IRSTI 27.35.21

10.51889/2959-5894.2024.88.4.009

B.R. Ismailov[1], R.P. Babakhodzhaev[2], Zh.T. Aimenov[1], Kh.B. Ismailov[1*], A.S. Shambilova[1]

[1] M. Auezov South Kazakhstan University, Shymkent, Kazakhstan
[2] Tashkent State Technical University named after I. Karimov, Tashkent, Republic of Uzbekistan
[*]*e-mail: ismailovkhb@mail.ru*

MODELING HYDRODYNAMICS AND HEAT TRANSFER IN HEAT EXCHANGERS WITH TURBULATORS

Abstract

Within the framework of the theory of turbulent gas flows, the most frequently used mathematical models of gas dynamics and heat exchange in the heat exchanger of power plants have been analyzed. The Navier-Stokes equations in Helmholtz variables describing the plane flow of incompressible Newtonian viscous fluid with constant properties in the absence of external forces are taken as a basis for calculating the dynamics of gases in recuperative heat exchangers. In order to systematize the analysis of the process of distribution of hydrodynamic parameters of gas in the inner tube, oscillations of nozzle elements and their influence on heat transfer, the problem is considered under conditions of gas flow turbulence. The nozzle elements are connected by an elastic wire through a certain distance. Due to the kinetic energy of the gas flow, the elements of the nozzle are driven in the longitudinal and transverse directions. At such problem statement, for physical interpretation of dynamics and heat exchange of gases, data on geometry of flow area, pipe dimensions, gas flow rate, temperature, physical and chemical parameters, elasticity of wire and oscillation (vibrability) of nozzle elements are required. Under the assumption that the temperature depends only on time and longitudinal coordinate, taking into account the heat transfer from the pipe wall to the gas, a simplified heat transfer equation is formulated. Possibilities of realization of the proposed model using computer mathematical systems of different levels are discussed.

Keywords: mathematical model, gas dynamics, local turbulizer, recuperative heat exchanger, computer models.

Б.Р. Исмаилов[1], Р.П. Бабаходжаев[2], Ж.Т. Айменов[1], Х.Б. Исмаилов[1], А.С. Шамбилова[1]
[1] Южно-Казахстанский университет им. М. Ауэзова, г. Шымкент, Казахстан
[2] Ташкентский государственный технический университет им. И. Каримова, г.Ташкент, Республика Узбекистан

МОДЕЛИРОВАНИЕ ГИДРОДИНАМИКИ И ТЕПЛООБМЕНА В ТЕПЛООБМЕННИКАХ С ТУРБУЛИЗАТОРАМИ

Аннотация

В рамках теории турбулентных газовых потоков проведен анализ наиболее часто применяемых математических моделей динамики газов и теплообмена в теплообменном устройстве энергетических установок. В качестве основы для расчета динамики газов в рекуперативных теплообменниках приняты уравнения Навье-Стокса в переменных Гельмгольца, описывающие плоское течение несжимаемой ньютоновской вязкой жидкости с постоянными свойствами при отсутствии внешних сил. С целью систематизации анализа процесса распределения гидродинамических параметров газа во внутренней трубе, колебания элементов насадок и влияния их на теплопередачу, поставленная задача рассматривается в условиях турбулентности газового потока. Элементы насадки соединены между собою упругой проволокой через определенное расстояние. За счет кинетической энергии потока газа, элементы насадки приводятся в движения по продольному и по поперечному направлениям. При такой постановке задачи, для физической интерпретации динамики и теплообмена газов, необходимы данные по геометрии области течения, размерам труб, расходу газа, температуре, физико-химические параметры, упругости проволоки и колебательности (вибрируемости) элементов насадок. При допущении, что температура зависит только от времени и продольной координаты, с учетом теплопередачи от стенки трубы к газу, составлено упрощенное уравнение теплопередачи. Обсуждены возможности реализации предлагаемой модели с использованием компьютерных математических систем разного уровня.

Ключевые слова: математическая модель, динамика газов, локальный турбулизатор, рекуперативный теплообменник, компьютерные модели.

Б.Р. Исмаилов[1], Р.П. Бабаходжаев[2], Ж.Т. Айменов[1], Х.Б. Исмаилов[1], А.С. Шамбилова[1]
[1] М. Әуезов атындағы Оңтүстік Қазақстан университеті, Шымкент қ., Қазақстан Республикасы
[2] И. Каримов атындағы Ташкент мемлекеттік техникалық университеті, Ташкент қ., Өзбекстан Республикасы

ТУРБУЛИЗАТОРЛАРЫ БАР ЖЫЛУ АЛМАСТЫРҒЫШТАРДАҒЫ ГИДРОДИНАМИКА МЕН ЖЫЛУ АЛМАСУДЫ МОДЕЛЬДЕУ

Аңдатпа

Турбулентті газ ағындары теориясы аясында энергетикалық қондырғылардың жылу алмасу құрылғысында газ динамикасы мен жылу алмасудың ең көп қолданылатын математикалық модельдеріне талдау жасалды. Регенеративті жылу алмастырғыштардағы газдардың динамикасын есептеу үшін негіз ретінде сыртқы күштер болмаған кезде тұрақты қасиеттері бар сығылмайтын ньютондық тұтқыр сұйықтықтың жазық ағынын сипаттайтын Гельмгольц айнымалыларындағы Навье-Стокс теңдеулері қабылданды. Ішкі құбырдағы газдың гидродинамикалық параметрлерінің таралу процесін, саптамалардың тербелісін және олардың жылу берілуіне әсерін талдауды жүйелеу үшін қойылған міндет газ ағынының турбуленттілігі жағдайында қарастырылады. Саптама элементтері белгілі бір қашықтық арқылы серпімді сыммен өзара байланысты. Газ ағынының кинетикалық энергиясы есебінен саптама элементтері бойлық және көлденең бағыттар бойынша қозғалысқа келтіріледі. Мұндай тапсырманы қою кезінде газдардың динамикасы мен жылу алмасуын физикалық түсіндіру үшін ағын аймағының геометриясы, құбырлардың мөлшері, газ шығыны, температура, физикалық-химиялық параметрлер, сымның серпімділігі және саптама элементтерінің тербелісі (дірілділігі) туралы мәліметтер қажет. Температура тек уақыт пен бойлық координатаға байланысты деп есептегенде, құбыр қабырғасынан газға жылу беруді ескере отырып, жылу берудің жеңілдетілген теңдеуі жасалады. Ұсынылған модельді әртүрлі деңгейдегі компьютерлік математикалық жүйелерді қолдана отырып жүзеге асыру мүмкіндіктері талқыланды.

Түйін сөздер: математикалық модель, газ динамикасы, жергілікті турбулизатор, рекуперативті жылу алмастырғыш, компьютерлік модельдер.

Introduction

The problem of rational and efficient use of fuel and energy resources is one of the most important tasks of the fuel and energy complex of the Republic of Kazakhstan. With the growth of energy capacities and production volume the dimensions of heat exchangers used are increasing. Creation of more efficient and compact heat exchangers provides significant savings of fuel, metals and labor costs. A significant role in solving these problems can be played by the wide introduction of effective methods of heat exchange intensification in channels in the design and manufacturing of heat-exchange apparatuses and devices.

In contact devices (CD) of thermal power plants (TPP) complex dynamic and stationary processes of interaction of phases at different values of mode, geometric and technological parameters are realized. At long-term operation of CDs there is a deviation of parameter values due to corrosion and erosion of their elements, growth of scale and sediments on their surfaces, which leads to a decrease in the efficiency of the whole technological line of heat and electric energy production.

One of the solutions to this problem is the intensification of hydrodynamic and thermal processes with the improvement of the design of recuperative heat exchanger and the development of a mathematical model of heat energy transfer from one coolant to another through the separating wall of the apparatus, as well as computer modeling and numerical study, which represents the relevance of the issue under consideration.

Taking into account the scale of the industry, it can be concluded that there are great reserves for increasing the saving of fuel and energy resources and reducing the negative impact on the environmental situation in industrial regions and in the country.

At present, researchers have quite clearly formulated two main approaches to the realization of the created mathematical models of physical problems arising in finding the dynamic and heat exchange characteristics of CD of TPP:

1) development of own numerical algorithms and programs for their implementation;

2) use of computer mathematical systems created by well-known developers.

Each of these approaches is characterized by certain advantages and disadvantages. The first approach analyzes the issues of existence and uniqueness of the solution of differential equations, convergence, stability and accuracy of the applied numerical algorithms. The mesh design is a labor-intensive process, especially when solving problems in the complex region of phase motion. In the second approach, numerical solutions are presented in an easy-to-visualize form, the grid area is created by the computer program itself.

The application of both methods should be justified by establishing the adequacy of the solution, for example, by comparison with experimental data and /or/ statistical methods. The aim of the study is to develop a mathematical model, numerical algorithms and computer programs for their implementation, used to analyze the dynamics of heat transfer fluid parameters in recuperative heat exchangers with turbulizing devices.

Research methodology

To achieve the goal of the study, the most effective methods of heat transfer intensification in CD of TPP were analyzed according to the publications on problems close to the problem formulation. In work [1] devices for intensification of heat transfer in the form of primary and secondary corrugated channels are proposed and it is shown that gas flow in them is unsteady. In works [2-5] different designs of turbulizers in the form of nozzles (cavities), recesses, wells and metal inserts were proposed. The characteristics of flow and heat transfer in a slotted jet flow limited by inclined plates and hitting a flat surface have been studied. The effect of Reynolds number and the angle of inclination of the retaining plate and the distance between the plates on the pressure distribution is determined. It is also observed that although the pressure distribution is independent of the Reynolds number, it is affected by the angle of inclination of the holding plate and the distance between the plates. The standard k-ε turbulence model used predicts results closer to the experimental data. The thermal and hydraulic characteristics in a tube with ball turbulators are calculated in [6]. However, in this work, the theoretical and computational results are not compared with experimental data, which narrows the application of the created models of balloon nozzle flow with gas flow. In work [7] numerical experiments were performed and optimal characteristics of heat transfer and pressure field distribution in a shell-and-tube heat exchanger were determined. Depending on the velocity of gas supplied to the heat exchanger, laminar, transient and turbulent modes can be realized, and modeling of each of these flows involves the use of appropriate mathematical apparatus [7-8]. Works [9-11] present the results of a comprehensive approach to the creation of shell-and-tube heat exchangers with surface intensification of heat transfer. In [12], an original method utilizing the radiation-turbulent component inside the wedge-shaped channel was developed. A mathematical model was created and the coolant flow and heat transfer were numerically investigated for four-channel configurations. The results show that the total Nusselt number of the channel using the radiative-turbulent component increased by more than 48 %. This is due to the expansion of cold surfaces to improve radiative heat transfer and the change in the distribution of flow perturbations to improve the homogeneity of convective heat transfer, both of which are induced using the radiative-turbulent component.

In this paper, the problem of modeling the dynamics of gas flow and heat distribution in a channel with turbulators consisting of hollow elements with different geometric configurations (ball, oval, prism, etc.) and strung on elastic wires at a certain distance is posed. The model is based on the

Navier-Stokes equations describing the flow process of gas and liquid flows averaged over the Reynolds principle and convective heat transfer. The aim of the study is to find the distribution of dynamic characteristics of gas (velocity, swirl, kinetic energy and local scale of turbulence) and temperature change of heat flow in a pipe with turbulators of different shapes.

The principles of derivation of the Navier-Stokes equations (NSE) and their application, numerical solution and related issues are considered quite comprehensively in work [13]. It should be noted that only in simple cases it is possible to obtain exact analytical solutions of the NSE (e.g., in works [14-15]), but even in these cases there is a need to use numerical methods to calculate the applied integral relations. It is known that when bodies are streamlined by a gas flow, especially in the presence of sharp edges on the surface of bodies, breakaway flows with predominantly unsteady characteristics arise. In the breakaway zones, as it was shown in [16-17], the intensity of heat and mass transfer increases significantly and this fact should be taken into account when modeling and calculating the flow of nozzles with gas flow. It should be noted that in column apparatuses of chemical technology also widely used periodically arranged nozzles of different shapes (balls, cylinders, plates, etc.), installed to intensify the interaction of the treated phases [18]. In such cases, the NSE are nonlinear, and the systems approximating them, consisting of finite-difference equations, are also nonlinear. For their solution, iterative methods [19] are used to achieve the required accuracy at large system dimensions.

Various types of external and internal fins are used in industrial power plants to turbulize flows and increase the efficiency of heat transfer. As internal finning various inserts are applied or diaphragm tubes are used. The experience of creation and operation of various heat-exchange devices has shown that the methods of intensification of heat exchange in channels developed in the research cycle provide reduction of dimensions and weight of these devices in 1,5-2 and more times in comparison with similar serially produced devices at the same thermal power and power for pumping of heat carriers, as well as a significant reduction of clogging and salt deposition in their channels. This reduces costs and labor intensity of operation 2-3 times, increases resource and reliability. The proposed methods of intensification are technological in production and assembly of heat-exchange apparatuses, convenient in operation. Below we will consider some methods of heat exchange intensification: method of purposeful artificial turbulization of flow in the near-wall zone, based on periodic creation of small vortex zones near the wall, which are the source of additional turbulization of the flow. This method is realized for tubular and plate-and-ribbed heat exchangers. The numerical study was carried out using the COMSOL Multiphysics software package. Characteristic dimensions of tubes: inner diameter - 20 mm; length - 400 mm. The ratio of tube length to diameter $L/d_i = 20$. At the inlet of the tubes the flow velocity is equal to 0.01 m/s. Different types of local turbulators of four types are installed in the middle of the tube. In the calculations a model was used, which is designed to simulate the flow of gas (liquid) at large (turbulent) Reynolds numbers and at small density changes.

The model of turbulent heat and mass transfer in this pipe-in-pipe type problem includes:

- Navier-Stokes equations (momentum conservation law);
- the equation of continuity (law of conservation of fluid mass);
- the law of conservation of energy;
- scalar diffusive transport equation (law of conservation of mass);
- $k-\omega$ turbulence model.

The turbulent incompressible fluid model is based on the standard turbulence model consisting of the following system of equations:

$$\rho(u\cdot\nabla)u = \nabla\cdot\left[-\rho l + (\mu+\mu_T)(\nabla \mathrm{u} + (\nabla \mathrm{u})^T) - \frac{2}{3}(\mu+\mu_T)(\nabla\cdot u)l - \frac{2}{3}\rho k l\right] + F,$$

$$\nabla\cdot(\rho u) = 0,$$

$$\rho(u\cdot\nabla)k = \nabla\cdot[(\mu+\mu_T\sigma_\omega)\nabla\omega] + \alpha\frac{\omega}{k}\rho_k - \rho\beta_0\omega^2, \quad (1)$$

$$\mu_T = \rho \frac{k}{\omega}$$

$$P_k = \mu_T \left[\nabla \mathrm{u} : (\nabla \mathrm{u})^T) - \frac{2}{3} (\nabla \cdot \mathrm{u})^2 \right] - \frac{2}{3} \rho k \nabla \cdot \mathrm{u}$$

$$\rho C_p \mathrm{u} \cdot \nabla \mathrm{T} = \nabla \cdot (\mathrm{k} \nabla \mathrm{T}) + \mathrm{Q} + \mathrm{Q}_{Vh} + W_p$$

where k - kinetic turbulent energy; u - velocity of dissipation of turbulent energy; ρ - density, T - temperature, and P - pressure.

In works [17-18], system (1) is solved numerically for the case of flowing of periodically arranged nozzles in a multistage channel by the establishment method. Under the assumption that the temperature depends only on time and longitudinal coordinate, taking into account heat transfer from the pipe wall to the gas, the heat transfer equation can be written as follows [12]:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial} \left(k \frac{\partial T}{\partial x} \right) + h_{out} (T_{wall} - T), \tag{2}$$

where T - gas temperature; t - time; x - longitudinal coordinate; ρ - gas density; c_p - gas specific heat capacity; k - gas heat transfer coefficient; - heat transfer coefficient between the pipe wall and gas; - pipe wall temperature.

The heat transfer coefficient between the pipe wall and gas depends on a number of factors and is usually determined experimentally or on the basis of empirical correlations. Important parameters affecting the heat transfer coefficient are gas velocity, gas properties, pipe geometry and other factors. One way to determine the heat transfer coefficient is to use correlations such as the Nusselt-Numann equation (Nu-Re-correlation). This equation relates the Reynolds number (Re) and the Nusselt number (Nu):

$$Nu = C \, Re^m Pr^n \tag{3}$$

where $Re = \frac{uLp}{\mu}$ - Reynolds criterion, ρ - density of liquid or gas; u - average flow velocity; μ - dynamic viscosity of the medium. $Pr = \alpha\mu$ – Prandtl criterion, α - heat transfer coefficient of the medium; C, m, n - coefficients depending on the specific geometry and the considered flow regime. $Nu = \frac{hL}{k}$ - Nusselt criterion, h - heat transfer coefficient; L - characteristic size of the object or distance through which heat exchange occurs; k - heat transfer coefficient of the medium.

The value of Nusselt number can be different depending on conditions and systems, so its value is not fixed and requires calculations or experimental data for a particular problem.

All the above physical quantities in the criteria are determined during problem formulation and are input data for the computer program. There are different correlations *C, m, n* for different flow regimes and pipe configurations.

The information on methods for modeling turbulent flow is based on general knowledge of CFD (Computational Fluid Dynamics). To date, various methods have been used to model turbulent flow in channels of different shapes, each of which has its own advantages and limitations. The most popular approaches are: RANS (Reynolds-Averaged Navier-Stokes) models. These models average the turbulent flows over time, which reduces the computational cost. Among the RANS models, the best known are: k-ε model; k-ω model; SST (Shear Stress Transport) model. They are suitable for a wide range of problems, but may not accurately reproduce some turbulent flows, especially in complex geometries CFD: The Basics with Applications, and LES (Large Eddy Simulation) models. LES models require more computational resources than RANS, but provide more accurate modeling of complex flows. DNS (Direct Numerical Simulation) modeling solves the Navier-Stokes equations without any approximation or simulation. This method requires huge computational power and is mainly used for research purposes to gain a detailed understanding of turbulent flows. Hybrid approaches: There are hybrid methods such as Detached Eddy Simulation (DES) that combine elements of RANS and LES to balance accuracy and computational cost.

Results of the study

In this paper, the problem of modeling the dynamics of gas flow and heat distribution in a channel with turbulators has been solved completely enough, and the advantages and disadvantages of modern approaches to modeling complex physical problems have been shown.

Figures 1-2 show plots of temperature and pressure distribution for four types of turbulators obtained by realization of model (1) using COMSOL Multiphysics package. Figure 1 shows that for all types of turbulators the maximum flow velocities are concentrated near the boundary, which is an important factor for intensification of heat exchange between the elements of the pipe system. In the space between the turbulators the velocities are small, especially for turbulators of the 4th type (lower garland).

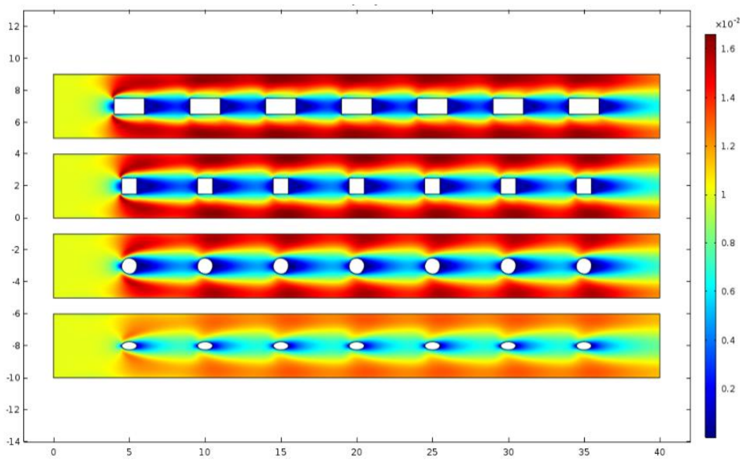

Figure 1. Distribution of flow velocity in a pipe with turbulators of different shapes
of *different shapes*, m/s

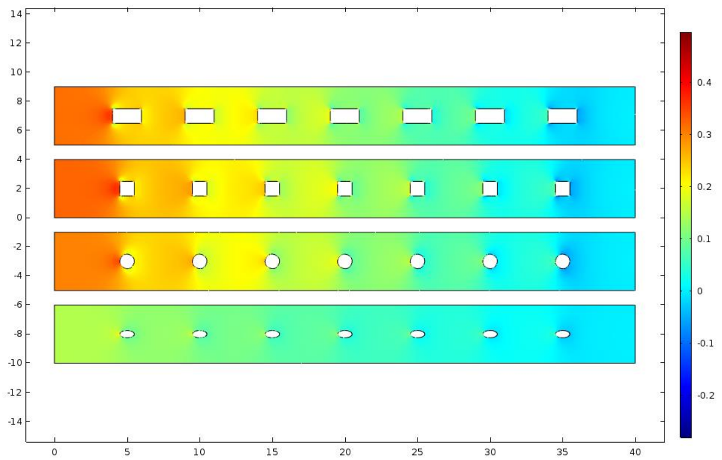

Figure 2. *Distribution of flow pressure field in a pipe with turbulators of different shapes*, Δ *P*a.

Figure 2 shows that the highest pressure values for turbulators of types 1-3 are achieved at the inlet (initial) sections of the pipe, due to a rather fast establishment of the pressure field.

Figure 3 shows the distribution of gas velocity at the flow around the turbulizer elements obtained by direct implementation of the turbulence model according to the Patankar model [20], using Reynolds averaging, compiling a program in an algorithmic language. This approach is more labor-intensive, but allows obtaining numerical values of hydrodynamic parameters. It can also be observed (similar to Figure 1) the increase in velocity in the boundary region of the channel, which ensures efficient heat transfer. In the future, we plan to continue our research on this topic, by including in the model (1) equations to describe the oscillation of turbulizing elements, in order to optimize the whole process of regenerative heat exchange. Visual observations of the flow of the nozzle system in the pipe showed their oscillations with a small amplitude. To account for this effect, as part of the model development, in future works the oscillation equations will be included in model (1), where the physical parameters of the elastic wire and other input data of the whole system will be taken into account.

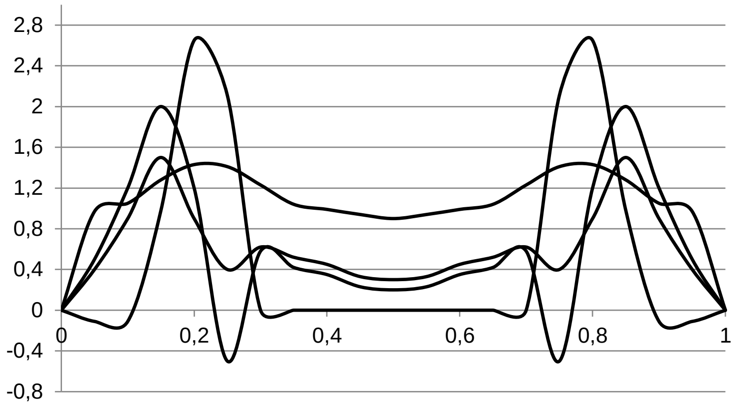

Figure 3. Profiles of the longitudinal gas velocity at the plate streamline,
Re = 2500. *x* is the *distance from the channel entrance*, 1- *x* = 0.3; 2 - *x* = 0.5; 3 - *x* = 0.6; 4 - *x* = 0.8.

The analysis of numerical values of dynamic flow characteristics shows dynamic establishment (stabilization) of body streamline: as the flow develops, from nozzle to nozzle, through a certain number of contact stages, the values of velocity and pressure can be considered to be approximately the same for subsequent stages. This fact can be used to save calculation time: given a permissible error, we finish the calculation if the values of dynamic parameters in the region of two neighboring nozzles become the same.

Conclusion

In this paper, the problem of modeling the dynamics of gas flow and heat distribution in a channel with turbulators has been solved, and the advantages and disadvantages of modern approaches to modeling complex physical problems have been shown. Model (1) is realized using the COMSOL Multiphysics software package. Quantitative and qualitative picture of dynamics and heat exchange in the considered problem formulation; distribution of flow velocity value in a pipe with turbulators of different shapes, m/s; distribution of flow pressure field in a pipe with turbulators of different shapes are obtained. The possibility of conducting systematic numerical experiments with input data in a wide range, to optimize geometric and mode-technological parameters of local turbulizer operation is evaluated. Using the turbulence model, the computational system allows predicting the structure of flow in the pipe channel, resolving the details of secondary currents quite precisely.

Список использованных источников

[1] S. Harikrishnan, Shaligram Tiwari. Unsteady Flow and Heat Transfer Characteristics of Primary and Secondary Corrugated Channels. J. Heat Transfer. – 2020. – Vol. 142(3), № 031803. https://doi.org/10.1115/1.4045751.

[2] Babakhodjaev R., Tashbaev N and Mirzaev D. Use of kinetic flow energy liquids for vibration of local turbulizers in pipe heat exchangers. E3S Web of Conf. – 2020. – Vol. 216, № 0108. https://doi.org/10.1051/e3sconf/202021601081.

[3] Халатов А.А. Теплообмен и гидродинамика около поверхностных углублений (лунок). - Киев: ИТФ НАН Украины, 2005. – 140 с.

[4] L. Vafajoo, K.Moradifar , S. M. Hosseini, B.H. Salman. Mathematical modelling of turbulent flow for flue gas–air Chevron type plate heat exchangers. International Journal of Heat and Mass Transfer. – 2016. – Vol. 97. Pp. 596-602. https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.035.

[5] Amit Bartwal, Abhishek Gautam, Manoj Kumar, Chidanand K. Mangrulkar, Sunil Chamoli. Thermal performance intensification of a circular heat exchanger tube integrated with compound circular ring metal wire net inserts. Chemical Engineering and Processing - Process Intensification. – 2018. – Vol. 124. Pp. 50-70. https://doi.org/10.1016/j.cep.2017.12.002.

[6] Piotr Bogusław Jasiński. Numerical study of thermo-hydraulic characteristics in a circular tube with ball turbulators. Part 3: Thermal performance analysis. International Journal of Heat and Mass Transfer. – 2017. – Vol. 107. Pp. 1138-1147. DOI: 10.1016/j.ijheatmasstransfer.2016.11.017.

[7] Moosavi A., Abbasalizadeh M., Dizaji H.S. Optimization of heat transfer and pressure drop characteristics via air bubble injection inside a shell and coiled tube heat exchanger. Experimental Thermal and Fluid Science. – 2016. – Vol. 78. – Pp.1-9. https://doi.org/10.1016/j.expthermflusci. 2016.05.011.

[8] Devendra K. Vishwakarma, Suvanjan Bhattacharyya, Manoj K. Soni, John P. Abraham. Thermal and Flow Analysis of Air in a Uniformly Heated Circular Channel with an Inlet Flap Obstruction in Laminar, Transitional, and Turbulent Flow Regimes. Heat Transfer Engineering. 2023. https://doi.org/10.1080/01457632.2023.2275235.

[9] Дилевская Е.В., Гортышов Ю.Ф., Леонтьев А.И. и др. Разработка фундаментальных основ создания прототипов энергоэффективных теплообменников с поверхностной интенсификацией теплообмена //ТрудыЧетвертой Российской национальной конференции по теплообмену. М.: МЭИ, 2006. - Т.1. - С. 253-257.

[10] Kushchev L.A., Nikulin N.Yu., Alifanova A.I. Modern methods of investigation of heat transfer enhancement in shell-and-tube heat exchangers. International Science and Technology Conference «EastConf». – 2019 . - № 1. - Pp. 1-5. https://doi.org/10.1109/EastConf.2019.8725336.

[11] Гортышов Ю.Ф., Попов И.А. Научные основы расчета и создания высокоэффективных компактных теплообменных аппаратов с рациональными интенсификаторами теплоотдачи // Теплоэнергетика, 2006, №4, с.2-13.

[12] Kun Yang, Jie Liu, Jiabing Wang. Heat transfer enhancement by inserting a radiation-turbulence component in a wedge channel. International Journal of Heat and Mass Transfer. - 2024. - Vol. 219, № 124907. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124907.

[13] Р. Темам. Уравнения Навье-Стокса. Теория и численный анализ. - М.: Мир, 1981. – 408 с.

[14] Просвиряков Е.Ю. Новый класс точных решений уравнений Навье-Стокса со степенной зависимостью скоростей от двух пространственных координат // Теоретические основы химической технологии. – 2019. – Т. 53, № 1. - С. 112-120. DOI: 10.1134/S0040357118060118.

[15] Aristov S.N., Knyazev D.V., Polyanin A.D. Exact Solutions of the Navier–Stokes Equations with the Linear Dependence of Velocity Components on Two Space Variables. Theoretical Foundations of Chemical Engineering. - 2009. - Vol. 43, № 5. - P. 642-662. DOI: 10.1134/S0040579509050066.

[16] Редчиц Д.А. Математическое моделирование отрывных течений на основе нестационарных уравнений Навье-Стокса // Научные ведомости БелГУ. Сер. Математика. Физика. 2009. - №13(68), - С. 118-146.

[17] B. Ismailov, L. Musabekova, Zh. Umarova, Kh. Ismailov, K. Arystanbayev. Mathematical and computer simulation of particle redistribution and inertial swarming in dispersed systems. Indonesian Journal of Electrical Engineering and Computer Science. 2022. - Vol. 28, No. 2. - Pp. 909-917. http://doi.org/10.11591/ijeecs.v28.i2.pp909-917.

[18] Ismailov B., Urmatova A., Ismailov Kh. Mathematical modelling and calculation of dynamic characteristics of gas in multistage channels. Applied Mathematical Sciences. – 2013. - Vol. 7, № 132. – Pp. 6571-6582. http://dx.doi.org/10.12988/ams.2013.310561.

[19] Утеуова Н., Шиялов К., Бекбауова А., Шарипова Б. Решение нелинейных краевых задач приближенным методом // Вестник КазНПУ им. Абая. - 2023. - Т.84, №4. - С. 46-54. DOI: 10.51889/2959-5894.2023.84.4.005.

[20] Patankar S. Numerical heat transfer and fluid flow. - New York: Hemisphere Publishing Corporation. - 1980. – Pp. 214. DOI https://doi.org/10.1201/9781482234213.

References

[1] S. Harikrishnan, Shaligram Tiwari. Unsteady Flow and Heat Transfer Characteristics of Primary and Secondary Corrugated Channels. J. Heat Transfer. 2020. Vol. 142(3), № 031803. https://doi.org/10.1115/1.4045751.

[2] Babakhodjaev R., Tashbaev N and Mirzaev D. Use of kinetic flow energy liquids for vibration of local turbulizers in pipe heat exchangers. E3S Web of Conf. – 2020. – Vol. 216, № 0108. https://doi.org/10.1051/e3sconf/202021601081.

[3] Halatov A.A. (2005) Teploobmen i gidrodinamika okolo poverhnostnyh uglublenij (lunok). [Heat transfer and hydrodynamics near surface depressions (wells)]. Kiev: ITF HAN Ukraine. 140 s. (in Russian)

[4] L. Vafajoo, K.Moradifar , S. M. Hosseini, B.H. Salman. Mathematical modelling of turbulent flow for flue gas–air Chevron type plate heat exchangers. International Journal of Heat and Mass Transfer. – 2016. – Vol. 97. Pp. 596-602. https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.035.

[5] Amit Bartwal, Abhishek Gautam, Manoj Kumar, Chidanand K. Mangrulkar, Sunil Chamoli. Thermal performance intensification of a circular heat exchanger tube integrated with compound circular ring metal wire net inserts. Chemical Engineering and Processing - Process Intensification. – 2018. – Vol. 124. Pp. 50-70. https://doi.org/10.1016/j.cep.2017.12.002.

[6] Piotr Bogusław Jasiński. Numerical study of thermo-hydraulic characteristics in a circular tube with ball turbulators. Part 3: Thermal performance analysis. International Journal of Heat and Mass Transfer. – 2017. – Vol. 107. Pp. 1138-1147. DOI: 10.1016/j.ijheatmasstransfer.2016.11.017.

[7] Moosavi A., Abbasalizadeh M., Dizaji H.S. Optimization of heat transfer and pressure drop characteristics via air bubble injection inside a shell and coiled tube heat exchanger. Experimental Thermal and Fluid Science. – 2016. – Vol. 78. – Pp.1-9. https://doi.org/10.1016/j.expthermflusci. 2016.05.011.

[8] Devendra K. Vishwakarma, Suvanjan Bhattacharyya, Manoj K. Soni, John P. Abraham. Thermal and Flow Analysis of Air in a Uniformly Heated Circular Channel with an Inlet Flap Obstruction in Laminar, Transitional, and Turbulent Flow Regimes. Heat Transfer Engineering. – 2023. https://doi.org/10.1080/01457632.2023.2275235.

[9] Dilevskaja E.V., Gortyshov Ju.F., Leont'ev A.I. et al. (2006) Razrabotka fundamental'nyh osnov sozdanija prototipov jenergojeffektivnyh teploobmennikov s poverhnostnoj intensifikaciej teploobmena [Development of the fundamental principles for prototyping energy-efficient heat exchangers with surface heat exchange intensification].Tr. IV-Ross. nacional'noj konferencii po teploobmenu. T.1. 253-257. (in Russian)

[10] Kushchev L.A., Nikulin N.Yu., Alifanova A.I. Modern methods of investigation of heat transfer enhancement in shell-and-tube heat exchangers. International Science and Technology Conference «EastConf». – 2019. - № 1. - Pp. 1-5. https://doi.org/10.1109/EastConf.2019.8725336.

[11] Gortyshov Ju.F., Popov I.A. (2006) Nauchnye osnovy rascheta i sozdanija vysokojeffektivnyh kompaktnyh teploobmennyh apparatov s racional'nymi intensifikatorami teplootdachi [Scientific foundations for the calculation and creation of highly efficient compact heat exchangers with rational heat transfer intensifiers]. Teplojenergetika. No 4. 2-13. (in Russian)

[12] Kun Yang, Jie Liu, Jiabing Wang. Heat transfer enhancement by inserting a radiation-turbulence component in a wedge channel. International Journal of Heat and Mass Transfer. - 2024. - Vol. 219, № 124907. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124907.

[13] R. Temam. (1981) Uravnenija Nav'e-Stoksa. Teorija i chislennyj analiz [The Navier-Stokes equations. Theory and numerical analysis]. M.: Mir. 408 s. (in Russian)

[14] Prosvirjakov E.Ju. (2019) Novyj klass tochnyh reshenij uravnenij Nav'e-Stoksa so stepennoj zavisimost'ju skorostej ot dvuh prostranstvennyh koordinat [A new class of exact solutions to the Navier-Stokes equations with a power-law dependence of velocities on two spatial coordinates]. Teoreticheskie osnovy himicheskoj tehnologii. T. 53, № 1. 112-120. DOI: 10.1134/S0040357118060118. (in Russian)

[15] Aristov S.N., Knyazev D.V., Polyanin A.D. Exact Solutions of the Navier–Stokes Equations with the Linear Dependence of Velocity Components on Two Space Variables. Theoretical Foundations of Chemical Engineering. - 2009. - Vol. 43, № 5. - P. 642-662. DOI: 10.1134/S0040579509050066.

[16] Redchic D.A. (2009) Matematicheskoe modelirovanie otryvnyh techenij na osnove nestacionarnyh uravnenij Nav'e-Stoksa [Mathematical modeling of separation flows based on nonstationary Navier-Stokes equations]. Nauchnye vedomosti BelGU. Ser. Matematika. Fizika. №13(68). 118-146. (in Russian)

[17] B. Ismailov, L. Musabekova, Zh. Umarova, Kh. Ismailov, K. Arystanbayev. Mathematical and computer simulation of particle redistribution and inertial swarming in dispersed systems. Indonesian Journal of Electrical Engineering and Computer Science. – 2022. - Vol. 28, No. 2. - Pp. 909-917. http://doi.org/10.11591/ijeecs.v28.i2.pp909-917.

[18] Ismailov B., Urmatova A., Ismailov Kh. Mathematical modelling and calculation of dynamic characteristics of gas in multistage channels. Applied Mathematical Sciences. – 2013. - Vol. 7, № 132. – Pp. 6571-6582. http://dx.doi.org/10.12988/ams.2013.310561.

[19] Uteuova N., Shijapov K., Bekbauova A., Sharipova B. (2023) Reshenie nelinejnyh kraevyh zadach priblizhennym metodom [Solving nonlinear boundary value problems by the approximate method] Vestnik KazNPU named Abaja. T.84. №4. 46-54. DOI: 10.51889/2959-5894.2023.84.4.005. (in Russian)

[20] Patankar S. Numerical heat transfer and fluid flow. - New York: Hemisphere Publishing Corporation. - 1980. – Pp. 214. https://doi.org/10.1201/9781482234213.