Effect of a detached rib behind a backward-facing step on separated flow dynamics and heat transfer

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Abstract. Here, we present the experimental results on the influence of a detached rib behind a backward-facing step on the flow dynamics and heat transfer. The height of a slot between the lower edge of the rib and the channel wall was varied in the range \( \Delta h/H = 0.7 - 1.3 \), and the distance between the rib and the step was varied within \( \tau/H = 0.2 - 3.2 \). The rib height was constant and equal to 0.3H, where H is the step height. The fields of static pressures were measured behind the point of flow separation at the step edge. The study was performed in the range of Reynolds numbers 14,200-42,500. The two-dimensional fields of velocities and their fluctuations were measured using the PIV method. Heat transfer was studied in the regime of constant heat flux on the channel surface, where the step was located. Behaviors of the pressure and velocity profiles, as well as heat transfer with varying the detached rib location relative to the step are shown.

1 Introduction

A separated turbulent flow around a backward-facing step has been studied in sufficient detail [1–4]. This is explained by the fact that organization of flow separation and its reattachment is one of the most common ways to intensify heat transfer. At the same time, a backward-facing step in heat exchangers can also have a negative effect: the hydraulic resistance increases and heat transfer in the stagnation zone directly behind the separation point deteriorates. These shortcomings can be eliminated by controlling the flow separation.

As it is known, there are active and passive methods for controlling separated flows. Local blowing-suction at the step edge or on the entire surface, introduction of various periodic perturbations, and etc. are used as the active methods. Despite their effectiveness for fine adjusting the size of the recirculation region and intensifying heat transfer behind the step, these methods are technically more difficult to implement in comparison with the passive methods. Additional intensifying elements (transverse ribs, teeth, vortex generators of various shapes), despite their significantly smaller dimensions as compared to the main separated flow, can cause significant restructuring of the flow, both with reduction and expansion of the circulation zone.

The effect of three-dimensional generators of longitudinal vortices is considered in [5–7]. Three-dimensional generators shift the coordinate of boundary layer reattachment towards the step bottom, and the attachment line becomes uneven and approaches the step between the generators, and immediately in a wake behind the generators it shifts downstream. The region of maximum heat transfer approaches the step; heat transfer between the tabs becomes more intensive and decreases behind the tabs.

The effect of a two-dimensional obstacle on the flow dynamics and heat transfer behind the step is studied in [8–13]. A rib in front of the step forms its own separation area and, depending on the rib location relative to the step, the area behind the step either increases if there is no individual area, or decreases if an individual area has been formed. The heat transfer maximum is located in the attachment region.

In [14], along with other types of two-dimensional deflectors, the case of a detached rib behind a step was considered. The two-hump distribution of the Nu number given for this case relates to the displacement of the recirculation region.

The present study is an extension of [14] on the detached rib effect on flow dynamics and heat transfer.

2 Experimental setup and procedure

The experiments were carried out using an aerodynamic setup, with included a medium-pressure fan driven by an asynchronous motor, a frequency motor controller with a minimum adjustment frequency of 0.01 Hz, and an aerodynamic channel consisting of a pre chamber, a nozzle, and a working channel. The working channel consisted of the 600-mm initial section with a cross-section of 20 x 150 mm, at the end of which there was a step 10 mm high, and a 400-mm section behind the step. The working channel was made of heat-insulating textolite 10 mm thick.

The heat flux on the wall behind the step was created using an electric current supplied to a thin titanium foil 50 \( \mu \)m thick. The foil was glued on a section of 150*400 mm. The surface temperature was measured by

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thermocouples, built into the back wall along the entire length of the center line. The thermocouples were arranged unevenly, converging towards the step with a distance of 2.5 mm and more sparsely towards the outlet with a step of 20 mm.

Fig. 1. Setup scheme.

A flat rib, mounted normally to the flow over the entire channel cross-section, was used as the flow diverting element. The height of the rib $\Delta$ was 3 mm, and its thickness was 1 mm. In the study, we varied both the height of the slot between the wall and the rib $dh/H$ from 0.7 to 1.3 and the distance from the step to the rib $t/H$ from 0.2 to 3.2. The Reynolds numbers of the flow $Re_D$ calculated from the hydraulic diameter and the average velocity was varied within $14,200 – 42,500$.

In the experiments, the distribution of pressure on the lower wall behind the step was measured in the model symmetry plane. To do this, holes were drilled along the channel with variable pitch; the pitch was 5 mm near the step and it reached 40 mm towards the end. Based on the measured pressures, the pressure coefficient $Cp = 2(p_i - p_0)/\rho U^2$ was calculated, where $p_i$, $p_0$ are the pressure on the wall at the point under study and the reference pressure; $U$ is the velocity in the center of the initial channel, $\rho$ is the air density.

3 Experimental results

3.1 Flow dynamics

The fields of average and fluctuating velocities were studied by the PIV method for height $dh/H = 1$, set at distance $t/H = 0.2$ from the step. Streamlines were plotted using the fields of average velocities. The flow pattern repeats qualitatively the pattern, modeled numerically by the authors of [14] for the same conditions. Two vortices are formed behind the rib, and the more intense one is located near the lower wall. The second vortex induced by the mixing layer is in the upper part of the rib. The flow deflected by the rib reattaches at a distance of 0.5 calibers, then the boundary layer separates at a distance of 2$H$, a recirculation region 5.5 calibers long appears, and the mixing layer reattaches at a distance of 7.5 calibers. Strong turbulence is observed above the upper part of the rib, and in the lower part the unsteady character of the flow is manifested to a lesser extent due to the lower level of velocities.

When flowing around a step without a rib, greatest rarefaction is achieved near the step at a distance of 2 calibers, and the pressure is restored at $20H$. If the rib is mounted at $t = 0.2H$, greatest rarefaction is achieved at a distance of 1.5$H$ with $Cp = 0.35$; at this point the flow deflected by the rib attaches. For the cases with rib setting at $t$ from 1.2 to 3.2, an increase in pressure at the point of attachment of the flow deflected by the rib is characteristic, and maximal heat transfer is observed there. Then there is a slight decrease in pressure and after about one caliber, the pressure starts to recover. For the configuration with $t = 1.2$ and $dh=1.3$, the largest increase in $Cp$ is achieved at a distance of $4H$, which corresponds to the coordinate of the main flow merging with the flow deflected to the wall behind the step. When the rib is mounted downstream the step at a distance of $1.2H$, the pressure rises at a distance equal to one caliber from the step bottom. For distances $t = 4.5H$, the character of the curve becomes similar to the distribution of pressure without a rib.

Fig. 2. Streamlines and RMS field of longitudinal velocity pulsations.

3.2 Heat transfer

With a turbulent developed flow in the channel, a separation region is formed behind a sudden expansion.
In the recirculation zone, heat transfer decreases, and the heat transfer maximum is located near the flow reattachment area. In our case, for Re = 14.200, the heat transfer maximum is located at a distance of 5.8 calibers from the separation point. Such a conclusion can be drawn from the analysis of data obtained, shown in Fig. 4. When installing a rib, the flow structure and heat transfer, respectively, change dramatically. Thus, for a rib installed at a distance of 0.2 caliber from the step and at \( dh/H = 1 \), two maxima are formed in the heat transfer profile along the channel length. The first maximum is localized near the backward-facing step; the second maximum is at a distance of 8.25 calibers. At the first maximum, heat transfer increases by a factor of 2.2 as compared to the case without a rib, the second maximum is comparable to the case of the flow around a step without perturbation. If the rib is displaced downstream at distance \( t = 1.2H \), the heat transfer maximum shifts at a distance of 1.75\( H \), and the second heat transfer maximum is not observed. With further displacement of the rib by one more caliber from the step, the maximum also shifts downstream. Thus, when the obstacle is located at distance \( 2.2H \), the maximum is shifted by 2.75\( H \), and when the obstacle is located at 3.2\( H \), the maximum is shifted by 3.75\( H \). The value of the heat transfer maximum decreases with the distance between the rib and the step. It can be seen in the profiles of heat transfer, respectively, change dramatically. Thus, for a rib installed at a distance of 0.2 caliber from the step and at \( dh/H = 1 \), two maxima are formed in the heat transfer profile along the channel length. The first maximum is localized near the backward-facing step; the second maximum is at a distance of 8.25 calibers. At the first maximum, heat transfer increases by a factor of 2.2 as compared to the case without a rib, the second maximum is comparable to the case of the flow around a step without perturbation. If the rib is displaced downstream at distance \( t = 1.2H \), the heat transfer maximum shifts at a distance of 1.75\( H \), and the second heat transfer maximum is not observed. With further displacement of the rib by one more caliber from the step, the maximum also shifts downstream. Thus, when the obstacle is located at distance \( 2.2H \), the maximum is shifted by 2.75\( H \), and when the obstacle is located at 3.2\( H \), the maximum is shifted by 3.75\( H \). The value of the heat transfer maximum decreases with the distance between the rib and the step. It can be seen in the profiles of heat transfer distribution that when the rib is installed, the flow structure changes starting from 1.2 calibers. The heat transfer curves after the heat transfer maximum fall much faster as compared to the distribution without a rib.

The effect of the Re number on the heat transfer maximum is shown in Fig. 5 for three cases (a step without a rib, a rib with slot height 1\( H \) and a distance from the step of 2.2 and 3.3 calibers). With an increase in the Re number, the effect of a detached rib on the heat transfer maximum becomes stronger than in the case of the rib absence.

The effect of the height of a slot between the step wall \( dh \) at a fixed distance from the rib to the step was studied. Other cases, except for configuration \( t = 0.2H \) at the step height, judging by the nature of distribution of the heat transfer curves, have a similar flow and a one-humped heat transfer distribution with a sharper drop in the heat transfer intensity in the region after the maximum. In these cases, the heat transfer maxima are localized at a distance of 2 calibers. In the case when the rib is below the step height, a two-hump distribution of heat transfer is observed, while, starting from the 3\(^{rd} \) caliber, the results are quantitatively repeated with the heat transfer distribution for the step in the absence of control. Such a distribution indicates that a part of the mixing region, deflected by the rib, hits the lower wall near the step; this influence extends to about 3 calibers; at the same time, reattachment of the separated flow is somewhat shifted downstream.

![Fig. 5. The effect of Re_D on Nu_max](image)

For technical applications, it is important to determine average heat transfer. The average Nusselt number \( Nu_I \) is determined by integrating the local values from the step bottom to the considered point

\[
Nu_I = \frac{1}{L} \int_0^L Nu \, dx
\]

The results of changing average heat transfer are shown in Fig. 6. Thus, considering the rib mounted at a height of 10 mm, we see that the highest \( Nu_I \) value is achieved when the rib is installed at distance 0.2\( H \), and at a distance of 35 calibers this exceeds the case in the absence of a rib by 16%. As the distance between the rib and the step increases, heat transfer decreases. Among the \( Nu_I \) profiles, one can choose the configuration with the most intense heat transfer in the vicinity of the step.

The shortest distance \( L \) (the effective length of heat transfer intensification \( L \) is the distance from the step to the maximum coordinate \( Nu_I \)) is observed at \( t = 0.2 \). In this case, the value of \( L \) is reduced by 85% as compared to the step without a rib, when \( L = 9.75H \). At a fixed rib-to-step distance of 1.2\( H \), for the ribs located above the step, \( L \) becomes 2.75\( H \) and 3.75\( H \) at a close value of \( Nu_I \).
In the case when the slot height reaches 0.7\( H \), a two-hump distribution is observed: one peak is located at distance 2\( H \), and the second one coincides with the value in the rib absence.

Fig. 6. The Nu\(_f\) number profiles.

The coefficient of hydraulic resistance \( f \) was determined by formula \( f = 2(P_a-P_0)/(\rho U_0^2) \), where \( P_0 \) is the total pressure in the reference cross-section (4 calibers before the step), \( P_a \) is the total pressure behind the step, determined in the area of static pressure recovery of 20 gauges behind the step, \( U_0 \) is the average flow velocity in the reference cross-section. These data are shown in Fig. 7. The highest hydraulic resistance (95% more than the unregulated case) is achieved for the cases with \( dh = 10H \) at distance 0.2\( H \). Raising the rib to height \( dh = 1.3H \) at \( t = 1.3H \) increases the resistance by a factor of 2 as compared to the classical case. The least resistance is achieved at height 0.7\( H \).

The Nu\(_f\) number was averaged over a distance of 20 calibers; this is the distance where the pressure recovery occurs (Fig. 8). At the step height, the largest Nu\(_f\) is achieved near the step and becomes 19% larger than that for a smooth step. When varying the slot Nu\(_f\) at \( t = 1.2H \), the best result is achieved when the rib is installed at the step height.

Fig. 8. The effect of slot height \( dh \) or distance to the step \( t \) on the averaged Nu number along section 20\( H \) from the step for Re = 14.200.

Fig. 9. The effect of slot height \( dh \) or distance to the step \( t \) on complex \( \eta \) for Re = 14.200.

To assess the thermal-hydraulic efficiency, complex \( \eta = (\text{Nu}_{f0}/\text{Nu}_{f})/(f/f_0)^{1/3} \) is usually used, which, in contrast to the Reynolds analogy factor, allows consideration of power spent on coolant pumping. The highest efficiency, as it is shown in Fig. 9, is achieved at a narrow slot \( dh = 7H, t = 1.2H \) and is 1.02; the lowest efficiency is achieved at the largest slot \( dh = 13H, t = 1.2H \) is 0.84.

4 Conclusions

The effect of a detached rib on the flow dynamics and heat transfer behind a backward-facing step was experimentally studied in the case of a turbulent flow around the step with closed boundary layers and Re = 14,200, calculated from the hydraulic diameter of the inlet cross-section and the average flow velocity.

The PIV method was used to study the effect of a detached rib installed at a distance of 0.2 calibers from
the step at the channel height. It was revealed that two vortices are formed behind the rib; the flow attaches at a distance of 0.5 calibers, then the flow detaches with further reattachment at a distance of 8 calibers.

The rib at a distance of 0.2 calibers had the greatest influence on the pressure distribution; the rib recessed under the step ($t = 1.2H$, $dh = 0.7H$) had the least influence and deviated slightly from the classical case near the step.

Two-hump distribution of heat transfer was observed for the case of 0.2$H$ at height 1$H$ and 1.2$H$, $dh = 0.7H$. In the first case, the first peak is not observed because it goes beyond the measurement region; the second peak corresponds to reattachment.

The research was financially supported by the Russian Science Foundation (grant No. 21-19-00162).

References

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