RANS and LES analysis of a separation region in front of a backward-facing step

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Abstract. Turbulent characteristics of a reattached flow separated from a rib ahead of a backward-facing step in a flat air channel were numerically analyzed by RANS and LES methods. The separation region ended just before the step edge. The both methods showed low pressure regions in corners, formed by the rib and the channel walls that caused a vorticity tube forming along the rib. Nevertheless in RANS, a separated flow was identified as two-dimensional with a thicker shear layer at the step edge. In LES, the low pressure regions caused both redistributions between velocity components, Reynolds stresses, and a thicker shear layer at the step edge. The flow structure behind the rib has been, thus, identified as three-dimensional.

1. Introduction
Separate flows are common in several engineering applications such as aircraft wings, turbine and compressor blades, diffusers, buildings, pipes with sudden expansion, combustors, etc. These flows drastically change transport of momentum, heat and mass. Due to this fact, interest in separation control has been drawing attention of researchers over decades. A backward-facing step is ideal canonical separated flow geometry, encountered in various technical structures. A flow separated from the step edge due to a favorable pressure gradient reattaches the wall at some distance downstream, forming a separation region. The length of this region in many cases is desirable to be as short as possible. Extensive investigations have revealed parameters that influence the separation region length: expansion ratio, aspect ratio, free stream turbulence intensity, Reynolds number, as well as boundary layer state and its thickness at separation [1]. In earlier studies, the reattachment length of a separated flow was usually a primary parameter of interest. With advances in measuring techniques and discovery of the coherent structure influence on the progress of separation region, main interest has been shifted to flow structures both upstream and downstream of the step. To date, several different passive and active control techniques (fence, rod, tabs, suction and ejection, oscillation [2-7]) have been implemented mainly to examine the transformation of separated flow structures altering the reattachment length.

Originally, experimentation served as a main source of information on transport processes in separated flows, but with progress in computer facilities, numerical simulations have become a powerful tool of research. Nowadays, numerical methods allow obtaining characteristics of a three-dimensional flow with high spatial resolution and, at the same time, visualizing a flow in different directions. Two methods – RANS and LES – are mostly used in investigations. Historically, RANS is the first method extensively applied to study the flow characteristics, including those of separated flows. The method is mostly suitable for studying steady flows while the separated flows are unsteady. RANS showing a good correlation of mean parameters (velocity, reattachment length) with experiment, shades features of flow structural. Being intensely developed over last decades LES

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allows highlighting unsteady flow variations, but at the expense of computer resources and computation time.

The present study aims at showing structural distinctions of the same flow, applying RANS and LES. The reattached flow separated from a rib installed ahead of a backward-facing step is considered. A variable position of a rib relative to a backward-facing step affected a reattachment length behind the step [2]. The experimental measurements have also shown that the reattachment length decreases if the shear layer at the step edge becomes thicker.

RANS and LES simulations of two-dimensional laminar flows above a backward-facing step were compared using OpenFoam [8]. For a lower Reynolds number (Re = 389), the RANS and LES results were in a good correlation with experiment. For a higher Reynolds number (Re = 1000), the RANS simulations were poor but the LES simulations showed a good agreement with experiment.

2. Subject of investigation

Investigations were carried out in a flat air channel with a rib, located in front of a backward-facing step. Channel cross section (0.021 × 0.150 m (h₀ × B)) and step height (H = 0.009 m) were identical to the ones of the experimental setup described elsewhere [2]. The rib of height (Δ) equal to 0.003 m with its thickness of 0.005 m (ε) was located across the channel width at different distances from the step edge (S) (figure 1).

![Figure 1. Schematic of a channel with a rib in front of a backward-facing step.](image)

3. Simulation methods

A three-dimensional velocity field was computed by RANS using ANSYST Fluent 18 and two models: k-ω SST and k - ε with standard wall functions. LES computations were done by OpenFOAM (Open Field Operation and Manipulation) using two eddy viscosity models: Smagorinsky [9] and one-equation (oneEqEddy) [10]. The velocity and pressure fields were linked by a PIMPLE (merged PISO-SIMPLE) algorithm.

In numerical computations, a developed velocity profile (power law of 1/7) was assigned at the channel entrance. The Reynolds number based on step height and bulk velocity (U₀ = 25 m/s) was ReH=15500. A turbulence intensity of 5% was set for each velocity component.

The computational domain included the channel part before the rib as well as the length of the recirculation zone behind the backward-facing step. In RANS, this domain was one meter in length and had a computational grid of 12 000 000 cells. In LES, the domain was shorter – 0.5 m, and the grid had 2209500 cells.

4. Results

The experiment [2] showed that the reattachment length behind the step increased when the shear layer separated from the rib merged with that from the backward-facing step (S = 0.02 m). When the separated layer from the rib attached the channel wall before the step edge (S = 0.04 m), the reattachment length decreased and changed insignificantly with a further increase in S. Therefore turbulent flow characteristics were numerically simulated for two rib positions: S = 0.02 and 0.06 m to correctly select a turbulence model. The boundary of the recirculation zone behind the step was determined by the zero longitudinal velocity coordinate at the channel bottom in the central section. The best agreement of reattachment lengths with experiment was observed for the k-ε model.
(RANS) and oneEqEddy (LES) (figure 2). The k-ω SST model usually used to study a near-wall flow showed a poor agreement with experiment as also noted in [8].

Due to separation the low pressure regions were generated in the corners, formed by the rib and the channel sidewalls. Fluid was sucked into these regions, which were the sources of a vorticity tube formed along the rib, involved into the tube and flowed in the middle part of the channel (figure 3). This flow structure was experimentally visualized [11].

Since flow parameters before the edge of the backward-facing step influence progress in the recirculation zone behind the step, mean and turbulent flow characteristics were calculated at a distance of 1.5Δ ahead the step edge for two heights 0.2Δ, 0.5Δ and in two cases: a) without rib; b) with rib at S = 0.06 m.

4.1. RANS investigations

A longitudinal velocity profile ($U_x$) across the channel height was normalized by a maximum velocity ($U_{max}$) above the edge of the backward-facing step [2]. The numerical profiles differed from the experimental one due to the asymmetry of the latter only near the lower wall. Perhaps, this asymmetry was caused by the influence of the separation region behind the step. In the numerical study, velocity profiles calculated at the step edge were symmetric. Owing to the rib, the velocity decreased near the channel bottom (stronger in experiment) and increased in the channel upper part (figure 4a).

Distributions of flow turbulent characteristics across the channel were presented only for the k-ε model. The rib effect was shown in small deviations from uniformity for longitudinal and transverse velocity components near the sidewalls (figure 4b). Reynolds stresses sensitive to structure transformations also showed rather uniform distributions $\overline{u_xu_y}$ across the channel width at different heights (figure 5a). The stress $\overline{u_xu_z}$ was almost zero along...
the channel width. The stress $u'_{x}u'_{x}$ deviated from zero to the sidewalls the stronger the larger was the parameter $h$ (figure 5b, c). But these deviations were more than by an order of magnitude smaller in comparison with the stress $u'_{y}u'_{y}$.

Thus, the changes in flow parameters due to the rib were mostly shown only in the thickening of a shear layer at the step edge because the velocity decreased as measured in experiment [2] and the reattached flow remained two-dimensional.

4.2. LES investigations
In the channel without rib, the longitudinal velocity profiles computed by the Smagorinsky and oneEqEddy models at the edge of the backward-facing step were more flat in the channel central part and lower at the walls in comparison to the experimental and RANS ones (figure 6a). Apparently, it was a result of a shorter computational domain. The velocity normalization was the same as in RANS.

The separation region length calculated by Smagorinsky’s model was by 4Δ shorter than the length calculated by the oneEqEddy model. Nevertheless, Smagorinsky’s model showed a stronger velocity decrease at the step edge than the oneEqEddy model and the experiment [2]. Varying the velocity near the channel wall determines a shear layer thickness at the step edge that strongly influences the development of separation region behind backward-facing step. Therefore flow characteristics along the step edge in the transverse direction were analyzed using only the oneEqEddy model.

In the channel with no rib, the velocity field was two-dimensional: the velocity component $U_{x}$ uniformly distributed across the channel, and other components were equal to zero (figure 6b). The rib caused the velocity components $U_{x}$ and $U_{z}$ to increase strongly near the sidewalls in comparison with their values in the channel center (figure 6c). The normal velocity ($U_{y}$) slightly decreased with increasing parameter $h$.

Small Reynolds stresses were distributed rather uniformly in the channel with no rib, which is typical
for a two-dimensional flow (figure 7a). These stresses increased due to the rib by two orders of magnitude and became stronger to the sidewalls reflecting a three-dimensional flow structure (figure 7b).

Figure 7. Reynolds stresses distributions along the channel width at the backward-facing step; a) without rib; b) with rib.

The increase in stresses $\overline{u_2u_2}$ and $\overline{u_3u_3}$ showed the growth of transverse and normal interactions in the flow.

The vorticity $\omega_z = \left( \frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z} \right)$ was generated mostly near the walls being almost zero across the channel without rib (figure 8a). The rib caused pairs of opposite-sign vortices to be formed near the channel bottom. The vorticity intensity of these pairs was by an order of magnitude higher than the maximum vorticity in the channel without rib (figure 8b). The generated vortices resulted in energy redistribution within the separation region, which was shown in longitudinal velocity decrease in front of the edge of the backward-facing step (figure 6a).

Figure 8. Vorticity field across the channel width at the step edge: a) without rib; b) with rib.

Figure 9. Vorticity maps before and after the edge of the backward-facing step in the channel: a) without rib; b) with rib.
The three-dimensional flow formed ahead of the step resulted in the intense vorticity formation in the recirculation zone behind the step (figure 9). The vorticity maps were presented in the plane over the channel bottom. The rib and step edge coordinates corresponded to numbers -0.06 and zero, respectively.

5. Conclusions
Parameters of a reattached flow separated from a rib ahead of a backward-facing step were documented by two numerical methods: RANS and LES using different turbulence models: k-ε, k-Ω and Smagorinsky and oneEqEddy, respectively. The both methods showed a velocity decrease at the edge of the backward-facing step, but in RANS, the reattached flow was identified as two-dimensional, while in LES – as three-dimensional.

The present study evidences that the k-Ω SST model does not describe the influence of the rib position on the reattachment length behind the backward-facing step when the separation region ends before the step edge.

LES simulations using the oneEqEddy and Smagorinsky models showed a different length of separation regions behind the rib and different velocity profiles at the step edge. The development of the separation region described by Smagorinsky’s model is in worse correlation with the natural one known from experiments.

Acknowledgement
The study was made within the framework of Grants T16P -005 (BFFR) and 16-58-00018 (RFBR).

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