Intense vibrational loads can cause damage or destruction of the tubes within the bundle, ultimately leading to failure of the apparatus. Therefore, the vibrational reliability of heat exchanger tube bundles is a crucial factor determining the operational reliability of the heat exchanger [15][9].

**Table 2**

**Dependence of tube vibration parameters on the design of the transverse baffles**

| Type of baffle | Mass flow rate, кg/s | Natural frequency of vibrations, Hz | Oscillation amplitude A, mm·$10^{-3}$ |
|---|---|---|---|
| Segmental | 15,28 | 4,9 | 2,7 |
| Helical | 26,42 | 6,2 | 2,1 |
| Triangular | 46,18 | 1,6 | 1,2 |

A real heat exchanger tube bundle is a system of approximately identical, spatially curved, multi-span elastic tubes interacting with internal and external heat transfer fluid flows. In many cases, the motion of the tube bundle can be described within the framework of the Bernoulli-Euler beam model, with the internal flow considered as an additional distributed mass. Each tube bundle exhibits both types of flow patterns (longitudinal and transverse), but one typically prevails over the other.

The study includes an analysis of thermal fatigue and the thermally stressed state of externally threaded and internally silicate-coated tubes. The formation of cracks on the inner surface of the silicate coatings is examined in relation to the asymmetry coefficient, scale factor, and notch effects on the tube coatings.

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[9] ГОСТ ИСО 10816-1-97. Вибрация. Контроль состояния машин по результатам измерений вибрации на невращающихся частях. Общие требования. – Введ. 1999-07-01. – М. : Стандартинформ, 2007. – 13 с.

The influence of radial, axial, tangential forces, and shear stress on the thermal strength of the tube coating is presented.

The study also investigates changes in the heat transfer coefficient of silicate-coated, copper, and brass tubes in the heat exchanger apparatus over time.

The parameters and technical characteristics of heat exchangers with silicate-coated tubes meet industrial operating conditions.

Research has shown that during prolonged operation of silicate-coated tubes in heat exchanger apparatuses, an overall improved heat transfer regime is achieved, as the heat transfer coefficient of silicate-coated tubes remains practically unchanged over time. The expected benefit of implementing silicate tube coatings is determined by the economic effect at the stages of apparatus design and operation, using efficient triangular baffles with externally threaded surfaces of silicate-coated heat exchanger tubes.

It is evident that when a liquid (such as seawater) flows through silicate-coated tubes, a sliding effect occurs on the smooth silicate surface, resulting in a slight reduction in frictional resistance along the inner length of the tube.

The economic effect of implementing a marine heat exchanger apparatus with triangular baffles and externally threaded surfaces of silicate-coated tubes is estimated to be.

$$E = R_T + Z_T = 2046.8 + 10266 = 12312.8 \ manat \qquad (14)$$

where- $R_T, Z_T$ - revenue from the implementation of the heat exchanger and operational costs for maintaining the heat exchanger during the operation period of the ship's power plant (SPP), respectively.

The prospects for using silicate-coated threaded tubes with triangular baffles in heat exchangers indicate the potential application of silicate coatings for pipes in the chemical, oil, and gas industries as substitutes for expensive tube materials made from special grades of steel.

# GENERAL CONCLUSIONS

Practical and scientific results obtained in the dissertation research.

1. An analysis of existing materials has shown that the study of heat exchange and hydrodynamic processes occurring in the shell-side of marine heat exchangers, as well as the assessment of the impact of baffle arrangement and geometric parameters on the heat transfer coefficient and hydraulic resistance of the tube bundle, has not been considered.

2. An analysis of the influence of baffle designs and geometric parameters on the thermal processes of the heat exchanger has been conducted. It was established that the geometric shapes, sizes, and positioning of the baffles significantly affect the heat exchange processes of the tube bundle.

3. To enhance heat transfer on the outer surface of heat exchanger tubes, three types of threaded tubes with different profile shapes (rectangular, triangular, and symmetrical trapezoidal) were proposed. Threading on the external surface increases the contact area, allowing the fluid to cover a larger surface and significantly improve heat transfer, ensuring greater contact between the fluid and the tube bundle wall.

4. A triangular-section baffle was developed in accordance with high technological standards, ensuring both the structural quality of the baffle and the thermal processes within the apparatus. The triangular-section baffle design is recommended for widespread use in any heating facilities to ensure the regular operation of technological processes and improve the efficiency of heat exchangers.

5. An experimental setup was developed to study corrosion processes and scale formation on the internal surfaces of silicate coatings and metallic heat exchanger tubes. It was established that the corrosion rate in seawater for all coatings increases with flow velocity but does not exceed 0.020 g/m$^2$ per day.

6. Experimental studies have shown that during prolonged operation of the heat exchanger, only minor scale deposits are

observed on the surface of silicate-coated tubes, with thicknesses ranging from 0.14 to 0.42 mm, while metallic tube surfaces develop a strong scale layer with a thickness of 1.24 to 1.98 mm.

7. Experimental studies of the thermal conductivity coefficients of various types of silicate coatings were conducted, depending on the increase in the metal wall temperature of the tubes. It was established that the thermal conductivity coefficients of the coatings increase by tenths of a watt as the temperature rises to 600°C, ranging between 1.32 and 1.42 W/m·°C.

8. A formula for determining the optimal value of the heat transfer coefficient of silicate coatings on heat exchanger tubes was recommended. A study was conducted on the impact of operational factors on heat transfer efficiency, considering salt and corrosion product deposits on the inner surfaces of smooth silicate-coated tubes. The heat transfer coefficient initially decreases but stabilizes after 10–20 days. With increasing flow velocity, its reduction is mitigated due to the washing away of minor scale and corrosion product deposits.

9. The results of the vibration process in the tube bundle made of silicate-coated threaded tubes with triangular baffles were presented. The amplitudes of tube oscillations were proposed based on the positioning and distance between the baffles in the tube bundle.

10. A study was conducted on the thermal fatigue of silicate coatings for different diameters of heat exchanger tubes. The formation of cracks on the coating surface was analyzed concerning the asymmetry coefficient, scaling factor, and coating notch effects.

11. A stress analysis of silicate-coated threaded tubes was performed. The influence of radial, axial, tangential, compression, and shear stresses on the thermal strength of the tube coatings was presented. According to the energy strength theory, the main results were obtained. The results of an economic assessment of the implementation of silicate-coated threaded tubes with triangular baffles were presented, along with the prospects for their application in marine heat exchanger tube bundles.

## The main content of the dissertation is presented in the following works:

1. Ibragimov, N.Yu., & Ibragimli, E.N. Thermal Stresses of the Silicate-Enamel Coating of a Heat Exchanger Tube. Industrial Energy, No.2,2018.
2. Ibragimov, N.Yu & Ibragimli, E.N. Experimental Investigation of the Thermal Conductivity of Glass Coatings on Pipes. Glass and Ceramics, Vol. 79, Nos. 7 – 8, p.253–256 November, 2022.Springer
3. Ibrahimli, E.N. Characterıstıcs of heat exchange wıth trapezoıdal baffles heat exchanger. II International Scientific and Practical Conference « Science in modern society», July 18-19, 2023, Beijing. China.
4. Gasanov, V.G., & Ibragimli, E.N. Corrosion of Coatings of the Tube Bundle of Marine Heat Exchangers. In ASMA, "Modern Problems of Electric Power Engineering and Development Perspectives" International Scientific-Technical Conference Proceedings (pp. 126–129), November 17–18, Baku-2022.
5. Gasanov, V.G., & Ibragimli, E.N. Study of Optimal Operating Conditions for Tubes of Marine Heat Exchangers. In Proceedings of the 1st International Scientific-Practical Conference "Problems of Sustainable Development of the Maritime Industry" (pp. 211–214), November 3–5, 2021, Kherson, Ukraine.
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7. Gasanov, V. G., & Ibragimli, E. N. (2021). Regulation of the Influence of Baffle Design on Thermal Processes of Tubes in Marine Heat Exchangers. Scientific Works of ASMA, (1), 114–117. Baku, Azerbaijan.
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12. Ibrahimov, N.Y., Ibrahimli, E.N. Application of a Metal Coating to the Surface of a Cylinder Using a Laser Device. Proceedings of the Azerbaijan Engineering Academy, 2022, Volume 14, No. 4, pp. 56–61.
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14. Hasanov, V.G., Ibrahimli, E.N., Mamedova, M.A. Regulation of the Influence of Baffle Design on Thermal Processes in the Tubes of Marine Heat Exchangers. Problems of Energy and Resource Saving, Special Issue 2024, Tashkent (No. 85), pp. 95–103. ISSN (print): 2091-5985
15. Gasanov, V.H., Ibrahimli, E.N., Omarov, A.S. Design of a Heat Exchange Apparatus. Industrial Property. Inventions. Utility Models. Industrial Designs. Bulletin No.1, Section F, p. 11, Baku – 31.01.2025.

# Personal Contribution of the Author in Co-authored Published Works:

In works numbered [1,2,3,4,5,6,8], the author carried out the formulation of the research relevance, objectives, tasks, theoretical studies, and the development of scientific statements. The remaining parts were completed equally by all co-authors.

Works numbered [7,9,10,11,12,13,14] were written based on the recommendation of the scientific supervisor to develop expertise in the experimental part of the dissertation research.

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