Flow and heat transfer in the separation region behind a backward-facing step with convergently mounted plates of longitudinal vortex generator

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Abstract. The paper presents the results of an experimental study of the dynamics of separated flow and heat transfer behind a backward-facing step when using longitudinal vortex generators (LVGs) at an angle of -30\(^\circ\) at Re = 4000. Longitudinal vortex generators represent a pair of plates with a height of 6 mm, located symmetrically relative to the flow. Along with the average values, the pulsation characteristics of the flow are considered. The thermohydraulic efficiency was estimated by the found dynamic and thermal characteristics.

1. Introduction
Separated flows arising behind the backward-facing step have negative tendencies in terms of an increase in hydraulic resistance and a decrease in heat transfer in the zone immediately behind it. A large number of experimental and numerical studies are aimed at the search for active and passive methods of overcoming these negative phenomena. Active methods include jet injection or suction at the edge of the backward-facing step, gas suction through the wall immediately behind the backward-facing step, oscillations of the plate or various elements at the step edge. Active methods are quite effective, but they are difficult to implement and require additional maintenance. Passive methods based on the use of various two or three-dimensional turbulators are free from this drawback, so a number of researchers focused their efforts in this direction.

The influence of a two-dimensional object in the form of a rib on the recirculation area was studied in [1, 2]. The effect of rib position and height mounted in front of the step on heat transfer behind it was studied in [3]. The influence of tabs installed on the step edge on the size of separation region and the behavior of the flow behind the attachment region is considered in [4]. In [5], the authors focused their attention on the behavior of the flow inside the separation region, and in [6], the effect of tabs on heat transfer behind the backward-facing step was studied. This work is a continuation of the cycle of work on the control of heat and mass transfer in the separation region behind the backward-facing step using turbulizing elements installed in front of the step.

2. Another section of your paper
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 μm 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.

Rectangular vortex generators (VG) with height $h = 6$ mm, length of 15 mm and thickness $e = 1$ mm, attached near the step edge, were made of plastic. The VG plates were installed in the convergent-like manner to each other with an angle of $2\beta = -60^\circ$ between them. The minimum distance between them was $s = 6$ mm (Fig. 1). The Reynolds number calculated from the step height $H$ and the average flow rate $U_m$ was $Re=U_mH/\nu=4000$. The average air temperature in the channel was $21 \pm 1^\circ$C.

To measure the velocity fields, a channel was made from a material transparent for the PIV measurement technique. The dimensions of the channel were the same as when measuring the heat transfer. The velocity fields were measured using the tracer visualization method. The composition of the PIV measuring complex: pulsed laser; synchronizer with a digital camera. One digital camera was used to measure the two-component velocity field. The interval between two laser flashes was 20ms. For the collection of statistics, 4000 pairs of images were taken. The resolution of the camera matrix was $1360 \times 1025$, the visible area of the object under study corresponded to the size of $30 \times 40$ mm. Velocity fields were calculated using a cross-correlation algorithm, and then were filtered according to two criteria: signal noise and average filter.

The pressure coefficient was calculated by formula $C_p = 2(p_i-p_0)/U_m^2$, where $p_i$ is the static pressure, the reference pressure $p_0$ was measured at a distance of 40 mm in front of the step, $U_m$ is the average flow velocity in the midsection in front of the step.

Measurement of two-dimensional surface temperature fields were measured and processed as in [6].

The local heat transfer coefficient was calculated by formula $\alpha = q/(T_w-T_0)$, where $q$ is the heat flux supplied to the bottom wall behind the backward-facing step; $T_w$ is the temperature of the heated wall; $T_0$ flow temperature measured at a distance of 80 mm to the step. The Nusselt number was calculated using the following formula:

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

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

3. Results and discussion

The graph in Figure 2 shows the distributions of the averaged longitudinal velocity at different calibers from the step in the center of channel symmetry. The upper right part of the graph shows the scale of the averaged longitudinal velocity, where $U_{ref}$ is the velocity in the middle of the channel before separation. In a flow without disturbance, the negative value of the longitudinal velocity component takes place at $X/H = 2\pm 5$. Installation of LVGs introduces a disturbance, whose value depends on the
area of this disturbance input \( X/H = 2\div 3 \). It was noted in [7] that the maximum return velocity behind the step does not exceed 0.2 \( U_c \); in the cases of LVGs installation, this value also did not exceed this value. For installed LVGs at a distance of 2 calibers at 1/3 of the channel height behind the step, a profile bend with a minimum in the middle of the channel was observed.

**Figure 2.** Profiles of the average longitudinal velocity.

In the case of LVGs at a distance of 1 caliber, an ascending flow with a maximum at a height of 0.6 of the channel, whose velocity is 20\% of the velocity in the flow core, occurs at the step height (Fig. 3). This transverse component leads to intensive mixing; as a result, in the center of the channel the longitudinal component of velocity decreases and by the 7\textsuperscript{th} caliber the transverse component becomes comparable to the longitudinal one. For a smooth step, with a distance from it downstream, the transverse component increases and at the step height, a minimum of 5\% of the velocity in the core is reached.

**Figure 3.** Profiles of average transverse velocity.

The results of measurements of turbulent pulsations of the longitudinal velocity are presented in Fig. 4. For the case of a flow around a step without LVG, the maximum of pulsations along the first caliber
is at the level of the step height, i.e. in the area of mixing of the separated boundary layer with the flow in the recirculation area. When LVGs are installed in the center of symmetry of the model, we observe the following picture: along the first caliber, the maximum of pulsations shifts below the step; along subsequent calibers, this peak shifts to the area of mixing of the main flow with the stagnant zone. Starting from the second caliber in the upper part of the channel, an area of increased nonstationarity begins to develop, reaching a maximum at the 7th caliber at a height of 0.73 $h_1$.

Figure 4. Fig. 4. Profiles of rms pulsations of the longitudinal velocity.

According to the data obtained, measured by the two-dimensional PIV system, two velocity components were used to plot lines, which in some approximation in the plane of symmetry can be interpreted as streamlines, the velocity component in the direction of the $Z$ axis (fig.1) can be considered close to zero. These data are shown in Fig. 5.

Figure 5. Streamlines and the field of average longitudinal velocities near the step in the plane of symmetry for the case with LVGs.

For the case with installed LVGs, the size of the recirculation area was approximately 3.7 calibers. In the recirculation region at the center of symmetry of the model, the flow was directed from the center...
of the secondary region located at a distance of $2H$. The point of flow attachment in the longitudinal section at a distance of $Z/H = 0.3$ (inner edge of LVG) was at a distance of $3.7H$ from the step. In the section $Z/H = 1.05$ (the outer edge of LVG) the distance from the step to the point of flow attachment was $4.2H$, at a distance of the 1st caliber from the LVGs pair, it was $4.6H$.

Figure 6. Thermograms behind the backward-facing step: (a) smooth step; (b) step with LVGs

![Figure 6](image)

Figure 7. Profiles behind the step:

(a) – Nu number averaged along the channel width; (b) – $Cp$ along the central line of the model.

The results of thermographic visualization of the temperature field on the wall behind the backward-facing step are shown in Fig. 6. The data are shown for a smooth step (Fig. 6a) and with mounted LVGs (Fig. 2b). In the first case, behind the step edge in the central zone, a stagnant region is formed; in the
thermogram (Fig. 6a) this is the most heated zone. The colder zone is in the area of attachment. In the case when LVGs are installed, two fairly symmetric cooled regions are formed, and between the LVGs the region is more heated, since flow deceleration and a strong upward flow from the bottom wall are observed there. The Nu profiles averaged along the channel width are presented in Fig 7a. The characters of Nu distribution with and without LVGs remain similar. With LVGs installation, the coordinate of $\text{Nu}_{\text{max}} X_{\text{max}}$ shifts to 4.9 calibers, while $X_{\text{max}}$ for a smooth step is 5.5 calibers. The $\text{Nu}_{\text{max}}$ value with LVGs becomes 19% higher than for the smooth step. With distance, the effect of LVGs decreases and at 30 calibers, the Nu number is only 4% more than the classic case.

As the displacement of the coordinate of the heat transfer maximum, the recovery of static pressure (Fig. 7b) behind the backward-facing step in the presence of LVGs occurs somewhat earlier than for the step without a vortex generator. When LVGs are installed in the center of symmetry of the model behind the step, stronger rarefaction occurs, while the pressure recovery begins earlier by half a caliber.

According to the data on pressure coefficient distribution, the local hydraulic resistance was calculated at a distance of 0.2 m from a backward-facing step, since at this distance, all transverse disturbances caused by the VG almost cease affecting the pressure distribution. Local hydraulic resistance was calculated by formula $f = \frac{5}{9} \left( \frac{U_m}{U_{av}} \right)^2 C_p$, where $U_{av}$ is the average flow rate. When LVGs are applied, the hydraulic resistance increases by 31%, while the $\text{Nu}_{\text{L}}$ number averaged over 20 calibers from the step is 13% higher than that in the classic case. The assessment of the thermohydraulic efficiency using the $\text{Nu}_{\text{L}}/\text{Nu}_{\text{L0}}/\left( f/f_0 \right)^{1/3}$ complex gives an increase of 3% in comparison with the classical case.

4. Summary
The flow dynamics and thermal characteristics behind the step were experimentally studied in the presence of LVGs on the step edge at an angle of -30° to the flow at $\text{Re} = 4000$. Using a two-dimensional PIV complex, the fields of longitudinal and transverse velocities were measured, and the thermal imaging method was used to measure the temperature fields behind a backward-facing step on a wall heated by a constant heat flux. Installation of LVGs deforms the velocity profile behind it; a zone with a reduced velocity arises in the channel center, and near the wall behind the step the velocity is higher than the velocity behind a smooth step. This phenomenon has a positive effect on heat transfer enhancement. The maximum heat transfer increases with the presence of LVGs and becomes 19% higher. Installation of LVGs exceeds the hydraulic resistance of the channel by 31%, while the thermohydraulic efficiency increases by 3%.

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