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# Governing characteristics of heat transfer in separated channel flows

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**Abstract.** Heat transfer in the separation region behind a rib has been studied experimentally in different regimes of air flow. Heat transfer characteristics have been considered in a wide range of geometrical dimensions of the rib and the channel. Distributions of heat transfer coefficients have been obtained. They were employed for estimation of the position and values of maximum heat transfer coefficients in the separation region. The data were analyzed in order to obtain an empirical equation.

## 1. Introduction

Flow separation in a channel with complex geometry is a fairly common phenomenon. Intentional flow separation is widely employed for heat transfer enhancement. Large number of studies estimated the effect of different characteristics of separated flows on the process of heat transfer [1-4]. However, due to the extreme complexity of such flows there are no universal correlations in this field so far.

The structure of separated flows and heat transfer can significantly depend on the shape and location of an obstacle in the flow [3]. In particular, such problems are encountered in electronic devices, in which certain thermal condition should be maintained. Here, the shape and location of heat-generating roughness elements (ribs) is essential in terms of cooling [5]. In general, different shapes of obstacles are employed for heat transfer enhancement in channels (twisted spirals, V-shaped ribs, grooves, dimples, etc.) [6, 7]. Sometimes it results in several times higher heat transfer if compared to a smooth channel. Both single and multiple roughness elements can be mounted on the heated wall. For example, channel with arrays of discrete roughness elements feature two- or three-fold heat transfer augmentation [8].

Thus, experimental research of heat transfer behind a rib in a channel can provide deeper insight into the laws and regularities observed in such complex flows. Practical relevance of results is associated with the development and operation of real-life power engineering devices.

## 2. Experimental setup and procedure

The paper presents the results of experimental research into heat transfer in a rectangular channel (position 5 in fig. 1) with the height  $H = 55, 73, \text{ and } 115$  mm, width of 150 mm and length of 0.6 m, equipped with a smoothly shaped inlet  $l$  (fig. 1). An aluminium rib  $3$  was mounted on one of the

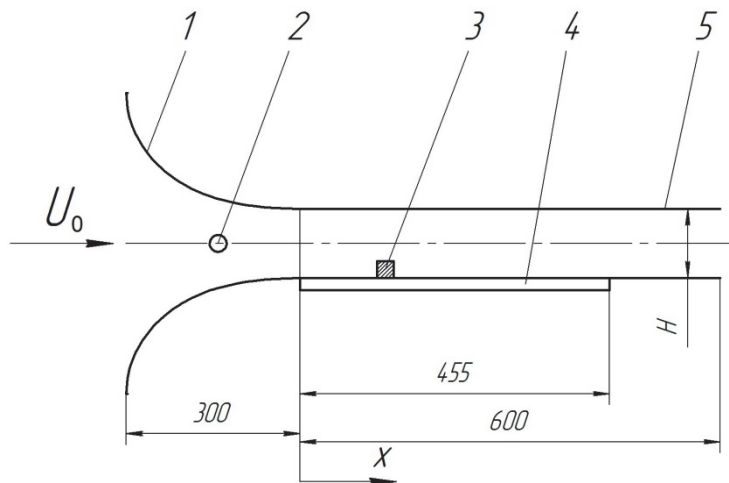


channel walls spanning across the whole channel width. The rib height,  $h$ , took four different values (9.5, 13, 20, and 29 mm), while the rib thickness was  $\leq h$ . The channel blockage ratio was  $h/H=0.083 - 0.53$ . The rib was mounted at the distance of 30 mm from the channel inlet. We also studied the case of two identical ribs mounted symmetrically on the opposite walls.

The experimental setup was equipped with a set of critical flow nozzles that served for flow rate control (appropriate nozzles were opened to provide a given flow rate). The flow rate was generated by a compressor operating in a suction mode, thus the air with ambient parameters was supplied to the channel inlet. The air temperature was measured using a platinum resistance thermometer Pt100 (position 2) located within the smoothly shaped inlet.

The measurement section of the wall was heated by DC supplied from an accumulator with the voltage  $E=24\text{ V}$  thus inducing heat transfer between the wall and the flow. The inlet part of one (bottom) wall was used for heat transfer measurements (position 4).

Two-dimensional problem was studied.



**Figure 1.** Test section: 1 – smoothly shaped inlet; 2 – thermometer; 3 – rib; 4 – heated wall; 5 – channel.

The measurement technique allowed simultaneous heating of the wall and estimation of its local temperature by measurement of the corresponding electrical resistance of the heating element. To that end, a measurement wall 4 was embedded into the test section. It was a 1.5-mm thick PCB (printed circuit board) with the length of 455 mm that occupied the whole channel width. The inward-facing surface of PCB was covered with 47 copper tracks localized in rectangular regions with the areas of  $150 \times 9.5\text{ mm}^2$ . Central segments of tracks with the size of  $80 \times 9.5\text{ mm}^2$  had electrical contacts for voltage drop measurement. These contacts were connected to terminals and further to an analog-to-digital converter and PC. Voltage drop was measured in order to estimate the heat generation and electrical resistance of segments of tracks and hence the temperatures of wall regions using the relation between temperature and resistance. Calibration of dependence of electrical resistance of tracks on the temperature was performed prior to the experiments.

The whole surface of the wall was heated according to the boundary conditions of the second kind  $q=\text{const}$ . Temperatures were measured in the central part of the wall where the temperature field is considered to be uniform across the channel width. In these conditions, the measurement part of the channel was essentially also a set of resistance thermometers separated by 9.5 mm along the channel length. Heat fluxes and temperatures of the wall were estimated from the measurements.

The external surface of the heated wall was thermally insulated.

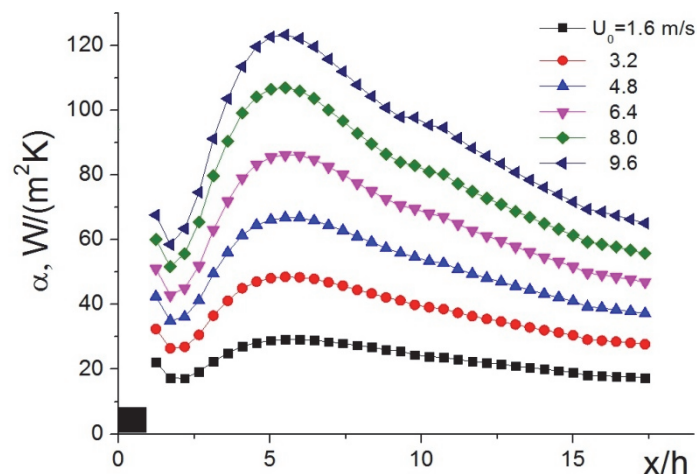
Local coefficients of heat transfer,  $\alpha_i$ , corresponding to the streamwise coordinates  $x_i$  were estimated using the heat balance equation allowing for the heat loss. The latter included the heat loss through thermal insulation, radiation, thermal conductivity to the adjacent walls and heat fluxes between the adjacent tracks. Detailed description of the measurement method is provided in [9].

### 3. Results and discussion

The following ranges of flow parameters were examined: bulk velocity of the flow above the rib  $U=(1.8 - 28.5)$  m/s, Reynolds number  $Re_h=Uh/\nu=(1.2 - 55.1)\cdot 10^3$ . Thus, the flow inside the separation region was turbulent ( $Re_h>4\cdot 10^3$ ) throughout the whole range of velocity ( $Re_h>4\cdot 10^3$ ) [1]. Different combinations of rib and channel sizes were considered.

Some representative distributions of heat transfer coefficient obtained in the measurements are plotted in fig. 2 for the case of symmetrical (on top and bottom walls) arrangement of ribs. The leading edge of the rib was taken as the origin ( $x=0$ ). For illustration purposes, the rib in the figure is shown as a dark square scaled along  $x$  coordinate. Using these data, peak values of the heat transfer coefficient and its coordinate were defined. These parameters were considered as principal characteristics of the separated flow in the course of further analysis. We should stress that the coordinate of the maximum heat transfer coefficient was considered, while its coincidence with or some deviation from the reattachment point was not examined. Nevertheless, we referred to this point as  $X_R$ .

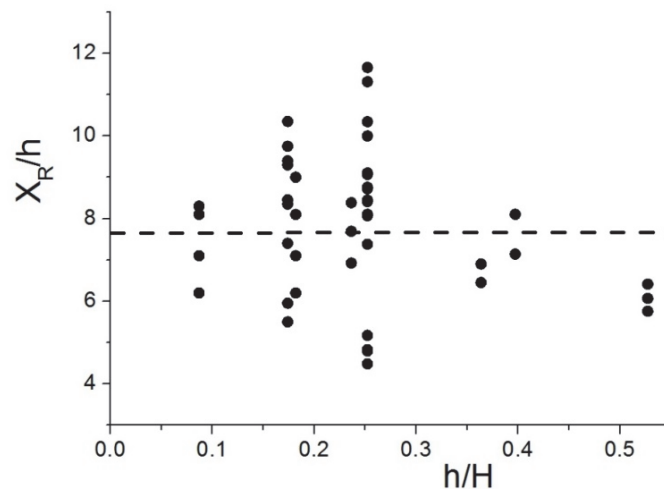
The present study searched for the correlation between the heat transfer coefficient at the point of its maximum and hydrodynamic parameters of flow together with the rib and channel geometry:  $Nu=f(Re)$ .



**Figure 2.** Distributions of heat transfer coefficient in the separation region behind the rib ( $h=20$  mm) in the  $115\times 150$  mm<sup>2</sup> channel.

The measurement results indicated that the coordinate of maximum heat transfer,  $X_R$ , is the best length scale to be used when calculating the Nusselt and Reynolds numbers ( $Nu$  and  $Re$ ). This is true even at wide scatter of  $X_R/h$  (fig. 3). When the rib-to-channel height ratio was  $h/H\sim 0.25$ , we observed extreme (both high and low) values of the coordinate of peak heat transfer depending on  $Re$  and the rib thickness. This fact is probably associated with the effect of main flow constriction on the location of the flow reattachment point (the point of maximum heat transfer). Indeed, the reattachment length in the case of small blockage ratios has some nominal value  $X_R/h$ . The increase in blockage ratio contributes to further divergence of the main flow from the ribbed wall and corresponding reduction of the reattachment length. At the same time, symmetrical arrangement of ribs on opposite walls keeps the flow at the channel axis and promotes the increase in  $X_R$ . We believe that these factors combined with the effect of  $Re$  and the rib thickness lead to wider scatter of  $X_R/h$  at  $h/H\sim 0.25$ . Further growth of  $h/H$  is already incapable of promoting flow divergence from the rib due to proximity to the opposite wall. Hence, the reattachment length is no more exposed to significant changes.

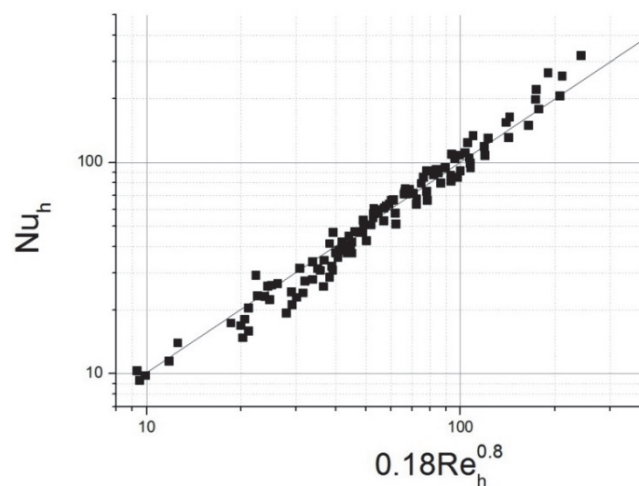
The flow velocity is another key factor affecting the heat transfer. When analyzing experimental data, different values of this parameter can be used: bulk velocity above the rib ( $U$ ), bulk velocity of flow after the reattachment,  $U_0$ , some averaged value combining the two above,  $U_c=(U_0+U)/2$ . However, it turned out that the best scale to be used when generalizing the experimental data was the transverse component of velocity at the upper boundary of the separation region  $V=U_c \cdot h/X_R$ . In physical terms, this value can be interpreted as velocity of cold fluid traveling from the flow core to the hot wall. This is the process that governs the heat transfer intensity. Different reattachment lengths and hence transverse velocities can be obtained here for one and the same values of streamwise velocity, rib height and channel height. This discrepancy results from different patterns of flow in the separation regions behind, for example, square and thin ribs.



**Figure 3.** Location of maximum heat transfer behind the rib in the channel.

Figure 4 demonstrates the entire range of experimental data for different ribs in channels of different height. Here, the Reynolds and Nusselt numbers were determined as  $Re_h=V \cdot h/\nu$  and  $Nu_h=\alpha \cdot h/\lambda$ , where  $\alpha$  is the maximum heat transfer coefficient ( $\sim$  at the reattachment point). Data analysis shows that the correlation between hydrodynamics and heat transfer can be approximated by the following relation:

$$Nu_h=0.18 \cdot Re_h^{0.8}.$$



**Figure 4.** Maximum heat transfer coefficient behind the rib.

Thus, the data obtained in separated flows indicate that it is possible to employ the rib height and transverse flow velocity above the separation region as governing parameters when searching for regularities in heat transfer process.

### Conclusions

Experimental study of heat transfer behind the rib demonstrated that the following parameters can be employed as governing characteristics in empirical equations describing the maximum heat transfer in the separation region behind the rib in the channel:

- rib height;
- coordinate of the maximum (reattachment length, length of dividing streamline),  $X_R$ ;
- transverse flow velocity above the separation region.

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