The combination of PIV and heat flux measurement in study of flow and heat transfer near a circular finned cylinder

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Abstract. The flow and heat transfer of the finned cylinder are investigated by the methods of PIV, gradient heat flux measurement and thermometry. On the hollow model of a circular cylinder heated by saturated water vapor at atmospheric pressure, five annular fins of 20 mm high and of 10 mm thick are mounted. For the first model, the “acting” fin was hollow; for the second, it was solid and made of titanium alloy VT22. The remaining four fins simulated flow blockage. To visualize the flow in the intercostal space, the fin simulators were made of Perspex. Battery gradient heat flux sensors (GHFSs) with volt-watt sensitivity of 10 mV/W, were installed on the “acting” fin at different distances from the surface of the carrier cylinder. The cylinder rotated around its axis at an angle of $\phi = 0...180^\circ$, which made it possible to obtain the distribution of heat flux over the surface of the fin. By combining PIV diagnostics and gradient heat flux measurement, it was possible to obtain a complex 3D structure of the flow in the intercostal space and the distribution of heat flux on the surface of the fin. The values of the local heat transfer coefficients (HTCs) were also obtained. The dependence of HTC on flow mode and intercostal space is revealed. Comparison of the obtained characteristics for models with hollow and solid fins allowed us to determine in experiment fin efficiency for different intercostal spaces and free-stream velocities. The combination of all three technologies opens up new possibilities in study of flow and convective heat transfer.

1. Introduction

A common elements of most recuperative heat exchangers are transversely streamlined bundles of round tubes. To increase the heat transfer coefficient (HTC) finned tubes with circular fins are often used. Structure of the flow near the finned tubes directly affects heat transfer between the fins and streaming fluid. In real heat exchangers, influence of the height of the fins, the non-cross wrap, blockage, etc. on the heat transfer is important.

The study of flow and heat transfer in transversely finned tubes is a multifactorial problem. So, in the works [1, 2] 3D flow at the base of the fins is described. Due to the difference in velocities near the fin and in the core of the flow, a pressure drop occurs along the cylinder during flow past the pipe. Due to the differential, there is a movement of fluid from the centre of the intercostal space to the root of the fin. The authors of work [1] note that with a low fin height ($0.2...0.35 \times h/d$, where $h$ is the fin height, $m$, $d$ is diameter of the carrier cylinder, $m$) the influence of the cylinder as a barrier to the main flow increases [1]. The flow visualization in this work was carried out with the help of a soot-paraffin suspension. In studies on this topic, the method of recalculating of the velocity field from
measurements of static pressure field [3] and hot-wire method are widely used [4]. However, both of these methods are invasive, and to estimate the distortion of the flow pattern in the intercostal gap with its small value \( u/\delta = 0.4 \ldots 1 \), where \( u \) is the intercostal gap, \( m \), \( \delta \) is the fin thickness, \( m \) seems complicated. With the expansion of the scope of application of lasers, it became possible to apply the method of PIV (Particle Image Velocimetry), which is based on measuring of particle velocity. Since PIV diagnostics does not imply introduction of measuring probes into the flow, the prospects for the development of this scientific direction are obvious.

In the study of heat transfer, the main task is to determine the HTC. Works devoted to the measurement of this parameter are based on the use of various methods for different forms of the fins and flow regimes. Thus, the method based on the analogy between the processes of heat and mass transfer [3], allows you to determine the coefficients of mass transfer by photometric method. There are paintings in which the colour intensity of different parts of the fin is proportional to the value of the local HTC. However, this method was not widely used due to the complexity of processing the data and the methodical lack of the rigor.

More common methods are based on the use of sensors – heat flux meters. In [1], measurements were performed on fully heated models of finned tubes. The sensors were installed on the edge and on the surface of the carrier cylinder, and their position relative to the direction of the oncoming flow was varied by turning the cylinder around the axis. Studies were conducted on single pipes [2] and pipe matrix [3].

Note that the results of experiments differ both qualitatively and quantitatively. Some authors note [1] that the distribution of HTC over the surface of the fin is uneven, and at the top of the fin the value of \( \alpha \) is higher than at the base, where a thicker boundary layer is formed. It is also noted that the maximum values of \( \alpha \) fall on the azimuth angle of rotation \( \varphi = 70 \ldots 90^\circ \). On the other hand, in studies of [2] under similar conditions, the local HTC maxima were found near the root of the fin. In addition, the results of the work [3] indicate bursts of HTC value in the region of \( \varphi = 100 \ldots 130^\circ \).

In practice, the more important parameter is the average HTC over the surface. For its definition, use is made of semi-empirical dependences that require clarification, or numerical methods that require verification by physical experiment.

Summarizing the above, it can be concluded that a joint study of heat transfer and edge flow around fins using gradient heat flux measurement, PIV and thermal imaging diagnostics can yield significantly new and useful results and will allow the refinement of existing calculation methods and models.

2. Experimental setup
The experimental model was a hollow cylinder with a diameter of 66 mm and a length of 600 mm, made of steel sheet with a thickness of 0.1 mm. The experiment was carried out in several stages:

- On the cylinder is mounted a single hollow fin heated by steam with a diameter of 106 mm (1).
- A single “acting” hollow fin and two simulator fins made of Perspex are mounted on the cylinder (2).
- On the cylinder one “acting” hollow fin and four simulator fins are mounted (3).
- Repetition of the series of experiments (1) – (3) in the same hydrodynamic regimes with the only difference being that the fin made of VT22 alloy was used as an “acting” one (4).

Figure 1 shows photographs of experimental models. Simulator fins are made of optically transparent Perspex, which made it possible to visualize the flow inside the intercostal space.

The finned cylinder was installed in the working part of the subsonic wind tunnel of the Department of Thermophysics of Power Units of Peter the Great St. Petersburg Polytechnic University (figure 2).
Figure 1. Photographs of finned cylinder models.

It should be noted that the wind tunnel is equipped with a heat exchanger (air cooler) connected to the cold water supply system, which made it possible to conduct long-term experiments keeping the free-flow temperature almost constant (0.1...0.2 °C). The operating characteristics of the wind tunnel are also shown in the figure.

Figure 2. The appearance of the wind tunnel.
3. Experimental techniques
Within the framework of this study, several modern methods were used at once, therefore each of them requires a detailed description.

3.1. PIV diagnostics
The wind tunnel described in section 2 is equipped with the POLIS PIV system [4]. In the PIV diagnostics (figure 3), the air flow is seeded with tracers with the diameter of 2…3 \( \mu \text{m} \). A laser knife obtained by transforming a laser beam using a system of cylindrical lenses illuminates each tracer with double flashes at a known time interval.

![POLIS PIV system](image)

**Figure 3.** POLIS PIV system [4].

Digital cameras (their number may vary depending on the PIV configuration) during flashes captures the image of the tracers. The synchronization unit provides simultaneous operation of the laser and cameras. The system allows you to adjust the flow of tracers, laser power and frequency of photographs in accordance with the flow mode [5].

3.2. Gradient heat flux measurement
Since 1996, gradient heat flux sensors [6] have been actively used by the scientific group of the Department of Thermophysics of Power Units of Peter the Great St. Petersburg Polytechnic University [7]. To date, the GHFSs are successfully used in studies of heat transfer during condensation and boiling, measurement of heat transfer parameters in ICE [8, 9] and also in industrial experiments [10]. A unique feature of the GHFSs is record low value of their time constant (up to \( 10^{-8} \ldots 10^{-9} \text{ s} [6] \)), which makes them practically an instantaneous measuring tool in most heat transfer tasks. The principle of the GHFS operation is based on the transverse Seebeck effect: when a heat flux
passes through a plate with anisotropy of thermal and electrical properties, thermopower occurs in it, normal to the heat flux vector direction and proportional to its module [6, 11].

In our study, three battery GHFSs based on monocrystalline bismuth were used (figure 4).

![Figure 4](image1.png)

**Figure 4.** GHFS and its location on the surface of the fin.

The size of the GHFSs in plan was of 2×2 mm, and the thickness was of 0.2 mm. The volt-watt sensitivity of the GHFSs was at the level of 10 mV/W and was determined by the method of absolute graduation according to the Joule heat flux [11].

3.3. **Thermal Imaging Diagnostics**

To calculate the HTC, in addition to the heat flux per unit area, it is necessary to know the difference between temperature on the surface of the fin at the locations of the GHFS and free-flow temperature. For a single annular fin model, a FLIR P640 thermal imager (Forward-Looking InfraRed) was used to measure the fin surface temperature. The principle of operation of a thermal imager is as follows: bodies with a temperature other than absolute zero, emit electromagnetic IR waves. The spectral power density of this radiation has a maximum, the wavelength of which depends on temperature. Position of the maximum with increasing temperature shifts towards shorter wavelengths. Bodies heated to temperatures of 40…100 °C are characterized by a radiation maximum in the mid-IR range (figure 5).

![Figure 5](image2.png)

**Figure 5.** IR pattern of the model made by FLIR.
The use of thermal imaging diagnostics allowed non-invasive measurement of temperature on the surface of the fin, and the software of the FLIR camera made it possible to simultaneously measure temperature at several points on these surfaces with accuracy of 1 K.

4. Results
To compare the results obtained for hollow and solid fins, and then to estimate the effect of blocking, the experiments were carried out in the same ranges of Reynolds numbers $Re = (0.4 \ldots 5) \times 10^4$, calculated for the diameter of the carrier cylinder $d$.

The flow visualization around a single hollow annular fin is shown in figure 6. The flow patterns are averaged over 1000 frames and agree well with the flow pattern described in [1].

![Figure 6. Velocity field near a single fin: (a) $Re = 0.9 \times 10^4$; (b) $Re = 2.1 \times 10^4$; (c) $Re = 4.2 \times 10^4$.](image)

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Due to the low height of the fin and presence of a sharp edge in the pictures, air flow separation is seen, and its further adjacency with a small spin of flow, which, however, does not have time to form a full-fledged vortex over the fin. At a sufficient distance from the fin (near its calibre), one can see the flow structure inherent in the flow around a smooth circular cylinder.

Figure 7 shows 3D field of HTC for hollow and solid fins, corresponding to the Reynolds number $Re = 4.2 \times 10^4$.

![Figure 7. 3D field of HTC for hollow (a) and solid (b) fins.](image)
It can be seen that the value of the local HTC $h_\phi$ along the height of the isothermal (hollow) fin varies much less than the same one for the fin made of titanium alloy. For a solid fin, the value of $h_\phi$ near the root is lower for all values of the angle $\phi$ than for a hollow fin. Also interesting is the reduction of the local HTC in the aft of the carrier cylinder. It is assumed that minimum of HTC is caused by the presence of a stagnant zone beyond the mid-section of the carrier cylinder.

In the next series of experiments, the flow in the intercostal space is visualized in the case when one “acting” and two simulator fins are installed on the cylinder. Results for different intercostal spaces are presented in figure 8.

**Figure 8.** Velocity field near the finned cylinder with $Re = 1.3\times10^4$ at the intercostal space of (a) $\delta = 20$ mm; (b) $\delta = 10$ mm.

Above the first fin one can see a vortex typical for the flow around a single fin. However, with a smaller distance between the fins, the flow in the space is essentially asymmetrical. This character affects the values of the local HTCs. In this regard, in the next series of experiments, the flow and heat transfer in the intercostal space were investigated in the case when there were five annual fins mounted on the cylinder (one “acting” and four simulator ones). Figure 9 shows the flow patterns in the intercostal spaces for different modes at intercostal distance of $u = 15$ mm. In this case, a vortex is also observed over the last fin, which loses intensity with increasing velocity. The flow in the space between the first and second fins is more symmetrical than for a cylinder having three fins. In the space between the second and third fins, one can see reverse currents.
Figure 9. Velocity field near the finned cylinder. The intercostal space is of 15 mm.
Using, together with velocity fields, the data of heat flux measurement and thermometry also succeeded in experimentally determining annual fin efficiency $E$. Since the experiments were conducted in similar modes and forms, the ratio of heat fluxes measured on the surface of solid and hollow (ideal) fins is fin efficiency. Figure 10 shows the analytic curve [12] and experimental values of efficiency of the fin of 20 mm high and of 10 mm thick. Here $m$ is product of fins height and expression $\beta = (2\times h / (k\times \delta))^{0.5}$.

![Figure 10. Analytic curve and experimental points for efficiency of the annual fin of 20 mm high.](image)

It can be seen that the experimental points are significantly different from the analytic curve. This may be due to a sufficiently large thickness of the ribs and the presence of a sharp edge.

5. Conclusion

The paper shows the combined use of PIV diagnostics, gradient heat flux measurement and thermometry (invasive and non-invasive) for a comprehensive experimental study of flow and heat transfer in a flow around a single annular fin on a carrier cylinder and finned cylinder with “acting” and simulating fins. The values of local HTCs are revealed over the surface of the fins on a finned cylinder model. The results obtained on a solid (non-isothermal) fin are compared with those obtained for a hollow (isothermal) one. Fin efficiency are experimentally obtained in different modes.

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