Rectangular ribs in turbulent boundary layer on the initially smooth surface

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Abstract. Results of experimental investigation of hydrodynamics and heat transfer in turbulent boundary layer before and after a rectangular rib with sharp corners and a rectangular rib with round top corners are presented. The rib is placed on the flat plate and heated by the law of \( q_w = \text{const} \). Experimental studies were conducted using hot-wire anemometry system by Dantec Dynamics and obtained are new experimental data on the mean and fluctuating characteristics in turbulent boundary layer in flow over ribs – in the laminar sublayer and transition region. A faster growth of the coefficient heat transfer is observed from the distribution features of drag and heat transfer coefficients.

1. Introduction

Intensification of heat transfer processes in the last decade has essentially become a separate section in the theory of heat and mass transfer, along with conduction, convection, and radiation. Great interest focuses on works that offer ways of heat transfer intensification due to effect on flow and primarily on boundary layer of various types of augmented heat transfer devices, such as: the formation on the initially smooth surface of the two-dimensional non-separable and separation depressions-trenches [1-3], staggered arrangement of non-separable and detachable systems of spherical cavities [4-6], rib turbulators of different geometry [7], etc..

Experimental and theoretical investigations of flow structure in the flow over the depressions and protrusions on the initially smooth surfaces are of considerable practical interest, since the protrusions, grooves and cavity of constructive or random occurrence are found on many different convective surfaces. During flow over the depressions and protrusions, the boundary layer separation and its reattachment can lead to occurring specific phenomena, which have a significant impact on drag and heat transfer [8-11].

One of the most common ways of formation of vortex zones are transverse ribs or grooves formed on the heat transfer surface. The ribs and grooves may have different shapes and sizes, which significantly affect the structure of the boundary layer and the processes occurring in it [12-15]. This work is devoted to the study of the structure of separated zones in turbulent boundary layers.

2. Apparatus and instruction

The experimental part was performed at subsonic low-turbulence \((\varepsilon = 0.2 \%)\) wind tunnel in the form of open type operating in suction mode. A detailed description of experimental procedures and experimental setup is given in [1, 2, 4, 5, 7, 16].
The rectangular rib height is \( h = 3.2 \text{ mm} \) and its width is \( b = 3.2 \text{ mm} \). The rib was mounted on the bottom heated wall perpendicular to the flow at a distance \( x = 460 \text{ mm} \) from the entrance to the test section. The schematic installation of the rectangular rib is shown in figure 1(a) with sharp corners and in figure 1(b) with round top corners (\( r = 0.5 \text{ mm} \)). The main flow velocity in cross-section 1 at the distance of 425 mm from the entrance to the working part of the channel was maintained approximately 15.5 m/s. The corresponding Reynolds number calculated by the momentum thickness in this cross-section was \( \text{Re}^{**} = 1492 \).

![Figure 1. Schematic representation of rectangular rib on the plate (a) with sharp corners and (b) with round top corners.](image)

Unlike [7], where all measurements were performed using a microprobe Pitot-Prandtl, which is specially designed and developed for investigation in boundary layer, studies in this paper were conducted using hot-wire anemometry system by Dantec dynamic [18], which allows us to investigate laminar sublayer and transition region of the boundary layer. Besides the average and fluctuating characteristics of the flow can be obtained. Profiles of mean velocity and its longitudinal fluctuations in various cross-sections in the boundary layer were measured with a single wire sensor (type 55P11) and a CTA module 90C10. The sensing element of the probe - tungsten wire with a length of 1.25 mm and a diameter of 5 \( \mu \text{m} \). Temperature measurement was carried out using the Dantec anemometer system composed by a const current module 90C20, which is basically operated as a resistance thermometer. It consists of a small tungsten wire of 5 \( \mu \text{m} \) diameter and 3 mm length in total. The wire is mounted on L-shaped probe (type 55P04). The traverse system is used for sensing of the boundary layer, and includes a stepper motor and power module (type 52B01). The accuracy of the probe positioning by the traverse system was not more than 0.02 mm.

3. Results and discussion
This paper presents the results of experimental study of hydrodynamic and thermal characteristics of separated flow in flow over a single square rib with a height of 3.2 mm in turbulent layer, which is formed at the external flow in air over surface of a flat plate, heated by the law of \( q_w = \text{const.} \)

The combination of measurement of the distribution of velocity and temperature and their fluctuations in a turbulent boundary layer gives the possibility to quantitatively and qualitatively analyze and compare the heat transfer in different regions of the boundary layer including the viscous sublayer.

3.1. Smooth plate
The profiles of average velocities and their longitudinal pulsations, temperatures and their fluctuations in three cross-sections on a smooth plate, prior to the installation of the rib in this area, are determined experimentally and are shown in figure 2. In addition, the main experimental results obtained in cross-sections 1, 2 and 3 are given in table 1.

| № Section | \( x \) (mm) | \( U_\infty \) (m/s) | \( \delta \) (mm) | \( \delta^{**} \) (mm) | \( \delta_T \) (mm) | \( \delta_T^{**} \) (mm) | \( \text{Re}^{**} \) | \( \text{Re}_T^{**} \) | \( H \) | \( C_p10^4 \) | \( St.10^4 \) |
|-----------|-------------|------------------|----------------|------------------|----------------|-------------------|---------------|----------------|---|--------------|--------------|
| 1         | 450         | 15.53            | 11.85          | 1.78             | 1.32           | 12.93             | 1.45           | 1330            | 1.35       | 4.06         | 2.24         |
| 2         | 500         | 15.53            | 13.31          | 1.95             | 1.44           | 13.61             | 1.53           | 1447            | 1.36       | 3.95         | 2.25         |
| 3         | 555         | 15.29            | 13.25          | 2.13             | 1.55           | 14.36             | 1.57           | 1467            | 1.37       | 3.87         | 2.22         |
Figure 2 and table. 1 show that experimentally obtained profiles of velocity and temperature in the boundary layer in sections 1-3 are approaching the law of one seventh, i.e., the profiles have the form characteristic for the plane wall, and investigated boundary layer completely developed turbulent. This is also indicated by the magnitude of shape factor in these cross-sections $H = \delta'/\delta'' = 1.35–1.37$. So this practically coincide with the law one-seventh in all cases – all this corresponds to the data [1, 2, 4, 7, 16, 17].

The fluctuations of velocity and temperature in cross-sections 1-3 (figure 2(b)) have the typical form for heat transfer in turbulent boundary layer in a gradientless flow over a plate, similar to the works [1, 2, 4, 7, 16, 17], one clearly expressed maximum near the wall at $(y/\delta) \approx 0.02$, i.e. source of turbulence generation (fluctuation) is the wall, where the maximum velocity gradient and temperature is located.

![Figure 2](image)

**Figure 2.** Distribution of velocity and temperature (a) and their fluctuations (b) in the boundary layer

3.2. Rib with sharp corners and rib with round top corners

The structure of turbulent boundary layer has been studied experimentally in front of and behind the rib in the range of the mutual arrangement of the rib and cross-section measurement $-10.94 < x/h < 20.98$, where $x$ is the distance from the rib to the studied cross-section, and $h$ is the height of the rib.

3.2.1. Mean profiles of velocity and temperature. In figure 3, the distributions of velocity and temperature in the boundary layer in cross-sections of the specified interval for rectangular rib with sharp corners and rectangular rib with round top corners are presented. The obtained results show that the temperature profiles remain almost unchanged when approaching the rib $(x/h = -10.94)$. Yet, since $(x/h = -4.7)$ velocity profiles become less filled in front of the rib, they significantly distorts in cross-section $(x/h = -0.94)$ especially at the wall (before the rib), i.e. flow has stagnated in this area. Unlike velocity, the temperature profiles are practically in line with the law one-seventh in both variants, i.e. they are more filled than the velocity profiles – all these are consistent with the data [7, 15], i.e., the temperature profiles are more conservative to the change of the rib shape.

Behind the rib, complex vortex flow is formed. In figure 3, it is easy to see that the attachment point of the main flow to the surface of the plate is located in the region of $5.25 < x/h < 8.38$ where the flow is divided into two parts. One part is the main flow moves along the direction of the free stream and, starting from the attachment point (in the region $x/h = 8$), the boundary layer reinitiates and the velocity profile is gradually filled and approaching the law one-seventh, while the temperature profile remains virtually unchanged. The other part of the flow, starting from the attachment point at a distance of approximately $x/h < 8$, heads back to the rib and forms a recirculation flow zone. Figure 3 shows that the separation of the flow happened in cross-sections from $x/h < 8.38$, in which reversed
secondary flow in the separation zone near the rear edge of the rib is observed. The flow moves up along the rib and is thrown in the main flow and interacts with it, forming a mixing zone – a zone of increased turbulence intensity, which is particularly well supported by the distribution of fluctuations and in particular of the velocity fluctuations.

3.2.2. Turbulence fluctuation characteristics of velocity and temperature. The distribution of velocity and temperature fluctuations in the boundary layer for square rib and square rib with round top corners are shown in figure 4. It can be seen that in front of the rib, almost in all cross-sections, the distribution of velocity and temperature fluctuations almost qualitatively coincides with the corresponding parameters for gradientless flow, regardless of several decreasing in absolute value. At the top face of the rib, velocity fluctuations sharply increase for the rib with sharp corners and also decrease dramatically (almost three times) for rib with round top corners.

In the separation zone velocity and temperature fluctuations undergo significant changes, as is indicated by the appearance of the second maxima in the distribution of the longitudinal velocity fluctuations and temperature in the separation region. Recalling (figure 3) that the first inflection of the velocity and temperature profiles consist with the first maximum of the corresponding fluctuations, and the second – with the second maximum corresponding fluctuations coincident with the initially smooth surface. In this case, it is observed that downstream the rib there are two peaks in the distribution of velocity and temperature fluctuations, and the generation of turbulence in the mixing zone (fluctuations of velocity) is much greater than the intensity of near-wall turbulence. In addition, figure 4 shows that downstream the rib, maximum fluctuating velocity is much greater than the maximum temperature fluctuation due to a greater deformation of the velocity profile compared to the profile temperature.

As was seen in figure 3, the velocity at the wall behind the rib changes direction to the opposite, which indicates the occurrence of re-circulating flow in this area. The qualitative mechanism of the processes taking place in the area of the re-circulating flow (in the region x/h < 8,0) is well described in [1, 7, and 9]. Irreversible energy of the main flow to overcome the flow resistance of the rib is spent
on the maintenance of the vortex zones, and eventually the turbulence intensity of the flow was increased, i.e. the increase of turbulent fluctuation energy can be realized by the generation of new fluctuations. The energy of these fluctuations is transmitted to gradually smaller scale pulsations and finally converted into thermal energy. Part of the dissipation occurs within the vortex zone. But a significant part of the energy in the form of kinetic energy of the turbulent fluctuations from the upper boundary of the vortex zone is taken to the main flow and is transported with main flow along the streamline due to turbulent diffusion perpendicular to them. It can be seen from the profiles of velocity fluctuations in the last section \((x/h = 20.88)\) that the profiles of velocity and temperature are almost close to the law one-seventh. Contrary to this are the velocity fluctuations and temperature in this section – they are significantly higher than those for the corresponding in first cross-section (dotted lines).

![Figure 4](image)

**Figure 4.** Distribution of velocity and temperature fluctuations in the boundary layer for rib with sharp corners: 1– \(U/U_\infty\); 2– \(\Delta T/\Delta T_\infty\) and for rib with round top corners: 3– \(U/U_\infty\); 4– \(\Delta T/\Delta T_\infty\); 5– \(u'/U_\infty\) in first cross-section; 6– \(T'/\Delta T_\infty\) in first cross-section.

### 3.2.3. Coefficients drag and heat transfer

Figure 5 shows the values of the relative local coefficients of friction and heat transfer. Local friction coefficients were determined by the Clauser method for the logarithmic part of the velocity in the boundary layer and the slope of the velocity profile in the laminar sublayer. The local heat transfer coefficients were determined by the loss of energy and slope of the temperature profile in the laminar sublayer. It should be noted that the use of these methods for the determination of friction and heat transfer coefficients is not always valid. Figure 5 shows that under these conditions the increase of the heat transfer coefficient exceeds the growth of the friction coefficient.
4. Conclusions

In this paper the processes of hydrodynamics and heat transfer in the flow over the rectangular ribs without and with the round corners in the condition of $q_w = \text{const}$ have been experimentally investigated. Obtained are new experimental data on average and fluctuating characteristics in turbulent boundary layer in flow over rectangular ribs - in the laminar sublayer, transition region. It shows that:

The changing characteristic of friction and heat transfer coefficients indicates that the growth of the heat transfer coefficient is faster than the growth of the friction coefficient.

The structure of vortex zones before and after the rib depends strongly on the shape and size of the rib.

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