Experimental comparative research of convective heat transfer enhancement in channels

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Abstract. This article presents the results of a comparative-experimental research of various methods to intensify heat transfer in the channel. Four different methods of heat exchange enhancement are considered: twisted tape, wire spiral, joint intensifier made of wire tape and twisted spiral, and acoustic method of intensification. The thermal and hydraulic characteristics of various methods of heat exchange intensification are experimentally investigated, and the efficiency of heat exchange intensification is determined. The thermal and hydraulic characteristics of a smooth channel without intensification obtained experimentally under the same conditions were used as a reference. In the course of the comparative analysis of the considered methods of intensification, the most effective ones are found in the range of changes in the Reynolds number from 10000 to 60000. The presented data can be used in the design of heat exchangers.

1. Introduction

The use of various methods of heat exchange intensification in various industries over a long period of time allows creating efficient heat exchangers that meet the modern requirements of the industry. This result is due to a large number of research papers and successful practical implementation of research results. The issue of convective heat transfer enhancement in the modern world remains promising and complex problem of transport theory.

Traditional methods for intensifying heat transfer in cooling channels are to increase the flow rate of the coolant (for example, by reducing the flow section of the cooling channel) and the surface area of the heat exchange (for example, by finning the heat-emitting surface).

The research of developed surfaces is presented in [1], where an objective evaluation is given by an intensifier in the form of edges. After the potential of the used intensification methods is exhausted, developers of heat exchangers begin to use or explore other methods of heat exchange enhancement. At the same time, most of the intensification methods are relevant for heat carriers that have high values of Reynolds numbers (Re). Therefore, most of the fundamental monographs on the topic of convective heat transfer intensification [2–13] are devoted to this problem at high Re, and only a small part of the researches consider heat transfer at low Re [14, 15].

When heat exchange is intensified, a complex movement of elementary volumes of liquid in the wall layer occurs. Since the distribution of temperature and velocity fields in the boundary layer is different, it is possible to organize a more efficient transfer of heat compared to the transfer of the
amount of movement, as a result of a well-thought-out intensifying effect on the heat exchange process.

This paper presents the results of an experimental research comparing the effectiveness of various methods of heat transfer intensification under the same conditions is made. The case of intensification of heat transfer from the heated outer wall of the pipe to the air flow in the pipe is considered. Four methods of heat exchange intensification are chosen: wire spiral, twisted tape, simultaneous placement of tape and spiral in the channel, and longitudinal flat profiles along the channel axis.

The purpose of the experimental research is to obtain the thermal and hydraulic characteristics of various methods of heat exchange intensification at the same Re for all methods. The obtained experimental characteristics are compared with each other and with similar characteristics for a smooth pipe without intensification. The presented data can be used in the design of heat exchangers.

2. The experimental setup and the object of research

The scheme of the experimental setup is shown in figure 1. The experimental setup consists of a working section (1), an induction heating coil (2) on the outer surface of the channel, a measurement system (3), a flow meter section (4), a balloon (5) filled with air, and a shut-off valve (6).

The working section is a 10×1 mm tube made of stainless steel. In the experiments, 4 tubes are used, in which various types of heat exchange intensifiers are installed: a wire spiral, a tape swirl and a combined and longitudinal flat profile along the channel axis. A smooth tube is used as a reference.

An induction heating coil made of nichrome is evenly wound on the outer wall of the working section of the tubes to regulate the heat output.

The measurement system consists of static pressure selectors, thermocouples, and waveguides that allow measuring pressure pulsations. Figure 1 schematically shows the locations of the sensors.

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![Figure 2. Types of intensifiers: a) IWS, b) IS, c) IC, d) IP.](image)
The wire spiral intensifier (IWS) is a wire with a diameter of 1 mm, wound on a diameter of 6.5 mm. At the two ends of the spiral, straight 5 mm long sections are left and welded to the body of the main tube. The winding pitch is 5 mm, and the total length of the wire helix is 270 mm (figure 2a).

The belt swirl intensifier (IS) is a tape made of a flat plate with a thickness of 0.5 mm and a width of 8 mm; the length of the free ends is 15 mm, the twist step is 30 mm, the length of the tape in the deformed state is 240 mm (figure 2b). The combined intensifier (IC = IWS + IS) is a combination of two intensifiers: a wire spiral and a tape swirl. For the wire spiral, a 1 mm diameter wire was used, placed on top of the twisted tape close to the wall of the tube body. A plate similar to the above-mentioned intensifier 2, but of a smaller width, is used as a twisted tape. The intensifiers, installed in this case, are the tape and the spiral with opposite direction of rotation to each other. This is done for the purpose of more intensive dissipation of heat energy supplied from the outer wall to the air flow (figure 2c). The profile intensifier (IP) of self-sustaining acoustic self-oscillation represents 4 groups of profiles. The profile group consists of three plates with a thickness of 1 mm and a length of 13 mm each, with rounded corners; the distance between the profiles is 2 mm, and that between the groups of profiles is 10 mm (figure 2d).

3. Criteria of efficiency for heat exchange intensification

The effect of turbulence on the intensification of heat exchange depends significantly on the type of impact of the artificial turbulator and the associated change in the turbulent structure of the coolant flow. This change in the turbulent flow structure can significantly affect the turbulence characteristics of the resulting flow. One of the parameters that characterize the turbulent flow is the dependence of the RMS values of pressure pulsations $\langle P \rangle$ on $Re$, which determine the averaged hydrodynamic parameters of the flow. Dependence of relative RMS values of pressure pulsations $\langle P \rangle/P$ from $Re$ allows evaluating the efficiency of the process of converting the energy of a stationary flow into the energy of turbulent pressure pulsations [16-19] and determining the influence of various types of artificial turbulators on this process.

The criteria for the efficiency of the method of heat exchange intensification are the ratio of increasing Nusselt numbers $Nu$ (thermal characteristic) to coefficients of hydraulic resistance $\xi$ (hydraulic characteristic) of heat exchange devices (tubes) with increasing $Re$ using the method of intensification and without it [1-14,18,19].

In this paper, the ratio proposed in [7,10,20] is used as a criterion for the efficiency of the method of heat exchange intensification, which consists in the fulfillment of the condition:

$$
\left( \frac{Nu_{int,en}}{Nu_{sm}} \right)^{3.5} \left( \frac{\xi_{int,en}}{\xi_{sm}} \right),
$$

where the $int$ index is used to denote parameters for a flow with heat exchange intensification, and the $sm$ index is used to denote parameters for a flow without heat exchange intensification.

4. Results

In figure 3, it can be noted that the relative amplitude of pressure pulsations $\langle P \rangle/P$ for the flow in a tube with profiles exceeds the relative amplitude of turbulent pulsations of flow pressure in a smooth channel by 2...4 once. When the self-oscillation fails, the pressure pulsation amplitudes decrease sharply. 1.4...1.5 once the relative amplitude of pressure pulsations $\langle P \rangle/P$ over the amplitude of turbulent flow pressure pulsations in a smooth tube is registered for a tube with IS.
Figure 3. Change in the relative amplitude of pressure pulsations: 1 – smooth tube, 2 – IS, 3 – IWS, 4 – IC, 5 – IP.

At heat exchange enhancement by acoustic vibrations for the flow in a tube with profiles, the Nusselt numbers exceed their values as \( \frac{Nu_{ip}}{Nu_{sm}} = 1.057\pm2.052 \) when the flow is heated in a smooth tube, and as \( \frac{Nu_{is}}{Nu_{sm}} = 1.88\pm2.076 \) when heat exchange is intensified in the flow in a tube with a tape and a spiral. The minimum increase of Nusselt numbers in the channel with profiles occurs in the ranges of Reynolds numbers, at which the failure of self-oscillation is recorded (figure 4a). The coefficients of hydraulic resistance in a tube with profiles increase, compared to the case of the flow heated in a smooth tube, by a factor of 6.91\( \pm \)9.04. When the heat exchange in the flow is intensified in a tube with a tape and a spiral, those increase by a factor of 10.2\( \pm \)11.024. The maximum increase in the coefficients of hydraulic resistance in the channel with profiles occurs in the ranges of Reynolds numbers corresponding to the modes of developed self-oscillations with the highest amplitudes of pressure pulsations (figure 4b).

Figure 4. Changes of the Nusselt number (a) and the coefficient of hydraulic resistance (b) from the Reynolds number for the flow with and without heat exchange intensification: 1 – smooth tube, 2 – IS, 3 – IWS, 4 – IC, 5 – IP.

For two methods of heat transfer enhancement in the tube: with a wire spiral, and with a twisted tape, the increase in the coefficients of hydraulic resistance was almost the same as in the tube profiles. The Nusselt numbers for these methods increased less compared to the case of heat exchange enhancement in tubes with profiles, as well as tape and spiral. Therefore, only two methods of intensification are compared further: a tube with a tape and a spiral, and a tube with profiles.
Comparison of the two methods of heat exchange intensification can be directly carried out by the values of Nusselt numbers and the coefficients of hydraulic resistance \( \frac{Nu_{is}}{Nu_{ip}} = 1+1.27 \) and \( \frac{\xi_{is}}{\xi_{ip}} = 1.21÷1.45 \).

The Nusselt numbers for the intensification of heat exchange in a tube with a tape and a spiral exceed their values when the flow is heated in a tube with profiles only in the areas of self-oscillation failure. The maximum excess is 27%. In this case, the coefficients of hydraulic resistance increase by 21÷45%. This allows concluding 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.

The same result can be obtained if the previously given ratio [7, 10, 20] is used as a criterion for the efficiency of the method of heat exchange intensification:

\[
K_{eff} = \left( \frac{Nu_{ass}}{Nu_{a}} \right)^{\frac{3.5}{(\xi_{ass}/\xi_{a})}}.
\] (2)

For the method of intensifying heat exchange by acoustic vibrations in a tube with profiles, this ratio is performed for eleven flow modes out of the total number registered in experiments, and for intensification in a tube with a tape and a spiral – only for nine modes (figure 5).

![Figure 5](image)

**Figure 5.** Criteria of efficiency for heat transfer intensification: 1 – IWS, 2 – IS, 3 – IC, 4 – IP.

The presented results of experimental studies prove a more effective intensification of heat exchange by acoustic vibrations in a tube with profiles in comparison with the other methods.

**Conclusions**

When comparing methods of heat transfer enhancement by acoustic vibrations in the tube profiles and the tube with the turbulator in the form of a twisted tape and spiral heat-exchange with heat flux in an installed smooth pipe it is found that:

- the Nusselt number in the tube with profiles is higher than its values in the smooth tube 1.05÷2.052 times, and in the tube with tape and spiral 1.88÷2.076 times;
- the coefficients of hydraulic resistance increase in the tube with profiles 6.91-9.04 times, and in the 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 \((\text{Nu}_{\text{inten}}/\text{Nu}_{\text{sm}})^{3/5}(\xi_{\text{inten}}/\xi_{\text{sm}})\) have also shown a higher efficiency of intensifying heat exchange by acoustic vibrations in a tube with profiles.

This brings us to the conclusion 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 and a spiral.

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