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CONTROL OF SEPARATING FLOW BEHIND A STEP BY MEANS OF SLOTTED RIBS

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One of the promising and simplest methods of passively controlling separating flow behind a backward-facing step with the aid of slotted ribs is considered. The size and number of slots were varied in wide ranges in experiments so that the relative area of the slots amounted to $R = F_s/F_r = 0–1$. The influence of the longitudinal vortices induced by the teeth in a rib on the distribution of pressure and heat transfer rate in the recirculation region in the case of varying the sizes of slots in a rib, the spacing between them, and the position of the rib relative to the backward-facing step has been studied. The effectiveness of using slotted ribs for reducing the length and intensity of the region of reverse flow behind the step is shown.

Keywords: *backward-facing step, separating turbulent flow, miniturbulators, thermographic visualization, vortex formation.*

Introduction. The problem of controlling the characteristics of separating flows is one of the important problems of the contemporary technology. Active and passive methods are employed for solving this problem. The first group involves the methods based on the introduction of periodic disturbances into the vicinity of separation. Thus, in work [1] the control of separation behind a step is studied experimentally with the aid of an oscillating transverse thin plate set up in front of the step. It was established that an increase in the frequency of barrier oscillation leads to a reduction in the recirculation region. In [2–4], the influence of alternative injection and suction at the edge of a step on the separating flow behind the latter was studied. It was shown that depending on the injection–suction amplitude and on the Reynolds number of the main flow there exists an optimal frequency of supply and uptake of liquid at which the recirculation region becomes minimal. Porous injection or suction immediately behind a step [5–7] leads to a considerable change in the size of the recirculation region and in the level of heat transfer from zero in the regimes of boundary layer displacement to appreciable values in the case of asymptotic suctions.

Passive control of flow is more simple and producible as compared to the active methods of action. Thus, creation of increased incoming flow turbulence leads [8] to a decrease in the recirculation region length, in consequence of which the maximum in the heat transfer rate is displaced to the step and the heat transfer coefficient increases with the turbulence degree. The influence of a minirib set up in front of the step on the separating flow behind the latter was investigated in works [1, 9, 10]. It was established that if the flow, which separated in front of the rib, reattached ahead of the step, the recirculation region behind the step reduces as compared with a smooth step, but if the reattachment does not occur, the recirculation region behind the step increases. In work [11], the interaction of two separating flows of different scales and the influence of their interference on the flow structure and convective heat transfer were studied. The conditions for intensification of heat transfer and its suppression depending on the scale and relative position of barriers were examined. The decrease in the heat transfer rate behind the step with a reattached shear layer ahead of it seems to be due to the decrease in the scale of the vortex structures inside the recirculation region.

Among the important and interesting trends in the investigation of jet and separating flows is the study of the effect of three-dimensional disturbances introduced into the mixing layer. The disturbances may be generated by protrusions (tabs) and teeth of various shapes and sizes. The purpose of such investigations is the study of the intensification of heat and mass transfer processes and determination of the techniques of decreasing the noisiness of turbulence flows by disrupting large-

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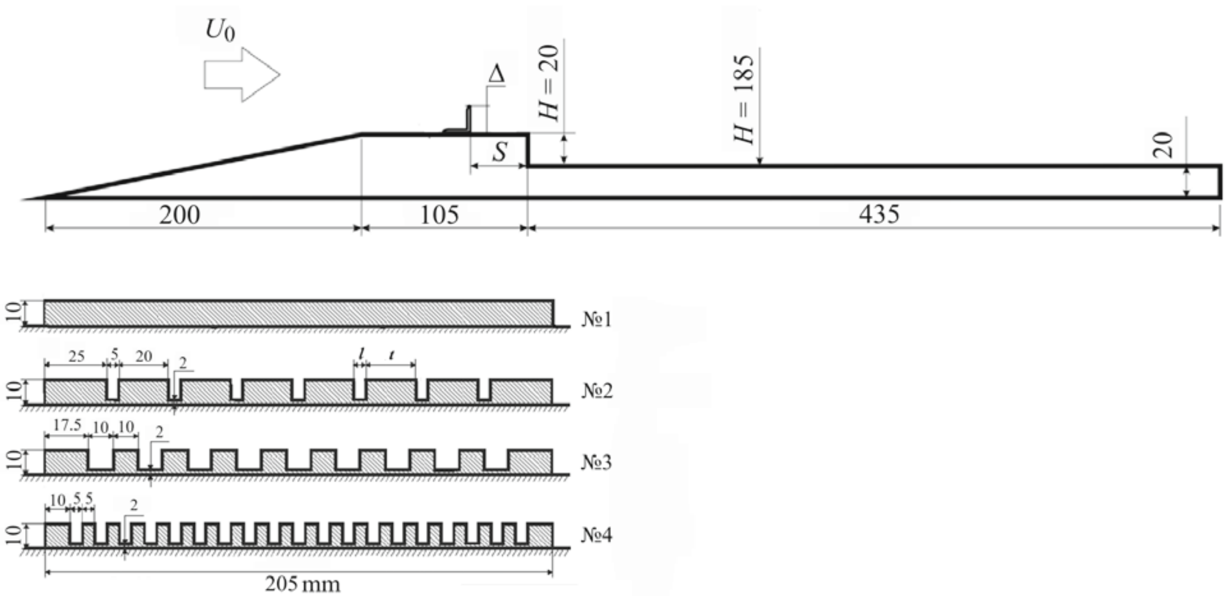

Fig. 1. Schematic of the working section of the channel and the geometry of the ribs. All dimensions in mm.

scale structures. In work [12], the influence of protrusions (tabs) installed at the step edge on the formation of the region of inverse flow was studied experimentally. It is shown that due to the formation of a longitudinal vortex behind a tab, the recirculation region reduces. The least recirculation region is attained at the height of protrusions equal to 0.3 of the step height H and at the spacing between protrusions equal to $2H$.

The results of the primary experiments with slotted ribs are presented in work [13]. In these experiments, ribs with different areas of slots were located on the step edge. It was found that the influence of toothed ribs on intensification of heat transfer is somewhat less than of solid ribs. The present work is an extension of these investigations and sets out to study the influence of slotted ribs of various geometries, depending on their location relative to the step and on the dynamic and thermal characteristics of the recirculation region.

Experimental Setup. Experiments were carried out in the wind tunnel of the Institute of Thermal Physics of the Siberian Branch of the Russian Academy of Sciences [13]. It is an open air circuit with a fan installed at the inlet. The cross section of the working channel of the wind tunnel was 205 × 200 mm, with its length being equal to 1000 mm. Ahead of the channel there was an additional part of the same cross section as of the working channel and of length of about 1000 mm. To form flow behind a step, a model was placed on the bottom wall of the channel at a distance of 100 mm from the channel inlet (Fig. 1). The model consisted of a conical deflector of length 200 mm and height 40 mm with small-step roughness and of a horizontal section of length 105 mm terminating in a step of height $H = 20$ mm. Behind the step, there was a measuring section with ~0.3-mm-diameter holes made in the central section for tapping static pressure. The holes were located behind the step at 5 mm intervals over a length of 100 mm and then at 9 mm intervals over a length of 300 mm. In two cross sections located at distances of 37 mm and 270 mm behind the step holes for pressure tapping were spaced 9 mm apart. The width of the model was 190 mm. The gaps between the model and the side walls were sealed by a thermostable mastic.

In investigating heat transfer behind the step, tape heaters from aluminum foil of thickness 36 μm, with strip width of 5 mm and total length of 515 mm, were mounted in the measuring section. The foil was heated in the mode of a constant heat flux. The channel surface temperature was controlled by Chromel–Coppel thermocouples located in its central longitudinal section. Thirteen thermocouples were set up with an interval of 20 mm, and the next eight thermocouples, with an interval of 30 mm. Heat losses through the channel wall were controlled by two thermocouples set up on the channel′s outer surface. The degree of the overheating of the internal surface of the channel relative to the main flow was not large and did not exceed $\Delta T = T_w - T_0 < 50^o$; therefore the effect of the temperature factor on the velocity field was not taken into account.

Determination of temperature distribution over the entire surface of the plate and estimation of the surface-average heat transfer coefficient were made by means of thermography. To carry out thermographic measurements, the surface with the step and the heater was imbedded in the side wall of the channel flush with it. The opposite wall was made of optical glass,

TABLE 1. Dimensions of the Ribs

No. of a rib	n	l, mm	t, mm	F_r, mm^2	R
0	0	0	205	2050	1
1	0	0	0	0	0
2	7	5	20	280	0.136
3	9	10	10	720	0.35
4	19	5	5	760	0.37

or in some cases the glass was replaced by a polyethylene film. The thermal section was heated for an hour at the needed rate, after which the wall temperature was measured by a THERMO TRACER TH7102 infrared imager (Japan) with the spectral range 8–14 μm. The resulting temperature field was assigned numerical values minimum by the data of two thermocouples, and thermograms were constructed with the use of special computer programs.

All measurements were made at a constant Reynolds number $\mathrm{Re}_H = HU_0/\nu = 4.6 \cdot 10^4$, with the boundary layer before the step being turbulent. The momentum thickness of the boundary layer before flow separation was calculated by the relation $\delta^{**} = \int_0^\delta \frac{\rho U}{\rho_0 U_0}\left(1 - \frac{U}{U_0}\right) dy$ with the use of the experimental velocity profiles measured by a Pitot tube of diameter 0.4 mm and was equal to 3.2 mm, which corresponded to the boundary layer thickness $\delta \approx 35$ mm. The degree of the incoming flow turbulence in the channel at the step edge in the absence of disturbing ribs measured by a DISA-55M thermoanemometer corresponded to the natural one and amounted to 1.2%.

We investigated five schemes of separating flow organization behind a step. The general view of the ribs and their dimensions are presented in Fig. 1 and Table 1. One of the characteristic parameters of the problem is the relative area of the slots $R = F_s/F_r$. According to Table 1, the zero configuration corresponds to the case of flow past a smooth step without a rib; this flow is called the base one. For this case, the parameter $R = 1$. Configuration No. 1 corresponds to a solid rib without slots and for this rib $R = 0$. In ribs Nos. 2, 3, and 4, the relative area of the slots corresponds to $R = 0.136$, 0.35, and 0.37, respectively. As is seen from the table, ribs Nos. 3 and 4 have slots with closely coinciding areas; however, their number and dimensions differ twice. We thus determined the influence of the dimensions of generated stationary, longitudinal vortex structures and of their quantity on the dynamic and thermal characteristics of the recirculation zone. The ribs were fabricated from aluminum of thickness 1.5 m. The spacing between a rib and the step was varied: $S/H = 0$, 2, and 4.

Experimental Results and Discussion. *Pressure coefficients.* The distribution of pressure coefficients in the middle section of the channel behind the step is shown in Fig. 2. The value of the pressure coefficient was determined by the formula $C_p = 2(p_i - p_0)/ rU_0^2$, where p_i and p_0 are the static pressures on the wall in the running section and in the flow at a distance of 90 mm ahead of the step at a height of 60 mm from the wall and U_0 is the gas velocity in undisturbed flow. This figure presents data for all the investigated configurations of ribs. As is seen, the absolute values of the pressure coefficients differ greatly for the ribs considered, but the pressure profiles are similar in all of the cases. Immediately behind the step, where the recirculation flow region is formed, the pressure coefficient is negative. As the reattachment point is approached, the coefficient increases rapidly and takes on a maximum value. Thereafter, farther downstream, flow relaxation occurs. The decrease in the pressure is due here mainly to the dissipative friction losses. As expected, in flow past a smooth step the value of rarefaction is small. It increases substantially when a solid rib is set up on the step edge. The data for slotted ribs (Nos. 2–4) occupy an intermediate position between these limiting cases; moreover, with increase in the area of slots the difference between the pressure distributions decreases, and they approach the distribution behind a smooth step (configuration No. 0). Thus, behind the ribs with the close values of the parameter R the distributions of C_p (curves 3 and 4 in Fig. 2) differ little.

The noted characteristic features are confirmed by the results of experiments of work [13] showing that the maximum value of rarefaction $C_{p\min}$ increases with the barrier height, and that the greatest effect is exerted by slotted ribs (combs) with finer and widely spaced slots. Pressure distribution in the recirculation zone depends noticeably on the characteristic features of the geometry of ribs. As the slotted ribs are moved farther from the step edge, the differences in the pressure distribution are levelled off; however, for configurations Nos. 3 and 4 they bear out that the recirculation zone is less extended than for configuration No. 2, in which the open area is almost 2.7 times smaller (curve 2). This points to the specifics of the

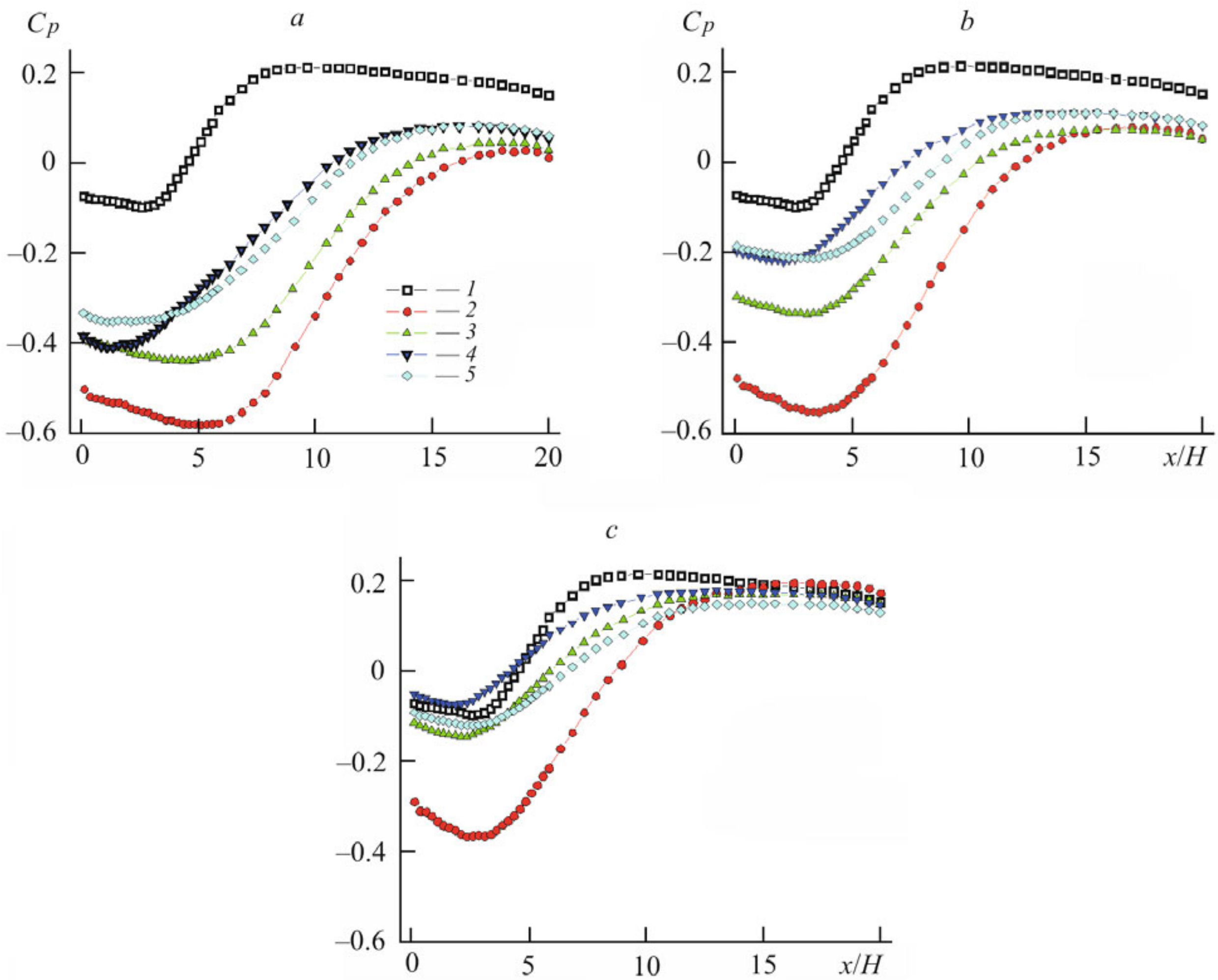

Fig. 2. Distribution of the pressure coefficient behind the step with mounted ribs No. 0 (1), No. 1 (2), No. 2 (3), No. 3 (4), and No. 4 (5) at Re = $4.6 \cdot 10^4$ and S/H = 0 (a), 2 (b), and 4 (c).

interaction of longitudinal vortex structures among themselves. A more detailed analysis of the turbulent characteristics of flow (fluctuations of velocity, Reynolds stresses, and of energy dissipation) behind ribs is required to understand the structural changes occurring in the flow.

Pressure distributions on the wall across the channel in the section at the distance x/H = 2 from the step edge are smooth for the base variant and demonstrate the nonuniformity for slotted ribs Nos. 3 and 4 and for the solid rib (Fig. 3). In the case of slotted ribs, this nonuniformity is attributed to the three-dimensional character of flow before the step and to the formation of secondary flows along the side walls of the channel in the case of the solid rib [8, 13]. Analogous distributions were obtained also for other distances of combs from the step edge, with the only difference that the influence of longitudinal vortices and of secondary flows becomes weaker as a barrier recedes upstream. A two-dimensional separated flow was observed behind a smooth step, since the channel width exceeded the step height by 10 times. This is also indicated by thermographic measurements of the temperature fields of the wall behind the separation point.

Thermographic Visualization and Heat Transfer. Figure 4 presents the results of thermographic visualization of the temperature field in the region of interaction of a separating flow with the channel wall. The data are shown for a smooth step (configuration No. 0, Fig. 4a), for a solid rib (No. 1, Fig. 4b), and slotted ribs (No. 4, Fig. 4c). In the first case, in the central zone behind the step edge a stagnant region is formed, which is well seen also with the aid of soot-oil visualization [8]. This is the most heated zone on the thermogram (Fig. 4a). A cooler zone is located in the reattachment region. When a rib is set up on the step edge, the heated region expands (Fig. 4b) since the recirculation region increases. The character of

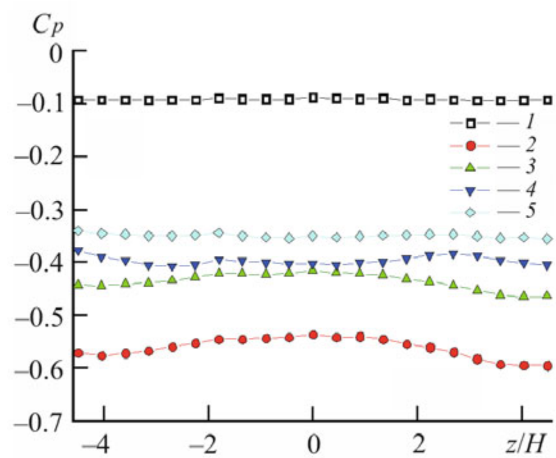

Fig. 3. Distribution of the pressure coefficient behind the step across the channel at $S/H = 0$ and $x/H = 1.75$.

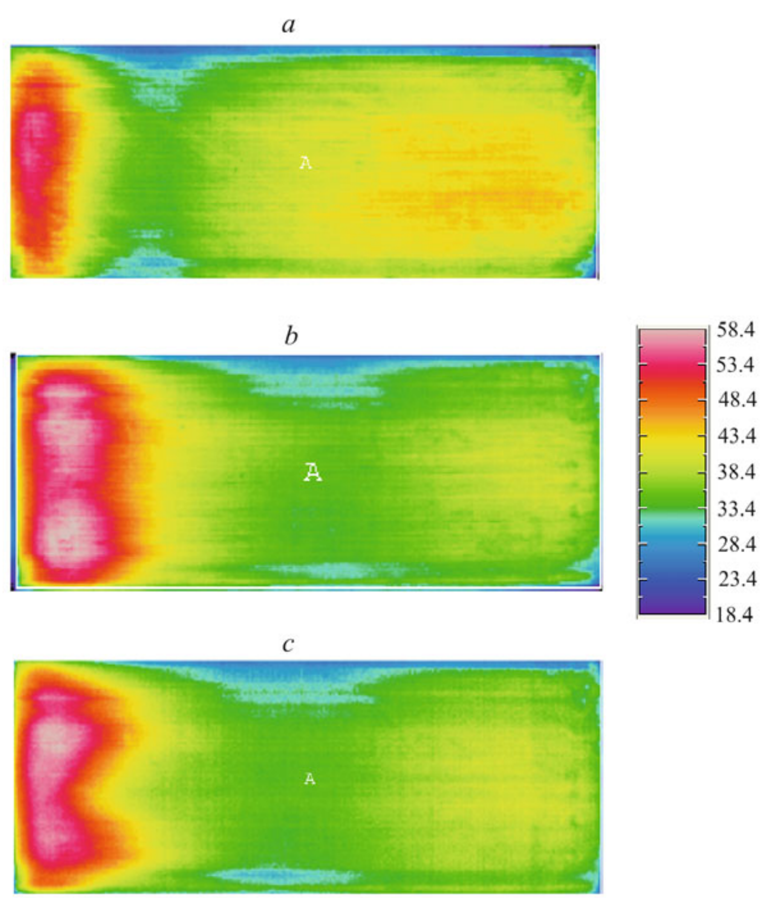

Fig. 4. Thermograms of the surface behind the step with ribs No. 0 (a), No. 1 (b), and No. 4 (c).

flow in the recirculation region undergoes a change: the more heated zone is separated and is displaced from the center to the side wall, as a result of which the thermogram reflects the features of flow behind a single rib with thick side vortices. In the case of No. 4, as is also shown in [13], the temperature distribution field in the recirculation region has two clearly manifested stagnant zones. Similar two-hump distribution is also characteristic of pressure distribution (Fig. 3). This is indicative of the rearrangement of the flow structure before the step under the action of the longitudinal vortices forming on the comb teeth.

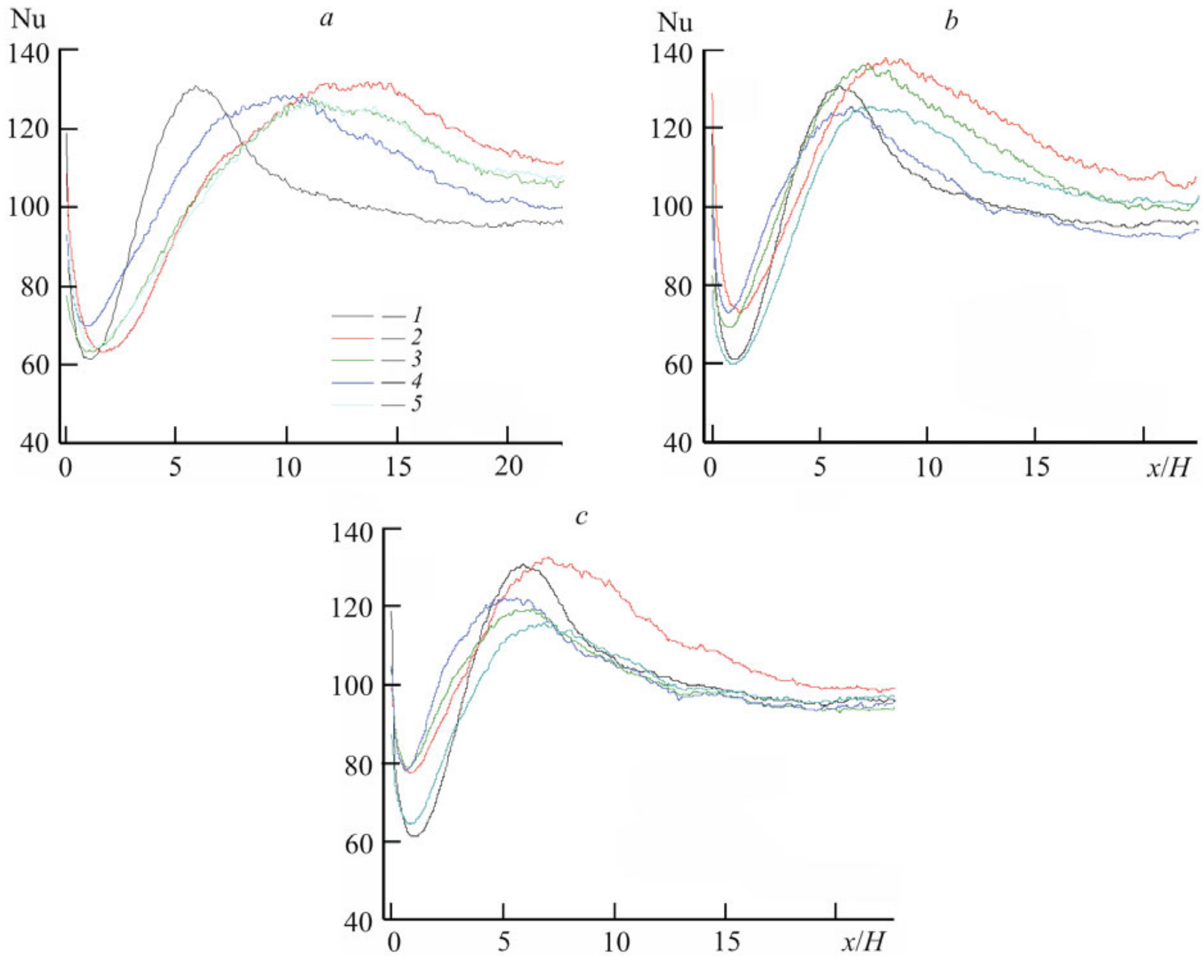

Fig. 5. Distribution of the Nusselt number behind the step with ribs No. 0 (1), No. 1 (2), No. 2 (3), No. 3 (4), and No. 4 (5) at Re = $4.6\cdot10^4$ and S/H = 0 (a), 2 (b), and 4 (c).

The thermograms obtained were averaged in the transverse direction. From the value of the average temperature we calculated the heat transfer coefficients and correspondingly the Nusselt number:

$$\mathrm{Nu} = \alpha H/\lambda = (q_{\mathrm{w}} - q_{\mathrm{loss}})H/(T_{\mathrm{w}i} - T_0)\lambda\ ,$$

where q_{w} and q_i are the density of the heat flux supplied to the wall and heat losses, and $T_{\mathrm{w}i}$ and T_0 are the wall temperature in the running section and in the flow core.

The results of experimental investigations of heat transfer are presented in the form of the dependence of the distribution of the Nusselt numbers along the length of the plate (Fig. 5c). Just as for the pressure distribution, three variants of the location of ribs are presented: immediately on the step edge ($S/H = 0$), at some distance upstream at $S/H = 2$, and at $S/H = 4$.

A narrow peak in the distribution of the Nusselt number is characteristic of a smooth step. A rib set up on the step edge induces intense separation. The recirculation zone is elongated, and the region of the mixing layer reattachment is displaced downstream. The maximum values of the Nusselt number in this region change much more slowly than in the case of a smooth step (Fig. 5a). Distributions of this type are also observed for toothed ribs. The distributions of Nusselt numbers for configurations Nos. 2 and 4 closely coincide but differ from the distribution for configuration No. 3. The main distinct feature is the growth of the Nusselt number behind the comb No. 3 in the recirculation zone. This feature becomes more prominent with distance from the step edge. The mounting of ribs at the distance $S/H = 2$ (Fig. 5b) enhances the maximum of heat transfer rate for all modifications of ribs except for configuration No. 3. Such an increase in the maximum of heat transfer rate was observed in work [11] approximately at the same distance from the step edge. At this distance, there occurs

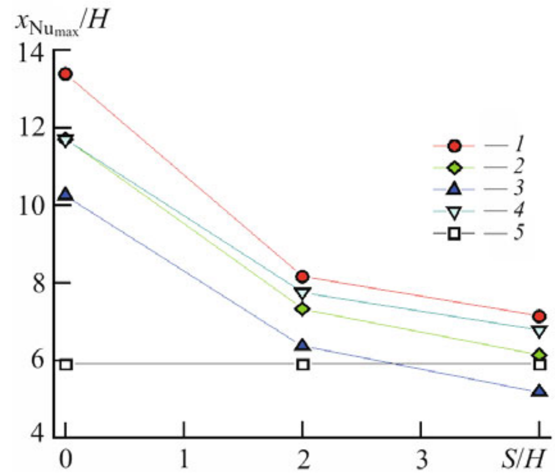

Fig. 6. Influence of the location of ribs No. 0 (1), No. 1 (2), No. 2 (3), No. 3 (4), and No. 4 (5) on the coordinate of maximum heat transfer rate (Nu_{max}) behind the step.

the separation of the curves for Nos. 2 and 4. At the distance $S/H = 4$ (Fig. 5c) the heat transfer rate maximum falls for all the ribs considered. At the same time, for the given distance most evident is the shortening of the recirculation region, in which the highest Nusselt number is noted for configuration No. 3. Beginning from the distances $x/H > 10$ calibers, the curves for different ribs, except for configuration No. 1 (solid rib), are closely coinciding and also they coincide with the distribution of the Nusselt number for the smooth step. For the solid rib (configuration No. 1) this coincidence occurs much farther — at distances greater than $x/H > 20$ calibers.

The coordinates of the maximum Nusselt number Nu_{max} (Fig. 6), just as the coordinates of pressure recovery, depend on the position of a rib ahead of the step. It was shown in [10] that the closer the rib to the step edge, the more extensive the recirculation region is and the later the separated layer is reattached. It was noted in [11] that the size of the reattachment region is 10–15% longer than the distance from the step to the section with maximum heat transfer rate $X_{Nu_{max}}$. The same tendency is also observed for the ribs considered. The solid rib at the step edge increases the value of $X_{Nu_{max}}$ more than twice. The toothed ribs bring the coordinate $X_{Nu_{max}}$ closer to the step.

Displacement of ribs upstream causes intensification of heat transfer in the recirculation zone at a smaller distance from the step. Formation of the zone of the maximum Nusselt numbers depends substantially on the comb geometry: the coordinate $X_{Nu_{max}}$ is fixed for configuration No. 3 earlier than for the smooth step (Fig. 6). Thus, a reduction in the size of the separated zone is observed when the disturbed flow is reattached by combs before the step edge [1, 9, 10]. Consequently, the conditions for the recirculation zone formation depend on the structure of the near-wall flow in front of the step edge.

The effect of the interaction of separating flows of various scales can be determined, by analogy with work [14], by the value of the coefficient of dynamic interference:

$$IF_d = (C_{p\min})_i/(C_{p\min})_0 ,$$

where $(C_{p\min})_i$ and $(C_{p\min})_0$ are the minimum coefficients of pressure behind the step in the presence of a rib and in its absence, respectively. The influence of the flow interference on thermal processes may be characterized analogously by the ratio of the maximum Nusselt number in the case of flow disturbance to its value for the flow past a smooth step:

$$IF_t = (Nu_{max})_i/(Nu_{max})_0 .$$

The coefficient IF_t also characterizes the degree of heat transfer enhancement due to the disturbances produced by a barrier set up ahead of the step.

The change in the coefficients of dynamic interference IF_d and thermal interference IF_t of separating flows depending on the position of minibarriers and their configurations is shown in Fig. 7. The disturbances produced by barriers exert a strong effect on the value of the interference coefficients. So, for a solid rib (configuration No. 1) mounted at the step edge the rarefaction in the recirculation zone increases more than sixfold as compared with a smooth step. If a rib is displaced upstream, the rarefaction decreases, but in this case too the influence of interference remains appreciable. For slotted ribs (configurations No. 2, 3, and 4), the coefficient IF_d decreases, i.e., the recirculation flow behind the step weakens. At large

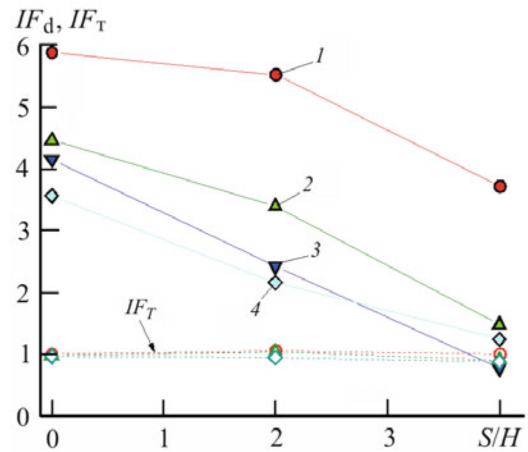

Fig. 7. Evolution of the coefficients of interference of separating flows for ribs No. 0 (1), No. 1 (2), No. 2 (3), No. 3 (4), and No. 4 (5); solid line, IF_d; dotted dashed line, IF_t.

distances of the location of ribs from the step edge ($S/H = 4$) the intensity of the layer separating from the step edge decreases, and the coefficient of dynamic interference tends to unity: $IF_d \to 1$. It should also be noted that the coefficient IF_d decreases with increase in the area of slots in a rib but changes insignificantly with the change in the number of slots. The behavior of the thermal parameter of interference IF_t differs in principle from that of the coefficient IF_d (Fig. 7). The trends in the heat transfer turned out to be very conservative for the ribs considered. Indeed, it follows from Fig. 7 that the interference effect is small and differs from unity by not more than 10%. Moreover, according to the data of Fig. 6, the coordinate of the heat transfer maximum changes significantly when ribs of different geometry are set up. Obviously, such a behavior of the thermal and dynamic characteristics is caused by the change in the structure of the reverse flow, which is to be attributed to the change in the structure of flow behind the ribs of different geometry.

Conclusions. The influence of the location of ribs of different geometry in front of a step on the development of the dynamic and thermal characteristics of the separation region behind it is shown experimentally. It has been established that the rearrangement of flow in front of a step is reflected on the behavior of the pressure coefficients in the separation region. A maximum decrease in pressure is observed when a solid rib is set up at the step edge. With increasing distance between a rib and the step, the maximum rarefaction comes closer to the value typical of a smooth step. This tendency is also true in the case of slotted ribs, for which the degree of rarefaction in the recirculation zone decreases with increase in the area of the slots. The size of the slots and the spacing between them influence the distance at which recovery of pressure occurs behind the step. The dependence of the heat transfer coefficient in the separation region on the geometry of slotted ribs is shown thermographycally. The uniformly distributed zone of superheating being formed behind a smooth step is divided into two regions, the local maxima of whose temperatures are displaced to the side walls on setting up slotted ribs with a large area of slots. The local maxima of Nu_{max} in the region of reattachment of the separated layer depend on the geometry of the ribs and their location ahead of the step edge. For the ribs located at the step edge the values of Nu_{max} are somewhat smaller than those of Nu_{max} behind a smooth step, but the extension of the surface on which high values of the heat transfer rate are observed increase considerably, so that the averaged heat transfer rate increases. As the slotted ribs recede from the step edge, one observes the dependence of the values of Nu_{max} and of the extension of the section of maximum heat transfer rate on the geometry of ribs. It is shown that by selecting the geometry of slotted ribs and their location relative to the step edge it is possible to control the magnitude of dynamic interference. The trends in heat transfer have appeared very conservative: the change in the heat transfer coefficients lies within ±10%.

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NOTATION

C_p, pressure coefficient; F_r and F_s, areas of a solid rib and of slots, respectively; H, height of the step; IF_d and IF_t, coefficients of dynamic and thermal interference; l, width of a slot; n, number of slots; Nu, Nusselt number; Re, Reynolds number; R, relative area of slots; S, distance from a rib to the step edge; t, width of a tooth; T_w and T_0, temperatures of the wall and of the flow core; U and U_0, flow velocities near the channel wall and in the flow core; x, y, z, longitudinal, normal, and transverse coordinates relative to the channel surface; α, heat transfer coefficient; λ, thermal conductivity coefficient; ν, kinematic viscosity; ρ, density. Indices: t, thermal; d, dynamic; loss, losses; r, rib; s, slot; w, wall.

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