Computational study of the efficiency of various methods of intensification of convective heat transfer

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Abstract. This paper presents the results of a computational study of the efficiency of various methods of heat transfer intensification in model channels containing various types of intensifiers. The following methods of intensification of convective heat transfer are considered: acoustic, the intensifiers twisted tape, wire spiral, and joint intensifier of a wire spiral and twisted tape. The study of thermal and hydraulic processes in the channels is carried out using computer modeling based on the solution of the Navier-Stokes equations averaged by Reynolds, the energy and state equations supplemented by the turbulence model. The thermal and hydraulic characteristics of various methods of heat transfer intensification are determined in the range of Reynolds numbers from 10000 to 60,000, and the efficiency of the intensification is determined based on the author's criterion. The characteristics of a smooth channel in the above-mentioned range of Reynolds numbers are considered as reference thermal and hydraulic characteristics. Comparative analysis has shown that the acoustic method of heat transfer intensification is most effective in the range of Reynolds numbers, where different modes of self-sustaining acoustic oscillations occur. The presented results may be used in the development and design of heat exchangers.

1. Introduction

The use of various methods of heat exchange intensification in almost all areas of industry has become an integral part of the design and development of efficient heat exchangers that meet the ever-increasing requirements of the industry. This has become possible thanks to a large number of research papers and the success of the practical implementation of the results of scientific research. Despite this, the problems of studying thermal and hydrodynamic processes, improving the efficiency of heat transfer intensification, and complex problems of the theory of heat transfer are still promising.

There is a wide variety of methods of heat transfer intensification, which differ in different degrees of complexity of the process organization. Among the most commonly used methods are: increasing the flow rate of the cooler, increasing the area of the heat-releasing surface [1], organizing a special hydrodynamic flow structure, non-stationary methods of heat exchange intensification, etc.

The use of intensification methods is limited to their effectiveness only in a specific technical implementation. This leads to the fact that after the possibilities of a particular method of intensification are exhausted, the developers of heat exchangers begin to explore and further apply new methods of heat exchange intensification. Since the most obvious way to increase heat transfer is to increase the flow rate of the working fluid, most of the intensification methods are investigated at high values of the
Reynolds numbers (Re). In this regard, most of the fundamental monographs on the topic of intensification of convective heat transfer [2-13] are devoted to this problem at high Re numbers, and only a small part of the works deals with the problem of intensification of heat transfer at low Re numbers [14, 15].

From the physical point of view, when the heat exchange is intensified in the boundary layer, a complex mixing of elementary volumes of liquid occurs. It is known from the theory of heat transfer that, in general, the distribution of temperature and velocity in the boundary layer is different, so it is theoretically possible to organize the transfer of heat more efficiently than the transfer of the amount of motion. This can be the basis for an effective intensification of heat transfer.

This paper presents the results of a computational study of hydrodynamics and heat transfer in model channels with various types of intensifiers. Four methods of heat exchange intensification are considered: a wire spiral, a twisted tape, simultaneous placement of a tape and a spiral in the channel, and longitudinal flat profiles along the channel axis. Using computer simulation, the thermal and hydraulic characteristics of the considered methods of heat exchange intensification in the range of numbers Re = 10000...60000 are determined. When determining the efficiency of heat transfer intensification, the author's method is used.

2. Computer simulation of hydrodynamic and heat exchange processes in model channels

Figure 1 shows schematic images of the types of intensifiers under consideration.

(a)  
(b)  
(c)  
(d)  

Figure 1. Types of intensifiers: (a) – wire spiral; (b) – twisted tape; (c) – tape and spiral; (d) – acoustic profiles.

The geometric model of the channel is a tube with a size of 12x1 mm and a length of 300 mm, in which the above-mentioned intensifiers are installed. In a channel with a wire spiral, the diameter of the wire used is 0.5 mm, and the pitch between the turns is 5 mm. In a channel with a twisted tape, the intensifier is made of a twisted tape with a thickness of 1 mm, the tape pitch being 30 mm. In the following geometric model, the two above-mentioned methods of heat transfer intensification are implemented: a tape and a spiral. The tape and the spiral have the same geometric parameters as in the previous cases, but they have a different direction of the flow twist. The geometric model of the tube with self-excited resonant self-oscillations of sound and ultrasonic frequencies is carried out by installing flat profiles along the axis of the channel. The length of the profile is 13 mm, the distance between the profiles is 2 mm, and between each of the groups of profiles it is 10 mm.

The calculation model is a cylindrical channel with an intensifier. For thermal and hydrodynamic flow stabilization, the model provides an input section with a length of 50 mm. In the calculation models, the assumption is used: the intensifiers and the tube walls are made as a single solid.

For all types of intensifiers, computational grids with a volume from 3 to 5 million computational cells are constructed, with a prismatic boundary layer providing a value of $y^+ \leq 1$.

The computer simulation is based on the numerical solution of the Reynolds-averaged Navier-Stokes equations (RANS) supplemented by the k-ω SST turbulence model. In a solid, the equation of thermal conductivity is solved with a constant value of the coefficient of thermal conductivity. A viscous
turbulent flow of a compressible gas with variable thermophysical properties is considered in the simulation. The problem of conjugate heat transfer is solved in a three-dimensional formulation with a second-order accuracy in space and a second-order accuracy in time for the case of intensification by acoustic vibrations.

On the outer surface of the tube, we set a boundary condition of the first kind – the wall temperature $T_w = 500 \, K$, the pressure value at the outlet $p_{\text{out}} = 10^5 \, \text{Pa}$, and the temperature value $T_{\text{out}} = 300 \, K$. The set pressure range at the inlet is $p_{\text{in}} = 1,01 \ldots 4,0 \times 10^5 \, \text{Pa}$, and temperature $T_{\text{in}} = 300 \, K$. The working fluid is considered to be air with variable thermophysical properties, specified in the form of polynomial dependences, and the wall material is steel with a constant value of the thermal conductivity coefficient $\lambda_w = 20 \, \frac{W}{m \cdot K}$.

3. Results of computer simulation

The velocity field obtained during the simulation for all types of intensifiers with the value of the Reynolds number $Re = 22000$ is shown in Figure 2.

![Velocity fields in the longitudinal section of the model channel with different types of intensifiers](image)

Figure 2. Velocity fields in the longitudinal section of the model channel with different types of intensifiers: (a) – spiral; (b) – tape; (c) – tape and spiral; (d) – profiles.

According to Figure 2, the flow pattern for all methods of intensification is significantly different. In the case of using a wire spiral, two types of impact can be distinguished: the destruction of the boundary layer and the twist of the flow. When using a twisted tape, the flow is twisted throughout the entire internal volume of the channel. Due to the influence of centrifugal forces, large volumes of the working fluid are displaced to the periphery of the channel, which leads to an increase in heat transfer. The combination of the tape and the spiral with the opposite twist of the flow in the core and the wall area allows increasing the dissipation of thermal energy in the boundary layer. The use of transverse profiles is fundamentally different from the methods of heat transfer intensification discussed above: the effects under consideration are essentially non-stationary.

The complexity of modeling the nonstationary gas-dynamic effects of heat transfer intensification is as follows: the input boundary conditions should lead to the flow of exciting self-sustaining acoustic vibrations; the circuit viscosity of the numerical solution methods should lead to the physical dissipation
of the resulting vortices; the time step should be small enough to correctly describe the period of pulsations.

The temperature field obtained in the course of computer simulation of heat transfer and hydrodynamics in channels with different types of intensifiers for the Reynolds number Re = 22000 is shown in Figure 3.

![Temperature fields in the longitudinal section of the model channel with different types of intensifiers](image)

**Figure 3.** Temperature fields in the longitudinal section of the model channel with different types of intensifiers: (a) – spiral; (b) – tape; (c) – tape and spiral; (d) - profiles.

As can be seen from the presented temperature distribution, it is obvious that the heating of the cooler at the same Reynolds number is different in all cases, and this indirectly indicates the different efficiency of the considered methods of heat exchange intensification.

Since the simulation is performed in the range of Reynolds numbers, it becomes possible to determine the thermal and hydraulic characteristics.

The hydraulic characteristic refers to the dependence of the hydraulic resistance coefficient on the Reynolds number: $\zeta(Re)$, which is defined as follows:

$$\zeta(Re) = \frac{2 \cdot \Delta p}{\rho u^2} \cdot \frac{d}{L}$$  \hspace{1cm} (1)

where $\Delta p = p_{in} - p_{out}$ is the total pressure loss for pumping the coolant through the tube; $d$ is the inner tube diameter; $L$ is the tube length, $\rho$ is the inlet air density; $u$ is the inlet air velocity; and $Re$ is the Reynolds number, which is also determined by the parameters at the input.

The thermal characteristic refers to the dependence of the Nusselt number on the Reynolds number:$Nu(Re)$, which is defined as follows:

$$Nu(Re) = \frac{q_w}{\Delta \bar{T}} \cdot \frac{d}{\lambda}$$  \hspace{1cm} (2)

where $q_w$ is the heat flux set from the outside of the tube; $\Delta \bar{T}$ is the average temperature difference; and $\lambda$ is the average thermal conductivity of the gas corresponding to the wall temperature.

As in the case of the hydraulic characteristic, the thermal characteristic is an integral parameter that demonstrates the intensity of the heat exchange process over the entire length of the working section, but not in the local area.
Changes in the hydraulic and thermal characteristics obtained in the course of the computational study are shown in Figures 4(a) and 4(b), respectively. In the presented figures, the symbols indicate the values of the hydraulic resistance coefficient for the studied intensification methods, and the values for the reference smooth channel are marked with a solid line. As a result of the analysis, it has been found that the method of intensification with the help of a spiral and a tape has the greatest hydraulic resistance, which is explained by the large compression of the passage section and the complex structure of the flow around the intensifiers. This increase in hydraulic resistance is also accompanied by an increase in heat transfer from the hot wall to the cooler. A commensurate increase in heat transfer was also observed in the method of intensification using self-sustaining acoustic vibrations. This method differs from other methods of intensification in that the increase in hydraulic resistance and heat transfer is caused by non-stationary phenomena.

![Figure 4](image)

Figure 4. Comparison of hydraulic (a) and thermal (b) characteristics for different methods of heat exchange intensification.

The presented thermal and hydraulic characteristics for different methods of intensification have all the characteristic physical features: the highest value of heat transfer corresponds to the highest increase in hydraulic resistance. One of the traditional ways to compare various intensification methods with each other is to compare the obtained thermal and hydraulic characteristics with a reference smooth channel, the characteristics of which are well known. One of the important features of this work is the fact that the characteristics of a smooth channel are also obtained by calculation, which allows you to directly compare the increase in heat transfer and hydraulic resistance.

Nusselt numbers $N_u_{pr}$, when heat exchange is intensified by acoustic vibrations, in the flow in a tube with profiles exceed their values $N_u_{sm}$ when the flow in a smooth tube is heated: $N_u_{pr}/N_u_{sm} = 1.507÷2.257$, and $N_u_{t,sp}$ exceed $N_u_{sm}$ at the intensification of heat transfer in the flow in a tube with a tape and a spiral: $N_u_{t,sp}/N_u_{sm} = 1.88÷2.076$. Minimum increment of Nusselt numbers in a channel with profiles $N_u_{pr}$ occurs in ranges of numbers $Re$, in which the failure of self-oscillations is recorded (Figure 5 (a)).

![Figure 5](image)

Hydraulic resistance coefficients in a tube with profiles $\zeta_{pr}$ increase relative to their values when the flow in a smooth tube is heated $\zeta_{sm}$ in $\zeta_{pr}/\zeta_{sm} = 6.91÷9.04$, and with the intensification of heat transfer in the flow in a tube with a tape and a spiral $\zeta_{t,sp}$ the increase occurs in $\zeta_{t,sp}/\zeta_{sm} = 10.2÷11.024$. The maximum increase in the coefficients of hydraulic resistances in the channel with plates occurs in the ranges of $Re$ numbers corresponding to the modes of developed self-oscillations with the largest amplitudes of pressure pulsations (Figure 5 (b)).
4. Criteria for the efficiency of heat transfer intensification

The use of relative thermal and hydraulic characteristics is much more obvious than the use of absolute values, but nevertheless it does not give a clear idea of the characteristics of the heat exchanger. For a more transparent comparison, let us consider the author's method of assessing the effectiveness of intensification, which consists in modifying the approach of G. A. Dreitzer [7].

A method for evaluating the efficiency of heat transfer intensification is proposed; it may be reduced to a generalizing dependence of the following form:

$$K_i = K_f K_{Re} \Pi^*$$  \hspace{1cm} (3)

where $K_i$ is the criterion for the efficiency of heat transfer intensification; $K_f$ is the parameter of the intensification efficiency; $K_{Re}$ is the relative thermohydraulic characteristic; and $\Pi^*$ is the geometric parameter.

The criterion for the efficiency of heat exchange intensification is selected based on the set goals. Such goals may be to increase heat recovery ($Q$); eliminate hydraulic losses for pumping the coolant ($\Delta p$); reduce the required mass flow rate of the cooler ($G$); decrease the mass-dimensional characteristics ($V$) etc. Different methods of heat transfer enhancement can be compared with each other based on the criterion of efficiency of heat transfer intensification. For example, a method for intensifying heat transfer will be effective according to the heat removal criterion if the efficiency criterion is $K_Q > 1$. At the same $K_{\Delta p}$ and $K_G$ they act as parameters of heat transfer intensification; the values of these parameters allow us to close the system of equations from a mathematical point of view. In terms of physical meaning, the real values of these parameters serve to implement the goals of heat exchange intensification in practice. These parameters can also be attributed to the design parameters, which can be used to formulate a task for changing the characteristics of the heat exchanger, e.g., to propose heat exchange enhancement, providing an increase in heat removal by 30%, while increasing the pressure loss by no more than 25% at the same flow rate of the cooler. In this example, during the ongoing intensification, it is necessary to obtain the value of the criterion for the efficiency of heat transfer intensification $K_Q > 1.3$, at the same time $K_{\Delta p} = 1.25$, $K_G = 1$.

The relative thermohydraulic characteristic represents an increase in heat transfer compared to an increase in hydraulic resistance for a particular method of heat exchange intensification, in this case $K_{Re} = \eta_{Nu} \left( \eta_\zeta \right)^{1/3}$. In fact, this parameter characterizes the efficiency of thermal energy dissipation in the boundary layer in comparison with the increase in resistance. The thermal and hydraulic characteristics can be obtained experimentally or calculated as above. Since the nature of the flow and heat transfer depends very much on the flow regime, the main factor determining the thermal and hydraulic characteristics is the Reynolds number. Each method of intensification is compared with the
reference smooth case, and already on the basis of these values, different methods can be compared with each other.

Parameter $\Pi^*$ characterizes the heat geometric features of various methods of heat exchange intensification. For the case of finned channels, this parameter characterizes the influence of geometric parameters and the finning coefficient.

For the considered methods of heat transfer intensification, it is proposed to use a criterion that characterizes the change in the required flow rate of the cooler:

$$K_G = \left(K_{\Delta P}^{-1/n} \eta_{Nu}^{-3} \eta_{\zeta}^{1/n-m-2}\right)^{\frac{1}{n-m-2}}$$

Figure 6 shows a comparison of the efficiency of various methods of heat transfer intensification, calculated from the presented dependence 4, as well as a direct comparison with the results of computer modeling. Computer simulation considered the ratio of flow rates when the same wall temperature is reached.

Conclusions
When comparing methods of intensification of heat transfer by acoustic vibrations in the tube profiles and the tube with baffle in the form of twisted tape and spiral with the heat transfer during the flow heating in a smooth tube is has been established that:

– the Nusselt numbers in tube profiles exceed their value in a smooth tube 1.507–2.257 times, and in the tube with tape and spiral – 1.88–2.076 times; and

– the coefficients of hydraulic resistance increase in a tube with profiles 6.91–9.04 times, and in a tube with a tape and a spiral – 10.2–11.02 times/

Evaluation of the efficiency of methods for intensifying heat exchange by acoustic vibrations in a tube with profiles and in a tube with a tape and a spiral using the criterion characterizing the change in the required flow rate of the cooler has also shown a higher efficiency of heat exchange enhancement by acoustic vibrations in a tube with profiles.

This allows us to conclude that the intensification of heat exchange by acoustic vibrations in a tube with profiles is more effective than in a tube with a tape and a spiral, as well as a single tape or spiral.
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