Multi-method research of flow and heat transfer for the tube with circular fins

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Abstract. PIV, heat flux measurement and thermometry were combined in real time, for a comprehensive research of air flow and heat transfer at non-isothermal surface of the tube with circular fins. Gradient heat flux sensors (GHFSs) with response time of $10^{-8} \ldots 10^{-9}$ s fix the value of heat flux per unit area practically instantaneously. We have identified regime and geometrical effect on heat transfer supplemented with results of gradient heat flux measurement, thermometry data, and velocity fields. The experiments covered a range of Reynolds numbers of $Re = 0.4 \ldots 5 \times 10^4$. The gap of measurements (by the azimuth angle of $\varphi$) of heat flux and temperature was 20°. The spaces between the fins varied within $\delta = 5 \ldots 20$ mm. According to the results of heat flux measurement and thermometry, local and then average over the surface heat transfer coefficient (HTC) for various regimes were calculated. Using a model with hollow and solid fins made it possible to evaluate experimentally the effectiveness of a circular fin.

1. Introduction
Heat transfer enhancement allows reduction of the mass-dimensional parameters of heat exchangers and the cost of their manufacture. In addition, there are environmental issues from the possibility of thermal power plants, boiler plants and industrial units. The ways to increase heat transfer by increasing the rate of heat carriers are often ineffective.

Flow characteristics near finned tubes are well studied [1]. In study of hydrodynamics in finned tube bundles, HTCs for the first rows of bundle are the most important. There are many papers devoted to measuring HTCs (local and average over the surface). They are based on applying the variety of methods in a wide range of geometric forms and flow regimes [2]. Methods based on the use of heat flux sensors are most acceptable. However, the research results are controversial. It is also important to note that the flow and heat exchange around the fins are usually studied in separate experiments.

When designing modern compact boilers, the flow of any heat carrier around the tubes at a right angle may be impossible. Since in practice these options are actual, then a detailed study of turn angles effect is necessary.

Effectiveness of circular fins is also important. Usually, HTC value included in calculation is considered to be the same above all fin surface. [3]. In fact, in most cases, local HTCs are not constant, which reduces the accuracy of calculation.
Based on the above, when designing heat exchangers, taking into account the number of rows, their pitch, height, shape, etc. are usually considered as some “additives”. In our experiments we were guided by just such logic.

2. Experimental technique and models
The model used is a hollow cylinder, heated by saturated steam. Steam from a 4.1 kW boiler was fed into the model interior, and condensate was removed through the opening at the lowest point. A slight overpressure was measured with a U-tube pressure gauge; the absolute pressure determined saturation temperature. In all experiments, it was close to 100°C. Five fins mounted on the cylinder had a width of 10 mm and a height of 20 mm. Four of them were made of perspex. They served to block the flow and provide visualization in interfin spaces; we called them fin-simulators. The fifth fin, which was mounted between the fins-simulators, we called it the “working” one, and the results given below were obtained for it. The choice of materials and sizes of the “working” fin was done according to the tasks of study. Low thermal conductivity \( k = 9 \text{ W/(m×K)} \) of titanium VT22 ensured the heterogeneity of temperature field controlled in experiments. The thickness of the fin, which is substantially higher than that used in practice, made it possible to evaluate HTC and fin effectiveness. The model was installed on a rotation device, which allowed us to rotate the model around the axis at an angle \( \phi \) of 0 ... 180°. The interf in spaces in various experiments varied from 5 to 20 mm.

Three modern technologies were applied at once to visualize the flow near the fin and measure the heat flux per unit area, and surface temperature during our experiments. Visualization was performed by PIV [4]. Heat flow measurements were carried out using gradient heat flow sensors (GHFSs) [5-7]. Temperature measurement technique used thermal imaging tools and ther mocouples. The detailed description of each techniques used in experiments can be found in [8]. Here we describe only the temperature measuring technique at the surface of the “working” fin of a finned tube.

To measure the temperature at the installation sites of GHFSs, a semi-artificial thermocouple was used. The measurement scheme is shown in Figure 1.

![Figure 1. Scheme of semi-artificial thermocouple measurement.](image)

The hot junctions were placed on the finned tube at the bottom surface of the “working” fin symmetrically with the GHFSs. It is also necessary to measure temperature difference between the free stream and the fin surface to calculate the local HTC. A thin needle made of titanium VT22 was mounted on the fin. The needle end was brought into the free stream and formed the cold junction with
a copper wire. Calibration of the thermocouple VT22-copper was carried out by the reference point method. The hot and cold junctions were immersed in boiling water at atmospheric pressure and in melting ice, respectively. Linear approximation between the reference points gives the equation \( T = 193.31 \times E + 2 \) (here \( E, \text{mV} \), is semi-artificial thermocouple signal; \( T, \degree \text{C} \), is measured temperature).

All experiments were conducted in the subsonic wind tunnel [9]. In various experiments, the stand pattern differed only in experimental models. As a result, we have:
- dependence of heat flux per unit area on time,
- heat flux per unit area distribution along the fin surface;
- velocity field;
- temperature distribution along the fin surface (temperature field).

The experiment uncertainty of performed evaluation, not exceeding 2.4 % for the HTC, makes it possible to consider its results quite reliable.

3. Results

The main objectives of the experiment included checking of compatibility of all methodological approaches, comparing the experimental data with the calculated ones and identifying new opportunities inherent in a comprehensive study of flow and heat transfer at non-isothermal surfaces.

In all regimes, the velocities of the air flow near the “working” fin are oriented in close directions. Significant interfin flow turbulization is observed only when the Reynolds number is \( \text{Re} = 5.0 \times 10^4 \).

Visualization is most detailed for the interfin space of 20 mm (Figure 2). For all Reynolds numbers, the flow stabilizes rather quickly.

![Figure 2. Velocity field near finned tube with the interfin space of 20 mm.](image)

The distributions of dimensionless HTC (\( \bar{h} = \frac{h_l}{h_\varphi} \), where \( h_l \) is HTC averaged over fins height, \( W/(m^2\times K) \) and \( h_\varphi \) is HTC averaged over fins area, \( W/(m^2\times K) \)) for a finned tube with different interfin spaces \( \delta \) are shown in Fig. 3. The highest HTCs are shifted to the forward region of the model. With an increase in Reynolds number, this trend is waning; with the interfin space of 15 mm, the HTC rises in the tail region.
Figure 3. Distribution of dimensionless HTC at the surface of a titanium VT22 circular fin.

One and a half to two times the average level $h$ is observed in zone of $\phi = 60 \ldots 90^\circ$; at $\phi > 90^\circ$, the curves for all Reynolds numbers go very close.

4. Conclusion
The paper shows the combined use of PIV, gradient heat flux measurement and thermometry for comprehensive experimental study of hydrodynamics and heat transfer in the flow around the finned tube with the “working” fin and fins-simulators. The cases of cross-flow around a finned tube with different interfin spaces are considered. It is shown that substantial non-uniformity of local HTCs distribution at the circular fin surface must be taken into account when analyzing heat transfer at the finned tubes [10].

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