Comprehensive study of flow and heat transfer at the surface of circular cooling fin

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Abstract. For the first time is proposed to combine gradient heat flux measuring with thermal imaging and PIV diagnostics for a comprehensive study of flow and heat transfer at the surface of circular cooling fin. The investigated hollow fin is heated from within with saturated water steam; meanwhile the isothermal external surface simulates one of the ideal fin. Flow and heat transfer at the surface of the solid fin of identical size and shape, made of titanium alloy BT22 is investigated in the same fluid modes. Gradient heat flux sensors (GHFS) were installed at different parts of the fin surface. Velocity field around a cylinder, temperature field at the surface of the fin and heat per unit area for each rated time were obtained. Comprehensive method including gradient heat flux measurement, PIV diagnostics and thermal imaging allows to study flow and heat transfer at the surface of the fin in real time regime. The possibility to study flow and heat transfer for non-isothermal fins is shown; it may allow to improve traditional calculation of the cooling fins.

1. Introduction
Until recently, heat transfer and flow at the surface of the fin were usually studied during divided experiments. The technique and equipment for experimental investigation of air-flow mechanics are varied enough and approved. However the investigation of nonstationary heat transfer at isothermal and non-isothermal surfaces was retarded by the absence of heat flux sensors with the required response time. To solve such problems, a combination of approaches is proposed that includes simultaneous measurement of heat transfer parameters (heat flux per unit area and heat transfer coefficient) using gradient heat flux sensors (GHFS), velocity fields using the PIV method and temperature fields visualized by thermal imaging method.

2. Method of investigation
2.1. Heat flux measurement
GHFS with response time of $10^8 \ldots 10^9$ s were created and integrated into the laboratory and industrial experiment at "Thermophysics of power units" department of Peter the Great St. Petersburg Polytechnic University. Such response time practically makes the GHFS non-inertia device for study
of most types of heat transfer [1]. Figure 1 shows the scheme (a) and the general view (b) of the battery GHFS based on bismuth, which we used in our experiments.

![Figure 1. The scheme (a) and the general view (b) of the GHFS. Figures denote: 1 – anisotropic bismuth strips; 2 – silica substrate; 3 – pure junctions; 4 – current outputs; 5 – lavsan spacers](image)

The action of GHFS is based on Seebeck’s transverse effect: when a heat flux passes through a plate with anisotropy of thermophysical and thermoelectric properties, thermopower arises that is normal to the heat flux vector and proportional to its modulus. In our experiments we used 5 sensors. The dimensions of three GHFSs in the plan are $2 \times 2 \text{ mm}$, the fourth sensor is $4 \times 7 \text{ mm}$ and the fifth is $5 \times 5 \text{ mm}$. Their volt-watt sensitivity is $20 \text{ mV} / \text{ W}$ for sensors of size $2 \times 2 \text{ mm}$ and $9 \text{ mV} / \text{ W}$ for other sensors. The thickness of all sensors was 0.2 mm.

2.2. PIV method
The PIV technology, implemented in the POLIS system [2], made it possible to visualize the flow near the surface of the fin by a non-contact method. The principle of operation of the PIV system is that tracers are fed into the flow: fine particles with a diameter of $2 \ldots 3 \mu m$, which are illuminated by a laser beam reshaped by a cylindrical lens into the laser sheet. In our case, the supply of tracers was provided by a fog machine. A digital camera at the time of flashes freeze the image of tracers. The POLIS system renders possible to adjust the supply of tracers and the frequency of photographs under the nature of the flow. All photos were processed in the ActualFlow program, which gives the velocity field for each time step. Correlation methods of image processing are used to obtain particle shifts. There are two types of processing algorithms: autocorrelation, when the initial and final positions of tracers are recorded on one frame, and cross-correlation, when the trailer start and end positions are recorded in different frames. The use of cross-correlation algorithms is preferable, since in the autocorrelation algorithms initial and final positions of tracers are equivalent, and the displacement is determined to within a sign. The PIV method allows the recording of instantaneous velocity fields in the measurement plane.

2.3. IR imaging
To measure the temperature of the fin, we have used thermographic camera FLIR P640. A software of the camera allowing for powerful temperature analysis and automatic reporting. The flexibility of the FLIR P640 will allow for efficient use regardless of application and user preferences.
3. Experimental model
The first finned cylinder of 66 mm in diameter is made of a steel sheet which is 0.1 mm thick. The cylinder length is of 600 mm. On the cylinder, two circular fins with external diameter of \( D = 146 \text{ mm} \) were mounted. The first fin is hollow, and it simulates ideal (isothermal) fin, and the second is made of a titanium alloy BT22 with thermal conductivity about \( k = 9 \text{ W/(m \cdot K)} \). The second model of the finned cylinder is made similarly, but the outer diameter of the fins was of \( D = 186 \text{ mm} \). The GHFSs were mounted on the fins surface (Figure 2). The model was heated by the saturated water steam under the atmospheric pressure; therefore steam temperature was close to 100 °C. The cylinder was being turned around on it’s axis which allowed us to move the sensor in a circumferential direction. For the ideal fin, the surface temperature \( T_W = \text{const} \) for all \( 0 \leq \phi \leq 180 \) (Figure 2a), and for the fin made from a titanium alloy, \( T_W \) depends on the fin height and the angular coordinate: \( T_W = (b, \phi) \).

4. Results
The experiments were carried out in the subsonic wind tunnel of “Thermophysics of power units” department of Peter the Great Saint-Petersburg Polytechnic University. The wind tunnel has two features:
1) The use of a SCR’s control drive and the reverser of the fan allows to conduct experiments at speeds not exceeding 0.1 ... 0.2 m/s.
2) The heat exchanger (cooler) connected to the cold water supply system ensures a long operation of the tunnel in air, which practically does not change the temperature (the spread of the values is \( \pm 0.1 \) °C).
Research carried out for Reynolds numbers \( \text{Re} = (0.4...4.1) \times 10^4 \), where
\[
\text{Re} = \frac{W \cdot d}{\nu}
\]  
\( (W – \text{flow velocity, m/s}; d – \text{diameter of cylinder, m}; \nu – \text{kinematic viscosity of air, m}^2/\text{s}) \)

The dependence of the averaged (over the fin’s length) heat transfer coefficient on the Reynolds number for isothermal (a, c) and non-isothermal (b, d) fins of different heights is shown in Figure 3. It deserves the special attention, that the coefficient of heat transfer decreases in the interval of \( \phi = 120 ... 180 \) °. This is explained by the fact that nature of flow is such that behind the midlength section of the cylinder a vortex is formed, and near the supporting cylinder there is a stagnant zone.
Figure 3. Dependence of the averaged heat transfer coefficient on the angle of rotation $\varphi$:

a, b – $B = 20$ mm, c, d – $B = 60$ mm

In our experiments the averaged over the fin’s length heat transfer coefficient was calculated by the formula:

$$h_\varphi = \frac{1}{n} \sum_{n=1}^{n} h_{\varphi n}, \text{ (W/ (m}^2 \cdot \text{ K})$$

(2)

($n$ – number of GHFS installed at the fin (3 - for “small” fin and 5 - for “big” one); $h_{\varphi n}$ – the local heat transfer coefficient, (W/m$^2$·K))

The local heat transfer coefficient was defined as:

$$h_n = \frac{q_n}{T_f - T_w}, \text{ (W/ (m}^2 \cdot \text{ K})$$

(3)

($q_n$ – the local heat flux per unit area, W/m$^2$; $T_f$ – flow temperature, K; $T_w$ – fin surface temperature, K)

The flow temperature was measured by the multifunction instrument “testo-435-4” and fin surface temperature sensed by IR imaging.
The local heat flux per unit area was measured by GHFS and equal to:

\[ q_x = \frac{E}{S_0 \cdot F}, \text{ (W/m}^2 \text{)} \]  

(4)

\( E \) – thermopower, mV; \( S_0 \) – volt-watt sensitivity, mV/W; \( F \) – area, m²

The sensor signal \( E \) was measured with a voltmeter. The sensitivity was known according to a predetermined calibration. Measurement uncertainty of calibration was about 1.3 %.

Figure 4 illustrates the velocity fields near the fins. The figure shows that structure of the flow near the fin of 20 mm high is significantly different from the flow near the rib of 60 mm high. Vectors show the flow direction in the section of the light sheet. Our PIV-experiments for the 60-mm-high fin show the presence of a vortex formed by flow separation. This vortex is absent at the “small” fin.

Our work methodologically repeats the studies [3], however, the introduction of the thermal imager into the experiment makes it possible to solve a more general problem connected with the investigation of a non-isothermal fin.

**Figure 4.** The velocity field near the fin: a,b - Re = 2.2 × 10^4; c,d - Re = 4.1 × 10^4
5. Conclusions

Complex technique, including gradient heat flux measurement, PIV diagnostics and thermal imaging, allows one to investigate the flow and heat transfer at the surface of a circular fin. The presence of vortices over the fin was confirmed, the influence of the height of the fin on the flow structure was revealed. Distribution of local heat transfer coefficient of an ideal and real fin has a difference.

References

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