Experimental determination of circular fin effectiveness

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Abstract. The flow and heat transfer at the surface of a single circular fin and a finned cylinder were investigated comprehensively. The technique was carried out by combining PIV (Particle Image Velocimetry), gradient heat flux measurement and thermometry. The experiments were performed for a hollow (isothermal) fin and a fin made of titanium alloy VT22. The fins with a height of 20 and 60 mm were alternately mounted on a hollow cylinder. The cylinder was heated by saturated water vapor at atmospheric pressure. The angling device allowed us to investigate both the cross and non-cross flows around the model. The yaw angle β was 5, 10 and 15 °. Visualization of the flow and measurement of the heat flux per unit area was carried out separately and independently in the same experiment. The PIV results revealed the influence of the yaw angle and intercostal space on the flow between the fins. Gradient heat flux sensors made it possible to obtain a distribution of the heat flux per unit area. Then the local heat transfer coefficients were calculated using thermometry data. It was possible to determine experimentally the effectiveness of the circular fins. This approach opens up new opportunities for study of convective heat transfer at surfaces of various shapes and purposes.

1. Introduction

Studies of the flow and heat transfer near single fins and finned tubes (single and/or tube bundle) have been carried out for a long time. There are many methods for calculating heat transfer at a finned surface and estimating fins effectiveness [1]. In experiments the fully or locally heated models are used. To measure heat transfer characteristics, the thermometry, heat flux measurement, mass transfer coefficients and correlations with local heat transfer coefficients (HTC) [2, 3] are used. However, the results are contradictory and not compared with the flow pattern. Velocity and flow were studied in separate experiments using smoke methods, LDA, thermo-anemometry [4, 5], and others.

The finned tubes and tube bundles in non-cross flow (deviation of the tube axis from the normal to the free-stream vector) is also interesting because it has an applied value; as it occurs when installing tubes in heat exchangers.

Evaluation of effectiveness of the fin is also practically important. Usually, HTC is considered the same over the entire fin surface [1]. In fact, in most cases, local HTCs are not constant, which reduces the accuracy of calculation.

In our work, for study of the flow and heat transfer at a non-isothermal surface, the gradient heat flux measurement, thermometry, and PIV are combined. The results of studies for the solid and hollow (“ideal”) circular fins are compared. It made possible to determine the fins effectiveness experimentally during flow around a single fin and finned tube.
2. Experimental setup
The experimental setup consisted of a closed-type subsonic wind tunnel, allowing investigation of convective heat transfer based on PIV and heat flux measurement. To measure heat flux per unit area we used gradient heat flux sensors (GHFSs) [6]. An experimental model was placed in the wind tunnel test section. It was a hollow cylinder made of 0.1 mm thick steel sheet. Saturated steam was fed into cylinder at a temperature close to 100 degrees of centigrade. The fins were mounted on the cylinder (hollow, solid and simulated ones) (Figure 1).

Figure 1. Model of the tube with a single hollow fin.

The work investigated the following models:
- a cylinder with a hollow (“ideal”) circular fin;
- a cylinder with a circular fin made of titanium alloy VT22;
- a cylinder with a circular fin made of VT22 and fins-simulators made of Perspex.

The supporting tube had a length of 800 mm and an outer diameter of 66 mm; the height of the fins, the yawed angle β and the intercostal space were changed.

Figure 2. The block diagram of the experimental setup.
The block diagram of the setup (Fig. 2) remained unchanged, making it possible to investigate the models of all three types. Further, we will describe each of used methods in more detail.

3. Instrumentarium

3.1. PIV

The certain technology was used to study the flow near a single fin and in the intercostal space on a finned tube. POLIS system [7] consisted of a pulsed laser, a synchronizing device, cross-correlation cameras and software (Fig. 3).

![Figure 3. POLIS PIV system [7].](image)

Tracers created by a standard generator were unsuitable for visualizing the flow near the heated models. We have used wood smoke particles that did not evaporate over a hot surface. To combat glare from the laser beam, the fin and supporting tube were treated with a mixture of industrial oil, alcohol and special liquid, changing the wavelength of the laser beam. The reflected light passed through the green filter mounted on the camera.

3.1.1. Gradient heat flux measurement

Measurements of heat flux per unit area were carried out with the use of GHFSs based on single-crystal bismuth, created by our scientific group [6]. With the passage of heat flux through the GHFS (plate with anisotropy of thermal and electrophysical properties), transverse thermoEMF is generated in it. The transverse thermoEMF is proportional to the heat flux modulus. A unique feature of GHFS is low response time (1 ... 10 ns). GHFSs were successfully used in studies of heat transfer in the combustion chamber of a diesel engine [8], during condensation and boiling [9, 10]. In our work, we used five GHFSs with a 0.2 mm thickness with dimensions of $2 \times 2$, $4 \times 5$, and $4 \times 7$ mm. The volt-watt sensitivity of all GHFSs (about 10 mV/W) was practically independent of temperature.

3.2. Thermometry

It is necessary to know the temperature difference between the free stream and the fin surface close to the GHFSs locations when calculating local and average HTC. The FLIR P640 thermal imager was used to measure the temperature at the surface of a single fin. The software of the camera made it possible to measure accurately the temperature of the fins surface simultaneously at several points virtually without time lag. However it is impossible to use a thermal imager during investigating the flow between the fins. In the work, the semi-artificial thermocouple method was used: a standard thermoelectrode was connected with a massive body made of another material. On the finned tube model, the hot junctions were placed at the bottom surface of the solid fin symmetrically with the GHFSs. In addition, a thin needle of the same material was mounted on the fin of VT22. The end of needle was brought into the air flow and formed a cold junction with a copper wire. The signal generated was proportional to the temperature difference.
4. Results
In the first series of experiments, a cross flow around single circular fins of different heights was studied. Heat flux measurements and HTC, supplemented by velocity fields near a single fin, are presented in detail in [6]. Figure 4 shows the local HTC 3D distribution for a 60 mm high fin.

Experiments on the hollow and solid fins of the same shape and size allowed us to determine the actual value of the fins effectiveness $E$. According to the definition,

$$E = \frac{T_h - T_f}{T_w - T_f},$$

where $T_h$ is the average temperature at the non-isothermic fin surface, $T_f$ is the temperature of free stream, and $T_w$ is the temperature at the isothermic fin surface. In our experiments, the effectiveness was determined differently:

$$E = \frac{\overline{q}_{\text{nonisoterm}}}{\overline{q}_{\text{isoterm}}},$$

where $\overline{q}_{\text{nonisoterm}}$ is the average heat flux per unit area for the solid fin, $\overline{q}_{\text{isoterm}}$ is the heat flux per unit area at the hollow fin (isothermic). Figure 5 presents the results of the calculated (curve) and experimental (points) single circular fin effectiveness in a cross flow.

**Figure 4.** 3D distribution of local HTC for: a – isothermic fin; b – nonisothermal fin.

**Figure 5.** The calculated (curve) and experimental (points) efficiency of a single annular fin (height of: a – 20 mm, b – 60 mm) in a cross flow.
Here \( m = \beta \times l \); where \( l = (D - d) \) is a fin height, \( m \), \( \beta = \sqrt{2l/(k \times \delta)} \) (\( k \) is thermal conductivity of titanium alloy VT22, \( W/(m \cdot K) \), \( \delta \) is a fins thickness, \( m \)). As we see, the discrepancy between the calculation and experiment is very significant.

In the next series of experiments, non-cross flow around a single fin of 20 mm high was studied at yaw angle \( \beta = \pm 5 \ldots 15 ^\circ \). The case of \( \beta > 0 ^\circ \) corresponds to the tilt of the model in the direction of flow, and \( \beta < 0 ^\circ \) corresponds to the tilt in the opposite direction. Figure 6 shows the velocity fields near the fin surface.

![Velocity fields](image)

**Figure 6.** The velocity field for non-cross flow around a single isothermic fin (\( Re=2,24 \times 10^4 \)).

A change in the flow near the fin during non-cross flow changes both the distributions of the heat flux per and the local HTC. As \( \beta \) increases from 5° to 15°, the average Nusselt number decreases by approximately 6.5% over the whole range of the Reynolds numbers studied.

In the final series of experiments, the tube having 5 fins was investigated. The installation of "non-working" fins of Perspex made it possible to imitate the flow around a tube with circular finning. The dependence of the average Nusselt number on the Reynolds number, obtained by processing of the experimental data, is shown in Fig. 7. It can be seen that in inter-fin spaces of 10 ... 15 mm and values of Reynolds number \( Re > 2 \times 10^4 \), the curves run almost parallel.

![Nusselt number vs. Reynolds number](image)

**Figure 7.** Dependence of Nusselt number on Reynolds number for different intercostal spaces.
Fig. 8 shows the efficiency of the fins installed with different inter-fin spaces. Here the compliance with the theoretical calculations in comparison with a single fin is somewhat better.

Imitation of the “ideal” steam-heated fin opens up new possibilities for experimental determining of fin effectiveness.

![Figure 8. The calculated (curve) and experimental (points) efficiency of the annular fin of 20 mm high mounted on the finned pipe with inter-fin space of: a – 15 mm, b – 20 mm.](image)

**Conclusion**

The paper shows the combined use of PIV, gradient heat flux measurement and thermometry (using thermal imaging techniques and semi-artificial thermocouples) for a comprehensive experimental study of flow and heat transfer for a single circular fin on a circular cylinder and finned tube. Values of the effectiveness of the fins at different angles of flow are experimentally obtained.

**References**

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