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THERMAL CHARACTERISTICS OF A COUNTER-CURRENT WALL JET

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Counter-current flows are widely encountered in nature and take place in different production processes and equipment. For example, counter-flowing wall jets are used in welding in an inert gas, in the gasdynamic regulation of the nozzle of a turbojet engine, and in modeling atmospheric processes. The use of gas screens [1] may be very effective in protecting elements of power-plant equipment from high-temperature gas flows. In certain cases, due to the design features of the processing equipment, thermal protection of the wall can be provided by feeding a coolant gas through a slit counter to the flow or at a large angle to the direction of its motion [2, 3]. Despite the frequent use of countercurrent wall jets in different types of equipment, their study has been limited.

Here, we experimentally investigate the process of thermal mixing of a counter-current wall jet with a gas flow, and we determine the efficiency of the thermal protection of an adiabatic wall in the direction of motion of the jet. It is shown that under certain conditions, a counter-flowing wall jet can effectively protect the wall of a channel.

A diagram of the flow we studied is shown in Fig. 1. In the tests, the counter-current wall jet was created by injecting air through a tangential slit of height s = 4.7 mm. The slit was made in the bottom wall of an aerodynamic channel with a cross section of 150 × 145 mm and a length of 1200 mm. The working wall of the channel was adiabatic and was made of glass-textolite. The velocity of the main air flow in the tests was kept at a constant value U_0 = 16 m/sec. The velocity of the secondary flow was varied from 6 to 51 m/sec. Here, the injection parameter $m = \rho_S U_S/\rho_0 U_0$ was varied within the range 0.3-2.6. The temperature of the main flow T_0 = 15-20°C, while the temperature of the secondary flow T_S = 70-80°C.

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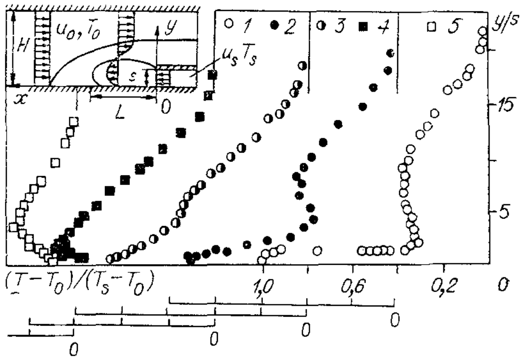

Fig. 1

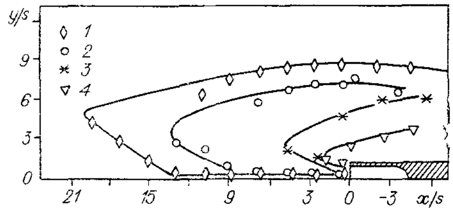

Fig. 2

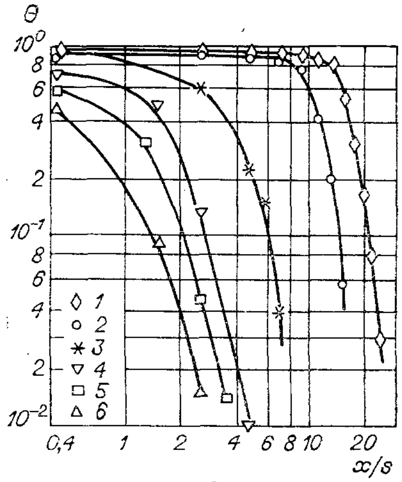

Fig. 3

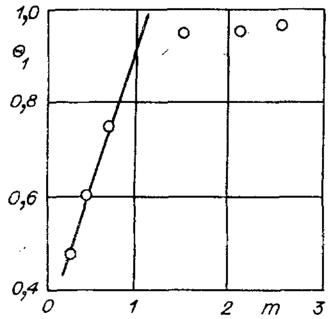

Fig. 4

Measurements of the temperature fields were made with a thermocouple probe having a junction with a diameter of 0.2 mm. The probe was moved in the vertical direction by computer-controlled traversing gear with a minimum displacement interval of 0.01 mm. In the region of mixing of the wall jet and the incoming flow, the level of turbulence could reach 40% according to our data. Thus, to obtain reliable mean values of temperature, it was necessary to average the measured signal over a sufficiently long time interval. In the tests, the signal from the thermoprobe entered a data collection and analysis complex based on an "Élektronika 60" computer. Five hundred temperature measurements were made at each point during a period of 10 sec. We then found the mean temperature T. Detailed temperature distributions were found for different injection parameters in 10-15 sections.

Figure 1 shows dimensionless profiles of temperature $\vartheta = (T - T_0)/(T_s - T_0)$ over the height of the channel in several characteristic sections x/s [1) 0.4; 2) 8.9, 3) 13.2, 4) 15.3, 5) 19.6] with m = 2.6. It is evident from the figure that the temperature profiles have two maxima in the initial sections. The first maximum, located near the surface and largest in magnitude, corresponds to the motion of a heated jet along an adiabatic wall. The second maximum evidently corresponds to the wake of this jet after rotation. With an increase in the distance from the edge of the slit, the second maximum becomes less noticeable, while the first begins to gradually decrease. It subsequently moves away from the channel wall and merges with the second maximum. The positions of the temperature maxima can be used to follow the trajectory of the counter-current wall jet. The lines in Fig. 2 connect the temperature maxima in different sections for m = 2.6, 2.1, 1.5, 0.7 (points 1-4). It is apparent that the character of penetration of the jet into the incoming flow depends on the ratio of their velocities. The greater the value of m, the farther the wall jet penetrates into the main flow and the wider the rotation zone turns out to be. Whereas with high injection parameters the jet initially moves along the channel wall and then begins to turn and be entrained by the incoming flow, at small m the jet rotates almost immediately after leaving the slit and is entrained by the main flow.

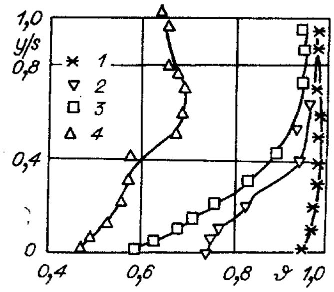

Fig. 5

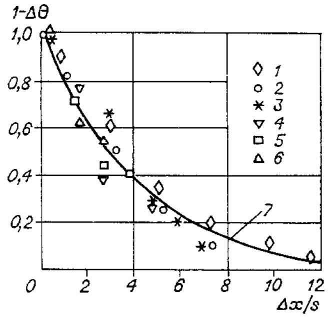

Fig. 6

The efficiency of the thermal protection of an adiabatic surface is usually characterized by the parameter $\Theta = (T_W - T_0)/(T_S - T_0)$, where T_W is the temperature of the channel wall. To find Θ in our investigation, we took the wall temperature to be equal to the flow temperature near the adiabatic surface and we determined Θ from the measured temperature profile. The resulting values of Θ were reliable, since $dT/dy \to 0$ near the adiabatic surface. Figure 3 shows the change in Θ along the channel established in the tests for m = 2.6, 2.1, 1.5, 0.7, 0.5, 0.3 (points 1-6). A characteristic feature of the change in the efficiency of the aerodynamic screen is a sharp drop in the parameter Θ with an increase in the distance from the slit. Such a strong reduction in Θ in the presence of a co-current screen was not seen in [1]. As a result, there is a finite maximum distance of screen efficiency L at which the wall temperature reaches the temperature of the main flow, i.e., $T_W = T_0$ and $\Theta = 0$. This distance will be referred to as the range of the screen. At $m > 1$ and with the specified degree of constraint of the channel (H/s = 30, where H is the height of the channel), we obtained the following linear empirical relation for the thermal range

$$L/s = 15.3\,(m - 1). \tag{1}$$

It also follows from the experimental data in Fig. 3 that the initial section x_0 on which screen efficiency is nearly constant and is close to unity is present only for high jet injection velocities (for $m > 1.2$, as was shown in the tests). The length of the initial section with counter-current injection is considerably shorter than the length of the initial section with co-current injection and is described by the empirical relation

$$x_0/s = 9m - 11. \tag{2}$$

At injection parameters less than 1.2, wall temperature begins to change immediately after the slit and there is no initial section. With a further decrease in m, wall temperature begins to differ from the temperature of the injected gas T_S at the edge of the slit. This leads to a situation whereby the initial efficiency of the screen $\Theta_1 = (T_{W1} - T_0)/(T_S - T_0)$ becomes less than unity at the outlet of the slit. Here, T_{W1} is the temperature of the wall in the cross section corresponding to the edge of the slit. This phenomenon is absent in the case of a co-current screen. Figure 4 shows the experimental dependence of Θ_1 on m. It is evident that the boundary where the effect of m on Θ_1 begins to differ is where the velocities of the jet and incoming flow are roughly equal. At $m < 1.2$, initial efficiency decreases with a decrease in m, while at $m > 1.2$ it is nearly independent of the velocity ratio and is equal to approximately unity.

To explain the reduction in initial efficiency, we analyzed temperature profiles at the edge of the slit with m = 1.5, 0.7, 0.5, 0.3 (points 1-4 in Fig. 5). It is evident from the graph that at m = 1.5 the temperature profile at the edge is uniform ($T \approx T_{W1} \approx T_S$) and $\vartheta \approx 1$. At m = 0.7 and 0.5, a region with a lower temperature appears in the temperature profile on the side of the bottom wall of the channel. The presence of this region is connected with penetration of the cold main flow inside the slit along the bottom wall of the channel and the mixing of this flow with the jet. With an injection parameter m = 0.3, there will obviously be greater penetration of the main flow into the slit and, thus, a decrease in temperature over the entire height of the slit. The experimental data shown in Fig. 5 confirm the hypothesis made in [2] regarding the possibility of penetration of the main flow inside the slit and its interaction with a counter-flowing wall jet in the case of low values of m as well.

After analyzing our experimental data, we obtained a generalizing relation to calculate the efficiency of a screen consisting of a counter-current wall jet in the region $x < L$

$$\Delta\Theta = 1 - \exp(-0.25\Delta x/s) \; (\Delta\Theta = \Theta - \Theta_1, \; \Delta x = x - x_0). \tag{3}$$

Thus, to determine the efficiency of a counter-current screen, it is necessary to know its value at the edge of the slit Θ_1, the length of the initial section x_0, and the thermal range L. All of these parameters were determined in the tests and are described above. The experimental results are satisfactorily generalized by the proposed relation, as can be seen from Fig. 6. In the figure, the points 1-6 correspond to m = 2.6, 2.1, 1.5, 0.7, 0.5, 0.3, while point 7 was calculated from Eq. (3).

It is interesting to compare the length of the initial section and the thermal range calculated from Eqs. (1) and (2) with the corresponding sections of the path of the wall jet (see Fig. 2). It should be noted that the length of the initial section of the jet nearly corresponds to the region of its propagation along the channel wall.

Also, the thermal range L obtained from the change in temperature along the adiabatic wall and found from (1) turns out to be somewhat greater than the depth of penetration of the counter-current jet found from the lines of maximum temperature. This is apparently connected with the fact that when the jet moves away from the wall at the end of its rotation zone, vortex structures are formed near the surface [4]. The formation of these structures leads to intensive mixing of the flows and an increase in range near the wall.

The completed study revealed characteristic features of the thermal mixing of a wall jet with an incoming flow. The experimental data obtained permits the conclusion that a counter-current wall jet can be used for regulatable hydrodynamic protection of a surface upstream from the site of injection. The data also makes it possible to determine the characteristics of such a screen.

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