Control of a separated flow behind a back-facing step by means of tabs

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Abstract. The result of numerical simulation of a flat channel with a back-facing step in the presence of tabs by the RANS method is presented. The Reynolds number, calculated by the step height and the average flow rate velocity, was Re = 5000. The data obtained made it possible to analyze the dynamics of interaction between the separated flow behind a tab and the region of the main separation behind a step. Tabs have the greatest influence on the area in close proximity to the step.

1. Introduction

Recently, close attention has been paid to the creation of new methods to control the flow characteristics in separated flows. To regulate gently the parameters of separated flow, such as intensity of flow circulation and size of recirculation region, various methods, which can conditionally be divided into active and passive ones, are used. Active methods include blowing or suction [1], periodic effects on the main flow [2]. Thanks to these methods, the parameters of separation flow can be regulated very smoothly.

Heat transfer enhancement, reduction of hydraulic losses in heat exchangers can also be achieved using simple, reliable and technologically advanced passive methods. The latter include solid ribs, teeth, and vortex generators of various shapes [3]. The use of tabs [4,5], which are small cubic obstacles, used as vortex generators, allows not only heat transfer intensification, but also reduction in pressure losses in the channel as compared to solid ribs [2]. So in [5], heat transfer in the separation region has been studied experimentally in the presence of tabs. Heat transfer was compared when using tabs, ribs and in the absence of vortex generators. Thermographic imaging showed that when using ribs, heat transfer increases up to 50% as compared with a flat channel. While the use of tabs leads to noticeable intensification of the area immediately behind the back-facing step, the difference in the maximum Nusselt number when using ribs and tabs is slightly lower for tabs (about 20%) as compared to using ribs.

This work deals with numerical simulation of the separated flow behind a step in the presence of tabs located at different distances from a step. Local and integral heat transfer was analyzed.

2. Computation details

In this paper, we present the results of numerical simulation of the separated flow in a flat channel with a back-facing step and expansion ratio ER = h₁/h₀ = 1.43. The Reynolds number, calculated by the step height and the average flow rate velocity, was Re = 5000. In front of the step, there were the tabs in the form of cubes with a size of Δ/H = 1/6 of the step height. The distance between the tabs was the variable parameter. All walls, except the lower channel wall behind the step, where the heat flux...
was set, were assumed to be insulated. A fully developed velocity profile and constant temperature of the medium were set at the inlet to the computational domain.

Since there is symmetry in this problem, there is no need to take into account all the tabs when constructing the grid. Instead, only half of one tab was included in the computational domain, and a symmetry condition was specified on the side walls of the computational domain. The computation domain is presented in Figure 1.

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

![Figure 1. Scheme of computation domain (top view, side view).](image)

3. Result and discussion
Data obtained on distribution of the velocity field allowed an analysis of the dynamics of interaction of the separated flow behind a tab and the region of the main separation behind a step. The results of simulation on Nusselt number distribution over the channel wall (Figure 2) confirm the possibility of using tabs to control heat transfer, both from the viewpoint of intensifying and changing its distribution over the surface. Thus, it is shown in Figure 2a that in a flat channel a stagnation region, corresponding to the most heated region, is formed immediately behind the step. The colder region is in the zone where the flow attaches. When installing the tabs (Figure 2b, 2c) on the step edge, distribution of the local Nusselt number becomes significantly non-uniform in the longitudinal direction. A change in heat transfer leads to the fact that heat transfer in the stagnation region is enhanced. When using transverse ribs this is a significant problem. The data obtained are consistent with experimental work [5]. At that, for P/H = 1.25 (Figure 2d), the distribution of Nusselt number is more uniform and resembles the distribution for the step without vortex generators.
The effect of tab position relative to the step edge on heat transfer on the lower channel wall was studied. The distribution of local Nusselt number vs. S/H is shown in the figure. As it was already noted, when installing the tab on the step edge, non-uniform distribution of the Nusselt number is formed and the stagnation region behind the step is partially destroyed. It can be seen in Figure 3b that when tabs are installed at distance S/H = 1, heat transfer in the stagnation region deteriorates, and the maximum Nusselt number also becomes slightly less. In cases 3c and 3d, the pattern becomes hardly different from the channel without tabs.

For P/H = 2.5, the situation is noticeably different (Figure 4). When tabs are installed on the step edge (Figure 4a), a significant part of the stagnation region is destroyed. Moreover, the maximum heat transfer is in the area between the tabs. With an increase in distance S/H (Figure 4b), heat transfer in the stagnation region deteriorates, while maximum heat transfer is observed in the region immediately behind the tab. With a further increase in the distance (Figure 4c), the region with increased heat transfer becomes less extended and there is also non-uniform distribution of the Nusselt number in the stagnation zone, in contrast to one tab, when the influence of tabs is not almost observed at the same position. For S/H = 4 (Figure 4d), the presence of tabs is almost insignificant.

![Figure 2](image_url)

**Figure 2.** Distribution of Nusselt number over the wall behind the step at S/H = 0, a) without tabs, b) P/H = 7.5 , c) P/H = 2.5, d) P/H = 1.25.
Figure 3. Distribution of Nusselt number over the wall behind the step for P/H = 7.5 at S/H: a) 0, b) 1, c) 2, d) 4.

To compare heat transfer in the presence of tabs, the local Nusselt number was averaged in the transverse direction, and the result is shown in Figs. 5 and 6. According to these figures, the appearance of tabs does not greatly influence the maximum of averaged heat transfer. For P/H = 7.5 and P/H = 2.5, the dependence on the tab position is identical. The maximum of heat transfer in the presence of tabs increases by 5%. A significant increase in heat transfer over the area immediately behind the step can be also seen in the diagrams.
Figure 4. Distribution of Nusselt number over the wall behind the step for P/H = 2.5 at S/H: a) 0, b) 1, c) 2, d) 4

The effectiveness of tabs can be demonstrated by the value of average Nusselt number $\overline{\text{Nu}}$, which is determined by the heat transfer coefficient at a given length of the heat transfer section. Figure 7 shows the average Nusselt number $\overline{\text{Nu}}$ for a flat channel in the presence and absence of tabs, calculated by formula:

$$
\overline{\text{Nu}} = \frac{1}{x h^2} \int_0^H \int_0^{h_2} \text{Nu} \, dx \, dy
$$

Figure 5. Distribution of Nusselt number, averaged in transverse direction, for P/H = 7.5.

Figure 6. Distribution of Nusselt number, averaged in transverse direction, for P/H = 2.5.
Figure 7. Average Nusselt number $\overline{\text{Nu}}$ for a flat channel with and without tabs.

It can be seen from Figure 7 that in the area immediately behind the step, heat transfer in the presence of tabs is much higher. The main reason for increased heat transfer is the destruction of the stagnation region by the large-scale vortex structures created by tabs. According to the figure, P/H = 7.5 leads to the largest increase in the average Nusselt number.

4. Conclusion
The dynamics of a turbulent flow and heat transfer in a flat channel with sudden expansion, controlled in a passive way by means of a system of tabs at Reynolds number $\text{Re} = 5000$, was simulated numerically by the RANS method. It was found that the presence of tabs leads to non-uniform distribution of the Nusselt number in the region near the step edge. The main reason for increased heat transfer is destruction of the stagnation region by large-scale vortex structures created by tabs. The simulation results confirm the possibility of using tabs to control heat transfer, both from the view point of intensifying and changing its distribution over the surface, as indicated by the local distribution of the Nusselt number and the value of the average Nusselt number.

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