Microstructure of flow in a channel with low-profile spanwise ribs

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Abstract. The paper presents the experimental data on velocity fluctuation spectra and reattachment lengths observed in turbulent flows past low-profile elements of discrete roughness mounted on the wall. The discrete roughness elements were shaped as semicircular spanwise ribs with the height of 2% of the hydraulic diameter of the channel. It has been revealed that such ribs make the velocity fluctuations increase manifold at the height of rib tops in the range of non-dimensional frequency \( St = 0.6-1.2 \) that favors the reattachment length reduction and heat transfer augmentation.

1. Introduction

The main idea of using the discrete roughness of the wall for heat transfer enhancement consists in thinning the thermal boundary layer by destruction and renewal of the dynamic boundary layer in the near-wall zone. The most popular discrete roughness elements are spanwise ribs, caverns and dimples. The height (depth) of such roughness elements in turbulent channel flow should be comparable to the thickness of the viscous sublayer. When the height (depth) exceeds this thickness by one order and more, the rate of heat transfer enhancement slows down considerably while flow resistance still rapidly grows, and hence thermal-hydraulic performance is deteriorated. According to a series of reviews by A.I. Leontyev and V.V. Olimpiev [1, 2 et al.], the reasonable height of discrete roughness elements in turbulent flows is approximately 1-2% of the hydraulic diameter. When the Reynolds numbers are moderately high, such a height is only several times larger than the thickness of the viscous sublayer, i.e. it is considerably lower than the boundary of fully rough flow, which is usually assumed as the non-dimensional roughness height \( h' = 70 \) written in wall coordinates.

When studying the effect of discrete roughness on the flow, it is a common practice to analyze either the flow structure around the roughness elements (detailed approach), or just the profiles of velocity and turbulence in the boundary layer disturbed by the roughness elements (averaged approach). Experimental research of the flow structure is rather challenging. Hot-wire measurements are hardly suitable for separated flows, laser Doppler anemometers have some problems with near-wall measurements, and two-dimensional optical methods do not provide sufficient spatial and temporal resolution. The experimental data on the flow structure currently available in the literature were obtained for high-profile elements of discrete roughness. However, when the roughness height is reasonably low, the flow microstructure may turn out to be essentially different for three main reasons. First, the Reynolds number based on local parameters of flow past the roughness elements is quite low. Second, the velocity of flow approaching the low-profile obstacle within the range of its height...
changes almost linearly as opposed to almost uniform velocity of flow past high-profile obstacles. Finally, formation of the separation region behind low-profile obstacles can also be significantly different from the well-studied case of high-profile ribs due to being exposed to the effect of turbulent fluctuations of velocity, which are rather strong at the level of low-profile rib tops.

There is an obvious scarcity of recent experimental studies of flow structure and turbulence in channels with a rough wall. Authors of [3-8] investigated the roughness geometry that was rather close to regular sand roughness. This geometry is far from the one employed for heat transfer enhancement. However, those studies indicate that wall roughness promotes velocity and vorticity fluctuations close to the wall, and this augmentation is pronounced at the distance of 5 roughness heights from the wall. Compared to smooth walls, different shape of the profile of turbulent kinetic energy is observed; its peak is less pronounced and shifted away from the wall. Flows over rib-roughened walls were studied in papers [9-12]. It was shown that the influence of roughness on turbulent Reynolds stresses and third-order moments at the distance of 5 and more length scales is weak or completely absent, and a high-energy shear layer is formed above the roughness tops.

From our brief review, we conclude that regular patterns of sand roughness analogues are investigated most often; profiles of velocity and turbulence are estimated in the boundary layer disturbed by roughness elements. The structure of flow past low-profile spanwise ribs has been studied only by numerical simulation and at relatively low Reynolds number. In the present paper, we obtained more detailed information on the structure of flow over low-profile spanwise ribs.

2. Experimental setup and procedure

The recently introduced method of Smoke Image Velocimetry (SIV) [13] features high spatiotemporal resolution required for the studies of turbulent microstructure allowing for the energy of vortices of the order of Kolmogorov scale [14]. The present study deals with SIV measurements of the flow past a rib-roughened wall of 100×100 mm channel. Semicircular spanwise ribs with the height \( h = 2 \) mm were mounted on the wall with a pitch of 12\( h \). The Reynolds number based on hydraulic diameter was \( \text{Re} = 11000 \). The experimental setup is schematically shown in fig.1. The air flow rate of 56.0 m\(^3\)/h was maintained by standard critical flow nozzles with the uncertainty of no more than 0.25%.

![Figure 1. Experimental setup. 1 – air-aerosol mixture preparation chamber; 2 – aerosol generator; 3 – test section; 4 – high-speed camera; 5 – continuous laser; 6 – receiver tank; 7 – critical flow nozzles; 8 – valves; 9 – vacuum pumps.](image)

Only one wall of the channel was rib-roughened, and not along the whole length. Ribs were mounted starting from the distance of 5 m from the channel inlet, i.e. it was guaranteed that the flow approaching the first rib was a developed turbulent channel flow. Measurements were performed between ribs 8 and 9. Discrete roughness and coordinate system are demonstrated in fig.1.
3. Results and discussion

It is well known that discrete roughness of walls promotes turbulence in the near-wall zone of flows. This is confirmed by spectra of velocity fluctuations (fig.2) obtained at different x-coordinates at the distance \( h \) from the wall. Interestingly, the low-frequency parts of spectra almost coincide for smooth (bold line) and rough walls. For the considered flows, the main increase in turbulent energy due to discrete roughness was observed for frequencies exceeding 30 Hz and was fivefold in the range between 50 and 100 Hz. If this frequency range is normalized by the average distance to the flow reattachment point (it is shown below that \( X_R=6h \)) and the average velocity of approaching flow at the level of rib tops (\( U=1 \) m/s), we obtain the corresponding non-dimensional frequency range \( St=0.6-1.2 \) (Strouhal number, \( St=f X_R/U \)). According to [15], when the flow is forced by pulsations of the specified frequency, the size of the separation region and heat transfer in this region are rather sensitive to forced flow pulsations. In other words, turbulent energy generated by low-profile ribs is concentrated in the frequency range that favors heat transfer enhancement.

![Figure 2. Spectra of streamwise velocity component fluctuations at distance h from the wall.](image)

The average reattachment point behind the rib can be derived from the streamwise velocity component at the distance of 0.126\( h \) from the wall (fig.3). \( u=0 \) is at \( X=6h \), which is a reasonable approximation of the reattachment point coordinate, \( X_R \), since the measurement point is rather close to the wall. The reattachment length appeared to be much shorter than the one typical of flows past high-profile ribs (10\( h \)). Such reduction is qualitatively consistent with the effect of flow unsteadiness. In this case, unlike [15], we mean not the forced flow pulsations but internal unsteadiness in the form of turbulent fluctuations induced by discrete roughness of the wall. We assume that the key contributor to the impact on the structure of flow past low-profile roughness is the internal unsteadiness of flow. However, we are not yet able to separate the influence of this unsteadiness from other effects that promote the reduction of reattachment length. The latter include low Reynolds number based on local parameters of flow past roughness elements and almost linear (over y-coordinate) behavior of local velocity of flow approaching the rib compared to almost uniform velocity in the case of high-profile ribs. But in any case, the reduction of normalized reattachment length behind low-profile roughness elements provides further heat transfer enhancement.
Conclusions
Turbulent channel flows past low-profile ribs (rib height was 2% of the hydraulic diameter) were studied experimentally. Manifold (up to 5 times compared to the smooth wall) enhancement of velocity fluctuations at the height of the rib tops was observed in the range of non-dimensional frequency $St=0.6-1.2$ that is favorable for the reattachment length reduction. According to the research of the effect of forced pulsations on heat transfer [15], such non-dimensional frequencies of internal fluctuations in the flows past low-profile ribs favor the heat transfer enhancement in the rib wake.

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