Control of dynamic and thermal characteristics of a separated flow behind a step under the effect of positive pressure gradient

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Control of dynamic and thermal characteristics of a separated flow behind a step under the effect of positive pressure gradient

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Abstract. Heat transfer in the channel behind a back-facing step with organized perturbation in the form of a rib was experimentally investigated. The separated flow developed in the positive pressure gradient at Re = 12,000. The influence of location and height of a single rib on pressure distribution and intensification of heat transfer behind the back-facing step was studied. It is shown that installation of a single rib increases heat transfer behind the back-facing step in the positive pressure gradient. The positive pressure gradient leads to a decrease in heat transfer behind a step both with a presence of additional disturbing elements and without them.

1. Introduction
The flows with longitudinal pressure gradient often occur in the flow parts of various power plants. These are the gas turbine rotor blade cooling channels, guide apparatuses and extension-beds, as well as transition channels with different configurations of the flow section. Separation, as a rule, leads to harmful consequences, causing loss of energy, generating instability, etc. With a view to further increasing the efficiency of heat and power equipment and developing the fundamentals of separation flows, an important stage is the research of possibility of controlling the processes of heat and mass transfer in separated gradient flows, including behind the back-facing step. Dynamics of the flow behind the step in the positive pressure gradient was studied in [1-3]; the effect of pressure gradient on heat transfer intensification behind the step was investigated in [4]. The additional intensifying elements (transverse ribs, teeth, vortex generators of various shapes), despite the fact that they are much smaller than the main separation flow, can lead to a considerable change in the flow, both with contraction and expansion of the circulation zone. There are a limited number of experimental and computational works, where regularities of variation of the integral gas-dynamic parameters of separation flow interaction with solid walls are obtained [5-9]. The influence of the height of a two-dimensional obstacle and its location on the heat transfer process at flow separation behind the back-facing step in the absence of longitudinal pressure gradient was studied in [10]. The aim of the current work is the experimental study of the pressure distribution and heat transfer behind the back-facing step in the positive gradient with a perturbation before flow separation.

2. Experiment
The experiments were carried out in a 1-m rectangular channel of 20 × 150 mm (figure 1). The channel was made of a textolite sheet of 10 mm thick. At a distance of 600 mm from the channel inlet, there was a back-facing step with constant height $H = 10$ mm. A thermal section of 400-mm length
was located on the bottom wall of the channel behind the back-facing step. A heater tape of aluminum foil with the thickness of 50 μm was stuck to the textolite sheet, and this ensured a constant heat flux on the heat-exchange surface. To reduce the heat loss on the outer surface of the textolite sheet, a layer of extruded cellular polystyrene with a thickness of 20 mm was glued. Eighty chromel-copel thermocouples were mounted along the central line of the heated surface under the heater tape. The distance between adjacent thermocouples differed: near the back-facing step it was 2.5 mm, and at the end of the model, it was 20 mm. To evaluate the heat leakage on the outer surface of the textolite sheet, three thermocouples were mounted into the model. When processing the data, losses through radiation by aluminum foil were also taken into account.

Vortex generators with height $\Delta = 3$ and $6$ mm and thickness $e = 3$ mm were made of plexiglas. The distance from the vortex generators to the back-facing step $S$ varied in the range from 3 to 80 mm. Reynolds number $Re = UH/\nu$, calculated by step height $H$ and bulk velocity $U$, was $Re = 15,000$. The average flow temperature was $21 \pm 1°C$. At the distance from the inlet equal to 25 calibers, the flow was steady and its velocity profile was close to the power-law profile with exponent $n \approx 1/7$.

The local heat transfer coefficient was calculated by formula $\alpha = q/(T_w – T_0)$, where $q$ is the heat flux on the heated wall; $T_w$ and $T_0$ are the wall and flow temperatures in the channel in front of the step, respectively. The Nusselt number was calculated using the following formula:

$$Nu = \frac{\alpha H}{\lambda}$$  \hspace{1cm} (1)

where $\alpha$ is heat transfer coefficient; $\lambda$ is air heat conductivity, determined by the airflow temperature. The maximal uncertainty of coefficient measurement in this experiment did not exceed 5 % [6].

To take the static pressure, a plexiglas wall was made. There were the holes arranged in two rows: longitudinal central row with 49 holes and transverse row at the distance of 40 mm from the step with 15 holes. The pressure coefficients were calculated by: $Cp=2(p-p_0)/\rho U^2$.

3. Results and discussion

The pressure coefficients measured along the channel length for different distances $S$ along the central cross-section of the channel are shown in figure 2. As the channel expansion angle increases (figure 2 (a)), the pressure coefficient increases, but this increase occurs almost up to angle $\varphi = 2.86°$. Further growth of the angle does not affect the value of pressure coefficients. The lowest rarefaction is observed at the maximal expansion angle of 4° at 2.75 calibers (step heights) and it is -0.065. For the gradient-free flow, the pressure coefficient behind a step is $Cp_{min} \approx -0.105$ and it is at 2.5 calibers away from its edge. An increase in the distance from the step to the place, where greatest rarefaction is observed, is a consequence of an increase in the recirculation zone in the flows with positive pressure gradients. For the gradient-free flow behind the step, the pressure is restored completely along 15.8 calibers. With a positive pressure gradient, its reduction is not observed, and installation of the vortex generator does not lead to a qualitative change in the character of distribution.
Figure 2. The wall static pressure coefficient: (a) smoothed step; (b) $\Delta = 3$ mm, $S = 40$ mm; (c) $\Delta = 3$ mm, $S = 3$ mm; (d) $\Delta = 6$ mm, $S = 80$ mm; (f) $\Delta = 6$ mm, $S = 3$ mm.

When a rib with height $\Delta = 3$ mm is mounted at distance $S/H = 4$ (figure 2 (b)), profiles $Cp$ are lower than those for the case with a smooth step because the mounted rib leads to an increase in the pressure in front of it. The coordinate of minimal pressure moves towards the step and becomes equal to $X_{C_{\text{min}}} / H \approx 1.5$. When a rib of the same height $\Delta = 3$ mm is installed at distance $S/H = 0.3$ (figure 2 (c)), the pressure behind the step increases and $X_{C_{\text{min}}} / H = 4$. An increase in the obstacle height leads to an increase in the pressure behind the step (figure 2 (d) and (f)). It was shown in [10, 15] that the attachment region is maximally retracted from the step in cases when the two-dimensional turbulator is at the step edge.
Setting a rib in front of the back-facing step leads to a change in the flow and, accordingly, to a change in heat transfer (figure 3). Installation of a vortex generator increases the local heat transfer maximum as compared to a smooth step. As for the attachment point (figure 6 [9]), location of the local heat transfer maxima depends on location and height of the rib. Some local heat-transfer maxima are near the point of flow attachment; other local maxima are displaced closer to the step. The first group includes the cases, when the flow separated in front of the rib attaches before the step, including a smooth step. The second group includes geometries, where the separated flow penetrates into the mixing layer. The greatest deviation for the rib of $\Delta = 3$ mm is observed for $S = 0$ mm, where the ratio of attachment point coordinates to the coordinate of local heat transfer maximum is $X_r/X_{numax} = 0.88$. This phenomenon was noted in [11] and it is particularly obvious at a high degree of turbulence. In our case, the obstacles set up before the step serve as a source of large-scale turbulent structures, which is
indirectly confirmed by the profiles of longitudinal velocity pulsations in [9]. Naturally, the larger the mounted obstacle, the greater the intensity of large-scale turbulent structures. The structures that reach the wall behind the step enhance heat transfer. A smooth step does not intensively create turbulence in the shear layer, so heat transfer behind it is lower. In the initial cross-sections of the channel for \( S/\Delta < 7 \) and smooth step, the tendency of heat loss slowing down in comparison with heat transfer in cross-sections, close to the outlet from the channel, is observed. This type of distribution is associated with the development of a secondary vortex in the corner region. As it was noted in [9], for \( S/\Delta > 7 \), a secondary vortex was not detected, so there is no tendency to slow down the heat transfer loss. In all cases, heat transfer decreases with increasing positive pressure gradient.

When flowing around a smooth step (figure 4), with an increase in the angle of channel opening, the local maximum falls and at \( \phi = 4^\circ \), it becomes less by \( \sim 20\% \). When a mini-obstacle is located on the step edge, the behavior of curves is similar to the case of a smooth step. At that, the effect of the higher obstacle on \( \text{Nu}_{\text{max}} \) is insignificant and it does not exceed 3\%. For a rib 6 mm high, mounted at step edge, an increase in the \( \text{Nu}_{\text{max}} \) values is observed at high angles \( \phi \). This phenomenon may be because flow separation occurs on the upper wall and presses the main flow to the bottom wall, and heat transfer increases in the separation region.

4. Summary
The effect of single rib location and height on pressure distribution and heat transfer intensification behind the back-facing step in the presence of longitudinal positive pressure gradient was studied experimentally. It is shown that the development of perturbations caused by a single rib increases heat transfer behind the back-facing step for all values of pressure gradient. It is determined that attachment of the flow disturbed by an obstacle behind the step increases heat transfer intensification behind the back-facing step. The positive pressure gradient reduces the level of heat transfer behind the step, except for the case of high obstacles in the channel with large opening angle \( \phi = 4^\circ \), when flow separation on the upper wall leads to flow constriction and local acceleration.

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