Influence of deltoid tabs on flow dynamics and heat transfer in the separation region behind a back-facing step

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Abstract. The results of an experimental study of the influence of deltoid tabs on flow dynamics and heat transfer in the separation region behind a back-facing step at Re = 4000 are presented. The studied tabs are triangular in shape with a height of 6 mm. The transverse pitch of their arrangement varies. The flow pattern behind a ledge with mounted tabs, whose structure differs significantly from the flow pattern behind a classical step, is obtained. The presence of tabs brings the maximum heat transfer region closer to the step, while with a decreasing pitch between them the vortex generators become more effective.

1. Introduction

By now, studying heat and mass transfer in separated flows behind a back-facing step has become a classical problem. The use of effective methods for controlling the flow and heat transfer behind a back-facing step forms the basis for creating effective thermo-hydraulic equipment. There are several ways to control the flow by the type of an impact on the main flow (active and passive ones). The passive method is the easiest way to control flow separation. This method is reliable and simple, but it requires large energy costs for pumping coolant.

Two-dimensional and three-dimensional obstacles are used in the passive methods of flow control. Two-dimensional obstacles cause large hydraulic losses because they lead to global flow restructuring. The use of three-dimensional vortex generators (tabs) can reduce hydraulic resistance due to reduction of their sizes, but longitudinal vortices induced by them significantly affect the recirculation region behind a step [1]. The influence of the height, location and pitch of rectangular tab arrangement on heat transfer behind the step was studied in [2]. The influence of rectangular tabs on the flow dynamics was considered in [3]. The influence of the attack angle of tabs installed directly on the step edge on the degree of heat transfer intensification in the separation region behind the step was considered in [4]. The current work is a development of [2-4], where the influence of deltoid tabs on the flow dynamics and heat transfer behind the back-facing step is considered.

2. Experimental setup and procedure

The experiments were carried out in a channel of a 1-m length with a rectangular cross-section of 20 × 150 mm (Fig. 1). The channel was made of a 10 mm thick textolite sheet. At a distance of 600 mm from the channel inlet, there was a back-facing step with constant height $H = 10$ mm. On the lower wall of the channel behind the back-facing step, a 400 mm long thermal section was located. Two channels of identical size were made: for measuring flow dynamics and heat transfer. Vortex
generators in the form of isosceles triangles with height $\Delta = 6$ mm, base of 6.9 mm and thickness $e = 0.6$ mm, attached to the step edge, were made of steel. The distance between tabs $P$ was varied from 25 to 50 mm. The angle between the step plane and the tab was 90°. The Reynolds number $Re = \frac{UH}{\nu}$, calculated by step height $H$ and average flow rate velocity $U$ before expansion, was $Re = 4,000$. The average flow temperature was $21 \pm 1°C$. At a distance of 25 calibers from the inlet, the flow was stabilized, and the velocity profile was close to a power law with an exponent $n \approx 1/7$.

![Figure 1. Scheme of setup. All dimensions are in millimeters.](image)

The velocity fields were measured with the digital tracer visualization method (PIV). The equipment of the PIV-method included a pulsed laser with a double flash, synchronized with a digital camera for measuring the two-dimensional velocity field. The time interval between laser flashes in a pair of frames was 20 μs, and their duration was 5 ns. The measuring the area of the PIV complex had dimensions of $30 \times 40$ mm. For each region 4000 pairs of frames were obtained. The size of the camera matrices was $1360 \times 1025$ pixels, and in the calculation of velocity fields the image was divided into computational domains with dimensions of $32 \times 32$ pixels. The velocity fields were calculated using an iterative cross-correlation algorithm with 50% overlap of the computational domains. Then the velocity vectors were filtered in two ways: by signal to noise ratio and by median filter.

To study the distribution of static pressure behind the step, a lower wall was made with 49 holes in the mid-section, with a periodic pitch: from 0 to 120 mm the pitch was 5 mm; from 120 to 148 mm the pitch was 7 mm; from 148 to 348 mm the pitch was 10 mm, and the last hole was located at 360 mm from the step. There were also two cross-sections at distances of 40 mm and 75 mm from the step with 15 holes, the pitch between which was 10 mm. All holes were 0.8 mm in diameter.

The pressure coefficient was calculated by formula $Cp = 2(p_i-p_0)/U_m^2$, where $p_i$ is the static pressure, $p_0$ is the reference measured pressure at a distance of 40 mm to the step, and $U_m$ is the average velocity in the same cross-section.

A thermal model of the same size for measuring the temperature fields in the longitudinal direction on the wall behind the back-facing step was made of a heat-insulating material. A thin conductive film 37 μm thick was glued onto its surface; therefore, the boundary condition $T_w = \text{const}$ was satisfied on its surface. The wall temperature was measured with a NEC Thermo Tracer TH7102 IR Imager (Japan) with a spectral range of 8-14 μm. The obtained temperature field was digitized by at least two thermocouples, and the thermograms were plotted using special computer programs.

The local heat transfer coefficient was calculated by formula $\alpha = \frac{q}{(T_w - T_0)}$, where $q$ is the heat flux measured on the heated wall of the model behind the step; $T_w$ is the temperature of the heated wall; and $T_0$ is the temperature of the flow in the channel before the step. The Nusselt number was calculated using the following formula:

$$Nu = \frac{\alpha H}{\lambda},$$

where $\alpha$ is the heat transfer coefficient; and $\lambda$ is the heat conductivity of air, determined by the air flow temperature.
3. Results and discussion

The flow behind the deltoid tabs was studied in different cross-sections. For tabs arranged with a pitch of 25 mm, directly behind the tab we can observe a pattern, which in its structure differs markedly from the flow behind a classical step, when there is a recirculation region with a length of 5.5–7 calibers (step heights) and secondary vortex region in the corner of a step with a size of about 1 caliber. Based on the data measured by the two-dimensional PIV system, there are the lines plotted by two velocity components, which can be interpreted to some extent as streamlines, since in this cross-section, the transverse velocity component should probably be close to zero. These data are shown in Fig. 2. In this cross-section, there is no flow attachment as in the classical case, and in 4 calibers near the wall, the flow is divided: it deviates backward and rises up, which indicates a helical movement behind the step. In the corner zone behind the step, a weak secondary vortex of 0.3 calibers is observed. The flow pattern behind the tabs, arranged with a pitch of 50 mm, resembles the flow pattern behind the classical step, and only flow attachment occurs earlier: at 3.5 calibers, but not at 6.8 calibers as for the classic step. A secondary vortex with a size of 0.4 calibers is also observed. For tabs with a pitch of 25 mm, in cross-section between the tabs, there is no secondary flow; the longitudinal velocity component does not have a negative component, which indicates formation of a pair of longitudinal vortices directly behind the tabs. The return flow occurs in cross-sections close to the tab, and then part of the flow passes along the step and performs the reverse flow between the tabs.

![Streamlines and field of longitudinal average velocities near the step with deltoid tabs:](image)

Figure 2. Streamlines and field of longitudinal average velocities near the step with deltoid tabs: (a) \( P/H = 2.5, Z/H = 0 \), (b) \( P/H = 5, Z/H = 0 \).

The separated boundary layer attaches at 2.5 calibers. For tabs arranged with a pitch of 50 mm, the longitudinal and transverse velocity components were measured in a cross-section at a distance of
0.25P from the step center, and using these components, we have constructed the lines, whose tangent direction at each point coincides with the direction of the vector of two velocity components. These lines can no longer be considered streamlines because a significant transversal velocity component appears in this cross-section. The flow near the step is very similar to the flow with a pitch of 25 mm in the cross-section between the tabs, but at a distance of 1.44 calibers there is a similarity of a secondary vortex with a size of 2 calibers and separated boundary layer attaches at 3.9 calibers.

The profiles of longitudinal average velocities in the presence of deltoid tabs with a pitch of 2.5 and 5 calibers at a distance of one and three calibers in the mid-section (Fig. 3) are compared. We should note that the influence of the pitch is higher than the influence of the tab shape. The velocity profile at a distance of one caliber for a smooth step becomes very similar to the profiles with a pitch of 5 calibers. Behind a smooth step, the recirculation region spreads at three calibers. Directly behind the tab, the velocity profile narrows, and the maximum velocity increases, i.e. a similar process, observed for a continuous two-dimensional obstacle, occurs.

**Figure 3.** Streamlines and field of longitudinal average velocities near the step with deltoid tabs $P/H=2.5 \ Z/H=0$: (a) – $X/H=1$, (b) – $X/H=3$.

**Figure 4.** Distribution of $Cp$: (a) – in mid-section, (b) – in transversal cross-sections.

For tabs with height $\Delta = 6$ mm, maximum rarefaction is achieved when they are installed on the step edge (Fig. 4a). With an increase in the tab pitch, hydraulic resistance drops, and as a result, there is an approximation to the case of a flow around a smooth step. Directly behind the tab ($P/H = 2.5$)
there is an increase in maximum rarefaction, and in a gap between the tabs ($P/H = 5$) this increase is 2 times less. At a distance of 20 calibers, the sequences of the step effect on distribution of static pressure cease.

In a cross-section at a distance of 40 mm from the step for tabs installed with a pitch of 25 mm from each other, one characteristic feature can be noted (Fig. 4b). In places where tabs are installed, there is an increase in pressure directly behind the tab, and rarefaction occurs between them. Near the side walls, the pressure rises, and this is likely caused by an increase in the boundary layers on the side walls. At a distance of 75 mm from the step, the transverse profiles of the pressure coefficient are smoothed out because the longitudinal vortices are weakened, and the effect of tabs on the flow is reduced. For tabs set with a pitch of 2.5 calibers, at a distance of 7.5 calibers, the shape of the curves differs from 4 calibers and probably there is an interaction of longitudinal vortices. The flow pattern behind the tabs with pitch $P/H = 5$ remains the same as measured at a distance $X/H=4$.

![Figure 5](image)

**Figure 5.** Distribution in mid-section of: (a) – longitudinal-averaged $\text{Nu}$ number, (b) – integral-averaged $\bar{\text{Nu}}$ number.

Installing the tabs approximates $X_{\text{max}}$ coordinate of the maximum $\text{Nu}_{\text{max}}$ value to the step base (Fig. 5). Tabs with $P/H = 2.5$ decrease the coordinate $X_{\text{max}}$ by about 50% as compared to a smooth step, and increase $\text{Nu}_{\text{max}}$ by the same 50%. For $P/H = 5$, $X_{\text{max}}$ decreased by 23%, and maximum heat transfer $\text{Nu}_{\text{max}}$ increased by 21%. Farther from the back-facing step, the effect of tabs begins decreasing and, at 17 calibers, it approaches the value for a smooth step. This relates to the fact that the longitudinal vortices induced by the tabs lose kinetic energy due to turbulent diffusion. The integral-averaged $\bar{\text{Nu}}$ number obtained by integrating the local $\text{Nu}$ number along the longitudinal coordinate allows determining the distance, where a given vortex generator is more efficient in terms of heat transfer. The greatest efficiency for tabs located with pitch $P/H = 2.5$ is achieved at a distance of 5.5 calibers with $\text{Nu} = 29.6$, and with pitch $P/H = 5$, the maximum is achieved at a distance of 7.28 calibers. After its maximum values, the integral $\text{Nu}$ number decreases, and for closely located tabs, the decrease occurs much faster. This is caused by the fact that behind the step, the secondary flow mixes more intensively in the mixing layer due to the generated longitudinal vortices, but being attached to the wall, this layer is more heated and, accordingly, its ability to intensify heat transfer decreases.

According to distribution of the pressure coefficient, local hydraulic resistance was calculated at a distance of 0.17 m from a sudden expansion because at this distance, all transverse disturbances caused by the tabs almost cease to affect the pressure distribution. Local hydraulic resistance was calculated by formula $f = 5/9 \cdot \text{Cp}$. For deltoid tabs at pitch $P/H = 2.5$, local hydraulic resistance is $f = 0.34$, and with a pitch between tabs of 50 mm: $f = 0.308$. All these data once again confirm previous assumptions that an increase in the pitch between the tabs leads to a decrease in local hydraulic losses.
Conclusion
The influence of deltoid tabs on flow dynamics and heat transfer in the separation region behind the back-facing step at Re = 4,000 has been experimentally studied. There is a significant difference in the flow patterns (velocity fields measured by the PIV optical method) directly behind the tab and in the case of a flow around a classical step. Behind the tab, rarefaction increases, and at 4 calibers from the step in the places where the tabs are installed, they affect the flow and heat transfer, and at a distance of 7.5 calibers their effect almost degenerates. Closely located tabs increase $\text{Nu}_{\text{max}}$ number by $\sim 50\%$ as compared to a smooth step. They show the greatest thermal hydraulic efficiency: 1.2 times higher than that of a smooth step.

Acknowledgement
The work was financially supported by the Russian Foundation for Basic Research (project 20-58-00038) and partially supported by the Government Program (contract No. AAAA-A17-117030310010-9)

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