RANS and LES simulation of separated flow in a flat channel with a back-facing step

V V Terekhov¹,², A V Barsukov¹ and V I Terekhov²
¹ Novosibirsk State University, Pirogov str. 2, 630090, Novosibirsk, Russia
² Kutateladze Institute of Thermophysics SB RAS, Ac. Lavrentyev Ave. 1, 630090 Novosibirsk, Russia
E-mail: vt@itp.nsc.ru

Abstract. The results of numerical calculation by the RANS and LES methods of turbulent separated flow in a flat channel with a back-facing step are presented. The calculation was carried out for Reynolds number Re = 5000, determined by the average mass velocity and the step height. The effect of vortex generators in the form of a transverse rib on the heat transfer intensity has been studied, and the data obtained are compared with experiment.

1. Introduction
Significant interest to the problem with flow separation and reattachment is connected with the fact that this phenomenon is often found in flow channels of various technical devices. In most cases, this is due to a sudden change in geometry, which leads to separation of the boundary layer from the surface and formation of a mixing layer, which ultimately reattaches to the wall. The back-facing step is one of the simplest cases and it allows investigation of the main features of the flow and heat transfer of flow separation both experimentally and numerically.

To control the parameters of the separated flow, such as the circulation flow intensity and sizes of recirculation region, various methods are used, which can conditionally be divided into the active and passive ones. Active methods include injection or suction of the boundary layer [1], various periodic disturbances introduced into the main flow [2], periodic injection of jets, etc. These methods allow smooth control of the separated flow parameters and heat transfer intensity.

The passive control methods are of a particular interest due to their simpler implementation. The presence of additional elements (transverse ribs, teeth, vortex generators of various shapes, etc.), which are significantly smaller than the main separated flow, can lead to significant restructuring of the flow. Thus, the authors of [2, 3] showed that the use of transverse ribs in front of the back-facing step leads to a 50% reduction in the recirculation zone as compared to a channel without a rib. It was shown in [4] that the use of generators of longitudinal vortices (tabs) has a significant effect on heat transfer near the back-facing step and reduces the coordinate of the maximum Nusselt number.

This work deals with a numerical study of the separated flow structure and heat transfer in the presence of a transverse rib in front of the back-facing step when the rib scale and its location are varied.

2. Computation details
To simulate this problem numerically, the OpenFOAM package was used. The averaged Navier-Stokes equations were closed in the RANS approach using the k-omega SST model, since it is the
most universal when calculating the separated flows. The calculation area and the grid that was used to simulate the channel with a back-facing step are shown in Figure 1. A two-dimensional non-uniform grid, condensed to the channel walls to satisfy the condition $y^+ < 1$, was used for RANS simulation. The number of cells in the grid was $\sim 40,000$. At the inlet to the calculation area, the conditions, corresponding to a fully developed flow in the channel, were set.

Figure 1. Geometry of calculation area.

In simulations by the large eddy method (LES), the Smagorinsky model was used for closure. Spatial discretization had a second order of accuracy (central difference). The time step was chosen so that the Courant criterion did not exceed 0.5 in the entire calculation area, and the number of cells in the computational grid was 2.6 million. Precursor simulation of the fully developed flow in the channel was performed to specify the inlet conditions. In the transverse direction, periodic boundary conditions were used.

3. Result and discussion
The results of numerical calculations of the channel with a back-facing step are compared with experiments of [5] in Figure 2. It can be seen from the figure that the maximum of the heat transfer coefficient is at distance $X = 6H$ from the step and its maximum value in calculation is $\sim 8\%$ less than in experiment. Moreover, in the zone of flow relaxation ($X/H > 20$), the calculated and experimental results almost coincide. The difference between experiment and calculation in the region of $X < 2H$ may be caused by large errors in the measurement of heat transfer in the corner zone behind the back-facing step.

Figure 2. Dependence of the Nusselt number on the wall after the step, experiment [5].
The ratio of maximum values of the heat transfer coefficient in the presence of a passive disturbance in the channel in the form of a rib with height $\Delta = 1/3H$, located in front of the back-facing at various distances $S$ to its edge, is shown in Figure 3. It can be seen that the heat transfer coefficient has a maximum, which is achieved both in calculations and experiments at $S = 1.55H$. As the rib moves against the flow, the influence of disturbance on heat transfer decreases, and at $S/H > 5$ it can even lead to suppression of heat transfer intensity.

![Figure 3](image_url)

**Figure 3.** The position of the maximum heat transfer in comparison with the experiment: $Nu_0$, Nusselt number in a flat channel with a back-facing step without a rib, $Nu_{max}$, Nusselt number in the presence of a rib, experiment [5].

To study the effect of the transverse rib on the flow, a calculation using the large eddy method (LES) was performed. The vortex structure of the flow is visualized in Figure 4 using the $Q$ - criterion for the back-facing step with and without a rib. In the presence of a rib, it can be seen that vortices originate at the rib and develop further along the channel. The rib leads to formation of large-scale vortices, which act on the mixing layer, intensifying heat transfer.

![Figure 4](image_url)

**Figure 4.** Vortex visualization using the $Q$ – criteria a) without a rib and b) in the presence of a rib.

**Conclusions**

The separated flow in a flat channel with a back-facing ward step was studied by the RANS and LES methods in the presence and absence of a transverse rib for Reynolds number Re = 5000. It is
established that the presence of a rib leads to an increase in heat transfer intensity by ~ 11% at the optimal position of the rib (S = 1.55H). At that, the calculated data are in qualitative agreement with the experiment. Quantitative coincidence takes place in the relaxation region of the flow. Using the Q criterion, it was shown that a passive disturbance in the form of a transverse rib leads to formation of large-scale vortices in comparison with the case without a rib. As a result, large-scale vortices act on the mixing layer, intensifying heat transfer.

Acknowledgments
The scientific research was carried out with the support of the grant of the Russian Science Foundation No. 18-19-00161. The computational resources are provided by Siberian Supercomputer Center SB RAS.

References
[1] Terekhov V V and Terekhov V I 2017 J. Applied Mechanics and Tech. Physics 58 254
[2] Miau J J, Lee K C, Chen M H and Chou J H 1991 AIAA J 29 1140
[3] Neumann J and Wengle H 2003 Flow, Turbulence, Combust. 71 297
[4] Dyachenko A Yu, Zhdanov V L, Smulskii Ya I and Terekhov V I 2019 Thermophysics and Aeromechanics 26 509
[5] Terekhov V I and Smul’skii I. Ya. 2005 J. Applied Mechanics and Technical Physics 56 870