Intensification of heat exchange by method of interacting flows

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Abstract. The effectiveness of the heat exchange intensifier “rib-twisted wire” is considered in this paper. The main goal was to study the influence of the wire coiling step \( t \) on heat transfer and hydraulic resistance for different values \( \hat{H} \) of the dimensionless height of the edge \( \hat{H} \), as well as some results on heat exchange during bubbly boiling in an annular channel.

Given:
- a brief description and an image of the heat exchange intensifier “rib-twisted wire”;
- generalized results of studies of heat exchange and hydraulic resistance in the annular channel in the single-phase convection with different geometric characteristics of the intensifier;
- empirical correlations of the generalized experimental results that allow to calculate the coefficient of hydraulic resistance and heat transfer in the range of regime parameters in the single-phase convection that is being studied;
- some results of experiments in bubbly boiling regimes and near-critical thermal loads.

1. Introduction

Today various methods for heat exchange intensification have been proposed and are used effectively [1, 2]. However, the application of these methods to a convex heated surface does not lead to a noticeable increase in heat transfer, and sometimes a negative result is observed. The work carried out earlier by the team of authors [3, 4] showed the effectiveness of using the method of heat exchange intensification on a convex heated surface based on the interaction of swirling and axial (transit) flows [5]. The point of the method is the organization of two interacting streams with the help of the “rib-twisted wire” intensifier in the annular channel. Analysis of extensive experimental data [3, 4] showed that the use of intensifiers of this type makes it possible to significantly increase the heat transfer coefficient in comparison with a smooth annular channel with an acceptable increase in hydraulic resistance. The maximum value of the heat transfer coefficient was obtained with the value of the dimensionless height of the edge \( \hat{H} = 0.35 \), and the maximum of the hydraulic resistance coefficient – at \( \hat{H} = 0.23 \). Since all the experiments were carried out at the same step of the intensifier wire coiling \( t = 50 \) mm, it seemed appropriate to expand the studies in which the value of the coiling step would change for different values \( \hat{H} \) of the dimensionless height of the edge \( \hat{H} \).

2. Description of the intensifier “rib-twisted wire”

The research cycle was carried out at the “TVS MEI” test-bed operating in the range of technological parameters corresponding to the VVER-1000 reactor. Its description and main technical characteristics
are presented in [6] and discussed at conferences [7, 8].

Figure 1 shows the image of the intensifier used. Longitudinal ribs (2) were attached to the outer surface of the heating element (1), on which a twisting device (wire coiling) was mounted (3). All the elements of the intensifier were made of steel grade 08Х18Н10T, their fastening was carried out with the laser welding. The intensifiers are installed in a way that allows the clearance of 0.2 mm between the unheated concave surface and the wire coiling, which is caused by the structural features of the installation and the convenience of mounting.

![Intensifier Image](image)

**Figure 1.** Elements of the intensifier and their location on the working area: 1 – heating element, 2 – longitudinal rib, 3 – wire coiling.

Detailed description of the working area design and the intensifier is presented in [4]. The main geometric characteristics of the intensifier are the height of the longitudinal edge $h$, the diameter of the twisted wire $d$ and the coiling step $t$. For the convenience of generalization of the experimental data, the dimensionless height of the edge $\hat{H}$ and the twist coefficient $k$ related to the step $t$ are introduced:

$$\hat{H} = \frac{2h}{(d_2 - d_1)}, \quad k = \frac{\pi \hat{d}}{t},$$

where $d_1 = 12.9$ mm – internal diameter of the annular channel (outer diameter of the heating element), $d_2 = 16.3$ mm – outer diameter of the annular channel, $\hat{d}$ – diameter of the median line of the swirling flow, determined by the ratio:

$$\hat{d} = \frac{d_2 + d_1}{2} + h.$$

Table 1 shows the values of the geometric characteristics of the intensifiers used. The “+” sign in the table indicates that this step was used for the represented value of $\hat{H}$.

| Parameter | Value         |
|-----------|---------------|
| $h$, mm   | 1.00 0.90 0.75 0.60 0.50 0.40 |
| $d$, mm   | 0.50 0.60 0.75 0.90 1.00 1.10 |
| $\hat{H}$ | 0.59 0.53 0.44 0.35 0.29 0.23 |
| $t=40$ mm | + + + + + + |
| $t=50$ mm | + + + + + + |
| $t=60$ mm | + + + + + + |
| $t=100$ mm| + + + + + + |

**Table 1.** Geometric characteristics of intensifiers.
3. Effect of an intensifier on heat exchange and hydrodynamics in the single-phase convection

To calculate the heat transfer coefficient in a smooth annular channel, the modified Isachenko-Galin formula is used:

\[ Nu = 0.017 Re^{0.8} Pr_f^{0.4} \left( \frac{Pr_f}{Pr_w} \right)^{0.25} \left( \frac{d_2}{d_1} \right)^{0.18} \]

The measurement results are presented as \( \frac{Nu}{A} = f(Re) \), where \( A = Pr_f^{0.4} \left( \frac{Pr_f}{Pr_w} \right)^{0.25} \left( \frac{d_2}{d_1} \right)^{0.18} \).

Parameter \( A \) considers the properties change (kinematic viscosity and coefficient of thermal diffusivity) at various temperatures of the coolant in the working area, as well as the geometric dimensions of the annular channel.

The influence of the geometric parameters of the intensifier on the heat transfer in the form of the dependences \( \frac{Nu}{A} = f(Re) \) and \( \frac{Nu}{A} = f(\hat{H}) \) is shown in figure 2 and figure 3.

In figure 2, it is seen that with an increase of the coiling step, the heat transfer coefficient increases.

**Figure 2.** The dependence of heat transfer on the Reynolds number for different coiling steps of the intensifier (\( \hat{H} = 0.29 \)):
- 1 – \( t = 20 \) mm,
- 2 – \( t = 50 \) mm,
- 3 – \( t = 60 \) mm,
- 4 – smooth annular channel (experiment).

**Figure 3.** The dependence of \( \frac{Nu}{A} \) on the parameter \( \hat{H} \) (\( Re = 45000 \)):
- 1 – \( t = 40 \) mm,
- 2 – \( t = 50 \) mm,
- 3 – \( t = 60 \) mm,
- 4 – \( t = 100 \) mm,
- 5 – smooth annular channel (experiment).

As follows from the analysis of Fig. 3 the dependence \( \frac{Nu}{A} = f(\hat{H}) \) is not monotonic and has a maximum value at \( \hat{H} = 0.35 \) for all values \( \hat{H} \) of the coiling step \( t \). The same value was obtained in [4], in which the research was carried out only for a coiling step \( t = 50 \) mm.
One of the conditions for the efficiency of any heat exchange intensifier is the excess of the heat transfer coefficient increase over the growth of the hydraulic resistance coefficient. For this purpose, studies of hydrodynamic resistance were carried out in the entire range of $\dot{H}$ and $t$. To do this, during the experiment, direct measurements of pressure losses in the working area were made, mass flow and temperatures at the inlet and outlet of the working area. The results of processing the experimental data are presented in the form of the dependence of the hydraulic resistance coefficient on the Reynolds number in figure 4.

**Figure 4.** Dependence of the hydraulic resistance coefficient on the Reynolds number at $\dot{H} = 0.44$:
1. $t = 40\cdot$mm;
2. $t = 60\cdot$mm;
3. $t = 100\cdot$mm;
4. smooth annular channel (calculation by the modified formula of Filonenko).

In figure 4 there is a noticeable increase in the coefficient of hydraulic resistance $\xi$ as the step of the wire coiling $t$ decreases. For greater clarity, figure 5 shows the dependences $\xi=f(t)$ for different $\dot{H}$. As can be seen, the stratification with respect to the parameter $\dot{H}$ does not exceed 10%, which lies within the experimental accuracy.

**Figure 5.** Dependence of the coefficient of hydraulic resistance on the step of the wire coiling (Re = 60000):
1. $\dot{H} = 0.23$, 2. $\dot{H} = 0.35$, 3. $\dot{H} = 0.44$

Figure 6 shows the dependence of the coefficient of hydraulic resistance on the dimensionless parameter $\dot{H}$ for all steps of wire coiling. This dependence is not monotonic, a maximum $\xi/\xi_0$ is observed at $\dot{H} = 0.23$ for all values of $t$. 
Figure 6. The dependence $\xi/\xi_0$ on the parameter $H$ (Re = 60000):
1 – $t = 40\text{·}mm$;
2 – $t = 50\text{·}mm$;
3 – $t = 100\text{·}mm$.

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