Numerical simulation of a separated flow in a ribbed channel by the RANS and LES methods

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Abstract. The results of numerical simulation of a turbulent flow in a flat channel in the presence of vortex generators in the form of periodic solid ribs by the RANS and LES method are presented. The Reynolds number calculated by the rib height and the average flow rate is $Re = 12600$. The influence of the distance between the ribs on the flow structure is investigated. The boundaries of different types of roughness and their influence on the heat transfer intensity are shown.

Introduction
The study of complex separated flows is grounded by a large number of practical applications. One of the most important tasks in this area is to improve the efficiency of heat exchange equipment [1]. To control separated flow parameters, affecting heat transfer directly, various methods are used, which can be conditionally divided into the active and passive ones. Oscillating ribs [2], flow injection [3] or suction [4] can be used as the active methods. These methods allow a smooth control of separated flow parameters; however, the use of such methods is difficult. Passive control methods are preferred due to their simpler implementation. These methods include the presence of transverse ribs in front of the backward-facing step, which increases heat transfer on the lower wall of the channel at the point where the flow attaches. At that, an increase in heat transfer can reach 30%. In addition, tabs were used as vortex generators in [5, 6]. They allowed the achievement of a significant increase in heat transfer in the area located immediately behind the step, and the hydraulic resistance increased insignificantly.

In addition, transverse ribs can be also used as vortex generators. At that, depending on the distance between them, they can form a k- or d-type roughness. So the authors of [7] studied the flow structure at different distances between the adjacent ribs. A transition between two types of roughness was shown. But the question about the effect of a distance between the ribs on heat transfer was not considered.

This work deals with numerical simulation of a separated flow in a flat channel with a backward-facing step in the presence of periodic ribs. The effect of the inter-rib distance on the type of roughness and intensity of heat transfer is analyzed.

Computation details
The paper presents the results of numerical simulation of a separated flow in a flat channel with periodic ribs. The Reynolds number, calculated from the rib height and the average flow rate, was $Re = 12600$. The distance between the ribs was presented by variable parameter $w/x = 1\div21$. A
constant heat flux was set on all walls of the channel, except the upper one, which was thermally insulated. At the inlet to the computational domain, a fully developed velocity profile and a constant temperature of the medium were set. The computational domain is presented in figure 1.

![Figure 1. The scheme of computation domain.](image)

Numerical simulation was performed using the RANS method. Integration of all equations included in the mathematical model was carried out using the control volume method of the second order of accuracy over the space in a stationary (iterative) setting using the cyclic TemperatureFoam solver from the OpenFOAM package.

A rectangular grid, condensed to the channel walls, was build for this problem. The criteria for finding the optimal number of cells were based on the constancy of solution with using more number of cells and $y^+ < 1$ (figure 2). In preliminary calculations, the results obtained were compared with numerical calculations and experiment [8].

![Figure 2. Distribution of the Nusselt number in a rectangular channel for various grids.](image)

**Result and discussion**

Data on the dynamics and heat transfer of a turbulent flow in a flat channel with periodic ribs are obtained. Thus, figure 3 shows the flow structure for $w/e = 2, 7.7, \text{ and } 9.7$. According to figure 3b, it can be seen that when the distance between the ribs is equal to two rib heights, the so-called d-type roughness is implemented. In this case, the presence of ribs does not affect the main flow. With a larger distance between the ribs (figure 3a), roughness of the k-type is implemented. At that, the ribs...
almost do not affect each other and the flow structure for a flat channel with a backward-facing step is formed. Accordingly, in the intermediate version, a transitional type of roughness is implemented, which is shown in figure 3c.

Figure 3. Flow structure for w/e: a) 9.7, b) 2, c) 7.7.

To study the effect of a transverse rib on the flow, a calculation by the large eddy method (LES) was carried. Visualization of the evolution of the vortex flow structure using the Q – criterion is presented in figure 4. It can be seen that vortices originate at the rib (figure 4a) and develop further along the channel (figure 4b). The rib leads to formation of large-scale vortices that act on the mixing layer, which leads to more intense heat transfer.

Figure 4. Vortex visualization using the Q – criterion: a) initial moment, b) following moment.

The distribution of Nusselt number for the channel wall located between the ribs is presented in figure 5. It can be seen from the figure that with a roughness of type d or transition type, heat transfer increases significantly. When the point of separated flow attachment appears, a secondary vortex is formed near the next rib, which enhances heat transfer. This can be seen from the peak located at the end of a gap between the ribs.
Figure 5. Nusselt number distribution.

Figure 6 shows the maximum value of the Nusselt number for various distances between the ribs. It follows from the figure that at $w/e = 10$ the maximum Nusselt number almost stops changing. At such large distances, the ribs stop influencing each other.

Figure 6. The maximum Nusselt number vs. a distance between the ribs.

Conclusion
The turbulent flow dynamics and heat transfer in a flat channel in the presence of periodic transverse ribs were numerically simulated by the RANS and LES methods at a Reynolds number of 12600. It is shown that with a change in the distance between the ribs, different types of roughness are implemented, which in turn affects heat transfer. It is found that at $w/e = 10$, the maximum Nusselt number almost stops changing, since adjacent ribs have a weak effect on each other. When passing from the d-type roughness to the k-type roughness, heat transfer on the lower wall of the channel increases significantly.
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