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Heat exchanger and the influence of lattice structures on its strength

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ABSTRACT

The heat exchanger is the main heat engineering equipment in various industries. The design of modern heat exchangers implies the presence of various turbulators. The purpose of turbulators is to increase the efficiency of heat exchange processes. Research of turbulators is limited to finding the optimal ratio between heat exchange parameters and hydraulic resistance of the system, without touching upon the issues of changing the strength characteristics of heat exchangers. Within the framework of this article, an analysis of a section of a tubular heat exchanger with a flow turbulator in the form of a lattice structure is carried out. Within the framework of this article, the method of comparative numerical modeling was chosen, consisting in the study of the stress-strain state and frequency response of the objects of study in the original and modernized formulations, under the action of thermal and gas-dynamic loads, modeled in heat-conjugate and mechanical analysis. The result of this study is the results of numerical modeling, reflecting the general change in the stress-strain state and frequency response of the heat exchanger. The analysis showed that the use of lattice structures reduces the average equivalent stresses in the heat exchanger by 10–20 % depending on the flow mode. In addition, frequency analysis showed a significant increase in the natural frequencies of the modified heat exchanger in the range from 86 % to 125 %. These results show that the use of flow turbulators allows increasing not only the efficiency of heat exchange processes, but also its strength.

KEYWORDS

mechanics • numerical investigation • structural analysis • modal analysis • physics of strength additive technologies • heat exchangers

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Introduction

Given the importance of the energy industry in various spheres, its development is linked to the need to achieve high efficiency, cost-effectiveness, and environmental friendliness. Future energy plants should demonstrate higher efficiency than current technologies,

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reduced fuel consumption, and minimal environmental impact. These requirements form the basis for shaping energy development strategies in different countries.

There are many ways to improve power plants, such as by optimizing elements and their parts, improving the efficiency of individual components of power plants, and using alternative working fluids. All approaches improve the characteristics of turbomachines to varying degrees but do not have a comprehensive approach, which has an impact on one of the parameters. A complex impact on all parameters of this concept can be provided by the use of high-efficiency heat exchangers. Thus, for example, the presence of a heat-exchange apparatus in the gas turbine unit (GTU) increases the efficiency of the power plant by reducing the amount of heat required for supplying to the thermodynamic cycle, increasing environmental friendliness owing to the effective utilization of thermal energy at the outlet from the turbine part of the GTU, and increasing efficiency by reducing the fuel consumption burned in the GTU.

A heat exchanger is auxiliary heat engineering equipment used to transfer heat energy from a heat carrier to a less heated body for the realization of various thermal processes. The heat transfer process occurs during the flow of these heat carriers through channels of various shapes. By analyzing the operating conditions of the heat exchangers, it can be established that they are significantly affected by these isolated flows. Thus, the heat exchanger apparatus is affected by:

1. Temperature loads. Temperature gradient: heat exchangers can be subjected to significant temperature variations that cause thermal expansion and contraction of the materials from which they are made. These variations can result in significant tensile/compression stresses and plastic deformations.
2. Aerodynamic impact. Pressure gradient: the heat exchanger must be able to withstand the operating pressure of the heat-transfer fluids, which can be significant depending on the intended use of the heat exchanger. Pressure effects led to the formation of various simple and combined bending stresses.
3. Mechanical loads. Vibrations: the presence of direct mechanical connections with other units of the power plant, as well as unbalanced aerodynamic flows, leads to the appearance of various vibrations in individual housing parts. The prolonged impact of vibrations on structures can lead to the formation of various fatigue cracks, which can lead to the violation of duct tightness and active mixing of coolants.
4. Chemical stress. Corrosion: interaction with aggressive chemicals can lead to the development of corrosion on the surface of heat exchangers, which can also lead to cracks and channel isolation failure. Deposition: Interaction with aggressive media leads to the deposition of various solid particles on the surface of the heat exchanger, the accumulation of which leads to the thickening and deterioration of the heat exchange efficiency.

Neglecting these loads can significantly affect the service life and reliability of heat exchangers. All of the above-mentioned influences must be considered in the design stage of heat exchangers. However, as diagnostics show, it is impossible to perform a comprehensive analysis of all loads because the heat exchange process is non-stationary and can change the magnitude of its impact on the design during its operation.

The durability of heat exchangers is one of the key factors that determine their longevity and performance. The strength depends on the material from which the heat exchanger is constructed, as well as the operating conditions. The materials used to manufacture heat exchangers must be highly corrosion-resistant and resistant to high temperatures. The most common materials used are stainless steel, titanium, aluminum, and copper. Additionally, the strength of the heat exchanger depends on its design. For example, plate heat exchangers have a large surface area for heat exchange, which allows them to operate at high temperature and pressure. Certain elements of heat exchangers can act as stiffeners, increasing their strength. It is important to note that the strength of heat exchangers may decrease over time owing to exposure to aggressive media or mechanical damage. Therefore, regular inspection and maintenance of the heat exchangers should be performed to maintain their efficiency and safety.

By preventing possible defects in heat exchangers at the design stage, it is possible to increase their durability, which in turn will positively affect the efficiency and economy of the power plant itself. Thus, improving the efficiency and durability of heat exchangers will reduce the cost of energy production, which will ultimately reduce the price for consumers. Therefore, analyzing the defects of heat exchangers that occur during their operation and searching for methods to eliminate these defects (both at the design and operation stages) is an important direction of development in the energy industry.

For example, in [1], the process of describing the defects of heat exchangers, as well as the reasons that led to their formation, is shown. The authors conducted an all-sided analysis of the loads acting on the surface of the heat exchanger and found that the defect occurred as a result of thermal fatigue, caused by temperature fluctuations due to poor water circulation. Thermal stresses occurred which led to fatigue followed by water leakage.

According to the other authors, the defects on metal tube resulted from the high-temperature corrosion of the weld [2]. Scanning electron microscopy (SEM) analysis, metallographic, and electrochemical corrosion studies showed that the base metal has a higher corrosion potential than the weld under service conditions, which results in weld corrosion.

Other researchers have also performed diagnostics of heat exchangers, during which the development of corrosion on the surface of heat exchangers was observed [3]. The primary cause of corrosion development is the contact of the heat exchanger surface with a high-temperature chemically aggressive medium.

In [4], tube overheating and failure due to scale formation were studied. The failure samples in the field were obtained from the convection tube of the primary reforming. The object was a spiral ribbed tube. The tube exhibited a tear accompanied by bulging. The analysis performed using the finite element method in this study simulated real field conditions. It was found that prolonged overheating due to scaling both outside and inside the inner part of the tube prevents the smooth heat transfer process. Consequently, this leads to the deterioration of heat transfer and violates the original design concept. A metallurgical examination confirmed this conclusion. In addition, the finite element analysis confirmed this conclusion.

Summarizing, it can be seen that heat exchangers work in extremely aggressive environments, which negatively affects their strength and leads to destruction [5–7].

Preventing defects in heat exchangers is a critical aspect of their operation, because defects can lead to reduced efficiency, increased operating costs, and even accidents.

There are several methods for preventing defects in heat exchangers, which can be divided into several main categories:
1. Project measures. Optimal choice of materials: use of materials resistant to corrosion, erosion, and thermal deformation, such as stainless steel, nickel, or titanium-based alloys, especially in aggressive environments. Thermal expansion consideration: the heat exchanger is designed considering the thermal expansion of materials to avoid stresses and deformations that can lead to leakage or joint failure. Coatings and protective layers: application of protective coatings (e.g., anti-corrosion) on the internal surfaces of pipes and plates to prevent corrosion and reduce fouling. Design optimization: a proper fluid flow design to minimize stagnation zones and evenly distribute heat loads, thereby reducing the risks of localized overheating or corrosion.
2. Operational measures. Operating parameter monitoring: continuous monitoring of the temperature, pressure, flow rate, and other operating parameters to ensure that they are within the design values. Deviations can cause thermal shocks, erosion, or accelerated deposit formation. Filtration and cleaning: filters and separators are used to remove solids and contaminants from the media to reduce the risk of erosion and clogging of the heat exchanger pipes and ducts. Prevent thermal shocks: avoid sudden changes in temperature and pressure, which can cause thermal shocks and structural damage.
3. Preventive measures and maintenance.

In summary, it can be seen that the process of operation of heat exchangers produces the development of various types of defects, owing to the inability to take into account the various non-stationary processes occurring in heat exchangers, as well as technological inaccuracies. The level of impact from loads is a difficult task, and improvement of the technological process is a more affordable solution to extend the resources of heat exchangers. Based on this, the authors considered the option of improving the heat exchanger apparatus through design changes. It is worth noting that when designing heat exchangers, it is worth considering many factors besides durability: efficiency, material costs, production costs.

The most common method of manufacturing heat exchangers is the use of standard technological operations, such as casting, pressing, stamping, and rolling, as well as the active use of various types of welding to form channels through which the coolants move. However, additive technologies have been actively used for the manufacture of heat exchangers [8,9]. Additive technologies are the process of creating objects by applying a material layer-by-layer based on a three-dimensional model. Unlike traditional manufacturing methods, where materials are usually removed or specially deformed to create the shape of an object, in additive technologies, materials are added sequentially to create the final product. The principle of 3D metal printing has made it possible to create objects with highly complex geometries, with the possibility of integrating additional stiffeners (lattices) into the design, which will also absorb additional loads from the flow, thus reducing the overall stress concentration on the heat exchanger surface [10]. In addition to heat exchangers, additive technologies are also used in other energy machines. The technological process of additive manufacturing is also being actively studied [11]. Thus, the additive manufacturing process covers a wide variety of engineering industries. Technological features, designs and their mechanical properties are being actively studied. Advances in additive manufacturing have led to the creation of three-dimensional periodic minimum surfaces (TPMS) for heat exchangers.

Another paper [12] reviewed different types of lattices, their properties and applications, where it was found that lattice infill has unique properties that often cannot be fully obtained using conventional fabrication methods. In addition, gratings effectively absorb energy and distribute stress evenly, and such structures are highly rigid, which will have a positive effect on vibration resistance. One of the most common types of such gratings is the gyroid, which is a triply periodic minimum surface (TPMS) that can be approximated by the following equation:

$$\sin x \cdot \cos y + \sin y \cdot \cos z + \sin z \cdot \cos z = 0. \quad (1)$$

The properties of these structures are actively studied by various authors. For example, in [13], a finite element analysis of the elastic properties of metamaterials based on three-fold periodic minimal surfaces was provided.

The use of lattice structures to improve the quality of heat and mass transfer processes is considered by the authors in another work [14]. There was a simulation of heat transfer with lattice structures. In this work, the effectiveness of their use has been proven. And the Nusselt number of a relatively smooth channel has increased from 2 to 5 times.

It is worth noting that, at present, the topic of increasing the strength of various objects through the introduction of lattice structures is very relevant, since this technology allows a significant increase in the strength properties of the object. Authors have conducted both numerical and experimental studies to investigate the strength properties of lattice structures.

In [15], compression and fall head tests of different types of lattices were performed. In this study, the optimal design was selected, which has a high pedigree, while being as durable as possible. In [16], the influence of the direction of the load on the compressive strength of additively manufactured three-period frames with a minimum surface was studied. Another article [17] examines the effect of porosity of various types of structures on strength properties. Based on [17], the Gyroid lattice type can be distinguished as one of the most durable types of gratings. In another study [18], the optimization of the TPMS structure for titanium dioxide composite ceramics was accelerated using finite element modeling (FEM) using a multi-purpose optimization algorithm. Quasi-static experiments and jackhammer experiments were conducted to study the mechanical response and deformation behavior of lattice structures in [19]. The global processes of structural deformation were recorded by a digital camera. In another article [20], the mechanical properties and energy absorption ability of printed TPMS samples with a gradient and a stepwise variable structure were studied. The difference between the homogeneous and stepped gyroid samples was negligible, and only one structural crack appeared during the compression test. Also, speaking about heat exchange properties, it is impossible not to consider the studies of heat transfer in these structures. The work [21] measured the heat transfer efficiency of a number of heat exchangers based on three times periodic minimum surfaces. The results showed that the TPMS sheet-gyroid design provides a high heat transfer rate and a moderate pressure drop. In [22], three new structures of mathematically controlled TPMS radiators were investigated using models based on computational fluid dynamics (CFD). The results showed that TPMS-based heat sinks outperform conventional heat sinks by 48–61 % due to random flow disturbances and high packing density. This work demonstrates the potential of porous TPMS architectures as very promising heat sinks. Research has also been conducted on new methods to improve convective heat transfer based on precise control of the gyroid-type TPMS lattice structure in paperwork of other authors [23]. Some authors are already investigating real objects and conducting a comparative analysis of the influence of lattice structures on heat transfer. For example, in one of these works [24], a comparative analysis of the cooling system of the turbine blade with classical columns-intensifiers of heat exchange processes with a lattice structure was carried out. During this analysis, it was revealed that TPMS is a more effective intensifier than classical ones. The effectiveness of TPMS structures has also been proven in [25] on the design of a small-sized high-efficiency lattice heat exchanger. In recent years, various authors have analyzed new designs for heat exchangers manufactured using additive technologies [26,27]. In addition to studying the designs, technologies and mathematical modeling of such lattice structures, experimental studies are also being conducted that prove the high efficiency of these structures in heat exchangers [28,29].

Analyzing the above articles, it was found that a single assessment of heat exchange processes or strength characteristics of lattice structures is carried out. The main emphasis in heat exchangers is on the study of the optimal ratio of heat transfer parameters and hydraulic resistance coefficients, by varying the geometric parameters and types of lattice structures. The issues of changing the strength characteristics of heat exchangers during the integration of lattice structures remain unresolved, which does not allow for a full assessment of the acceptability of using lattice structures in heat exchangers to increase their efficiency and strength.

This paper is devoted to the study of the influence of lattice structures on the strength of heat exchangers manufactured using additive technologies. In this study, strength analysis of heat exchanger sections with and without a lattice structure was carried out for a wide range of Reynolds numbers. The aim of this work is to carry out a comparative analysis of the strength of a heat exchanger at different flow regimes realized in a heat exchanger using numerical simulation.

Thus, the research object of the study is a heat exchanger. The aim of the study is to conduct a comprehensive analysis of the influence of lattice structures on its operating parameters. The tasks of this study are geometric modeling, the results of gas dynamic, strength and vibration numerical studies, as well as comparison of results and impact assessment.

Methods

This study was conducted using computer-aided engineering software Ansys 19 R2. This calculation software has well proven the compliance of the output results for solving strength and dynamic gas computational problems, which is confirmed by validation studies. The temperature and pressure distribution data obtained as a result of gas dynamic numerical simulation in Ansys CFX were set as the acting load on the heat exchanger. The Steady State Thermal module was also used to account for heat transfer.

The strength calculation was performed in the Ansys Static Structural and Ansys Modal blocks.

The numerical study of the strength of the heat exchanger section described in this paper is based on the results of gas dynamic modeling obtained by the authors in the study [30]. This study investigated the efficiency enhancement of heat exchangers by introducing turbulent lattice structures fabricated using additive technologies into their design. The classical methodology for evaluating the efficiency of a lattice structure is used to evaluate the efficiency of the flow turbulators. However, this turbulizer is also a stiffener that can positively influence the strength characteristics of the structure, as verified in this study.

Because the present study is based on the results of previous gas-dynamic modeling, further analysis should include a comprehensive assessment of the effectiveness of the use of lattice structures, including both the impact on the intensification of heat transfer and the impact on the improvement of strength properties, which should be considered in continuity with each other. Figure 1 shows a combined flowchart of previous and current studies.

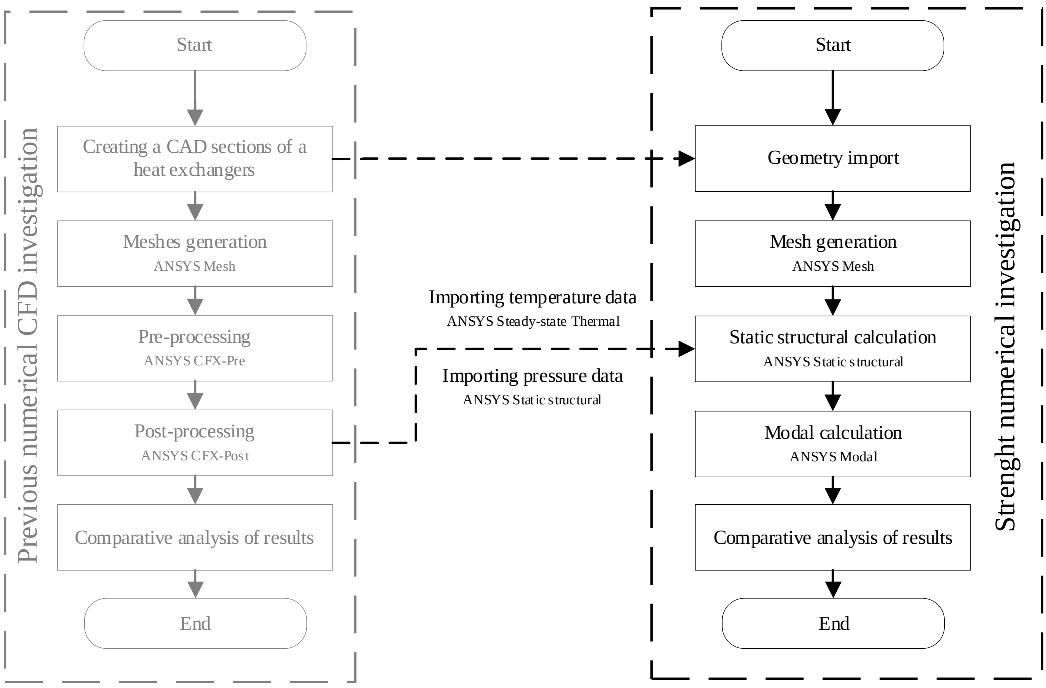


Fig. 1. Block diagram of studies

The previous study was performed by numerical modeling of the heat transfer process for two heat exchanger sections with and without the lattice structure inside. A small section of the tubular heat exchanger was selected as a reference. In this heat exchanger, one pipe of a smaller radius is located in a larger pipe. Hot liquid flows through the inner pipe, and cold liquid flows through the outer one. A section of a lattice gyroid structure was embedded in the center of one of the samples. The lattice structure was modeled using nTop software. Straight sections were specially modeled, since when setting boundary conditions, the flow parameters are averaged. At the entrance and exit near the lattice structure, the results are greatly distorted, since the flow inside and near the lattice has a large spread of parameters, and averaging it, unreliable results are obtained.

Figure 2 shows the geometrical models of the heat exchanger sections, with and without a lattice structure. Table 1 lists the geometrical parameters of the investigated sections of the heat exchangers.

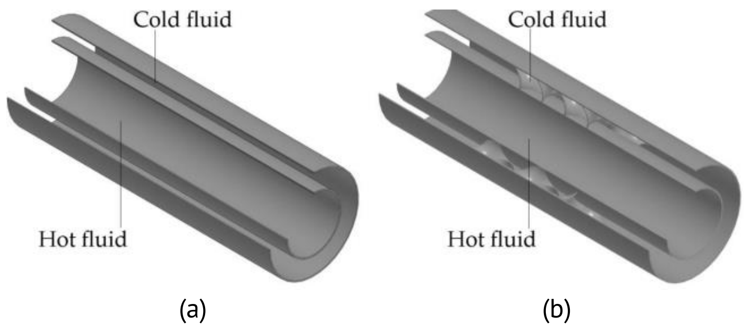


Fig. 2. Geometric models of the studied heat exchanger sections in cross-section: (a) with and (b) without a lattice structure

Table 1. The geometric properties of the heat exchangers sections

Parameter	Unit	Value
Inner diameter of the pipe	mm	48
Outer diameter of the pipe	mm	80
Thickness of all walls	mm	1
Length of the heat exchangers sections	mm	240
Length of the lattice section	mm	80
Periodicity size of the gyroid lattice	mm	40

Using the results of the gas dynamic numerical study conducted earlier, static strength calculations and modal frequency analysis were also numerically performed in the present study. The calculation was also performed for the two heat exchanger sections presented earlier in a previous study under different flow regimes (Re=1000, Re=7500, Re=40000). Boundary conditions for CFD calculation are presented in Table 2.

Table 2. Boundary conditions

Parameter	Unit	Value	
		Cold fluid	Hot fluid
Inlet velocity	m/s	0.87 / 6.5 / 34.7	0.87 / 6.5 / 34.7
Inlet temperature	K	500	1000
Outlet static pressure	Pa	101325	101325

The strength calculation process involves several steps. First, previously created geometrical models of the heat exchanger sections were imported. Subsequently, the material (structural steel) is assigned. The source of the material properties of the heat exchanger is the Ansys material database. For this study, a standard structural steel was chosen since the main purpose of this work is a comparative analysis in which the influence of the lattice structure on changes in stresses and frequencies in the design of the heat exchanger is investigated. In order to conduct a correct comparative analysis, it is necessary to adhere to equivalent research objects with the same properties and conditions. It should be noted that because this task is purely comparative, matching material properties to real properties with high accuracy is not necessary. In this case, for a correct comparison, the main point in setting up the solution to the problem is ensuring the same boundary conditions and corresponding loads.

Subsequently, a computational mesh was created by dividing the model into finite elements. Due to the fact that geometrically the gyroid is a complex surface, it is not possible to create a block-structured grid for this section of the heat exchanger. Therefore, the unstructured grid type was chosen. The mesh models of the two sectors differ quite significantly. In the case of a smooth heat exchanger, the mesh is significantly simpler and more uniform in length. In the sector with a lattice structure, the mesh thickens at the joints of the walls, as well as in geometrically complex parts of the heat exchanger. The total number of mesh elements for a heat exchanger without a lattice structure is 672188, and for a sector with it number of elements is 880470. The size of the meshes elements is 1 mm.

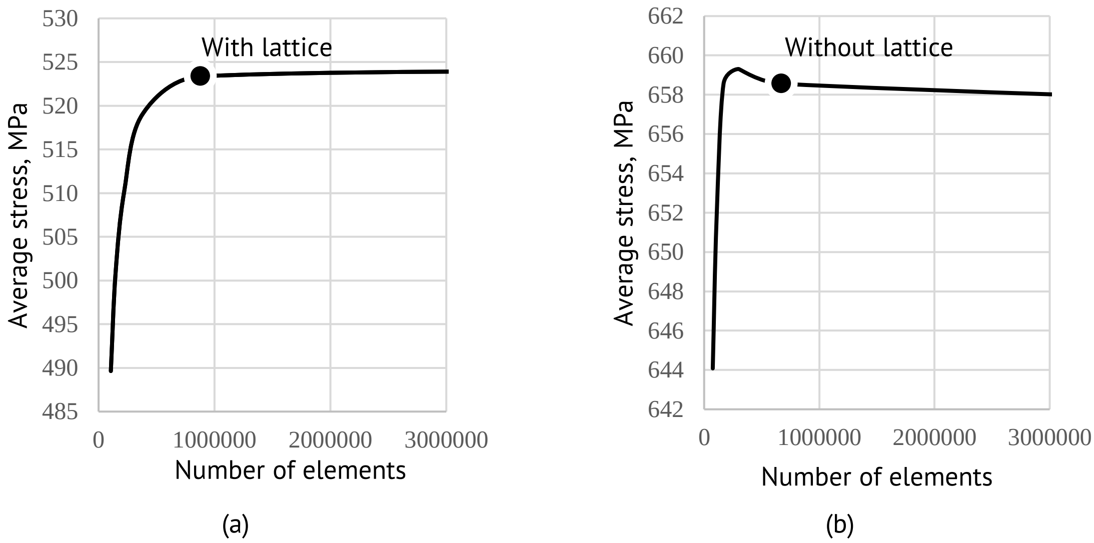


Fig. 3. Mesh independences analysis results: (a) with and (b) without lattice

When building a computational mesh, it is worth considering that the accuracy of the calculations and the time of analysis depend on its quality and mesh size. A finer mesh yields more accurate results but significantly increases the computational time. The choice of the mesh element size should be guided by the achievement of mesh independence. Mesh independence is a concept in numerical methods that denotes the state when the results of a numerical simulation become virtually independent of the size and structure of the mesh used for the computation. Thus, the optimal grid was selected based on the results of the analysis of grid independence. It was estimated by the average values of stress. Figure 3 shows mesh independent results. In these graphs, the values of the mesh model elements selected for further calculations are highlighted with dots.

After the mesh model was built, the static strength was calculated in the Static Structural module, which used the finite element method to determine the stress and strain distributions.

The setup of the gas dynamic calculation was described in more detail in the previous article [30]. This strength calculation was solved within the framework of an elastic formulation and all stresses and deformations obtained in this study are described within the framework of Hooke's law.

When creating a computational model for strength calculation, the following boundary conditions were set:

1. the temperature distribution along the walls of the heat exchanger obtained during the gas dynamic calculation;
2. the pressure distribution along the walls of the heat exchanger obtained during the gas dynamic calculation;
3. pinning condition "Fixed Support" at the edges of heat exchangers.

Ansys used the finite element method (FEM) to calculate static strength. The equation used to determine the stresses and deformations in the elements is as follows:

$$K\Delta = F, \tag{2}$$

where K is the element stiffness matrix, Δ is the vector of nodal movements, F is the vector of external forces and moments.

This equation is solved by a system of equations using the Gaussian method or other methods of numerical linear algebra. As a result, we obtain the values of the nodal displacements Δ, which are then used to calculate the stresses in each element according to:

$$\begin{cases} \sigma_{xx} = E(\varepsilon_{xx} + \nu\varepsilon_{yy}), \\ \sigma_{xy} = G\gamma_{xy}, \\ \sigma_{yz} = G\gamma_{yz}, \\ \sigma_{zx} = G\gamma_{zx}, \end{cases} \tag{3}$$

where σ is the stress vector, E is the Young's modulus, ν is Poisson's ratio, G is the shear modulus, γ is shear strain between the corresponding planes.

This was followed by modal analysis in the Ansys Modal, which allowed the determination of natural frequencies and vibration shapes.

Results and Discussion

In the earlier research process, it was found that the lattice structures intensified heat transfer by creating vortex flow structures, as well as by increasing the heat transfer area. Also, in the described article was carried out a comparative analysis of the obtained results of heat transfer intensification with the results of intensification by using classical turbulators, such as different types of fins. According to the results of the analysis, the investigated turbulizers were found to be more efficient than classical turbulizers. As a parameter to evaluate the effectiveness of the lattice structure as a heat exchange intensifier was used parameter Nu/Nu_{smooth} which shows the increase in the Nusselt number (the criterion of similarity of thermal processes, characterizing the relationship between the intensity of heat exchange due to convection and the intensity of heat exchange due to conduction) when using a flow turbulator relative to the smooth section of the heat exchanger. It should be noted that the study was conducted at different velocities of the working medium at the inlet to assess the effectiveness of this type of turbulizer for different flow types (laminar and turbulent). Thus, it was possible to determine the most effective flow type for this type of turbulator. Figure 4 shows a graph of the dependence of the parameter Nu/Nu_{smooth} on the Reynolds number. The results obtained from the static strength calculations and modal analysis are presented in Table 3. Figures 5–8 show the results obtained during the strength calculation.

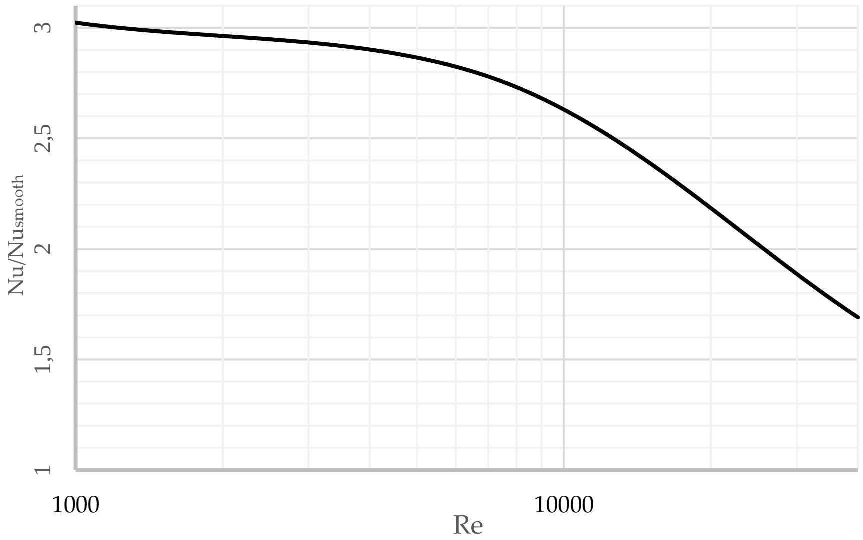


Fig. 4. Graph of dependence of the Nu/Nu_{smooth} parameter on Reynolds number

Table 3. Strength calculation results

Parameter	Unit	Value					
		Without lattice			With lattice		
		***Re*=1000**	***Re*=7500**	***Re*=40000**	***Re*=1000**	***Re*=7500**	***Re*=40000**
Average displacement ΔL_{avg}	mm	0.13375	0.13267	0.12458	0.13173	0.12459	0.12651
Average stress σ_{avg}	MPa	668.79	658.56	609.73	547.60	523.36	541.61
Average stress at inner wall $\sigma_{in\ avg}$	MPa	927.34	900.43	769.80	675.35	670.60	748.19
Average stress at external wall $\sigma_{ext\ avg}$	MPa	516.20	516.04	517.03	577.61	583.43	528.18
Average stress value at lattice $\sigma_{lattice\ avg}$	MPa	–	–	–	280.32	260.22	277.41
1st natural frequency ω_1	Hz	1554.6			3493.1		
2nd natural frequency ω_2	Hz	1554.7			3496.9		
3rd natural frequency ω_3	Hz	1738.7			3747.2		
4th natural frequency ω_4	Hz	1738.8			3797.0		
5th natural frequency ω_5	Hz	2044.2			3807.8		
6th natural frequency ω_6	Hz	2044.3			3818.0		
Mass m	kg	0.7694			0.8665		

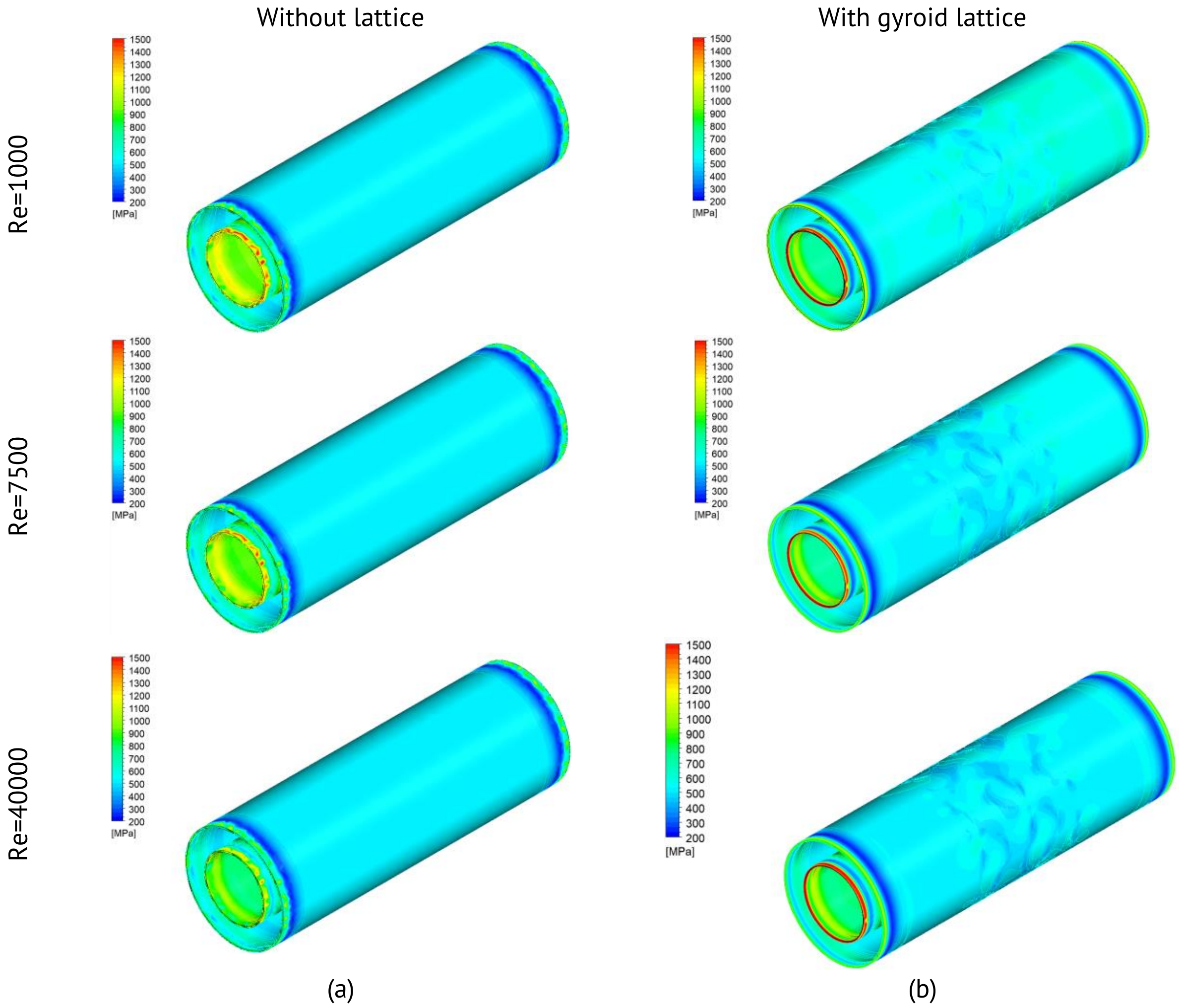


Fig. 5. Diagrams of stress values in the heat exchanger sections for different flows: (a) without and (b) with gyroid lattice

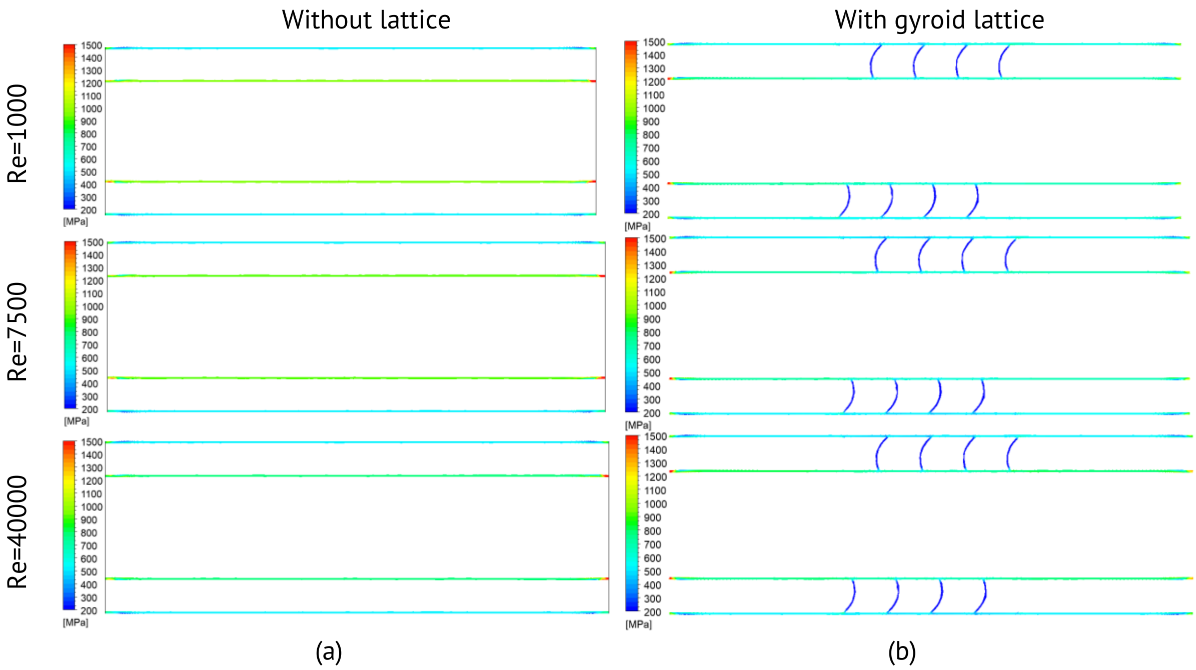


Fig. 6. Diagrams of stress values in the heat exchanger sections for different flows (cross-section): (a) without and (b) with gyroid lattice

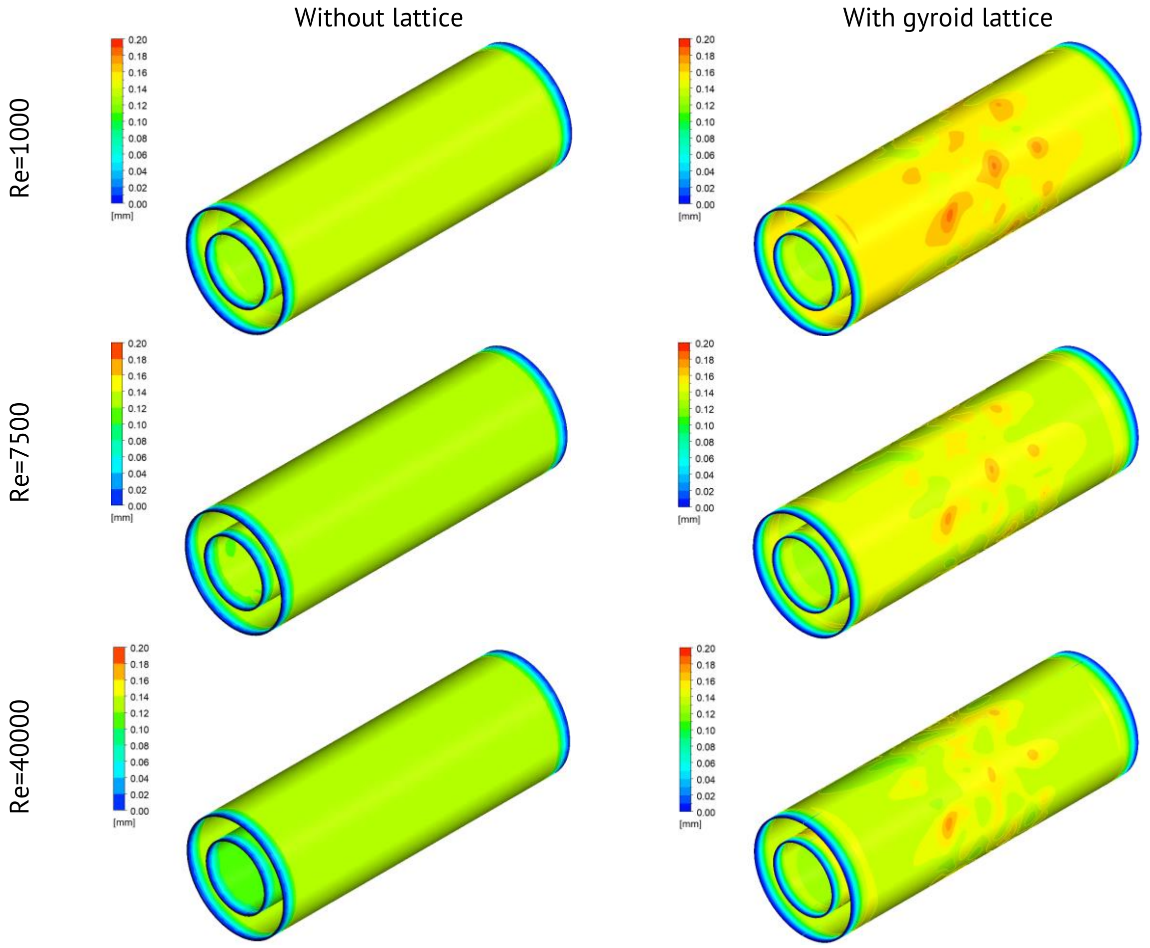


Fig. 7. Diagrams of the total displacement in the heat exchanger sections for different flows: (a) without and (b) with gyroid lattice

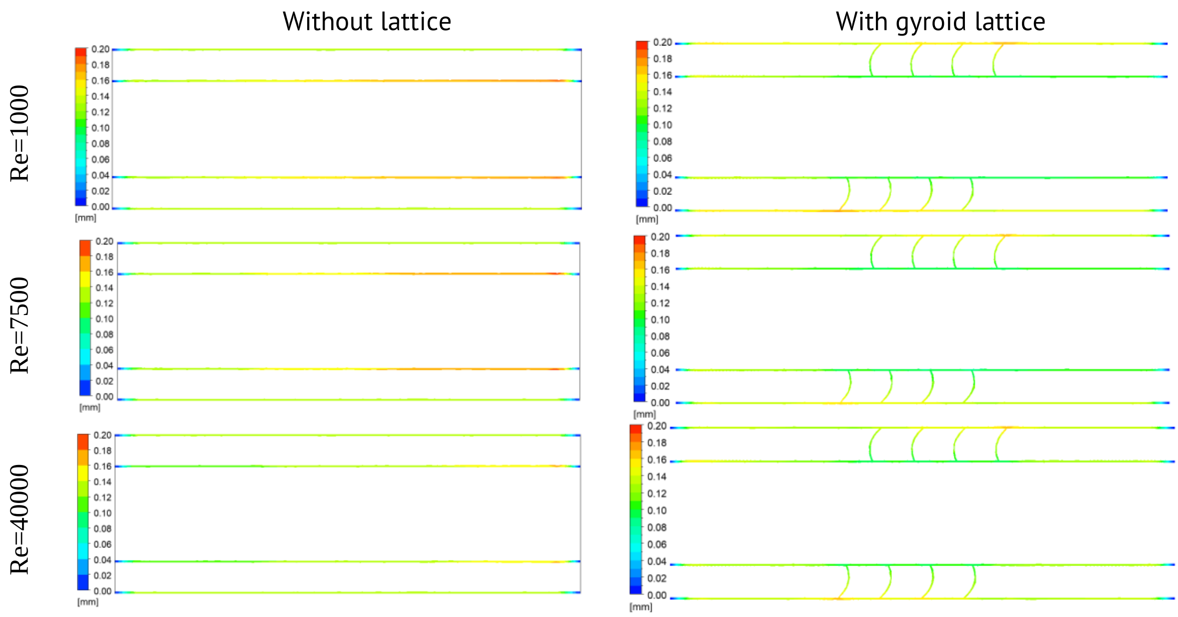
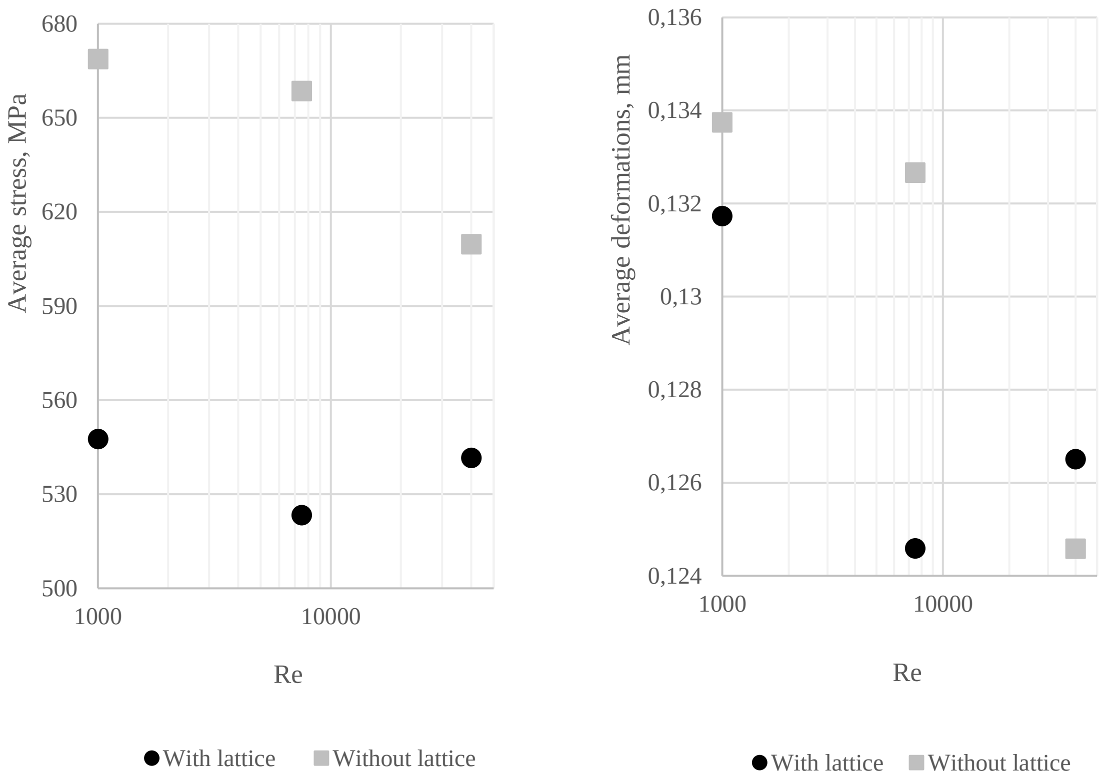


Fig. 8. Diagrams of the total displacement in the heat exchanger sections for different flows (cross-section): (a) without and (b) with gyroid lattice

For greater clarity of the differences in the results, the data were processed and presented in the form of graphs.

Figure 9 shows a graph of the dependence of the number of average stresses and average deformations in the heat exchange sectors for different flow regimes.



(a) (b)

Fig. 9. A graph of the dependence of the average stress (a) and average deformations (b) in the heat exchanger sections depending on the number of *Re*

From the obtained data, it can be observed that the stresses vary depending on the different impacts of the flow on the walls of the heat exchanger. It should be noted that the stresses of the heat exchanger section with a lattice structure were lower, as expected; however, at higher Re values, this difference was significantly reduced. This is primarily due to the fact that the structure is affected by static pressure from the flow side. The change in static pressure is described by Bernoulli's law and is related to the change in both dynamic pressure and hydrostatic pressure:

$$P_{total} = P_{static} + \frac{\rho v^2}{2} + \rho g h = \text{const}. \quad (4)$$

The main element of the structure, represented as a lattice structure located in the outer loop, had a significant influence on the change in the flow pattern. This is due to the conversion of the potential energy of the pressure into kinetic energy, which significantly affects the change in flow velocity. According to Bernoulli's law, the condition of constancy of the total pressure must be observed, which is expressed as the change in the dynamic component of the pressure and leads to a decrease in the static component of the total pressure. It is important to note that the mode parameters of the compared designs of the heat exchangers are identical at the inlet boundaries, that is, the total pressure is the same. Hence, it follows that the design with a gyroidal lattice accepts a lower load value as a result of lowering the static pressure caused by an increase in the dynamic component of the pressure (velocity) of the flow inside the heat exchanger. The velocity diagrams are presented in the previous study [30].

Analyzing the graph shown in Fig. 9, it can be seen that the values of the average stresses for the heat exchanger with the TPMS lattice are lower than those for the heat exchanger without the lattice. However, it can be observed from the graph that the values of the average stresses for the heat exchanger without a lattice monotonically decrease as the Reynolds number increases. On the contrary, for the heat exchanger with a lattice structure, this trend is not followed, and there is an extremum point after which the values of the average stresses start to increase. This can be explained by the fact that the flow regime, which is realized in the heat exchanger with a gyroid in addition to the impact of the flow on the structure, has an additional impact in the form of flow fluctuations in its parameters. Fluctuations are absolute peaks relative to the average values. In a heat exchanger with a lattice, there is a more pronounced fluctuation of the flow over the entire size of the channel compared to a smooth channel, where there are smoother changes in the flow parameters, which are concentrated mainly in the near-wall area.

The graph of the dependence of the mean strain values shows a similar dependence as that of the mean stress values. The dependencies presented in the graph are directly correlated with the stress values presented in Fig. 9. This indicated the physicality of the calculated results.

Plots of the changes in the average stresses in the cross-section for the heat exchanger sectors along their lengths for different Re numbers are presented in Fig. 10. The dotted line indicates the sector with a lattice gyroid structure. From these plots, it is clear that the stresses decreased owing to the addition of the lattice structure.

By evaluating the stress values of the presented heat exchanger sections, it can be observed that the average stresses for the Reynolds numbers of 1000 and 7500 regimes are lower when using a lattice structure along the entire length. This can be explained by the fact that part of the load is taken up by the lattice, thus minimizing the stress on the outer and inner walls. In these plots, the stresses absorbed by the TPMS lattice were expressed as a sharp drop in the stress value in the sector with it. However, by analyzing the values of the average stresses for the case with a Reynolds number of 40000, an increase in the number of average stresses in the section without the lattice is observed. The explanation of such behavior of the systems can also be additional aerodynamic influences from the flow side.

In addition to the effect of the lattice structure on the structural strength of the heat exchanger, the effect of the lattice structure on the frequency response was evaluated. Any construction has an infinite number of forms of natural vibration.

The natural frequency of the vibration depends on the stiffness and mass of the structure. Thus, the vibration frequency equation for the structures can be represented as follows:

$$\omega = \alpha\sqrt{K/m}, \qquad (5)$$

where K is the structural rigidity, m is the mass, α is the empirical coefficient.

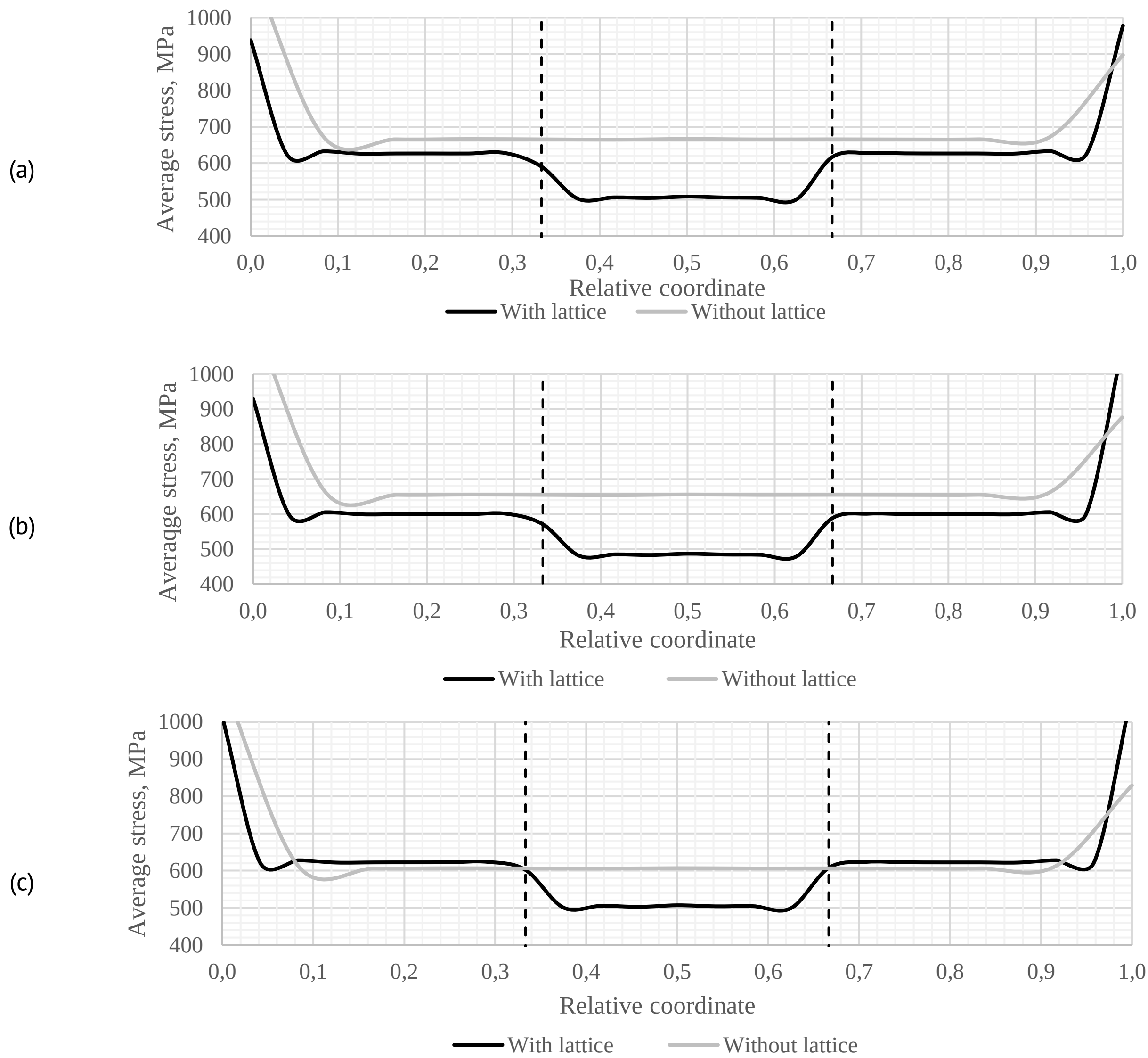


Fig. 10. Graphs of changes in average stresses in the cross section for heat exchanger sectors along their length: (a) *Re* = 1000, (b) *Re* = 7500, (c) *Re* = 40000

The results of the frequency analysis obtained in the process of modeling the operating conditions of the heat exchanger sections showed a significant increase in the natural frequencies of vibrations owing to the increase in the rigidity of the structure. Natural frequencies and forms of vibrations depend on the shape of the object in question, the material from which it is made, and the conditions of fixation. In this case, it turns out that the mass of the heat exchanger section increased with the addition of the lattice structure, which in turn negatively affected the vibration resistance properties of the object (natural frequencies were reduced). However, this structure is also a stiffener, which has a positive effect on the rigidity of the structure and therefore the vibration resistance properties of the heat exchanger section.

Increasing the natural frequencies of the structure is necessary to prevent resonant phenomena that can lead to the damage or destruction of the structure. Resonance occurs when the frequency of the external load coincides with the natural frequencies of the system. This leads to significant fluctuations that can exceed permissible limits and cause serious damage. To avoid resonance, it is necessary to increase the natural frequencies of the structure above the range of the possible external load frequencies. Figure 11 shows the histogram of natural frequencies for both heat exchanger designs.

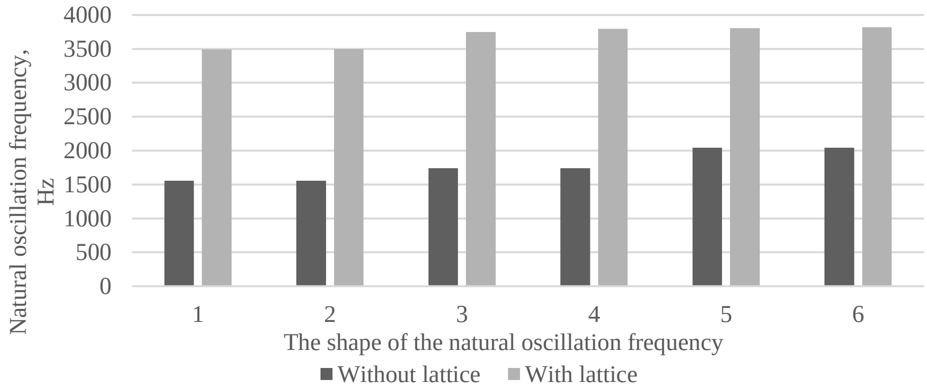


Fig. 11. Histogram of natural frequency values for various forms of vibrations

Based on the calculated data shown in Fig. 11, it can be seen that the natural frequencies of the heat exchanger section with the embedded grating are much higher than those of the smooth section. This indicates that despite the increase in mass and its negative effect on the frequency response, the increase in stiffness of the structure had a more significant effect on the frequency response, which ultimately improved the dynamic strength of the heat exchanger.

Conclusions

Summing up this article on the study of the effect of lattice structures on the strength of the heat exchanger, it was found that:

1. The positive effect of lattice structures on heat transfer in heat exchangers has been revealed. It has been established that the use of lattice structures improves the processes of heat and mass transfer, which is confirmed by numerical calculations and experimental data (Fig. 4).
2. A decrease in average stresses in the heat exchanger has been established when using lattice structures. According to finite element calculations, lattice structures can reduce average stresses by 10–20 % for flows with low Reynolds numbers, which increases the static strength of the heat exchanger.
3. The limitations of the use of lattice structures are determined. It is established that in regimes with high Reynolds numbers, the influence of lattice structures becomes negative due to an increase in stress values caused by increased flow fluctuations. This opens up prospects for optimizing the geometric parameters of lattice turbulators to improve the efficiency of heat transfer.
4. An increase in the rigidity and frequency characteristics of a heat exchanger with lattice structures has been revealed. Frequency analysis showed that the introduction of lattice structures increases the natural frequencies of the first six oscillation forms by 86–125 %, which contributes to an increase in the dynamic strength of the heat exchanger.

5. The expediency of using lattice structures to increase the service life of heat exchangers is shown. Increasing natural frequencies minimizes dangerous low-frequency deformations, which reduces the risk of structural failure during prolonged operation.
6. Further investigation of the empirical dependences of the heat transfer parameters on the characteristics of the lattice is recommended. It is proposed to use numerical methods to optimize the geometry of lattice structures in order to increase their efficiency and reliability in heat exchangers.

The aggregate of the above points forms an overall academic assessment establishing a comprehensive relationship between the use of lattice designs, heat transfer intensification and improved strength performance of heat exchangers. The results, validated by numerical simulations and frequency analysis, demonstrate practical value in optimizing heat exchangers for regimes with different Reynolds numbers. The study contributes to the theory of heat transfer and strength calculations, offering new engineering approaches and forming the basis for further development of empirical dependencies of heat transfer parameters on the characteristics of grids, which has prospects for improving the energy efficiency and durability of equipment.

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