UDC 539.3

INVESTIGATION OF A STRESS-STRAINED STATE OF A SCREW-SHAPE TUBE OF HEAT EXCHANGER

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Based on the results of the study of the parameters of the air flow inside of the brass screw-shaped tube of the heat exchanger, the determination of their optimal geometric characteristics and further modeling of the stress-strain state was performed. Verification of simulation results is carried out on the basis of comparison with the test problem.

Keywords: heat transfer, screw-shaped tube, evenly developed surface, forced convection, elastic deformation, stress-strain state.

1. Introduction

One of the ways to increase the efficiency of the gas transmission system is the use of air heaters (regenerators) to utilize the heat of the exhaust gases in the turbine. The creation of new highly efficient and reliable gas transmission units (GTU), as well as the modernization of existing ones, is impossible without the use of reliable and efficient elements of heat exchange in their designs. Screw-shaped pipes with an evenly developed surface meet such requirements

The proposed screw-shaped heat exchange tubes with an evenly developed surface have been comprehensively studied by the authors of publications [1-3]. Their design allows us to increase significantly (in 1.15-1.4 times) both external and internal heat transfer surface. Due to the screw-shaped protrusions-depressions with a given height-depth, which alternate sequentially with a some step, they provide additional turbulence of the air's boundary layer [3]. Due to the twisting of internal and external flows and a sharp change in flow rate when washing the surface there is a simultaneous increase in the intensity of internal and external heat transfer by 1.5-2.5 and 1.1-1.3 times, respectively, depending on the geometric characteristics of the tubes and the steps between them. Due to this, the heat transfer coefficient increases by 25-70% compared to smooth cylindrical tubes.

The technology of obtaining of screw-shaped profiles of tubes, based on the joint use of three-roller and single-roller running heads, was developed at the Mechanical Engineering Institute of Igor Sikorsky KPI [4].

The screw-shaped tubes, studied by the authors [1-3], had an outer diameter of 36 mm and small steps between depressions and protrusions (8-12 mm) at the heights of depressions or protrusions of a 4-5 mm. Increasing the use of screw-shaped tubes with a uniform surface in the industry requires expanding the range of their geometric characteristics. It is possible due to a new technology [5], which allows to obtain brass tubes with a diameter of 16 mm.

Fig. 1. Long dimensional screw-shaped tube (diameter 16 mm, step 8 mm), made in one pass

It is necessary to conduct studies of air flow and to determine on this basis a stress-strain state of these tubes under the influence of the appropriate internal pressure for further wide use of it. This will contribute to the expansion of the use of a new technologies for mass production of screw-shaped profile tubes with an uniform surface, which is currently absent in Ukraine.

The goal of the work is to determine the optimal geometric characteristics of screw-shaped tubes, the surface of which is created on a single-west helical line, and to determine their stress-strain state under non-isothermal conditions. The main geometric parameters that affect the configuration of the outer surface of the tube are the pitch and the height of the protrusions-depressions of the helix. The analysis was performed at a variable pitch values, which was taken of 8, 12 and 20 mm. The height of the protrusions-depressions of the helical line remained unchanged and was 2.5 mm for all three studied pitch value. The values of the parameters, taken for analysis, are determined by technological difficulties associated with the capabilities of the three-roller rolling technology, which is used in the manufacture of tubes. Therefore, determining of the optimal geometric characteristics of screw-shaped tubes is reduced to finding the optimal pitch of the helical line, which is determined by the achievement of the maximum thermal power that can be dissipated by the screw-shaped tube under all other conditions.

The following tasks were solved to achieve of this goal:

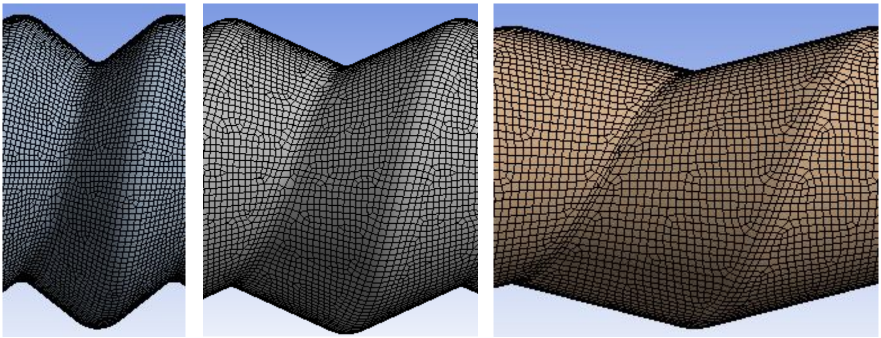
- development of CFD-model of screw-shaped tube with uniform surface;
- carrying out of test calculations and calculation of thermoaerodynamic characteristics of the investigated screw-shaped tubes;
- implementation of stress-strain state analysis of screw-shaped tubes.

2. Methods for studying of the flow structure inside the screw-shaped tubes

The following analysis was performed using the developed finite-element CFD-models of screw-shaped tubes using of the software package ANSYS-Fluent. The problem was solved in a stationary setting in compliance with the requirement to achieve no dependence of the solution from the calculation mesh density (convergence of results). During modeling, the following boundary conditions were chosen to be constant for all tube sizes:

- flow temperature at the entrance to the screw-shaped tube t_{ent} = 26°C;
- temperature of tube wall t_w = 100°C;
- air flow through the tube, which was chosen equal to $9\cdot10^{-4}$, $9\cdot10^{-3}$, $3\cdot10^{-2}$ kg/s.

The appearance of the fragment of finite-element mesh of the investigated tube of standard sizes is given in Fig. 2.



(a) (b) (c)

Fig. 2. Finite element mesh of a screw-shaped tube model with a pitch of a helix of 8 mm (a), 12 mm (b) and 20 mm (c)

The equations system for describing the processes of momentum and heat transfer inside the studied tube includes the equations of continuity, motion and energy in the Reynolds form of the following view:

$$\frac{\partial \overline{U}_j}{\partial x_j} = 0 , \tag{1}$$

$$\frac{\partial \overline{U}_i}{\partial \tau} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\nu + \nu_{\text{т}}\right)\left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}E\right], \tag{2}$$

$$\frac{\partial \bar{t}}{\partial \tau} + \overline{U}_j \frac{\partial \bar{t}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\nu}{\Pr} + \frac{\nu_{\text{т}}}{\Pr_{\text{т}}}\right)\frac{\partial \bar{t}}{\partial x_j}\right]. \tag{3}$$

Assuming the complex nature of the flow in this object, which combines features characteristic of both near-wall and free shear flows, in order to close the basic system of equations (1) - (3) RSM model of Reynolds' stresses was used. The turbulent Prandtl's number for the considered conditions was assumed to be equal to 0.9.

The numerical solution of the system of basic and model equations was based on an implicit ordinary-volume approach using the COUPED pressure correction procedure. The calculation area was covered with a non regular tetrahedral mesh, which was thickened to the walls of the channel. The minimum size of the mesh step was chosen according to the recommendations

[6], the maximum number of finite elements, required for the calculation area sampling was about 4 million. For all system equations the criterion of accuracy of the solution was 10^{-5}.

3. The results of study of the flow structure inside the screw-shaped tube

3.1 Verification of the CFD model was provided using of the CFD-model of a smooth cylindrical tube with an inner diameter and length (16 mm and 500 mm, respectively), which coincide with the studied models of the screw-shaped tube. The study was conducted under the boundary conditions, using of turbulence model and at the same density of finite element mesh, which was were specified in section 2.

To compare the obtained results of numerical simulation - the heat transfer intensity and aerodynamic resistance in the turbulent flow regime a calculated dependences, given in [7, 8], were used:

$$\mathrm{Nu}_{\mathrm{liq}} = 0.021\mathrm{Re}_{\mathrm{liq}}^{0,8}\,\mathrm{Pr}_{\mathrm{liq}}^{0,43}\left(\mathrm{Pr}_{\mathrm{liq}}/\mathrm{Pr}_{\mathrm{wl}}\right)^{0,25}\varepsilon_l\,, \tag{4}$$

$$\Delta p = \xi\frac{l}{d}\frac{\rho w^2}{2}, \tag{5}$$

where

$$\xi = \frac{0,31464}{\mathrm{Re}_d^{0,25}}. \tag{6}$$

The correction for the initial section Δ_l, was chosen according to the recommendations [7].

According to the estimates being made using of the above dependences, the calculated data error of heat transfer parameter is 1.2%, and the aerodynamic resistance − 5.8%. Thus, we can conclude that the developed CFD model can be used to calculate heat transfer and hydrodynamics of screw-shaped tubes.

Thermal power is determined by means of ANSYS-Fluent (Fig. 2) by determining the enthalpy of flow at the inlet-outlet of the tube. Based on the obtained data, dimensionless characteristics of heat transfer intensity and aerodynamic resistance for different pitch value *t* of the helical line of the tube were calculated (Figs. 3, 4).

Analysis of Fig. 3 shows that when the air flow in the studied tubes both turbulent and transient flow regime was observed, as evidenced by the characteristic break of the curves at $\mathrm{Re}_d = (8-12)\cdot 10^3$. In its turn this confirms the increase in the intensity of heat transfer in turbulent flow. These results also show that in the case of the use of screw-shaped tubes, the intensity of heat transfer increases by almost 50% compared to a smooth cylindrical one of the same length and outer diameter. It can also be stated that among the studied standard sizes of screw-shaped tubes, the largest heat flux (19 W) can be dissipated by a tube with a helical line pitch of 8 mm. This tube is also characterized by a larger heat transfer surface (3%) than all other ones.

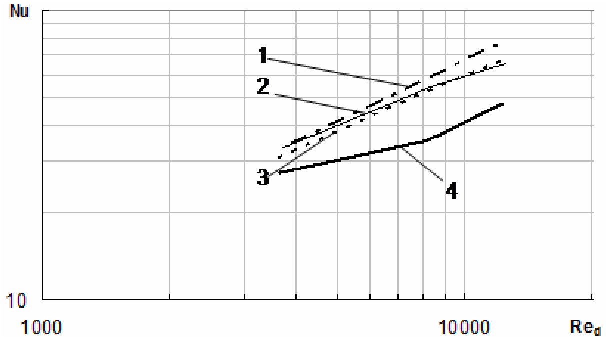


Fig. 3. Analysis of the thermal characteristics of screw-shaped tube (1 - t = 8 mm, 2 - t = 12 mm; 3 - t = 20 mm, 4 - smooth cylindrical tube)

The increase of heat transfer intensity is inextricably linked with the increase in aerodynamic resistance. Thus, for a screw-shaped tube with a pitch of 8 mm, the increase in heat transfer intensity by 50% is accompanied by an increase in aerodynamic resistance by 9...10 times. It should be noted that the screw-shaped tubes of helical line pitch of 20 mm, is able to increase the intensity of heat transfer by 30% while increasing the aerodynamic resistance in 5 ... 6 times.

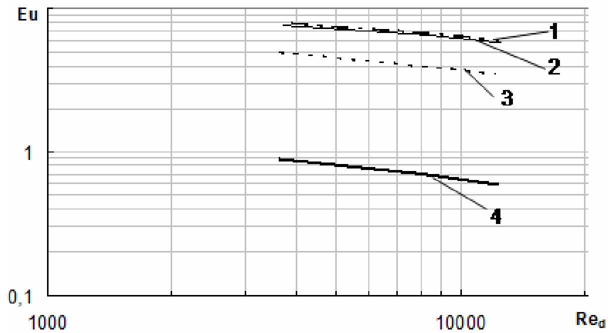


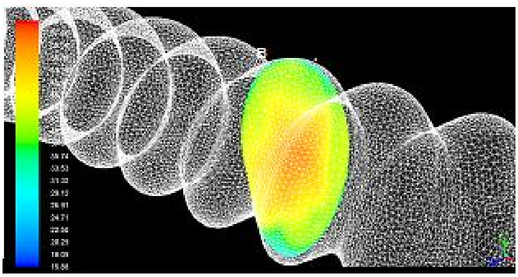
Fig. 4. Aerodynamic resistance of screw-shaped tubes: (1 - t = 8 mm, 2 - t = 12 mm; 3 - t = 20 mm, 4 - smooth cylindrical tube)

This value of aerodynamic resistance is due to an increase in local resistances, i.e. more helix turns at a given length. Therefore, the depth of the protrusions-depressions of 2.5 mm on the helical surface is too large, it would be desirable to reduce it to 1 ... 1.5 mm, as recommended by the authors [9].

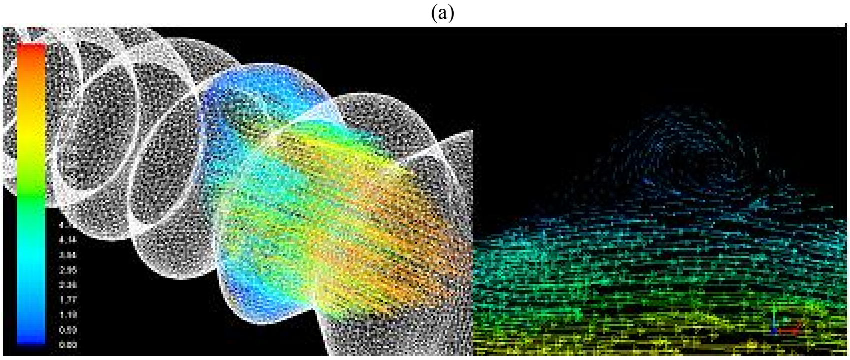
The results of the flow structure analysis in the middle of the screw-shaped tubes are shown below. The set of velocities distribution, temperatures, vectors of average and tangential velocity, as well as current lines in the middle of the studied helical pipes are given. This analysis allowed us to investigate more fully the picture of hydrodynamic flow in the investigated screw-shaped tubes and will allow explaining which the processes lead to an increase of heat transfer.

When constructing the shape of screw-shaped tubes, the assumption was applied that the heat transfer intensity will increase due to vortex formation in the protrusions-depressions of the tube surface. So that the results of numerical study of the flow structure obtained for a fixed Reynolds number $\mathrm{Re}_d = 3{,}5 \cdot 10^3$ which corresponds to the average flow velocity of 4 m/s, represented in the plane that intersects the generating coil (Fig. 5).

As it shown in Fig. 5, the temperature field is quite homogeneous − there are no significant areas of low temperature that would occur due to the formed stagnant zones. The flow current lines are twisted together to create a geometric shape like a spiral. In the protrusions-depressions of the helical tube, the interaction of the vortex harness and the non-twisted core of the flow lead to the creation of a three-dimensional vortex, which rotates counterclockwise and moves along the axis of the tube. The local flow rates near the wall of the tube are large, which promote the access of the cold coolant to the heated wall of the heat exchange surface than to increase the heat transfer characteristics of the screw-shape tube as a whole.



(a)



(b)

Fig. 5 Distribution of temperatures (a) and average velocities (b) in the central cross section of the screw-shape tube, and vectors of average speed in the corners of the protrusions-depressions of the tube with a pitch of the helical line t = 8 mm

The above conclusions about the flow development in the volume of a screw-shape tube (pitch of the helical line t = 8 mm) are valid for tubes of helical pitch is 12 and 20 mm (Fig. 6 and 7) also. The differences begin in the scale and location of the vortex harness in the protrusions-depressions of the helical surface of the tube. Thus, in a case of line pitch t = 12 mm, the vortex formed in the depressions-protrusions is shifted to their top and has a scale close to the radius of curvature at the top of the protrusion-depression of the helical surface. The flow enters freely to the space of the depression and comes into contact with the heated wall. For a screw-shape tube with a pitch of the helical line t = 20 mm, the vortex in question is not formed, and the increase in heat transfer intensity (compared to a cylindrical tube) is associated with the creation of process, preventing to the development and future closure of developing boundary layers on the walls of the screw-shape tube. This reduces the thermal resistance of heat transfer and improves the tube thermal characteristics as a whole.

The above circumstance, regarding the transformation of the flow structure due to the increase in the helical line pitch, which forms the shape of the tube, indicates a decrease in aerodynamic resistance. Indeed, for screw-shape tube with helix steps of 8, 12 and 20 mm to achieve a speed of 4 m/s it is necessary to provide a pressure drop of 124, 78 and 54 Pa respectively. Looking ahead, it must be stated that a smooth cylindrical tube with the same inner diameter has an aerodynamic resistance of 14 Pa.

The resulting situation is quite ambiguous: on the one hand, screw-shape tubes are able to dissipate significantly more heat than smooth cylindrical ones, on the other hand they have high aerodynamic resistance. This result has a simple explanation - the flow in such pipes of the specified length of 500 mm is typical for the initial section. According to the known literature data for a cylindrical tube, the length of the hydrodynamic stabilization section is determined from the condition $L = 50d$, where d is the inner diameter of the tube. In the case of the cylindrical tube studied in this work, we have a stabilized flow, which explains the value of its aerodynamic resistance.

Summarizing the above, it can be stated that the shape of the screw-shape tube allows to organize the movement of the coolant along the helical line, while mixing both the wall layers and the flow core, which generally leads to a significant increase in heat transfer intensity compared to a smooth cylindrical tube of the same diameter. Screw-shape tubes are able to dissipate almost twice the heat flow than a smooth ones, but have aerodynamic resistance in 6… 10 times greater. In this case, the increase in the intensity of heat transfer is affected only by the possibility of organizing the movement along the helical line, and the change of pitch does not cause a significant increase in heat dissipation.

4. Stress-strain state analysis

Using the determined characteristics of heat flow and temperature distribution the stress-strain state of screw-shape tube under the action of internal pressure and the temperature load of the flow on their walls was modeled. The results of calculating of the stress and strain distribution of the model of a screw-shape tube with a helical line pitch of 12 mm are presented in Fig. 6. The values of deformation intensity (Total deformation) and stresses

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intensity factor (Equivalent von-Mises stress) were chosen for the analysis. For all other studied forms of the surface of screw-shape tube (the helical line pitch of 8 and 20 mm) the level of stresses and strains is almost the same.

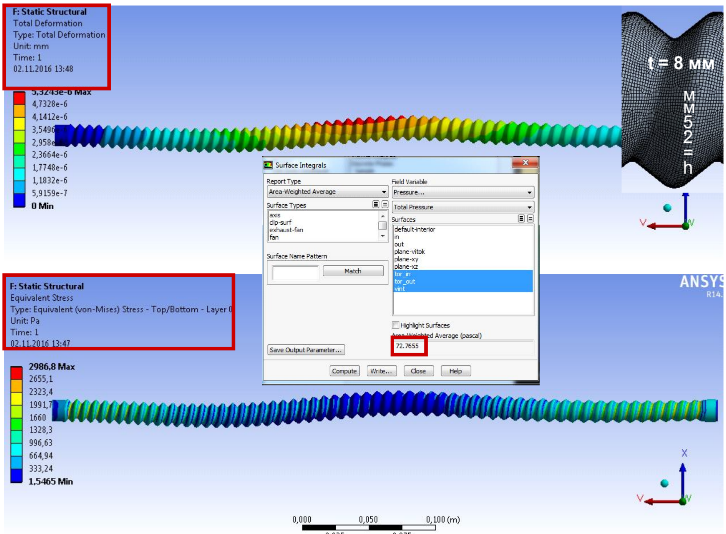

Fig. 6. Distribution of stresses and strains of the screw-shape tube (t = 12 mm)

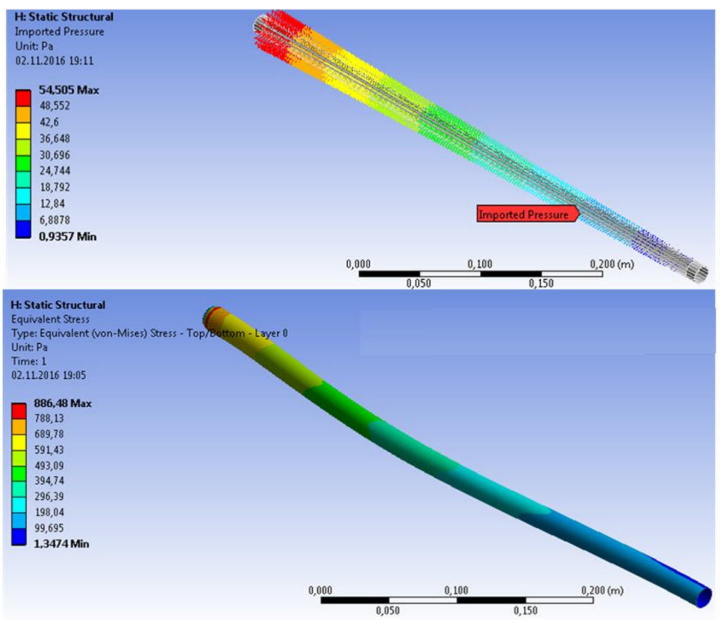

Fig. 7. Distribution of stresses and strains of a smooth cylindrical tube
(inlet temperature 333.15 K = 60°C)

Analysis of this results indicates that for a pressure drop of 74 Pa at an average wall temperature of 48 ° C, the largest displacement values of the tube walls are $5{\cdot}10^{-6}$ mm. This corresponds to a stress intensity of 1300 Pa. It should be note that the stress due to the excess internal pressure in a smooth cylindrical tube (Fig. 7) is 480 Pa.

5. Conclusions

1. Under conditions of ensuring a constant flow rate, the optimal helical line pitch is 8 mm. In this case, while maintaining other constant parameters, the screw-shape tube is able to dissipate almost twice much of heat.

2. For the investigated standard sizes of screw-shape tube (helical line pitch of 8 and 12 mm) growth of heat exchange intensity on 44 ... 50% is followed by growth of aerodynamic resistance in 9 ... 10 times, and for a pitch value of 20 mm heat exchange intensity increases by 30% at simultaneous increase in aerodynamic resistance in 5 ... 6 times.

3. Based on numerical simulation data, it is shown that the largest values of displacements are $5{\cdot}10^{-6}$ мм. In screw-shape tube, this corresponds to a stress of 1300 Pa, which is 2.5 times more than for a cylindrical tube.

It should be noted that obtained results are approximate, as they do not take into account heat transfer from the outer surface and do not reveal all the possibilities of using a uniformly helical surface as an industrial element of heat exchangers, but their efficiency compared to cylindrical tubes is obvious. Study the industrial use of screw-shape tube with a uniform surface needs additional experiments. In addition, due to the complexity of the helical surface configuration, the stress state of such tubes is significantly heterogeneous, and the stress values significantly exceed those that occur under the same conditions in cylindrical tubes. Therefore, the solution of the question of safe operation of the proposed tubes with a helical surface requires numerical analysis of the stress-strained state at different modes of heat load.

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ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ГВИНТОПОДІБНИХ ТРУБ ТЕПЛООБМІННИХ АПАРАТІВ

На основі результатів дослідження параметрів течії повітряного потоку всередині латунної гвинтоподібної труби теплообмінного апарату проведено визначення їх оптимальних геометричних характеристик і подальше моделювання напружено-деформованого стану. Верифікація результатів моделювання здійснена на основі зіставлення з тестовою задачею.

Ключові слова: теплообмін, гвинтоподібна труба, равноразвітая поверхню, вимушена конвекція, пружне деформування, напружено-деформований стан.

Pyskunov S., Trubachev S., Baranyuk O.

INVESTIGATION OF A STRESS-STRAINED STATE OF A SCREW-SHAPE TUBE OF HEAT EXCHANGER

Based on the results of the study of the parameters of the air flow inside of the brass screw-shape tube of the heat exchanger, the determination of their optimal geometric characteristics and further modeling of the stress-strain state was performed. Verification of simulation results is carried out on the basis of comparison with the test task.

Keywords: heat transfer, helical tube, evenly developed surface, forced convection, elastic deformation, stress-strain state.

Пискунов С.О., Трубачев С.И., Баранюк А.В.

ИССЛЕДОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ВИНТООБРАЗНЫХ ТРУБ ТЕПЛООБМЕННЫХ АППАРАТОВ

На основе результатов исследования параметров течения воздушного потока внутри латунной винтообразной трубы теплообменного аппарата проведено определение их оптимальных геометрических характеристик и дальнейшее моделирование напряженно-деформированного состояния. Верификация результатов моделирования осуществлена на основе сопоставления с тестовой задачей.

Ключевые слова: теплообмен, винтообразная труба, равноразвитая поверхность, вынужденная конвекция, упругое деформирование, напряженно-деформированное состояние.

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На основі результатів аналізу параметрів течії повітряного потоку визначено оптимальні геометричні характеристики гвинтоподібних труб та подальше моделювання їх напружено-деформованого стану.

Табл. 0. Іл. 7. Бібліогр. 9 назв.

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Based on the results of the analysis of the parameters of the air flow, the optimal geometric characteristics of the helical pipes and further modeling of their stress-strain state are determined..
Table 0. Fig. 7. Ref. 9

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На основе результатов анализа параметров течения воздушного потока определены оптимальные геометрические характеристики винтовых труб и дальнейшее моделирование их напряженно-деформированного состояния.
Табл. 0. Рис. 7. Библиогр. 9 назв.

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