Heat transfer in pulsating flow behind a rib in the channel inlet region

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Abstract. Heat transfer in pulsating air flow behind the rib in the channel entrance has been studied experimentally. An experimental facility and the technique to estimate heat transfer with simultaneous wall heating and wall temperature measurement by the same copper tracks have been developed. Distributions of heat transfer coefficient over the heated channel wall in steady and pulsating regimes of flow have been obtained. Enhancement of heat transfer in pulsating flow up to 25% in comparison with a steady flow has been revealed. The studies have been carried out within the frequency range of 0-15 Hz and the relative amplitudes of forced velocity pulsations of 0.8.

1. Introduction

Tracts of various engineering devices in general have a complex geometry including the one that leads to the flow separation. The structure of separated flow and heat transfer can significantly depend on the shape and position of the obstacle located in the flow [1]. In particular, this kind of issues occurs in operation of electronic devices in which it is necessary to maintain a certain thermal regime. In that case the shape and configuration of heat releasing elements (ribs) are essential in terms of cooling [2]. In general, obstacles of various shapes can be used to enhance heat transfer in channels: twisted spirals, V-shaped ribs, grooves, holes, etc. [3, 4]. The use of such devices can lead to a manyfold increase in heat transfer compared to a smooth channel. Both single and multiple elements on the heat transfer wall can be used. The latter case includes the rib-roughened channels in which two- or three-fold heat transfer enhancement is observed [5–8].

Acoustic forcing [9] and forced flow pulsations [10, 11] can have an additional effect on hydrodynamics and thermal processes. Forced flow pulsations can induce periodic vortex structures behind the obstacles. In particular, it was found that forced flow pulsations can reduce the reattachment length behind an orifice. Heat transfer increase up to one and a half times in the separation region and up to 5 times in the immediate proximity to the orifice was observed in [10].

Thus, accurate experimental studies of thermal processes behind the rib in pulsating flow can extend our understanding of patterns in such complex flows. Practical significance of the obtained results can be associated with the development and operation of real power engineering devices.

2. Experimental setup and procedure

Heat transfer in pulsating flow behind the rib was studied using the setup shown in figure 1. The setup was equipped with a smooth inlet 1 and a test section 3. The latter was a 1.2-m long rectangular channel with a cross section of 0.115×0.15 m². An aluminum rib 7 was installed on one of the walls at
the distance of 100 mm from channel inlet. The dimensions of the rib were 30x30x150 mm. Part of this wall was used as a 455-mm long measurement section for heat transfer study. Flow pulsations following close to harmonic law were generated by a flap of pulsator 4. The flap was mounted on the motor shaft. The pulsation frequency was set by the shaft speed adjusted using the Vacon 10 frequency converter. To maintain the stable average air flow rate, a 1.5-m³ receiver tank was mounted behind the pulsator. A set of critical flow nozzles allowed adjusting the flow rate by opening a proper nozzle. The flow rate was generated by a compressor operating in a suction mode. Thus, the air with environmental parameters was supplied to the channel inlet. Its temperature was measured by a Pt100 platinum resistance thermometer located in the smooth inlet. Hot-wire anemometer was installed in the test section at the distance of 20 mm from the inlet to estimate forced pulsations amplitudes from the corresponding oscillograms.

Heat transfer between the wall and the air flow was organized by heating of the measurement wall by constant electric current supplied from the battery with a voltage $E = 24$ V. The measurement wall was a printed circuit board (PCB) with copper tracks. At the same time, these tracks acted as resistance thermometers, which measured the local wall temperature. Then the heat transfer coefficient distribution behind the rib was obtained from the temperature difference between the wall and flow.

The rib-to-channel height ratio in the test section was $e/H = 0.26$, where $e = 30$ mm is the rib height; $H = 115$ mm is the test section height (figures 1 and 2).

3. Measurement method
The technique used to measure local heat transfer enabled heating the surface simultaneously with estimation of its local temperature based on the measurement of corresponding electrical resistance of the heating element. For this purpose, the measurement wall was embedded into the test section wall (figure 2). It was a 1.5-mm thick printed circuit board (PCB) with the length of 455 mm and the width of 230 mm. The inward side of the PCB was covered with copper etched to form zigzag tracks. A total of 47 tracks were localized in rectangular 150×9.5 mm² sections. Each track had its own current leads
allowing their parallel or in-series connection to the current source. Central 80×9.5 mm² segments of tracks had electrical contacts intended for voltage drop measurement. These contacts (copper tracks on the reverse side of PCB) were connected to terminals and further to a 14-bit L-card E14-140M analog-to-digital and a PC by shielded wires. Voltage measurements were performed in order to estimate the heat release and electrical resistance of track segments and hence the temperature of corresponding wall sections using the resistance-temperature relationship. Before the experiments, the dependence of electrical resistance of tracks on the temperature was calibrated.

The wall studied in experiments was electrically heated over the whole area according to the boundary conditions of the second kind \( q = \text{const} \). The temperature was measured in the central part of the wall where the temperature field was supposed to be uniform in spanwise direction. In these conditions, the measuring part of PCB was essentially a set of resistance thermometers located with a pitch of \( \Delta x = 9.5 \) mm along the channel. Heat fluxes and wall temperatures were obtained from the measurements.

The external surface of the wall was thermally insulated. Local heat transfer coefficients corresponding to streamwise coordinates \( x \), were derived from the heat balance equation:

\[
h_i = \frac{U_i I_i - Q_i^*}{F(T_i - T_f)}
\]

where \( T_i \) is the local temperature of the wall, \( T_f \) is the flow temperature, \( U_i I_i \) is the heat generation rate at the measurement section, \( Q_i^* \) is the heat loss, \( F \) is the section area. Heat loss comprised of the losses through thermal insulation, radiation, thermal conductivity to the adjacent walls, and heat fluxes between the adjacent tracks.

4. Results and discussion

The research has been conducted at the following parameters: mean flow velocity \( U = (1.7 - 4.25) \) m/s, Reynolds number \( Re = Ue/\nu = (3380 - 8500) \) (\( e = 0.03 \) m is the rib height), forced pulsation frequency \( f = (0 - 15) \) Hz, and relative amplitude of velocity pulsations \( \beta = \Delta U/U = 0.8 \).

Heat transfer coefficient distributions were obtained based on the results of measurements. The graphs of distributions are shown in figure 3. The inlet edge, i.e. the conjunction between the smooth inlet and the test section, was considered as an origin of coordinate \( x = 0 \) (starting point of the heated wall). The distribution of heat transfer coefficient in stationary regime is presented in graphs by a solid black line.

Experimental data revealed heat transfer enhancement in pulsating flow. With increasing pulsation frequency, the maximum of each heat transfer distribution moves to the rib. Herein, the significant growth of heat transfer is observed in the immediate vicinity of the obstacle – up to two times and more. Further downstream, however, the heat transfer in pulsating flow falls below the stationary flow values. It should be noted that two peaks in distributions are observed along the channel in some regimes: the first one is near the stationary maximum and the second one is closer to the obstacle (see. figure. 3, c).

The integral influence of forced flow pulsations on the heat transfer behind the rib can be represented as a relation of \( \overline{h} / \overline{h}_{st} \) in the graph below (figure 4). This is the ratio between the heat transfer coefficients in pulsating and stationary flow averaged over the separation region. The measurements and averaging in experiments were performed over the length of 10e starting from the trailing edge of the rib. The heat transfer enhancement has been observed in all pulsating regimes and at all the flow rates. Its value reached 25%.

Specific aspects of heat transfer distribution in pulsating regimes of air flow behind the rib agree with the similar results obtained behind a thin rib in the channel [10]. The heat transfer enhancement could be associated with the periodic vortices formed behind the rib due to pulsations. These vortices can significantly improve the mass and heat transfer in the separation region. The increasing intensity of the periodic vortices depends on the frequency and amplitude of forced flow pulsations and leads to heat transfer augmentation, especially directly behind the rib where vortices are formed.
Figure 3. Heat transfer coefficient distribution $h(x)$ behind the rib at various Reynolds numbers: $a - 3380; b - 6220; c - 8500$; and different frequency of pulsations $f$: $1 - 0$ (stationary); $2 - 5; 3 - 6; 4 - 8; 5 - 10; 6 - 12$ and $7 - 15$ Hz.

Figure 4. Heat transfer enhancement in pulsating regimes in the separation region at various $Re$: $a - 3380; b - 6220; c - 8500$.

5. Conclusions
Experimental study of heat transfer behind the rib in pulsating regimes of flow has revealed the following:
- the area-averaged heat transfer coefficient in the separation region directly behind the rib increased by up to 25% in pulsating regimes with the frequencies of $\leq 10$ Hz in comparison with the stationary regimes;
- heat transfer growth was localized directly behind the rib at a distance of up to $3e$;
- reduction of heat loss was noted in most of the regimes where the distance from the rib was more than $4e$. 
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