EFFECT OF THE GRADIENT OF THE VELOCITY OF THE FLOW ON THE EFFECTIVENESS OF A GAS CURTAIN IN AXISYMMETRIC NOZZLES

É. P. Volchkov, V. K. Koz'menko, and V. P. Lebedev

UDC 532.526.4

The protection of surfaces from the thermal action of gas flows by setting up cooling curtains is carried out in practice under conditions where acceleration of the flow and its compressibility can have a considerable effect on the effectiveness of the flow. The creation of methods for calculating the effectiveness of gas curtains for such flows and their experimental verification remains an important practical problem. The existing experimental investigations in this field have been mainly made for plane subsonic flows with small velocity gradients of the main flow [1-7].

The present article gives experimental data on the effect of a strong acceleration of an axisymmetric flow on the effectiveness of a thermal curtain. The curtain is formed by blowing air along the surface of an axisymmetric nozzle through an annular slit with a height of 2.7 mm, arranged at the inlet to the nozzle.

The experiments were made in a continuous aerodynamic tube, having the following main parts: an inlet conical diffuser, a forechamber with equalizing grids, a verger, a feed chamber for the injected gas, the working section, an outlet cylindrical channel, and a noise absorber.

The working section is a supersonic conical nozzle made of textolite. The experiments were made using two nozzles having an identical geometry of their supersonic and near-critical parts. The subsonic parts of the nozzles differ in the half-angles of the conical region, equal to 30 and 60°. This permits setting up different accelerations of the flow, corresponding to maximal values of the velocity gradient of $2.2 \cdot 10^4$ and $4.2 \cdot 10^4$ sec^{-1}. Figure 1 gives the scheme of one of the nozzles and shows its principal geometric dimensions (in mm). The calculated Mach number at the outlet of the nozzle is equal to 3.4. Along the nozzle, Nichrome–Constantan thermocouples, made of wire with a diameter of 0.2 mm, are let in flush with the internal surface, along one of the generatrices of the nozzle. In the same cross sections where the thermocouples are installed, there are openings with a diameter of 0.4 mm for measuring the static pressure at the wall. The holes in different cross sections are located at different generatrices of the nozzle.

In the experiments described, a thermocouple was used to measure the stagnation temperature of the main and secondary flows, and the temperature of the gas at the wall along the nozzle was determined with and without a curtain. The electromotive force of the thermocouples was measured with an R-348 class 0.002 potentiometer and an electronic digital ampere–voltmeter F-30. The total pressure and velocity of the flow were measured at the inlet to the nozzle. The dynamic head was recorded using a DT-50 differential manometer. The total pressure was measured with a standard manometer. The static pressure at the wall along the nozzle was recorded using a GRM-2 class 0.5 group recording manometer and, in regions of low pressures,

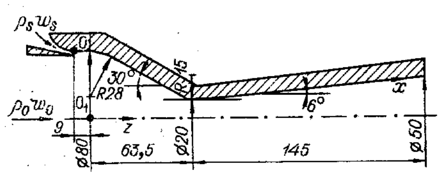

Fig. 1

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 67-73, March-April, 1977. Original article submitted May 4, 1976.

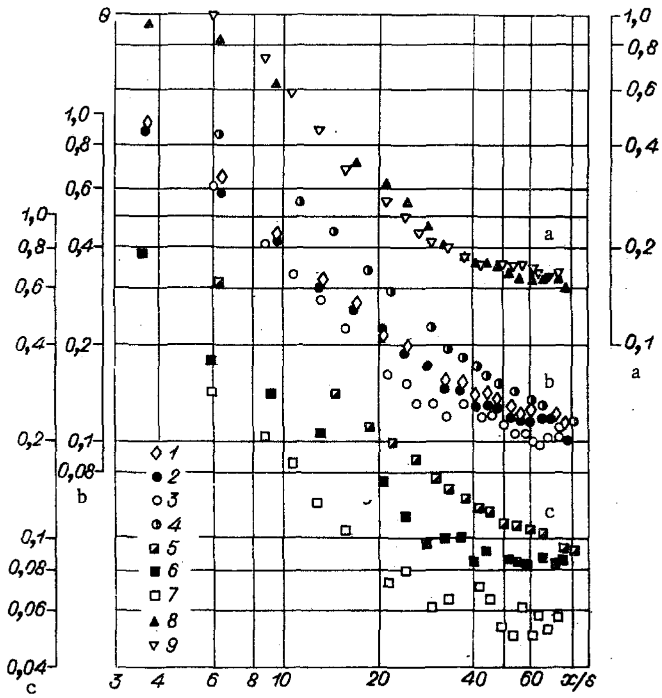

Fig. 2

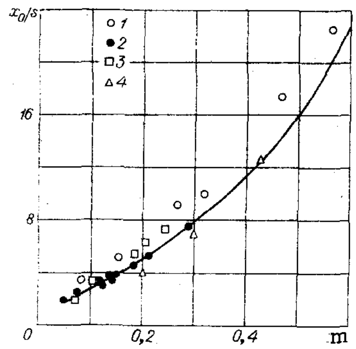

Fig. 3

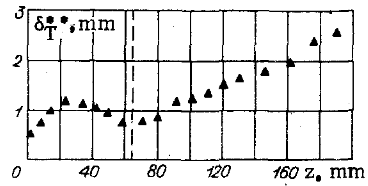

Fig. 4

with standard manometers and vacuum meters. The field of the velocities of the main and secondary flows in a cross section of the slit was measured using a total-head tube with a height of 0.36 mm. The mass flow rate of the injected air was determined using a calibrated flow-measuring disk.

The air of the main flow was fed into the working section from a system with a pressure up to 20 tech. atm. The mass flow rate of the air was 0.3-1.0 kg/sec. The velocity at the inlet to the nozzle was 14-15 m/sec and the stagnation pressure $p_0 = 5 \cdot 10^5 - 15 \cdot 10^5$ N/m^2. The stagnation temperature of the main flow varied from 20 to 35°C. The injected air was heated by electric heaters up to 80-100°C. The ratio of the mass velocities of the main and secondary flows $m = \rho_s w_s / \rho_0 w_0$ in the experiments varied from 0.05 to 0.30 (ρ_0, w_0 and ρ_s, w_s are the densities and the velocities of the main and secondary flows in a cross section of the slit).

The experiments started with an investigation of the dynamics of the flow in the inlet part of the nozzle. The uniformity of the field of the velocities of the main and secondary flows and the presence of fully developed turbulent flow at the inlet to the nozzle were demonstrated. The thickness of the boundary layer of the main flow in a cross section of the slit was ~3 mm and, in the secondary flow, 0.5 mm. Further, the distribution of the static pressure at the wall along each nozzle was measured. Measurements were made in experiments with the blowing of air through a slit and without blowing. It was found that slit injection has practically no effect on the distribution of the static pressure at the wall in the whole investigated region of change in the relative blowing parameter ($m < 0.30$). The experimental data are in good agreement with a calculation for a one-dimensional isentropic flow. Then an investigation was made of the dynamic effect of blowing on the distribution of the adiabatic temperature of the gas at the wall along the nozzle. For this purpose, the air fed had an adiabatic stagnation temperature at the wall in the cross section equal to the stagnation temperature of the main flow. The experiments showed the independence of the adiabatic temperature at the wall of isoenergetic slit blowing. The experimental data correspond with an accuracy of 1% to a calculation using the formula

$$T_w^*/T_0 = \left(1 + r\frac{k-1}{2}M^2\right) \Big/ \left(1 + \frac{k-1}{2}M^2\right)$$

with a recovery coefficient r = 0.9 (T_0 is the stagnation temperature of the gas in the core of the flow; M is the Mach number). Thus, the experiments carried out (with m < 0.3) showed the absence of a dynamic effect of slit blowing on the parameters of the main flow at the wall.

To find the effect of acceleration of the main flow on the effectiveness of a gas curtain, a comparison was made of experimental data in nozzles with different velocity gradients of the flow and data on the effectiveness of a curtain in a flow without a gradient. The latter were obtained in a cylindrical channel made of textolite with a diameter of 80 mm and the same geometry of the slit. In these experiments, m = 0.1-0.6 and w_0 = 25-80 m/sec. The experimental data in a cylinder are well correlated by a dependence obtained in [8] for gradientless flow:

$$\Theta = \left[1 + 0.25\frac{\mathrm{Re}_{\Delta x}}{\mathrm{Re}_s^{1.25}}\left(\frac{\mu_s}{\mu_s}\right)^{1.25}\right]^{-0.8}, \quad (1)$$

where $\mathrm{Re}_{\Delta x} = \rho_0 w_0 \Delta x/\mu_0$; $\mathrm{Re}_s = \rho_s w_s s/\mu_s$; $\Delta x = x - x_0$; μ_0 and μ_s are the viscosities of the main and injected gas flows at their stagnation temperatures; s is the height of the slit; and x_0 is the length of the initial section, i.e., the distance along the wall downstream from the outlet cross section of the slit, at which the effectiveness of the curtain is equal to unity. The determination of the effectiveness of the curtain, given in the form [8]

$$\Theta = (T_w^* - T_w) / (T_w^* - T_w)_1, \quad (2)$$

is applicable to any arbitrary flows of the main stream. Here T_w and T_w^* are the temperatures of the gas at an adiabatic wall with and without a curtain, respectively; the subscript 1 means that the indicated values of the temperature were taken in the outlet cross section of the slit. The experimental data on the effectiveness of a curtain in two nozzles with different angles of constriction and in a cylinder were analyzed using formula (2). It was found that in any of the three working sections the experimental data stratify depending on the relative mass rate of blowing m; the effectiveness rises with an increase in m. Comparing the experimental data in different working sections with identical values of m, the effect of acceleration of the flow on the effectiveness of a gas curtain can be clarified.

Figure 2 gives data from experiments on the effectiveness of a gas curtain in nozzles and in a cylinder; the experiments of each of the groups a, b, and c have close values of m. The effectiveness of the curtain Θ is given as a function of the relative distance x/s, where x is reckoned from the outlet cross section of the slit along the generatrix. Some of the laws governing the change in Θ along the surface can be demonstrated using the example of the experiments b, carried out with m = 0.15. From a comparison of experiments 1 and 2 in a nozzle with a half-angle of the subsonic part equal to 30°, made, respectively, with $p_0 = 11.7 \cdot 10^5$ N/m², it can be seen that for an arbitrary value of x/s the value of Θ in the subsonic part of the nozzle in these experiments is practically identical. This regularity is retained in the whole investigated region of change in p_0.

An analysis of the experimental data showed that the effectiveness of a gas curtain is lowered with an increase in the velocity gradient of the main flow. Thus, for example, with m = 0.15, the maximal lowering of the effectiveness of a curtain in comparison with a gradientless flow (experiment 4, $p_0 = 1.3 \cdot 10^5$ N/m²) in a nozzle 30 − 6° is equal to 30% (experiment 2, $p_0 = 7.2 \cdot 10^5$ N/m²), and in a nozzle 60 − 6°, 40% (experiment 3, $p_0 = 7.2 \cdot 10^5$ N/m²). From a comparison of the experiments a, b, and c it can be seen that, with an increase in m, there is a decrease in the effect of the velocity gradient of the flow on the effectiveness of a curtain [experiments a: 8) nozzle 30 − 6°, m = 0.22; 9) nozzle 60 − 6°, 0.21; experiments c: 5) cylinder, m = 0.09; 6) nozzle 30 − 6°, m = 0.07; 7) nozzle 60 − 6°, m = 0.07]. For all the experiments, in the nozzles a different character of the rate of decrease in the effectiveness of a curtain in the subsonic and supersonic parts is characteristic. The decrease in the rate of drop of the effectiveness in the supersonic part of the nozzles can be explained by the effect of the compressibility of the flow. Thus, on the basis of the experiments made, it can be argued that in the subsonic part of a nozzle acceleration of the flow lowers the effectiveness of a gas curtain.

The question of the effect of the velocity gradient of the flow on the value of the initial section is of interest, since this value plays a significant role in the correlation of experimental data on the effectiveness of a curtain. The value of x_0 was determined from the experimental data using a method proposed in [9]. It was found that acceleration has practically no effect on the length of the initial section. This is confirmed by the data of Fig. 3, where values of x_0/s are given as a function of m for: 1) a cylinder; 2) nozzle 30 − 6°; 3) nozzle

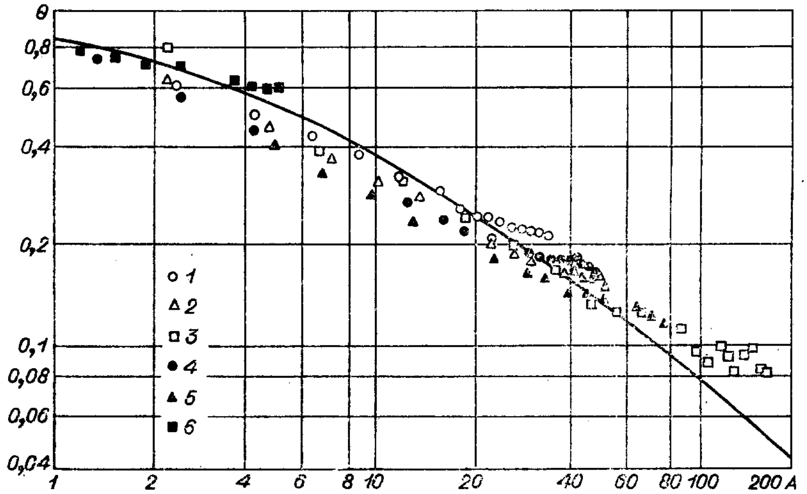

Fig. 5

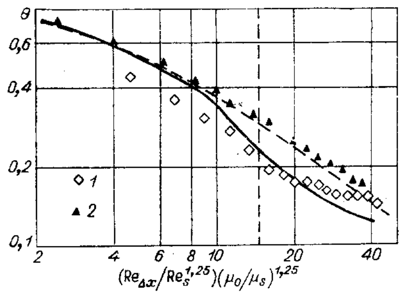

Fig. 6

60 − 6°; 4) a plate [9]. Satisfactory agreement is observed between the experiments and calculation for a plane semibounded jet, in accordance with the formula [10]

$$\frac{x_0}{s} = \left[\frac{\delta_0}{x_0} \pm 0.27\left(0.416 + \frac{0.134}{m}\right)\frac{m-1}{m+1}\right]^{-1}.$$

The experimental data obtained on the effectiveness of a gas curtain permit evaluating the character of the change in the thickness of the energy losses in nozzles with adiabatic walls. From the integral relationship of the energy at an impermeable surface under the conditions of a surface it follows that [8]

$$\Theta = \frac{(\mathrm{Re}_T^{**})_1}{\mathrm{Re}_T^{**}}\frac{D_1}{D}, \tag{3}$$

where Re_T^{**} is the Reynolds number, constructed with respect to the thickness of the energy losses δ_T^{**} at an adiabatic wall; D is the instantaneous diameter of the channel; and the subscript 1 relates to the outlet cross section of the slit. Since, with a slit-type organization of the curtain, $(\mathrm{Re}_T^{**})_1 = \mathrm{Re}_s(\mu_s/\mu_0)$, then from (3) the following expression is obtained for δ_T^{**}:

$$\delta_T^{**} = \frac{ms}{\Theta}\frac{D_1}{D}. \tag{4}$$

Figure 4 gives values of δ_T^{**} in a nozzle with a half-angle of the subsonic conical part of 30°, calculated from the experimental data of an experiment with m = 0.15 using formula (4). The dashed line marks the critical cross section of the nozzle.

Correlation of experimental data on the effectiveness of a gas curtain in accelerated flows is of great practical importance.

A method for calculating the effectiveness of a curtain in a flow of compressible gas with an arbitrary distribution of the velocity at the external boundary of a turbulent boundary layer is set forth in [8]. For axisymmetric flow in nozzles with the blowing of a cooling gas through a slit, from (3) an expression is obtained for the effectiveness of the curtain:

$$\Theta = \left[1 + 0.25\left(\frac{D_{cr}}{D_0}\right)^{1.25} \frac{\mathrm{Re}_{cr}}{\mathrm{Re}_s^{1.25}} \left(\frac{\mu_0}{\mu_s}\right)^{1.25} \int_{\bar{x}_0}^{\bar{x}} \Psi_T \Psi_M \left(\frac{\mu_w}{\mu_0}\right)^{0.25} \left(\frac{D_{cr}}{D}\right)^{0.75} d\bar{x}\right]^{-0.8}, \quad (5)$$

where

$$\Psi_T = \left(\frac{2}{\sqrt{\psi}+1}\right)^2, \quad \psi = T_w/T_0; \quad \Psi_M = \left[\frac{\mathrm{arctg}\, M \sqrt{r\frac{k-1}{2}}}{M\sqrt{r\frac{k-1}{2}}}\right]^2;$$

$$\mathrm{Re}_{cr} = 4G/\mu_0 \pi D_{cr}; \; \bar{x} = x/D_{cr}, \; \bar{x}_0 = x_0/D_{cr};$$

D_{cr} is the diameter of the critical cross section of the nozzle; D_0 is the diameter at the end of the initial section; and $G=\rho w \pi D^2/4=\mathrm{const}$ is the mass flow rate of the main flow.

The experiments in nozzles were worked up using formula (5). Taking account of the quasiisothermal conditions of these experiments, it can be assumed that $\Psi_T=1$, $(\mu_w/\mu_0)^{0.25}=1$. The experimental data were correlated using the complex

$$A = \left(\frac{D_{cr}}{D_0}\right)^{1.25} \frac{\mathrm{Re}_{cr}}{\mathrm{Re}_s^{1.25}} \left(\frac{\mu_0}{\mu_s}\right)^{1.25} \int_{\bar{x}_0}^{\bar{x}} \Psi_M \left(\frac{D_{cr}}{D}\right)^{0.75} d\bar{x}.$$

Figure 5 gives the results of a correlation of some of the experimental data in nozzles. The experiments in a nozzle 30 – 6° (open symbols) were made with: 1) m = 0.29; 2) m = 0.22; 3) m = 0.08; the experiments in a nozzle 60 – 6° (dark symbols) were made with: 4) m = 0.21; 5) m = 0.13. The same figure gives experimental data on the effectiveness of a curtain in a flat nozzle from [7] (points 6). The curve in Fig. 5 represents calculation using formula (5). To clarify the way in which this formula takes account of the acceleration and compressibility of the flow, in Fig. 6 we compare a calculation of the effectiveness using formula (5) with a calculation of the effectiveness using formula (1) for a gradientless flow (the solid and dashed lines, respectively).

These experiments are compared with the data of an experiment in a nozzle 30 – 6° with m = 0.22 (points 1), analyzed with respect to the inlet parameters of the main flow. The same figure gives experimental data in a cylinder (points 2). It is evident that calculation using formula (5) better reflects the character of the change of the effectiveness in a nozzle than calculation using formula (1), although it can be noted that formula (5) increases the value of Θ in the subsonic part of the nozzle and lowers it in the supersonic part. A calculation using formula (5) corresponds best of all to experimental data in the region of the critical cross section. At the same time it can be noted that formula (1) can be used for evaluation of Θ in nozzles, particularly in the subsonic and supersonic parts, if, in it, $\mathrm{Re}_{\Delta x}$ is calculated with respect to the inlet values of the density and velocity of the main flow.

Thus, experiments on determination of the effectiveness of slit-type blowing with accelerated axisymmetric flow of the main stream have made it possible to evaluate the effect of the velocity gradient of the main flow on the effectiveness of a curtain, and confirm the possibility of the successful use of dependence (5) for the correlation of experimental data on the effectiveness.

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STABILITY OF A PLANE JET IN A MEDIUM WITH RELAXATION

V. V. Sobolev and O. Yu. Tsvelodub UDC 532.5

1. Presentation of the Problem and Basic Equations. Let us consider the stability (relative to infinitely small perturbations) of the steady-state jet flow of a liquid having the following equation of state [1, 2]:

$$\delta p = c_0^2 \delta\rho + \beta \frac{d}{dt}\delta\rho + \varkappa \frac{d^2}{dt^2}\delta\rho, \tag{1.1}$$

where δp and $\delta\rho$ are small perturbations of pressure and density; c_0 is the velocity of sound in the medium; and β and $\varkappa$ are the relaxational viscosity and dispersion coefficients. A detailed derivation of the equations was given in [2, 3] for perturbations of the velocity v and pressure p. If we express the perturbed quantities in the form

$$f(x, y, z, t) = f(y) \exp\left[i\alpha(x - ct) + i\gamma z\right],$$

where f is the perturbation of the pressure, density, or velocity components; x, y, z are the spatial coordinates; α, γ are the wave numbers; and c is the velocity ($c = c_r + ic_i$); the equations for the two-dimensional perturbations v(y) and p(y) take the form [3]

$$v'' - V'(V-c)Av' - \left(B + \frac{V''}{V-c} - AV'^2\right)v = 0; \tag{1.2}$$

$$p'' - \frac{2V'}{V-c}p' - Bp = 0,$$

$$A = \frac{M^2(2 + i\alpha\beta M^2(V-c))}{(1 + i\alpha\beta M^2(V-c) - \varkappa\alpha^2 M^2(V-c)^2)(M^2(1+\varkappa\alpha^2)(V-c)^2 - i\alpha\beta M^2(V-c) - 1)}, \tag{1.3}$$

$$B = \alpha^2(1 - M^2(V-c)^2/(1 + i\alpha\beta M^2(V-c) - \varkappa\alpha^2 M^2(V-c)^2)),$$

where V is the velocity profile of the main flow; M is the Mach number ($M = V_{max}/c_0$). In this paper we have

$$V = 1/\mathrm{ch}^n y, \tag{1.4}$$

where n is a natural number.

The problem as to the stability of steady-state flow (1.4) reduces to a determination of the eigenvalues of c for the equations (1.2), (1.3). The stability may be studied on the basis of Eqs. (1.2), (1.3) for two-dimensional perturbations, since it may be shown that the problem of stability relative to three-dimensional perturbations is equivalent to the problem of stability relative to two-dimensional perturbations with a smaller Mach number and a larger parameter β.

The boundary conditions for Eqs. (1.2), (1.3) involve the requirement that v and p should be finite at $y = \pm\infty$.

Let us consider some relationships for c. The semicircular theorem limiting the range of unstable eigenvalues for parallel flows in an incompressible stratified liquid was proved in [4]. Let us consider the conditions

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 73-78, March-April, 1977. Original article submitted March 29, 1976.