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MULTIPHYSICAL MODELING OF A PIPE-IN-PIPE HEAT EXCHANGER WITH A FLOW INTENSIFIER IN THE FORM OF A TWISTED PROFILED STRIP

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Abstract: The article discusses the multiphysical modeling of a pipe-in-pipe heat exchanger using a flow intensifier in the form of a twisted profiled strip. The introduction presents the results of an analysis of the literature on the presented topic, the method of multiphysical modeling of the heat exchanger pipe-in-pipe is presented. The results of numerical researches of heat transfer and friction coefficient under twisted flow conditions using CFD-modelling with the software complex COMSOL multytphisics 6.1 are presented. The data obtained as a result of CFD modeling were compared with the literature data, the data obtained show that the heat transfer coefficient and the coefficient of friction increased significantly in a pipe equipped with a flow intensifier in the form of a twisted profiled strip. The analysis conducted is aimed at evaluating the efficiency of heat exchange and optimizing the design of the apparatus. The use of a twisted strip as a flow intensifier allows to significantly improve heat exchange characteristics by improving turbulence and reducing temperature gradients. The modelling was carried out using numerical methods, which allows to take into account the complex interaction of thermal and hydraulic processes. The results of the research show that optimizing the size and location of the intensifiers can lead to further improvement of heat exchange characteristics. The results of the research show that optimizing the size and location of the intensifiers can lead to further improvement of heat exchange characteristics.

Keywords: CFD modeling, intensification, heat transfer, multiphysical modeling, heat exchanger, pipe in pipe, flow intensifier, twisted profiled strip.

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Аннотация. Мақалада бұралған профильді таспа түріндегі ағынды күшейткіштің көмегімен «құбыр ішіндегі құбыр» жылу алмастырғышты мультифизикалық модельдеу қарастырылады. Кіріспеде ұсынылған тақырып бойынша әдебиеттерді талдау нәтижелері келтірілген, «құбыр ішіндегі құбыр» жылу алмастырғышты мультифизикалық модельдеу әдістемесі ұсынылған. COMSOL multytphisics 6.1 бағдарламалық кешенін, CFD модельдеуді пайдалана отырып, бұралған ағын жағдайында жылу беру сипаттамалары мен үйкеліс коэффициентін сандық зерттеу нәтижелері ұсынылған. CFD модельдеуінен алынған мәліметтер әдеби деректермен салыстырылды, алынған мәліметтер жылу беру коэффициенті мен үйкеліс коэффициенті бұралған профильді жолақ түріндегі ағын күшейткішімен жабдықталған құбырда айтарлықтай өскенін көрсетеді. Жүргізілген талдау жылу алмасудың тиімділігін бағалауға және аппарат құрылымын оңтайландыруға бағытталған. Бұралған жолақты ағынды күшейткіш ретінде қолдану турбуленттілікті жақсарту және температура градиенттерін азайту арқылы жылу алмасу өнімділігін айтарлықтай арттыруға мүмкіндік береді. Модельдеу жылулық және гидравликалық процестердің кешенді өзара әрекеттесуін ескеруге мүмкіндік беретін сандық әдістерді қолдану арқылы жүзеге асырылды. Зерттеу нәтижелері күшейткіштердің көлемі мен орналасуын оңтайландыру жылуалмасу сипаттамаларын одан әрі жақсарту мүмкін екенін көрсетеді. Алынған нәтижелер энергетика мен мұнай-химияны қоса алғанда, әртүрлі салаларда тиімдірек жылу алмастырғыштарды жобалау үшін пайдалы болуы мүмкін.

Түйін сөздер: CFD модельдеу, интенсификация, жылу алмасу, мультифизикалық модельдеу, жылу алмастырғыш, құбыр ішіндегі құбыр, ағын күшейткіші, бұралған профильді жолақ.

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МУЛЬТИФИЗИЧЕСКОЕ МОДЕЛИРОВАНИЕ ТЕПЛООБМЕННОГО АППАРАТА «ТРУБА В ТРУБЕ» С ИНТЕНСИФИКАТОРОМ ПОТОКА В ВИДЕ ВИТОЙ ПРОФИЛИРОВАННОЙ ЛЕНТЫ

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Аннотация: В статье рассматривается мультифизическое моделирование теплообменного аппарата «труба в трубе» с использованием интенсификатора потока в виде витой профилированной ленты. Во введений приведены результаты анализа литературы по представленной тематике, представлена методика мультифизического моделирования теплообменника «труба в трубе». Представлены результаты численных исследований характеристик теплопередачи и коэффициента трения в условиях закрученного потока с использованием CFD –моделирования с использованием программного комплекса COMSOL multytphisics 6.1. Данные, полученные в результате CFD-моделирования, были сверены с литературными данными, полученные данные показывают, что коэффициент теплопередачи и коэффициент трения значительно увеличились в трубе, оснащенной интенсификатором потока в виде витой профилированной ленты. Проведённый анализ направлен на оценку эффективности теплообмена и оптимизацию конструкции аппарата. Применение витой ленты как интенсификатора потока позволяет существенно повысить теплообменные характеристики за счёт улучшения турбулентности и уменьшения градиентов температуры. Моделирование выполнено с использованием численных методов, что позволяет учесть комплексное взаимодействие тепловых и гидравлических процессов. Результаты исследования показывают, что оптимизация размеров и расположения интенсификаторов может привести к дальнейшему улучшению теплообменных характеристик. Полученные данные могут быть полезны для проектирования более эффективных теплообменников в различных отраслях, включая энергетику и нефтехимию.

Ключевые слова: CFD моделирование, интенсификация, теплообмен, мультифизическое моделирование, теплообменный аппарат, труба в трубе, интенсификатор потока, витая профилированная лента.

Introduction.

The heat exchanger is classified according to the transfer process, the amount of liquids, the degree of surface sealing, the design, the location of the flows, the heat transfer mechanism. Industrial enterprises assign heat exchangers depending on cost, high/low pressure limits, thermal characteristics, temperature range, liquid throughput, degree of purification. Heat exchangers, and especially double-pipe heat exchangers, play an important role in industrial and engineering applications such as air conditioning systems, petrochemical industry, power plants, refrigeration equipment, solar water heaters, The reprocessing industry, chemical and nuclear reactors. Due to this variety of applications, convective heat transfer in heat exchangers has been investigated in several studies over the past decades, and various methods of improving heat transfer have been presented to improve the overall heat transfer efficiency of heat exchangers. The use of a double pipe with lattice strip inserts (Quadir, et al, 2014), a finned double pipe (Gao, et al, 2015), a double pipe filled with metal foam (Shirvan, et al, 2016), and spiral wires in two-tube heat exchangers (Zhang, et al, 2023) are some of these methods. In addition, the special properties of nanofluids have been the subject of interest in a number of studies aimed at improving heat transfer for other applications (Yadav, et al, 2019). Among the previously studied researches of the efficiency of heat transfer in heat exchangers, the following studies can be mentioned: Singh and co-authors (Singh, et al, 2020) conducted an experimental study of the efficiency of heat transfer, coefficient of friction, specific heat capacity and viscosity of a two-tube heat exchanger with countercurrent motion. They found that the heat transfer of the working fluid can be enhanced by increasing the Reynolds number or the percentage of nanomaterials. An experimental research of the effect of intermittent spiral turbulators on the flow and heat transfer characteristics in a two-tube water-air heat exchanger was carried out by Sheikholeslami and co-authors (Sheikholeslami, et al, 2016). The results showed that increasing the coefficient of the open surface and the angle of inclination reduces the coefficient of friction and the Nusselt number. In addition, thermal performance improves with an increase in the coefficient of the open surface, but decreases with an increase in the angle of inclination. Nakhchi et al. (Nakhchi, et al, 2020) conducted a numerical research of a multi-criteria analysis of the design of two-tube heat exchangers of a new shape (conical). This article analyzes the influence of hydraulic, geometric and thermodynamic characteristics. Under optimal conditions, the results showed a 55% increase in efficiency and a 40% improvement in heat transfer. It should be noted that when choosing in practice one or another method of heat transfer intensification, it is necessary to take into account not only the efficiency of the surface itself, but also its versatility for various single-phase and two-phase heat carriers, the manufacturability of the surface, the manufacturability of the heat exchanger assembly, strength requirements, surface contamination, operating characteristics, etc. All these circumstances significantly reduce the possibility of choosing one of the numerous methods of intensification studied (Syah, et al, 2022; Kassymov, et al, 2023).

The rapid development of computer technology and methods for numerically solving problems of heat transfer and hydrodynamics using multiphysical modeling programs has led to the fact that in many fields of science and technology, the results of multiphysical modeling of heat transfer and mass transfer processes become an essential element (Krutova, et al, 2020).

The study presents the results and conclusions obtained as a result of a study of the performance and optimization of a two-tube heat exchanger. Numerical modelling using ANSYS Fluent has successfully predicted the temperature of both hot and cold liquid outlet (Urvija, et al, 2024).

The results obtained by modeling make it possible not only to correctly comprehend and understand the physical effects observed on experimental devices, but also in certain cases to completely replace the natural experiment with computer modeling (Pulin, et al, 2024).

Currently, CFD packages for calculating heat transfer, mass transfer and hydrodynamics are widely used for engineering calculations and research. All CFD packages consist of preprocessors, a solver, and a postprocessor (Mukhametzyanov, et al, 2017).

As can be seen from the analysis of scientific and technical literature, heat exchangers with various flow intensifiers are currently of interest from the point of view of the development of heat exchange equipment, since they have higher efficiency. Thus, the multiphysical modeling and study of heat transfer processes in such devices is an actual task (Tsvetova, 2022; Abiev, 2002).

The purpose of this work is to research the effectiveness of a flow intensifier in the form of a twisted profiled strip using the COMSOL multitphisics software complex (Electronic resource Comsol 6.1., 2022).

To achieve this objective, it is necessary to solve the following tasks:

– construction of three-dimensional models of a heat exchanger with a flow intensifier in the form of a twisted profiled strip;

– numerical modeling of heat transfer in the tube and inter-tube areas of the apparatus with a flow intensifier in the form of a twisted profiled strip of the "pipes in a pipe" type;

– determination of thermal and hydraulic characteristics;

– evaluation and analysis of the results obtained.

Materials and methods.

For the multiphysical modeling of the pipe-in-pipe heat exchanger, the type of intensifier in the form of a profiled twisted strip installed inside the flow part of the pipe with a given pitch is studied; the profiled twisted strip located with a certain pitch and the flow part of the pipe are shown in Figure 1. The step between the turbulators in the studied cases was chosen for reasons of ensuring the maximum intensity of heat transfer according to the recommendations of the work (Jithin, et al, 2020) and is t = 40 mm, and the twist angle of the twisted strip is 360^0. The length of the section L in numerical researches was 150 mm. The heat exchanger operates in parallel flow mode, i.e. the cooled and heated flow moves in the same direction. In numerical modeling, the physical constants of water viscosity were equated, respectively, to heating temperatures in a smoothed tabular reference manner: at 20 °C — 1,002 MPa·s; at 40°C — 0,653 MPa·s; at 60 °C — 0,467 MPa·s; at 100 °C – 0,282 MPa·s. The specific heat capacity of water was taken at a temperature of 25°C c=4180 J/kg °C.

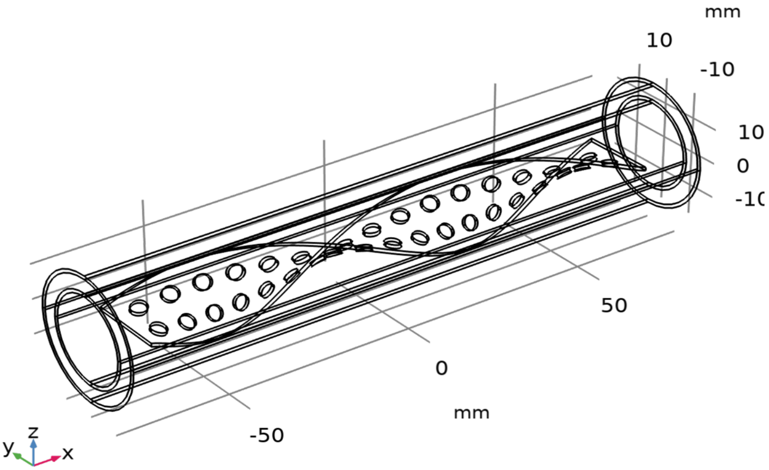


Figure 1 – 3D model of a "pipe in pipe" heat exchanger with a flow intensifier in the form of a twisted profiled strip

When solving any problem, the aim is always to find a solution in some computational domain. As a rule, the size and shape of the computational domain are naturally determined by the problem under research. The creation and generation of a grid of the computational domain is an essential component of every engineering calculation where software packages based on CFD technology are used. The size of the calculated model grid directly affects the accuracy of the final results, the speed of calculation and accuracy (Figure 2).

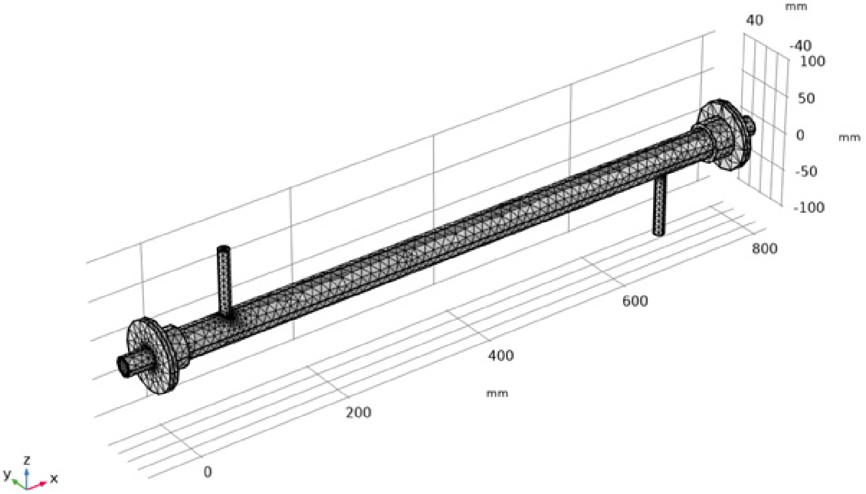


Figure 2 – Model grid *Mesh* of the heat exchanger

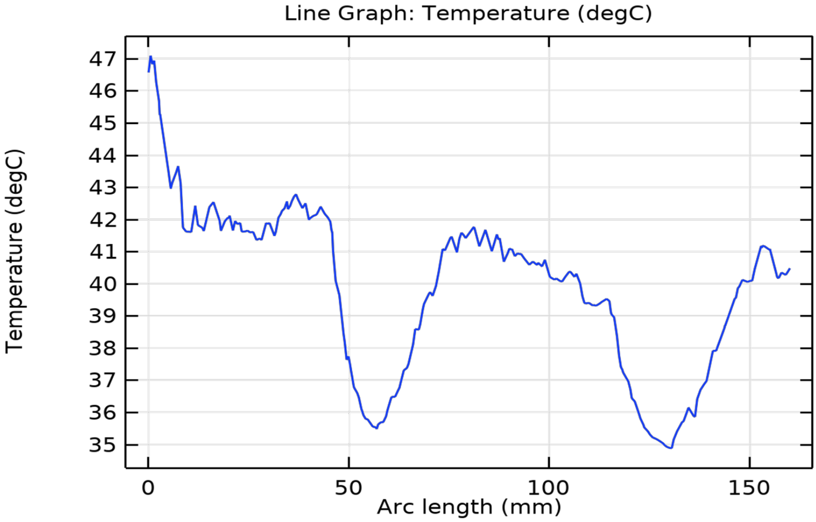
Heat transfer was studied during turbulent and laminar water flow with the following parameters at the entrance to the inner pipe: average temperature $T\infty$ = 50°C, at the entrance to the outer pipe: average temperature $T\infty$ = 19.3°C, pressure $P\infty$ = 0.1 MPa, degree of turbulence $Tu\infty$ = 0.1%, velocity profile – turbulent developed and laminar flow. Boundary conditions of the first kind Tw = const were set. The similarity numbers were calculated based on the average outgoing liquid velocity *wcp* and the determining inner diameter of the pipe *D*. The turbulent Prandtl number for the conditions under consideration was taken to be 0.9. The Reynolds number in the inner tube was varied from Re=440 to Re=800, and in the outer tube the Reynolds number varied from Re=2430 to Re=7300.

The numerical solution of the equations was based on an implicit finite-volume approach using the Global Definitions pressure correction procedure. The calculated area was covered with an uneven tetrahedral grid with condensation to the channel walls. The size of the minimum step of the grid nodes was selected according to the recommendations (Belov, et al, 2001). The maximum number of cells required to discretize the computational domain was ~4 million. For all equations of the system, the convergence criterion of the solution was 10^{-5}.

Experimental part. CFD modeling can be used for in-depth analysis of the movements of liquids and their interaction with the coils of the profiled strip. This will help to obtain data on the distribution of velocity, temperature and pressure, as well as identify potential areas for improvement of the structure. The correct choice of the turbulence model (identification) and verification (verification) according to known experimental data were carried out using four models: the standard high-Reynolds k-ε model (k-ε Standard), the Realizable k-ε model, the k-ω shear stress transfer model (SST) of Menter and the Reynolds stress model (RSM). The turbulence model was identified for smooth pipes and pipes with internal intensifiers with unchanged geometric characteristics and density of the calculated grid.

The distributions of heat transfer coefficients and hydrodynamic resistance are selected as criteria for the adequacy of the turbulence model and the correctness of CFD modeling.

Heat transfer and resistance in a smooth pipe more correctly describe the k-ε turbulence models, however, they incorrectly predict changes in the average characteristics of heat transfer and resistance for pipes with turbulators. The data on heat exchange and resistance of pipes with turbulators, calculated using the k-ω SST model, deviate by 32% from the results of experimental researches. The best identification by heat transfer (Fig. 3 and 5) and resistance (Fig. 4 and 6) is shown by the RSM model of Reynolds stresses. At the same time, the maximum deviation of the data does not exceed 0.4% compared to the known dependencies. Figure 3 a and b show the temperature change of the flows along the length of the apparatus in laminar flow mode in the inner and outer pipe. The temperature peaks correspond, according to the geometric model of the device, to precisely such places where the profile strip is twisted and the gap between the strip and the pipe is minimal.



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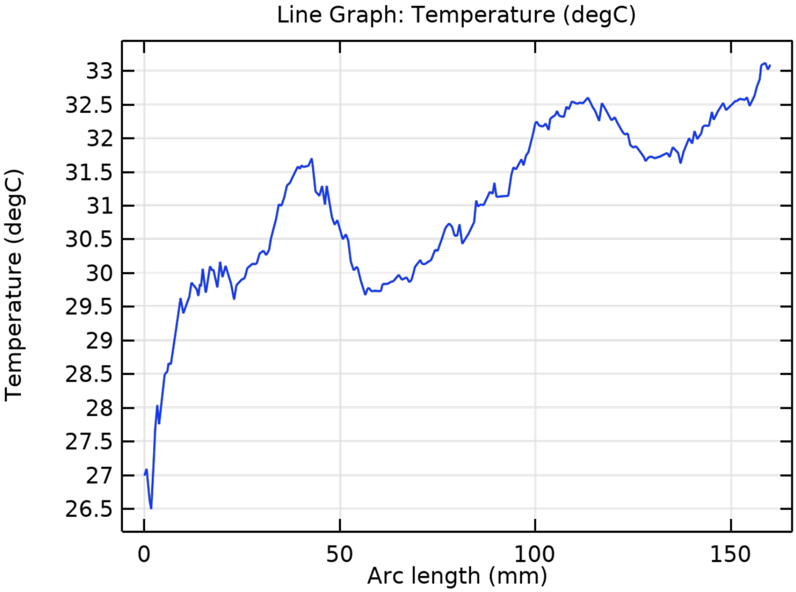
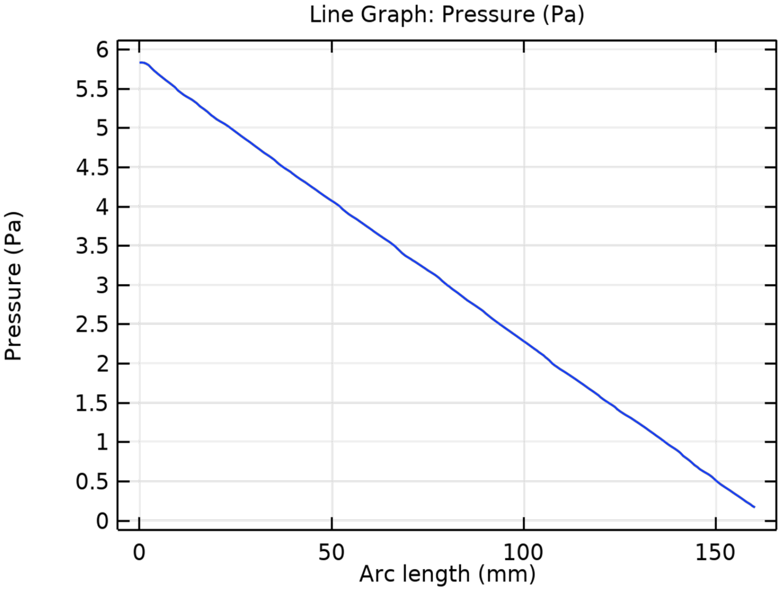


b)

a) inner pipe, b) outer pipe
Figure 3 – Temperature change of flows along the length of the heat exchanger during laminar flow movement



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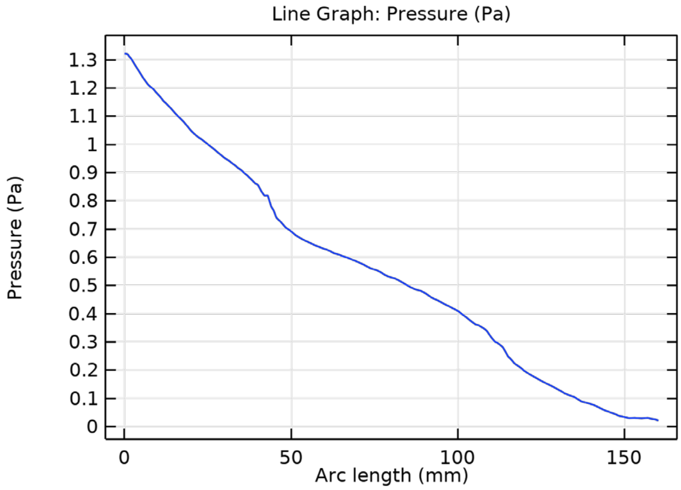
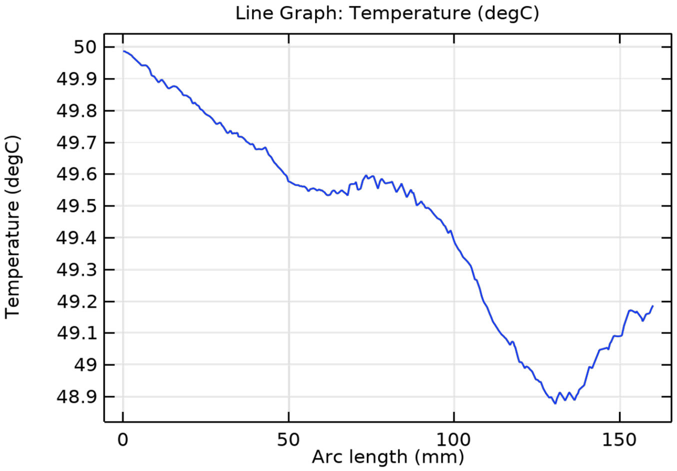


b)

a) outer pipe, b) inner pipe
Figure 4 – Flow pressure change along the length of the heat exchanger during laminar flow movement

From Figure 4, it can be concluded that in the outer pipe, in the laminar mode, the pressure decrease along the length of the apparatus occurs uniformly, when this phenomenon occurs abruptly in the inner pipe, this is explained by the fact that a profiled twisted strip is installed in the inner pipe to intensify heat transfer.

A similar pattern can be observed in the turbulent regime in Figures 5 and 6.



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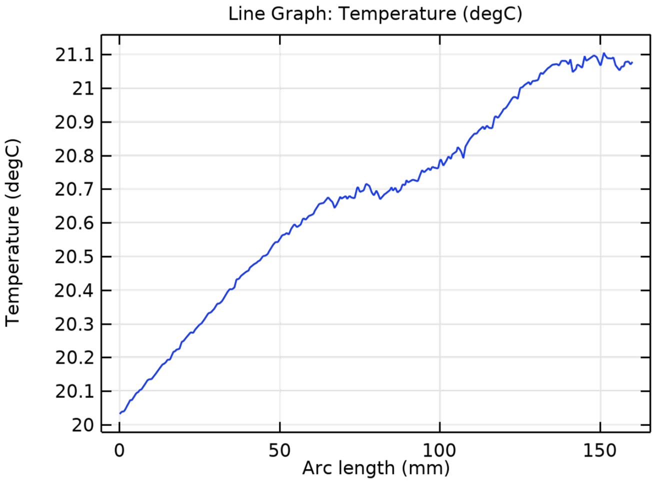
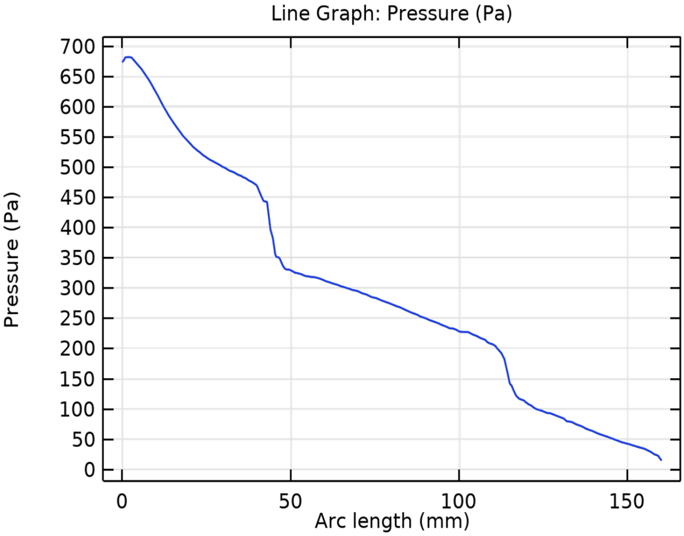


b)

a) inner pipe, b) outer pipe

Figure 5 – Flow temperature change along the length of the heat exchanger during turbulent flow movement

In the turbulent mode, the temperature difference is 1.2^{0}C for the hot stream, 1.1^{0}C for the cold, and in the laminar mode, such a difference is 6^{0}C and 7^{0}C, respectively. This is due to the fact that the residence time of the flows in the laminar mode is longer than in the turbulent mode.



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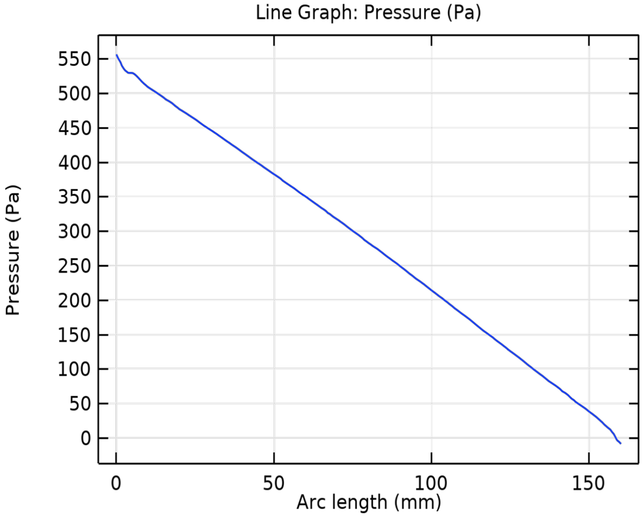


b)

a) inner pipe, b) outer pipe
Figure 6 – Flow pressure change along the length of the heat exchanger during turbulent flow movement

Twisted profiled strip increases flow resistance, which can lead to increased inlet and outlet pressure. This should be taken into account when designing the system. To calculate the velocity and other flow characteristics, it is necessary to take into account the hydraulic radius, which varies depending on the design of the heat exchanger.

The coils of the profiled strip increase the contact surface between the liquids and the walls of the pipes, which improves heat transfer. The turbulent vortices created by the strip help to reduce the temperature gradient, contributing to a more even distribution of heat.

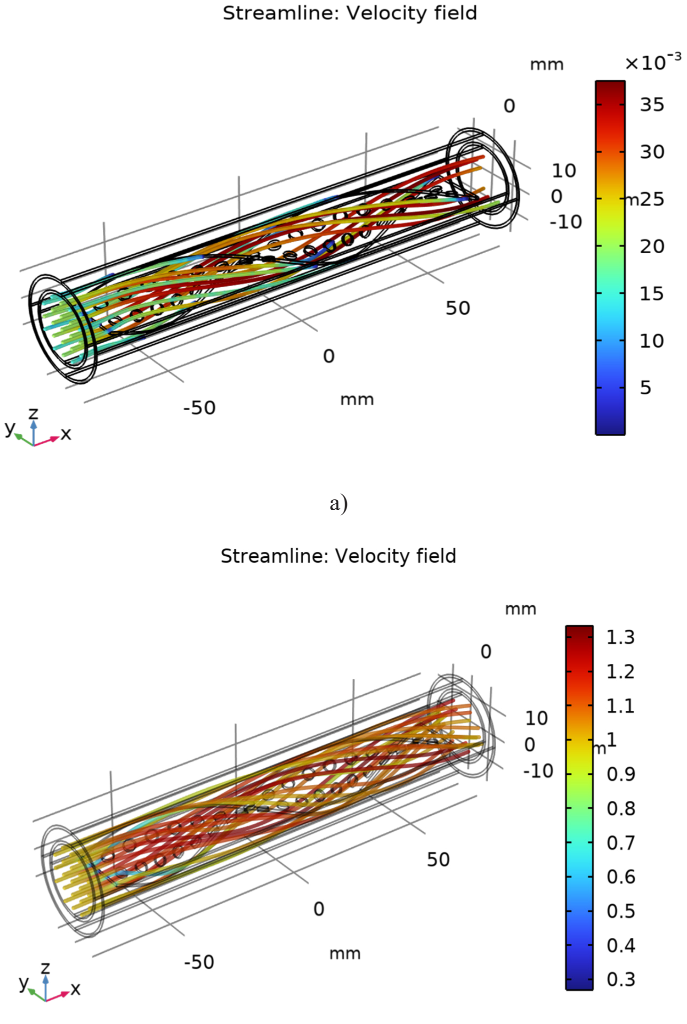
Heat exchangers with flow intensifiers in the form of a twisted profiled strip significantly increase the efficiency of heat transfer due to improved convection and turbulence. Understanding the movements of liquids and their relationship to heat transfer is key to optimizing the operation of such systems.

Results and discussion.

Figure 7 shows the effect of loosely fitting perforated twisted strips on flow characteristics. The results of CFD modeling are presented in the form of spatial distributions of velocity isolines and their pulsations, temperatures, flow lines and particle trajectories in the central mutually perpendicular sections of the pipes XOY and XOZ.

For pipes with turbulators (Fig. 7), an area of circulating flow is observed, formed as a result of the separation of a viscous layer from the surface of the turbulator, as it moves forward along the flow, the gradually detached boundary layer bends towards the pipe wall and then joins it in the region x≈ 20 mm. The boundary layer developing from the point of attachment flows onto the turbulator in front of which another separation region is formed, which leads to a local increase in velocity and causes an increase in pulsations monotonously increasing downstream.

A local increase in velocity (Fig. 7a) contributes to an increase in pulsations and leads to an increase in the intensity of heat transfer in general. The flow gradually warms up near the wall (Fig. 7b). In this case, the flow disturbances near the wall behind the obstacle reach 1%, and the flow core remains undisturbed (Fig. 7b).



a)

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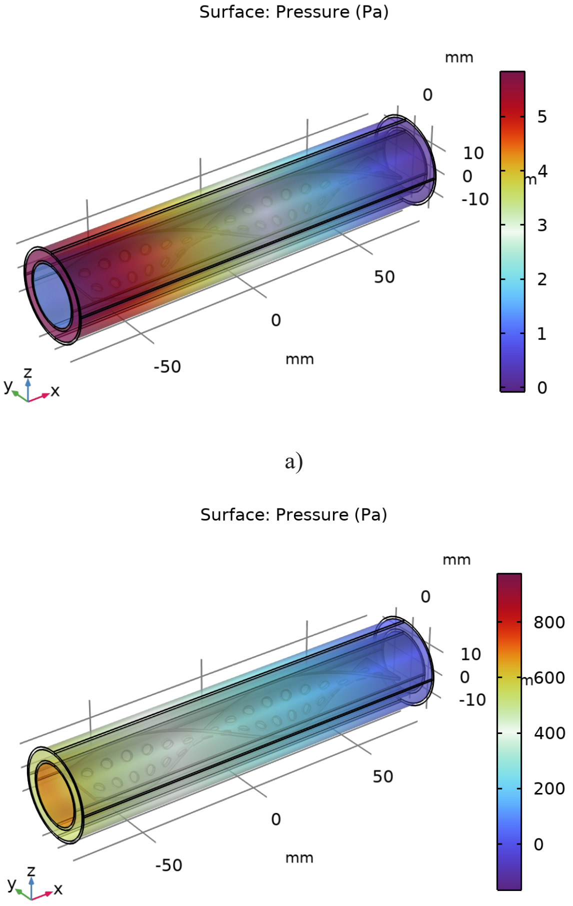
Figure 7 – Change in flow velocity along the length of the heat exchanger during laminar (a) and turbulent (b) flow movements

The swirling flow moves along the axis of the pipe, and the intensification of heat transfer in this case occurs due to the swirling of the flow.

The flow pattern in the pipe is shown in Fig. 7b, a diagram of current lines in the circulation area and their further propagation in the plane of the XOZ pipe is also illustrated here.

The dependence of the coefficient of friction on the Reynolds number for various twisting coefficients and hole diameters is shown in Figure 8. A pipe fitted with loosely fitting perforated twisted strips resulted in a higher coefficient of friction than a conventional pipe. This is due to the disturbance of the fluid flow, a larger contact surface area with a longer flow path, and the dispersion of the dynamic pressure of the working fluid due to a high loss of viscosity near the pipe wall.

As can be seen from Figure 8, the coefficient of friction and the relative ratio of the coefficients of friction increase with a decrease in the Reynolds number, which can be explained by the fact that at lower values of the Reynolds number, the liquid can pass through the entire strip and generate more friction forces due to the occurrence of small vortices behind the strip.



a)

b)

Figure 8 – Flow pressure change along the length of the heat exchanger during laminar (a) and turbulent (b) flow movements

Loosely fitting perforated twisted strips create less friction during flow movement compared to a conventional twisted strip. This is due to the fact that a conventional twisted strip creates a greater disturbance of the flow near the wall. The coefficient of friction tends to increase with a decrease in the coefficient of twisting and the diameter of the hole, similar to the coefficient of heat transfer. This is due to the fact that the use of a twisted strip with a lower twist coefficient and a smaller hole diameter leads to higher flow blocking and turbulence intensity in the flow field.

The theoretical part. The CFD modeling software package (COMSOL multitphisics 6.1) was used to perform three-dimensional numerical calculations of inserts from a conventional pipe and twisted strip in a pipe with a constant heat flow using the following basic equations [20].

The continuity equation for an incompressible fluid:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{1}$$

The conservation of momentum equation:

$$\frac{\partial v}{\partial t} + \rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \rho \overline{g} \ + \nabla \cdot \tau_{ij} + \vec{F} \tag{2}$$

The energy conservation equation:

$$\rho \frac{\partial}{\partial t}(\rho E) + \nabla \cdot \{\vec{v}(\rho E + \rho)\} = \nabla \cdot \{K_{\mathrm{eff}} \nabla T - \sum h_i(\vec{\tau}_{\mathrm{eff}} \cdot \vec{v})\} + S_h \tag{3}$$

The numerical values of mass flow and constant heat flow used for modeling formed the basis of this numerical research. Steel and aluminum, respectively, were chosen as the material for the manufacture of ordinary pipe and twisted strip. In all simulation cases, water was used as the working fluid.

The CFD modeling software package (COMSOL multitphisics 6.1) was used to solve the above-mentioned control equations based on certain boundary conditions.

For this research, a sequential solution algorithm (the algorithm of a separate solver) was chosen, and the solver setting includes an implicit formulation, a stationary (time-independent) calculation, a visco-laminar model and an energy equation. The SIMPLE algorithm has been selected as the pressure-velocity coupling method and the first-order upwind scheme was used for the energy and momentum equations solution. The following equations are used to calculate the Nusselt number (Nu) and the coefficient of friction (*f*) as the coefficient of surface friction (Salman, et al, 2013):

$$\mathrm{Nu} = \frac{hD}{K}, \tag{4}$$

where the heat transfer coefficient *h* was determined using the equation (5):

$$h = \frac{q}{T_w - T_b}, \tag{5}$$

coefficient of friction

$$f = \frac{16}{\mathrm{Re}} \cdot \tag{7}$$

Reynolds number

$$\mathrm{Re} = \frac{\rho u D}{\mu}, \tag{8}$$

where D is the diameter of the tube, h is the heat transfer coefficient, K is the conductivity of water, q is the heat flow on the tube, Tw is the temperature of the tube wall, and T_b is the volumetric temperature of the water $T_b = (T_0 + T_i)/2$, T_i inlet water temperature, T_0 temperature of the water at the outlet, p is the density, μ is the dynamic viscosity, and u is the velocity of the water.

Conclusions.

Based on the research results, computational models of flows near the wall region for an intensifier in the form of a profiled strip were constructed, data were obtained on the distribution of turbulence, velocity and temperature inside the pipe and the influence of the intensifier shape on them, and the mechanisms of heat transfer intensification were explained.

Heat transfer in a pipe-in-pipe heat exchanger equipped with profiled twisted ribbon elements under turbulent and laminar flow modes of heat carriers was investigated. The main conclusions can be drawn as follows:

Strip flow intensifiers significantly increase the efficiency of heat transfer in both laminar and turbulent modes by increasing the surface area and improving flow distribution.

In the laminar mode, the intensifiers help to reduce the temperature gradient between the heat carriers, which improves heat transfer. However, the overall heat transfer coefficient remains lower than in the turbulent regime.

During the transition to a turbulent regime, a significant increase in the heat transfer coefficient is observed. Intensifiers provide a more uniform distribution of flows, which leads to increased heat transfer and reduced energy losses.

It has been established that the efficiency of intensifiers depends on the flow speed and viscosity of heat carriers. In high velocities and low viscosity, the benefits of the intensifiers become more noticeable.

The multiphysical modeling made it possible to take into account the interaction of heat transfer, hydrodynamics and heat transfer, which gave a more complete depiction of the processes taking place in the apparatus. Modeling has shown that changes in the flow rate and viscosity of heat carriers significantly affect the characteristics of heat transfer. High flow rates significantly increase the efficiency of heat transfer due to intensifiers. The simulation results indicated the possibility of optimizing the sizes and shapes of the intensifiers to achieve maximum efficiency. Ideal parameters have been identified at which the greatest increase in heat transfer is achieved. The simulation has demonstrated the high efficiency of using such structures in various industrial applications, which opens up prospects for the development of more efficient heat exchangers. It is recommended to conduct additional experiments to validate the model and refine the flow data, which will help improve the accuracy of forecasting heat exchange processes.

The results of the research show that optimizing the size and location of the intensifiers can lead to further improvement of heat exchange characteristics. The data obtained can be useful for designing more efficient heat exchangers in various industries, including energy and petrochemicals.

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