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Local heat transfer from a roughened surface with inclined ribs

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Local coefficients of heat transfer and local velocity were measured for the case of a heated surface with ribs inclined at an angle of 45° to the flow. The height of ribs was 1.4% of the hydraulic diameter. The field and profile of non-dimensional coefficient of heat transfer were estimated from thermographic measurements of temperature. The optical method SIV was employed to measure the local velocities at a characteristic distance from the surface. A qualitative correlation between the measured values of heat transfer and velocity was established.

Keywords: inclined ribs, heat transfer enhancement, optical measurements, distribution of heat transfer coefficient, velocity field.

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The use of ribs mounted at an angle to the flow is one way to enhance heat transfer in channels [1]. Compared to ribs arranged perpendicular to the flow, this configuration of ribs may contribute to an increase in thermohydraulic efficiency [2,3]. Such heat-exchange surfaces are fit for use in thermal protection systems of power plants (e.g., turbine blades, jet engine nozzles, etc.).

The present study is focused on identifying the main features of the mechanism of heat transfer in an intensified (rough) channel. The aim of the study is to obtain a dependence of the heat transfer coefficient on the hydrodynamic flow parameters at the local level.

An experimental setup, which included a compressor, a system of critical nozzles, and a rectangular channel connected to a receiver, was used for this purpose. Air with ambient parameters was the working fluid. The test section 0.455 m in length was positioned in the region of steady flow toward the end of the channel with a length of 2.6 m and a cross section of 0.18×0.02 m (hydraulic diameter $d = 0.036$ m). The medial strip of the lower wall of the test section was a printed circuit board 0.455×0.15 m in size. The board was heated by DC current, which ensured that boundary condition $q_w = \text{const}$ on the wall was satisfied. The wall temperature was measured at a distance of 0.3 m from the origin of the test section. Necessary measures were taken to minimize heat loss to the environment. A detailed description of the measurement method and its metrological characteristics was provided in [3].

Experiments were carried out at average flow velocity $u = 9.8$ m/s in the channel. The corresponding Reynolds number calculated based on the hydraulic diameter was $\mathrm{Re} = ud/\nu = 2.35 \cdot 10^4$. The inlet flow temperature was 24 °C.

The lower wall of the test section was covered with plastic pads with ribs in the form of semi-cylinders with height $h = 0.5$ mm, which was 1.4% of the hydraulic diameter. These ribs were arranged in alternating rows at angles of 45 and −45° to the flow; 10-mm-wide gaps were left between the rows. The rib pitch was 10 mm. The geometrical arrangement of ribs is seen clearly in the field of the dimensionless heat transfer coefficient (Fig. 1). The presented fragment covers the complete width of two rows of ribs within a characteristic length. Small thicknesses of pads (0.5 mm) and the printed circuit board (1.5 mm) induced high thermal resistance in the directions along the heat-exchange surface, which provided an opportunity to minimize heat flows by conductivity in these directions (compared to the one normal to the surface). Thus, the supplied heat did not produce a uniform temperature distribution with uneven heat removal, which made it possible to measure local wall temperatures and, consequently, determine local heat transfer values. Local values of Nusselt number Nu were determined in accordance with the following relation based on the results of optical measurements of the wall surface temperature with a thermal imager:

$$\mathrm{Nu} = \alpha d/\lambda = \big(q/(T_w - T_f)\big) d/\lambda,$$

where $\alpha = q/(T_w - T_f)$ is the heat transfer coefficient, $q = Q/F$ is the heat flow density, Q is the heat flow produced by the electric heater, F is the heat-exchange surface area, T_w is the wall temperature, T_f is the flow temperature, and λ is the thermal conductivity of air.

The use of an analog-to-digital converter with an accuracy class of 0.05 and precision resistances in electrical measurement circuits and the analysis of influencing parameters allowed us to determine that the error of measurement of the heat transfer coefficient is due largely to the uncertainty of measurement of the wall temperature (temperature difference). According to the instrument certificate, the uncertainty of wall temperature measurements was 1.5 °C. Thus, with a temperature difference no less than 25 °C, the

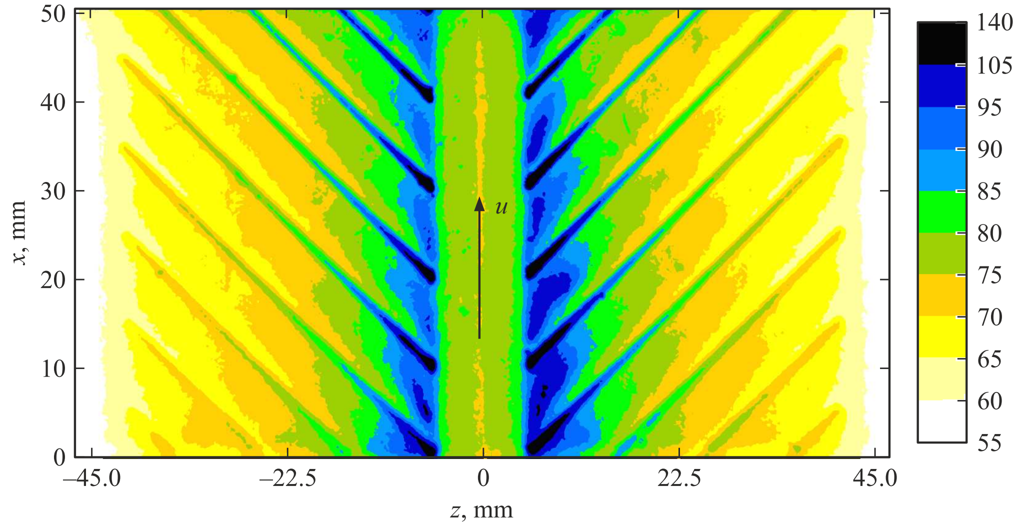

Figure 1. Distribution of the heat transfer coefficient on the wall. The direction of flow is indicated by the arrow.

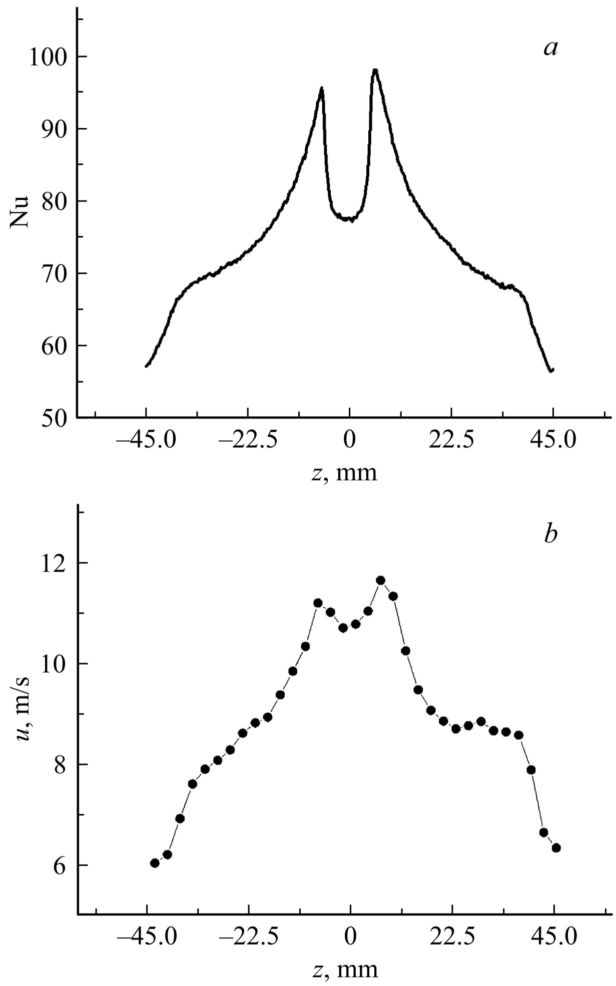

Figure 2. Distributions of the heat transfer coefficient (a) and the velocity at a distance of $5h$ from the wall (b). Coordinate z is measured from the symmetry axis of the wall.

uncertainty of heat transfer coefficient measurement did not exceed $1.5/25 = 0.06$ (6%).

The characteristic distribution of the heat transfer coefficient on the surface fragment in the central part of a rough wall is shown in Fig. 1. The x coordinate is measured from the origin of the depicted fragment, and the z coordinate is measured from the wall symmetry axis (roughness geometry).

The measurement results demonstrate that the heat transfer coefficient is maximized and minimized in the regions of divergence and convergence of ribs, respectively. The intensity of heat transfer directly on the ribs is higher than the one between them. Notably, the distribution of the heat transfer coefficient between the ribs is non-monotonic along the flow with a certain local maximum. These data are consistent with the concept of existence of a detachment region and a reattachment line, beyond which a new boundary layer starts to form, behind the ribs.

The heat transfer coefficient in longitudinal smooth wall regions between the rows of ribs is significantly lower than the corresponding coefficient in the adjacent rough wall regions. This may be attributed to attached flow around flat surface areas.

To reveal the features of transverse heat exchange distribution, one needs to average the temperature along longitudinal coordinate x. This helps suppress the influence of longitudinal fluctuations associated with individual ribs. Temperature averaging was performed over a fragment of the test section 0.04 m in length. The distribution of the heat transfer coefficient across the channel width was thus obtained (Fig. 2, a). The heat transfer coefficient at point i (along z) of the profile was calculated as

$$\alpha_i = q/(T_{wi} - T_f),$$

where T_{wi} is the length-averaged wall temperature at point i of the profile. In order to identify the mechanisms of heat transfer on the rough wall, we measured local longitudinal flow velocity u at the level of $5h = 2.5$ mm above the heat-exchange surface. These measurements were performed using the optical SIV method that was discussed in detail in [4]. The uncertainty of velocity measurements did not exceed 0.03 m/s [4]. The flow velocity measurements were carried out in the same region of the test section where the temperature was measured.

It can be seen from Fig. 2, b that inclined ribs induce the formation of a non-uniform kinematic flow structure (at least in the near-wall region). The flow accelerates and slows down in the regions of divergence and convergence of ribs, respectively. This fact is indicative of transverse redistribution of the working medium in the flow due to deflection of the near-wall flow by ribs. With equal cross-sectional pressure differences, this leads to the emergence of local zones (longitudinal bands) with increased and decreased velocities.

The obtained data on distributions of the heat transfer coefficient and the velocity in the near-wall layer were found to be in a close qualitative agreement. This fact suggests that the dependence of heat transfer on hydraulic parameters may be revealed in the form of a criterial relationship. In general, the identification of such a dependence is of fundamental research interest in the context of understanding the mechanisms shaping the process of heat transfer in complex flows. On the practical level, the results of this study may help improve the reliability of prediction of local values of heat flows, which is essential for thermal protection of various heat-stressed devices.

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Conflict of interest

The authors declare that they have no conflict of interest.

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