Heat transfer behind the backward-facing step in the presence of longitudinal vortex generators installed at an angle to each other

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Abstract. The paper presents the experimental results on the control of heat transfer enhancement behind the backward-facing step at Re = 4000. The flow is controlled by a pair of longitudinal vortex generators (LVGs) installed at the step edge. The pair of vortex generators (VG) consists of two plates positioned symmetrically relative to the flow. The influence of the height, the angle of VG installation relative to the flow, the distance between VG pairs and the shape of the plate on local and average heat transfer is investigated.

1. Introduction
The separated flow in the near region behind the backward-facing step causes a decrease in the heat transfer intensity. This phenomenon, in turn, reduces the efficiency of compact heat exchangers, which, for technological reasons, contain channels of variable cross-section. Some researchers have used various passive methods of the flow control. Behind the step, the effect of a two-dimensional object in the form of a rib, installed in front of the step, was investigated in [1, 2]. The effect of tabs installed in front of the step, which generate longitudinal vortices, is considered in [3, 4]. The LVGs have shown themselves to be quite effective in smooth channels and on a flat plate [5]. The authors of [6] studied the effect of LVGs of various shapes: rectangular, trapezoidal, and deltoid ones; the curved trapezoidal generators proved to be the most effective. This study focuses on investigating the heat transfer enhancement behind a backward-facing step with LVGs installed at the step edge.

2. Experimental setup and procedure
The experiments were carried out in a channel 1 m long 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 backward-facing step with a constant height \( H = 10 \) mm. On the lower wall of the channel, behind the backward-facing step, a thermal section with a length of 400 mm was located. The entire surface of the lower channel wall behind the step was heated using an electric heater made of titanium foil 50 \( \mu \)m thick. A 135*300 mm window was cut in the channel wall to perform thermal imaging measurements. The heater at the view point of the thermal imaging camera was blackened. When processing the data, the radiation losses, which in the considered case were less than 8%, were taken into account as well as the losses caused by free convection from the outer side of the wall.

Vortex generators (VG) with height \( h \) from 3 to 10 mm, length of 15 mm and thickness \( e = 1 \) mm, mounted in the vicinity of the step edge, were made of plastic. The distance between vortex generator
plates s was varied from 3 to 12 mm. The angle β (the angle between the flow direction and the tab plane) was varied from -45° to 45°. Tabs of rectangular, trapezoidal (with bases of 6 mm and 3 mm) and deltoid shape were studied. The Reynolds number calculated from the step height $H$ and the average flow rate $U_m$ was $\text{Re} = \frac{U_m H}{\nu} = 4000$. The average air temperature in the channel was $21 \pm 1^\circ\text{C}$. At a distance of 25 calibers from the inlet, the flow was stabilized, and the velocity profile was close to the power law with an exponent $n \approx 1/7$.

**Figure 1.** Scheme of setup. All dimensions are in millimeters.

A thermal model of the same size for measuring the temperature fields in the longitudinal direction on the wall behind the backward-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 $q = \text{const}$ 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; $T_0$ is the temperature of the flow in the channel before the step. The Nusselt number was calculated using the following formula:

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

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

3. **Results and discussion**

The results of thermographic visualization of the temperature field on the wall behind the backward-facing step for VG with heights $H$ and $0.3H$ are shown in Fig. 2. In the case when LVGs are installed at angle $\beta = +30^\circ$ and height $H$, three cooled quite symmetric regions of increased heat transfer are formed, and the region between the VG plates is more heated. In the central part, near the midsection, there are one region elongated along the flow and two regions of similar shape behind each LVGs plate (Fig. 2a). The asymmetry of these two regions near the left and right-side walls is caused by adhesion of the flow to one of the vortex generator walls, which leads to separation on the other. At a negative angle of LVG installation behind the step, we observe two regions of heat transfer enhancement, with the maximum impact on the outer edges from VG. A decrease in the enhancement is observed in the region between the VG plates, which indicates a decrease in the velocity, since this installation of LVGs slows down the flow. When installing VG with a height of 0.3$H$ at angle $\beta = 30^\circ$, the thermal imaging picture has a symmetric character relative to the midsection, this may indicate that at this height of LVGs the flow does not attach to one of the walls due to the fact that it has a lower kinetic energy as compared to the flow behind LVGs with a height of 10$H$. The obstacle height affects the secondary area (the area between the step and the regions of increased intensification) slightly. At a positive angle of installing VG of a low height, two regions of enhancement are also observed.
Figure 2. Thermograms behind the backward-facing step (s=6 mm): (a) LVGs h=10 mm, β = 30º; (b) LVGs h=10 mm, β = -30º; (c) LVGs h=3 mm, β = 30º and (d) LVGs h=3 mm, β = -30º.

Figure 3. Profiles of Nu number, averaged along the channel width, behind the step with variation of h for s=6mm.

The profiles of Nu number averaged over the channel width are shown in Fig. 3 for different heights of LVGs at β = ± 30º. We should note that in all the cases studied, the heat transfer maximum increases in proportion to the VG height and the coordinate of the heat transfer maximum $X_{\text{max}}$ approaches the step. Thus, for a smooth step, $X_{\text{max}}$ is 5.5 calibers, with installation of LVGs of the 6-mm height, the Nu$_{\text{max}}$ location shifts by 4.9 calibers and at a height of 10 mm it is localized at 4.4 calibers.

When installing a pair of LVGs at a negative angle, the Nu$_{\text{max}}$ values are higher than at a positive one, so for LVGs with a height of 3 mm, heat transfer is 14% higher than for a smooth step, while for a positive angle β this value is about 3%. With an increase in the VG height, the ratio Nu$_{\text{max}}$/Nu$_{\text{max0}}$ (Nu$_{\text{max0}}$ is for a step without a VG) increases, and so for LVGs at a positive angle $h = H$ is 1.18, and at a negative angle, it is 1.32. The smallest value $X_{\text{max}} = 4.5H$ is observed at an angle of -30 at height $h/H = 0.3$, in contrast to rectangular tabs [3], where there is an optimal ratio for their location in the transverse direction ($\Delta/H = 0.3, P/H = 2.33$), at which the length of the recirculation area becomes minimum.

A negative angle of LVG installation with varying distance s (Fig. 4b) increases heat transfer in comparison with a positive one (Fig. 4a). For widely spaced VG plates and a positive installation...
angle, the Nu diagrams for \( s/H = 0.6 \) and \( s/H = 1.2 \) almost merge. At a negative angle, the maximum heat transfer is achieved at LVGs with \( s/H = 0.6 \); the data for \( s/H = 1.2 \) are located between distances of 0.6 and 0.3.

![Figure 4](image1.png)

**Figure 4.** Profiles of Nu number, averaged along the channel width, behind the step with variation of \( s \).

![Figure 5](image2.png)

**Figure 5.** Profiles of Nu number, averaged along the channel width, behind the step at different \( \beta \) angles.

Depending on the positive or negative angle of installation of the pair of LVGs, the effect of this angle differs (Fig. 5). So, for a positive installation, maximum heat transfer is \( \text{Nu}_{\text{max}} = 28.5 \), while for a negative installation, this value is \( \text{Nu}_{\text{max}} = 27 \). The curves at installation angles \( \beta = 30^\circ \) and \( 20^\circ \) are quite close to each other, although the thermogram for a smaller angle shows a fairly symmetrical picture as compared to the angle of \( 30^\circ \). This also indicates that positively installed LVGs are attached to one of the walls without separation. In the case of installation at a negative angle, maximum heat transfer is achieved at an angle of \(-30^\circ\); at 10 calibers heat transfer is compared with the case of LVGs installed at \( \beta = 45^\circ \), and then it becomes less.

The trapezoidal and deltoid LVGs in Fig. 1 are mounted in two different positions. Letters \( b \) and \( f \) in Figure 6 denote the position of the VG plates facing the smaller and larger sides to the step edge, respectively. Let us note the following tendency, as for rectangular LVGs, the maximum corresponds to the negative installation angles. While maintaining the installation angle, maximum heat transfer is
observed for LVGs turned with the smaller side to the step edge. This is probably due to the fact that the LVGs plate, immersed earlier, directs the flow to the side.

![Figure 6](image1.png)

**Figure 6.** Profiles of Nu number, averaged along the channel width, behind the step for LVGs of different shapes: (a) trapezoidal; (b) deltoid.

![Figure 7](image2.png)

**Figure 7.** Dependence of averaged Nu number on parameters: (a) $h$; (b) $s$.

![Figure 8](image3.png)

**Figure 8.** Dependence of averaged Nu number on parameters (a) $\beta$ and (b) shape for VG with height $h=6$ mm.
The N\textsubscript{u}L number was averaged over a 20-caliber area, where the pressure recovers almost completely. With an increase in the VG height (Fig. 7a) at angle $\beta = 30^\circ$, the N\textsubscript{u}/N\textsubscript{uL0} value increases, and at a positive angle, the parameter of heat transfer enhancement grows linearly. The maximum value of N\textsubscript{u}/N\textsubscript{uL0} is achieved for $\beta = -30^\circ$ and it exceeds by 20% in the case of a flow around a step without VG. The minimum value corresponds to $\beta = -30^\circ$ with a height of $0.3H$, when installation of a VG hardly affects the level of heat transfer.

When studying the effect of distance $s$ in the VG, it was found that for the VG with a height of $0.6H$ and a negative angle of plate installation $\beta = -30^\circ$, the heat transfer maximum is within the range of distances $s/H \approx 0.7$. This data is shown in Fig. 7b. Minimum heat transfer occurs at a distance of $0.3H$.

An increase in the angle of LVG installation leads to heat transfer enhancement, both at negative and positive values of angle $\beta$ (Fig. 8a). It is interesting that at $\beta = 45^\circ$ the intensity of heat transfer is the same for both positive and negative angles of VG installation. When studying various shapes of LVGs, it was revealed that the LVGs facing backward with the larger side toward the flow decreases (Fig. 8b). For forward-facing VGs, mounted at angle $\beta = -30^\circ$, the averaged Nu number decreases with decreasing area of LVG immersion, and at a positive angle of installation there is a maximum for a trapezoidal shape.

4. Summary

A thermal imaging study of the temperature fields of a wall heated by a constant heat flux behind a backward-facing step under the action of a vortex generator pair mounted on the step edge at different angles to the flow at Re = 4000 has been carried out. Depending on the sign of the LVG installation angle, two or three regions of increased heat transfer were formed near the step. Installation of LVGs shifts the coordinate of the heat transfer maximum $\text{Nu}_{\text{max}}$, bringing it closer to the step base. The greatest increase in heat transfer is achieved for the VG with height $h = 0.6H$, with the plates installed at an angle of 45°, and for the higher LVGs, the $h = H$ maximum is achieved at $\beta = 30^\circ$. The influence of the VG shape (rectangular, trapezoidal and deltoid) on the regularities of convective heat transfer depending on the angle of their installation is shown.

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