Effect of the channel divergence ratio on heat transfer in a turbulent flow around the rib-step system

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Abstract. The article presents the result of the numerical simulation of the turbulent flow for a rib-step system by the RANS method at the Reynolds number, calculated by the step height and average flow rate velocity, Re = 5000. The data obtained in these studies showed the influence of divergence ratio on heat transfer in a flat channel with a transverse rib acting as a vortex generator. It is shown that with an increase in the divergence ratio, the length of the recirculation zone increases, while the position of the heat transfer maximum varies slightly.

1. Introduction

Flow separation from the wall and its reattachment are observed in the flow channels of many technical devices; therefore, a large number of studies have been dealt with this problem [1, 2]. The possibility of passive control of the separated flow in the channel behind a back-facing step using a mini-turbulator in the form of a rib mounted on the channel wall in front of the step is shown in [3]. The characteristics of this type of flow are influenced by various factors: Reynolds number, size, and position of a mini-turbulizer [3], and the thickness of the boundary layer of the incoming flow [1]. Besides, the pressure gradient affects the characteristics of the separation flow. There are various ways to control the longitudinal gradient.

Thus, the authors of [4] have carried out the experimental work and numerical simulation of the effects of longitudinal pressure gradient, which was changed by means of channel narrowing or expanding, on heat transfer. In this study, they have obtained the data according to which, with an increase in the pressure gradient, the heat transfer maximum (indicated by the local value of the Nusselt number) increases for a converging channel and decreases for a diverging one. At that, the position of heat transfer maximum behaves similarly.

To change the longitudinal pressure gradient, not only channel narrowing or expanding behind a back-facing step can be used, but the relationship between the channel heights before and after divergence can be varied (ER is the divergence ratio). Thus, the authors of [5] have studied numerically the back-facing step for Reynolds numbers of up to 180,000. One of the studied aspects was the influence of the Reynolds number and the divergence ratio on the length of the recirculation zone. According to data obtained and their comparison with other works, it was shown that the length of the recirculation zone decreases with increasing Reynolds number. But at that, for Re > 10⁴, the divergence ratio becomes the determining parameter. Moreover, with an increase in the divergence ratio, the length of the recirculation zone increases.
This work is devoted to numerical simulation of separated flow in the rib-step system, as well as to the analysis of the influence of divergence ratio, position, and height of the rib on the behavior of the separated flow.

2. Computation details
This paper presents the results of a numerical simulation of separated flow in a flat channel with a back-facing step. The Reynolds number, calculated based on the step height and average flow rate velocity, was Re = 5000. A transverse rib with height Δ/H = 1/3 ÷ 2/3 of the step height was installed in front of the step. The variable parameters were the degree of expansion ER = 1.17 ÷ 1.43 and rib position S/H = 0 ÷ 23. Constant heat flux was set on the lower wall of the channel; other walls were thermally insulated. At the inlet to the computational domain, a fully developed velocity profile and a constant temperature of the medium were set. The computation domain is shown in Fig. 1.

Numerical simulation was performed by the RANS method. All equations of the mathematical model were integrated using the finite volume method of the second order of accuracy in space in a stationary (iterative) statement using the simpleFoam solver of the OpenFOAM package. In preliminary calculations, the optimal grids, for which the solution no longer depended on the number of cells, were chosen.

3. Results and discussion
Data on dynamics and heat transfer of a turbulent flow in a flat channel with a back-facing step in the presence of a rib are obtained. The dependences of the recirculation zone length on the rib position are presented in Figs. 2 and 3. The length of the recirculation zone was determined from the condition that the shear stresses on the wall equaled zero. It can be seen from the figure that with a sufficiently large distance between the rib and step S/Δ > 12, the length of the recirculation zone depends weakly on the divergence ratio (Xr/H ~ 8). As the distance between the rib and the step edge decreases, the rib influence becomes more intensive, increasing the length of the recirculation zone. According to Fig. 2, for divergence ratio, ER = 1.43, the position of the rib can change the length of the recirculation zone within 8 < Xr/H < 15. Moreover, it can be seen from Fig. 3 that the greater the rib height, the greater the effect it has on the length of the recirculation zone 8 < Xr/H < 22). The effect of the divergence ratio on the length of the recirculation zone can be also seen in the figures. With increasing divergence ratio, the longitudinal pressure gradient becomes greater, and the point of flow attachment shifts further downstream. Such correlation is also observed in the experimental work [4]. It is also worth noting that in experimental work, the size of the recirculation zone could be reduced due to the rib position in
comparison with the flow around a smooth step [4, 2]. In the current work, we were able to achieve a decrease in the recirculation zone length only for the smallest divergence ratio ER = 1.17, for which the longitudinal gradient was minimal.

Figure 2. Coordinate of the point of separated flow attachment for the rib with height \( \Delta/H = 1/3 \).

Figure 3. Coordinate of the point of separated flow attachment for the rib with height \( \Delta/H = 2/3 \).

The dependence of the position of heat transfer maximum on the rib position is shown in Fig. 4. It can be seen that the position of maximum changes within a smaller range for different positions of the rib. We can also see the effect of the divergence ratio, which almost does not affect the position of heat transfer maximum. When comparing the positions of the points of flow attachment and heat transfer maximum, it can be seen that with a large distance of the ribs from the step, they become closer to each other. When the rib begins to have a noticeable effect on the main flow separation, the position of the heat transfer maximum is achieved long before the point of flow attachment.

Figure 4. Dependence of the position of heat transfer maximum on the position of the rib with height \( \Delta/H = 1/3 \).
Conclusion
The dynamics of turbulent flow and heat transfer in a flat channel with sudden expansion in the presence of a rib and different divergence ratios was simulated by the RANS method. It is shown that a change in the longitudinal pressure gradient by varying the divergence ratio leads to a change in the length of the recirculation zone and the position of heat transfer maximum. A decrease in the ER parameter leads to a decrease in the length of the recirculation zone, the position of heat transfer maximum also approaches the step with a decrease in the divergence ratio, but this dependence is not so significant.

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Reference
[1] Terekhov V I 2006 Problems of heat transfer in separated flows Vol 1 (Moscow: MEI) 103–11
[2] Eaton J K and Johnston J P 1981 AIAA J 19 1093-100
[3] Dyachenko A Yu, Zhdanov V L, Smulsky Ya I, Terekhov V I 2019 T&A 26 549–60
[4] Chovet C, Lippert M, Foucaut J-M, Keirsbulck L 2017 Exp Fluids 58 162
[5] Bogatko T, Terekhov V, Dyachenko A, Smulsky 2017 Y MATEC Web of Conferences 92 01030