EFFECTIVENESS OF A GAS CURTAIN IN LAVAL NOZZLES UNDER NONRATED FLOW CONDITIONS

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

UDC 532.526

It is well known that, in the supersonic part of a Laval nozzle under reexpansion conditions, heat-transfer processes have special characteristics, brought about by interaction between shock waves and the boundary layer [1]. Under these conditions, with the organization of protection of the walls from the action of a high-temperature flow using a gas curtain, both the thermal parameters and the dynamic characteristics of the flow conditions must be taken into consideration. Experimental data at a flat plate [2] show that shock waves impinging from without considerably lower the effectiveness of curtain cooling. The present article gives experimental data on the effectiveness of a gas curtain in supersonic conical nozzles working under reexpansion conditions. The curtain is formed by blowing air through a annular slit, located at the inlet to the nozzle. The experimental results are compared with test data obtained in these same nozzles under rated flow conditions.

A description of the experimental unit, the measuring apparatus, and the measurement methods is given in [3]. The working sections, interchangeable supersonic conical nozzles, are made of textolite. The experiments were made using nozzles 30-6° (α_1 = 30° and α_2 = 6° are the half-angles of the subsonic and supersonic conic parts, respectively) and 30-15°. The nozzles had identical diameters of their inlet (D_+ = 80 mm) and critical cross sections (D_* = 20 mm). The contour of the nozzle in the inlet part and in the region of the throat is made in the form of an arc of a circle, with radii amounting to 0.7 and 1.5 of the radii of the corresponding transverse cross sections. The diameter at the outlet for the nozzle 30-6° is equal to 50 mm, and, for the nozzle 30-15°, 90 mm.

For measurement of the temperature of the wall, along one generatrix of the nozzle Nichrome–Constantan thermocouples made of wire with a diameter of 0.2 mm were let in flush with the inner surface. In the same cross sections where the thermocouples were arranged, at different generatrices of the nozzle, openings with a diameter of 0.4 mm were drilled for measurement of the static pressure.

In the experiments made, the air of the main flow had a stagnation temperature in the forechamber $T_0 \approx 300$°K, close to the temperature of the surrounding medium. The blown air was heated to $T_s \approx 360$°K on the average. The velocity of the main flow at the inlet to the nozzle was equal to 14-15 m/sec. The blowing parameter $m = \rho_s w_s / \rho_0 w_0$ = 0.1-0.7. Here ρ_0, w_0 and ρ_s, w_s are the density and velocity of the main and secondary flows in the outlet cross section of the slit. The experiments were made with a stagnation pressure of the main flow in the forechamber p_0 = 2-8 kg/cm². In this case, reexpansion conditions were observed in the nozzle 30-6° with $p_0 < 5$ kg/cm² and, in the nozzle 30-15°, in the whole investigated range of pressures.

It is well known that, under reexpansion conditions, shock waves are formed in the supersonic part of the nozzle. With small pressure drops, the shock waves in the nozzle are disposed near the critical cross section, while, with an increase in the pressure drop, they are shifted toward the outlet from the nozzle [4]. The character of the interaction between the shock waves and the boundary layer depends on different factors, specifically on the position of the shock waves and their intensity. While shock waves of small intensity only thicken the boundary layer, when some (critical) intensity of the shock wave is attained there may be a breakaway of the flow from the wall [4, 5]. The existing experimental data [1, 5-8] show that shock waves have an effect on the change in the static pressure along the nozzle. They also affect the equilibrium temperature of the wall. Therefore, a study was made of the character of the change in the static pressure and the equilibrium temperature

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 91-96, July-August, 1980. Original article submitted August 10, 1979.

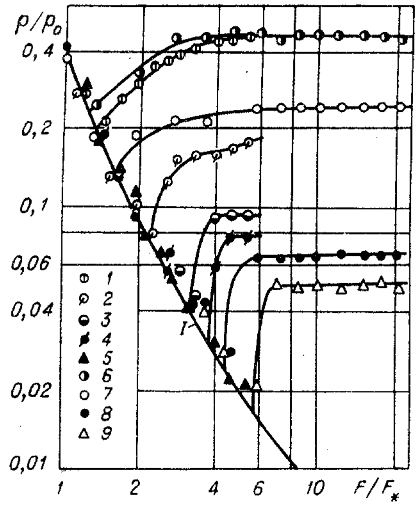

Fig. 1

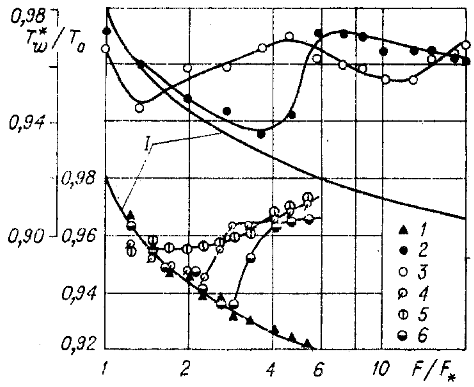

Fig. 2

along the wall of the nozzle with different sets of nonrated flow conditions.

Figure 1 shows the distribution of the pressure along the supersonic part of the investigated nozzles with different pressure drops in the nozzle. The ratio of the static pressure at the wall p to the stagnation chamber in the forechamber p_0 is given as a function of the ratio of the areas of the instantaneous F and critical cross sections F_*. Curve 1 represents calculation using the one-dimensional theory for isentropic flow according to the formula [8]

$$\frac{F}{F_*}=\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}\left(\frac{k-1}{k+1}\right)^{\frac{1}{2}}\left[1-\left(\frac{p}{p_0}\right)^{\frac{k-1}{k}}\right]^{-\frac{1}{2}}\left(\frac{p}{p_0}\right)^{-1/k}. \tag{1}$$

Under non-rated flow conditions, the pressure drop along the nozzle is well described by this formula (e.g., the experimental points 5 in the nozzle 30-6° with p_0 = 7.3 kg/cm²). An analysis of the experimental data on the pressure under non-rated flow conditions allows of the conclusion that, in the investigations carried out, there exist different types of interaction between the boundary layer and the shock waves. For example, in the experiments 1 (p_0 = 2 kg/cm²) and 2 (p_0 = 3.5 kg/cm²), starting from the region of compression of the boundary layer, the pressure rises continuously along the supersonic part of the nozzle 30-6°. As is shown in [5], in this case there is interaction without breakaway between the shock waves and the boundary layer, or incipient breakaway of the flow from the wall. Another character of the change in the pressure is observed in experiments 3 (p_0 = 4.4 kg/cm²), 4 (p_0 = 4.7 kg/cm²) in the nozzle 30-6°, and 8 (p_0 = 7.3 kg/cm²), 9 (p_0 = 8.5 kg/cm²) in the nozzle 30-15°. In these experiments, the greater fraction of the increase in the pressure takes place in the region of compression of the boundary layer; further downstream, the pressure practically does not change, forming a so-called "pressure plateau." An analogous character of the change in the pressure is observed in [1, 6, 8], where cases of breakaway flows are considered. The values of the pressure drop in the shock wave in experiments 3, 4, 8, 9 correspond to calculated values of the pressure drop, obtained in [4, 6, 9, 10]. This allows of the conclusion that, in our experiments, there is fully developed breakaway of the flow from the wall.

In the present case, to find the start and the extension of the region of interaction between the shock wave and the boundary layer, use is made of empirical relationships, generalizing the experimental data of [4, 6, 9]. For example, the start of the region of compression can be found from the known pressure drop in the nozzle, using Eq. (1) and a relationship from [6], written in the form

$$p_i/p_0=\frac{2}{3}(p_-/p_0)^{1.2}. \tag{2}$$

Here it is assumed that the pressure p_i at the start of the region of compression still corresponds to the calculated value for one-dimensional isentropic flow, and the pressure at

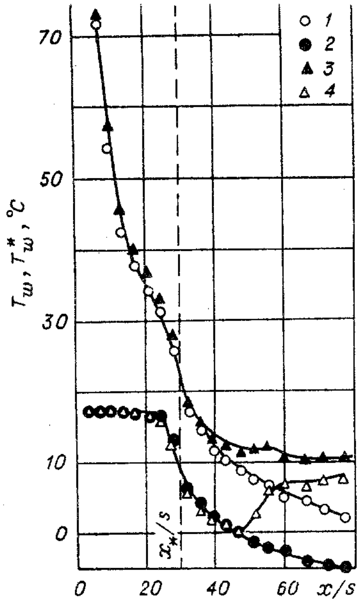

Fig. 3

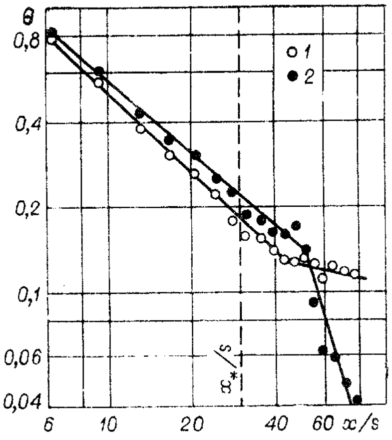

Fig. 4

the outlet from the nozzle p_- is close to the pressure behind the shock wave. In our experiments, with fully developed breakaway of the flow, the Mach number at the point with the pressure p_i varied from 2.4 to 3.4.

We note the special characteristics of breakaway flows in the nozzle 30-15°, where the shock waves are located near the critical cross section (experiments 6 represent p_0 = 2 kg/cm^2; experiments 7 represent p_0 = 3.6 kg/cm^2). In these cases, there is instability of the pressure readings at the start of the region of compression of the boundary layer. The low-frequency pulsations of the pressure of large amplitude in these experiments are due to a periodic shift of the start of the region of compression along the wall of the nozzle. Analogous conditions have been observed in the experiments of other authors [1, 4].

Thus, in our experiments, in the region of interaction between the boundary layer and the shock waves, there were both flow without breakaway or flow with incipient breakaway, and fully developed breakaway of the flow from the wall.

The equilibrium temperature of gas T_w^*, i.e., the temperature at an adiabatic wall in the absence of a gas curtain, for different types of nonrated flows, varies differently along the nozzle. This can be seen from Fig. 2, where the results of some experiments on the change in T_w^* along the supersonic part of the nozzle are worked up in the form of a dependence of T_w^*/T_0 on F/F_*. In this case, for each set of flow conditions, the experimental data on the pressure and the temperature in Figs. 1 and 2 have identical legends.

Under rated flow conditions (e.g., the experimental points 1 in the nozzle 30-6°), the change in the equilibrium temperature of the wall corresponds to the theoretical dependence for one-dimensional isentropic flow with the recovery coefficient r = 0.885 (curve I), in accordance with the formula

$$T_w^*/T_0 = \left(1 + r\frac{k-1}{2}M^2\right)\Big/\left(1 + \frac{k-1}{2}M^2\right). \tag{3}$$

Under all sets of reexpansion conditions, in the region of interaction between the shock waves and the boundary layer, the temperature of the wall rises along the nozzle. However, while the flow without breakaway, T_w^*, rises along the whole region of interaction (experimental points 5 in the nozzle 20-6°) with fully developed breakaway of the flow from the wall, T_w^* rises sharply in the region of compression of the boundary layer; further on, in the region of the "pressure plateau," it varies only insignificantly (experimental points 6 in nozzle 30-6°, and 2 in nozzle 30-15°). Under flow conditions where there was a periodic shift of the start of the region of breakaway along the wall (e.g., experimental points 3 in nozzle 30-15°), there was a vibrational change in the temperature T_w^* along the breakaway region.

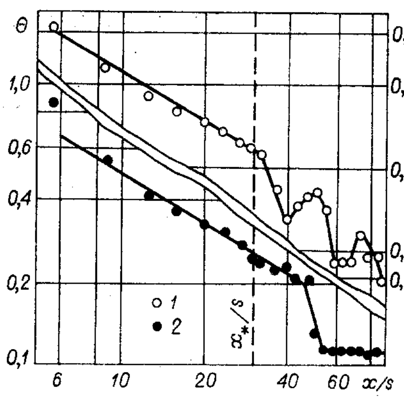

Fig. 5

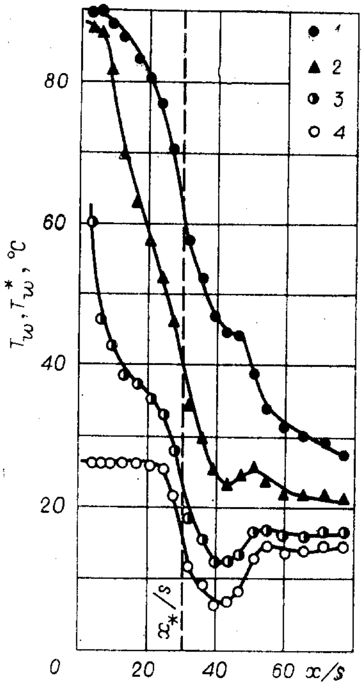

Fig. 6

As can be seen from this examination, the equilibrium temperature of the wall under reexpansion conditions can be calculated using formula (3) only up to the region of the compression of the boundary layer, while further along the nozzle its behavior is determined by the character of the interaction between the shock waves and the boundary layer.

Let us examine the effect of a gas curtain on the temperature of a heat-insulated wall of the nozzle under reexpansion conditions. In the experiments made, at the inlet of the nozzle "hot" air was fed through a slit, i.e., T_s was greater than T_0. As under rated flow conditions [3, 11], the effectiveness of a gas curtain was determined at each point of the nozzle from the difference between the adiabatic temperature of the wall T_w (with blowing) and the equilibrium temperature of the wall T_w^* (without blowing). In these experiments, these temperatures were found experimentally. Figure 3 gives the original experimental data for rated (p_0 = 7.3 kg/cm²) and nonrated (p_0 = 3.5 kg/cm²) flow conditions in the nozzle 30-6° with T_0 = 17.2°C, T_s = 85°C, m = 0.19. In each experiment, let us compare the temperature T_w with the temperature T_w^*. Under nonrated conditions, the difference between these temperatures (points 3 and 4, respectively) in the zone of the action of shock waves decreases appreciably downstream, pointing to intensive mixing of the gas fed to the curtain with the gas of the main flow. With flow without shock waves, this kind of intensive mixing does not take place, and the difference in the temperatures of the wall under the conditions of a curtain (points 1) and without a curtain (points 2) varies only slightly along the length of the nozzle. All this argues that shock waves worsen the quality of a curtain.

The effectiveness of a gas curtain is determined by the expression [3]

$$\Theta = (T_w - T_w^*)/(T_w - T_w^*)_1, \tag{4}$$

(the subscript 1 indicates that the values of the temperatures were taken in the outlet cross section of the slit). Since the blowing is done in the subsonic part of the nozzle, then, $(T_w - T_w^*)_1 = T_s - T_0$. The change in the effectiveness of the gas curtain Θ for the experiments discussed above is shown in Fig. 4. The coordinate x is reckoned along the generatrix of the nozzle from the outlet of the slit; x_* is its value in the critical cross section; s is the height of the slit, equal to 2.7 mm. From Fig. 4 it can be seen that, in the supersonic part, shock waves led to a strong lowering of the efficiency of the curtain (up to 300% at the end of the nozzle). It must be noted that, for the nonrated flow conditions without breakaway under consideration here, the values of Θ in the zone of action of the shock waves fall continuously along the length of the nozzle.

For cases where shock waves result in breakaway of the flow, the change in the efficiency of a gas curtain in the zone of the shock wave differs somewhat from that just considered. Figure 5 illustrates typical experiments in the nozzle 30-15° for two sets of conditions: 1) $p_0 = 3.5$ kg/cm², $m = 0.17$; 2) $p_0 = 7.3$ kg/cm², $m = 0.2$ (the pressure and the equilibrium temperature for these experiments are shown in Figs. 1 and 2, respectively). In experiment 1, for which an unstable geometry of the start of the region of compression of the boundary layer is characteristic, there is a vibrational change in Θ along the supersonic part of the nozzle (the shock wave is located immediately following the critical cross section). In experiment 2, in which there is fully developed breakaway of the flow from the wall, the effectiveness of the gas curtain in the region of compression falls sharply; further downstream, it changes only slightly. In experiments analogous to the latter, the difference in the values of Θ under the corresponding rated and nonrated conditions attains 200% at the end of the nozzle.

Thus, expression (4) holds out the possibility of evaluating the breakdown effect of shock waves on a gas curtain. However, shock waves also have another effect: compression of the boundary layer brings about an increase in the adiabatic temperature of the wall. In the case where the gas curtain cools the wall ($T_0 > T_S$), both of these factors lead to an undesirable increase in T_W. However, with heating of the wall by a "hot" blown gas ($T_S > T_0$), breakdown of the gas curtain is an undesirable factor, while an increase in the temperature in the region of compression is a favorable factor, since it promotes heating of the wall. If the shock waves are situated at a great distance from the point of blowing, where the curtain has already been strongly mixed, compression of the flow at the shock wave exerts the principal effect on the adiabatic temperature of the wall. Just such a phenomenon can also be observed in certain of our experiments with "hot" blowing with small blowing parameters. For example, under nonrated conditions, shown in Fig. 3, the adiabatic temperature of the wall (points 3) in the region of the action of the shock waves exceeds the corresponding values of T_W under rated conditions, i.e., in the absence of shock waves (points 1). However, with an increase in the blowing parameter m, the effect of blowing becomes predominant. This is shown in Fig. 6, which gives experimental data for nozzle 30-6° with $p_0 = 3.5$ kg/cm² and the following values of the blowing parameter and the temperature of the blown air: 1) $m = 0.66$, $T_S = 92.8$°C; 2) 0.32, 92.6°C; 3) 0.12, 67.1°C; 4) $m = 0$, $T_0 = 26.3$°C. It can be seen that, with small blowing parameters, the adiabatic temperature of the wall with a curtain in the zone of action of the shock waves can even rise, while, with large blowing parameters, it falls continuously.

Calculations, however, show that the effectiveness of a gas curtain, defined in accordance with formula (4), has an identical character for all the experiments (as in experiments 2 in Fig. 4), i.e., Θ falls sharply in the region of interaction between the shock waves and the boundary layer.

Thus, the effectiveness of a gas curtain under reexpansion conditions can be evaluated in the following way. From the outlet of the slit up to the start of the region of compression, determined using Eq. (2), the efficiency must be calculated using the method for rated flow conditions [3, 11]. Starting from the region of compression of the boundary layer, the efficiency of the curtain depends on the character of the interaction between the shock waves and the boundary layer and, in our experiments, decreases by 2-3 times.

LITERATURE CITED

1. L. Beck, P. Massier, and R. Kaffel, "Measurement of heat transfer in a supersonic nozzle in the zone of breakaway of the flow due to a shock wave," Raketn. Tekh. Kosm., No. 5 (1968).
2. Yu. V. Baryshev, A. I. Leont'ev, and V. I. Rozhdestvenskii, "Heat transfer in the region of an interaction between a shock wave and a boundary layer," in: Heat Transfer and Physical Gas Dynamics [in Russian], Nauka, Moscow (1974).
3. É. P. Volchkov, V. K. Koz'menko, and V. P. Lebedev, "Experimental investigation of the efficiency of a gas curtain in a supersonic axisymmetrical nozzle," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, 2, No. 8 (1977).
4. M. Arens and E. Spigler, "Breakaway of the flow in reexpanded jet nozzles with a conical supersonic section with the interaction between a shock wave and a boundary layer," Raketn. Tekh. Kosm., No. 3, (1963).
5. P. Chen, Breakaway Flow, [Russian translation], Vol. 1, Mir (1972).

6. S. Colt and D. L. Bedel, "Characteristics of a conical rocket nozzle in flow with breakaway from the wall," Vopr. Raketn. Tekh., No. 3 (1966).
7. A. I. Tolmanov and V. V. Filatov, "Breakaway of a turbulent boundary layer with its interaction with a shock wave in an accelerated supersonic flow," Uch. Zap. TsAGI, Vol. 4, No. 3 (1973).
8. O. S. Zelenkov and A. V. Yurkov, Uch. Zap. LGU, No. 338 (1968).
9. Yu. A. Panov and A. I. Shvets, "Breakaway of a turbulent boundary layer in a supersonic flow," Prikl. Mekh., 2, No. 1 (1966).
10. G. N. Abramovich, Applied Gas Dynamics [in Russian], Nauka, Moscow (1969).
11. É. P. Volchkov, V. K. Koz'menko, and V. P. Lebedev, "Experimental investigation of the efficiency of a gas curtain in supersonic nozzles," in: Heat and Mass Transfer V, Vol. 1, Convective Heat and Mass Transfer [in Russian], Part 2, Minsk (1976).

CALCULATION OF THE NONLINEAR AERODYNAMIC CHARACTERISTICS OF A WING OF FINITE SPAN

V. A. Algazin

UDC 533.6.013.2

Problems of setting up the methods of calculation and the calculation of a flow around thin wings of finite span moving with large angles of attack in an ideal incompressible liquid were considered in [1-5]. Common to all methods is successive linearization of the problems with respect to time and modelling of the wing and the shroud behind it by vortical surfaces. In [1-3] these surfaces are replaced by a discrete system of vortical segments of constant intensity. In [4] the surface modeling the wing is replaced by a system of vortex rings which is analogous to the system being used in [1], while the account of the vortex shroud is based on the spatial discretization of the vortex vector which varies with the duration of time in accordance with the Helmholtz equation. At the basis of the algorithm [5] there lies a spline approximation of the intensity of the vortical surface by a function whose form takes into account the singularities of the flow close to the edges of the wing.

In the present work we have obtained a general system of nonlinear equations of the problem of flow around a wing of finite span moving in an ideal incompressible liquid from the state of rest. This system is solved by successive linearization [1-5] for a series of discrete time instants. The coordinates of points of the vortex shroud are determined, in contrast to [1-5], according to a difference expression of the second order. The solution of the linear problem (on each step in time) is constructed by means of the method of [5] which is modified so that the approximation of the intensity of the vortical layer by spline functions of special form is used only when establishing a connection between the various components of the discrete singularities.

The numerical calculations have been carried out within the framework of a model which takes into account the vortex shroud emerging only from the rear edge of the wing. The convergence of the method within the framework of this model was established numerically. The problem concerned with the influence of the order of approximation of the intensity of the vortical layer and the magnitude of the step in time on the stability of computation is considered; the structure of the vortex shroud behind the wind and its influence on the aerodynamic characteristics of rectangular wings with different lengthening, and also dependence of the force of drag and the efficiency of a waving wing on the Strouhal number are investigated.

1. We consider the motion of a thin wing of finite span in an ideal incompressible liquid. We introduce the right-handed rectangular system of dimensionless (referred to the length of root chord b of the wing) coordinates $O_1x_1y_1z_1$, at an infinitely remote point of which the liquid is at rest. Let at the instant of time $\tau = 0$ the wing begin motion from the state of rest at a certain given velocity $V(x_1, y_1, z_1, t)$, where $t = V_0\tau/b$, while V_0 is

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 97-107, July-August, 1980. Original article submitted November 30, 1979.

 0021-8944/80/2104-0516$07.50