EFFECT OF THE WAKE ON FLOW IN AN ANNULAR JET

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UDC 534.82:532.525.2

The flow of an annular jet in a channel is studied. The effect of the Mach number of the wake on the structure of the jet is determined. It is shown that with a near-sonic velocity a reorganization occurs in the mode of flow from an open to a closed base region accompanied by a reduction in the level of pressure pulsations.

The study of a jet discharging into a wake in a channel represents an independent problem. The jet tests are conducted in a wind tunnel with a working section 600 × 600 mm in size. The jet ejects a stream into a channel and depending on its parameters and the relative dimensions of the jet and the channel the velocity of the wake can reach a considerable value.

The flow of a jet in a channel differs from flow in a flooded space; these differences are especially important when the wake velocity is near-sonic. We note that tests with a jet in a free wake of limited dimensions [1] also showed the definite effect of the boundaries of the stream on the structure of the jet. At the same time, studies of a jet in a subsonic wake in a channel allow one to obtain certain flow characteristics which are also inherent to a jet in a free wake.

The studies were conducted on a model consisting of a cylinder (110 mm in diameter and 300 mm long) and a conical leading section with an aperture half-angle of 21°. The model was fastened to a side plate 255 mm long and 20 mm thick whose leading and trailing parts had wedge tapers. The plate was located at a distance of 1.5 diameters from the base cut. This method of fastening leads to the appearance of disturbances in the flow. However, these disturbances do not have an important effect on the flow in the base region [2, 3].

Interchangeable annular nozzles, inner edge 87.6 mm in diameter, outer edge 110 mm in diameter, ratio of area of annulus to total area of nozzle 36.5%, were mounted in the base section of the model. The flat end of the annular nozzle was drained along the radius. The pressure in the annular jet was measured with total and static pressure probes having an outer diameter of 1.2 mm which were mounted on an automatic coordinator.

The tests were conducted with Reynolds numbers $Re = 1.3\text{-}3 \cdot 10^6$, calculated from the parameters of the oncoming stream and adjusted to the diameter of the model. The relative rms error in the determination of the relative base pressure $P = P_b/P_\infty$ (P_b is the pressure measured at the face of the nozzle and P_∞ is the static pressure in the undisturbed stream) was $\bar{\sigma}_P = 0.07$, 0.04, and 0.02 for Mach numbers of 0.5, 0.7, and 1.2, respectively.

Two modes are realized in the flow of an annular jet into a flooded space: those having open and closed base regions. The first mode is characterized by a reduction in the base pressure and the second, by an increase. In the mode of an open base region the annular jet retains a supersonic structure for a distance of several (three to four) cells. Closing of the base region — the critical mode — occurs when the supersonic sections of the jet interact. The jet is reorganized so that the base region is surrounded by the first cell of the jet. Depending on the rated Mach number and the shape of the

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 74-79, November-December, 1974. Original article submitted November 21, 1973.

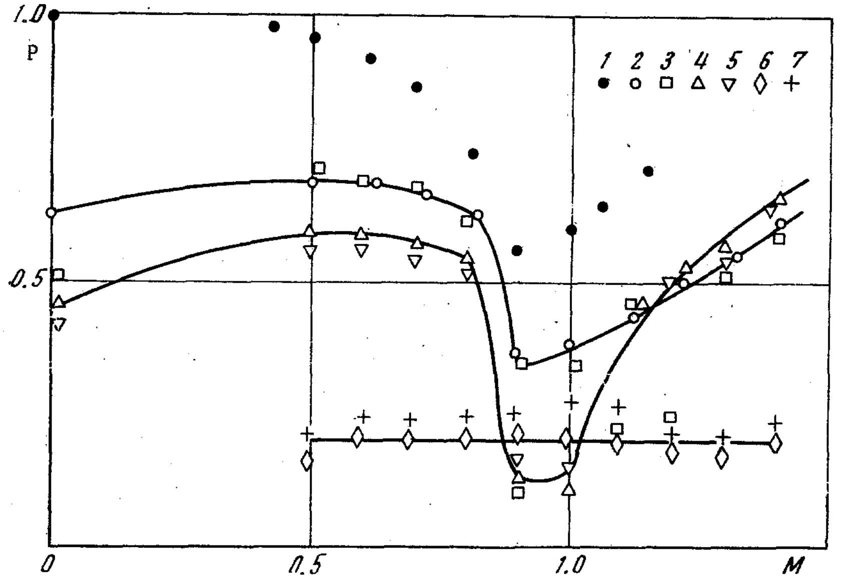

Fig. 1

nozzle the critical mode can set in both for an overexpanded and for an underexpanded jet. With discharge into a flooded space the critical mode for nozzles with rated Mach numbers M_j = 1.35, 2, 2.5, 3.1, and 3.6 is realized at nonrated factors n = 3, 1.8, 1.35, 1, and 0.9, respectively (for a nozzle with M_j = 2.5 the diameter of the inner section is 101.8 mm).

During flow of a jet in a tube the static pressure in the working section decreases in proportion to the increase in the velocity of the oncoming stream. Therefore, in order to preserve a constant nonrated factor for each Mach number the corresponding pressure in the receiver of the jet model was determined. The pressure distribution over the radius of the central part of the annular nozzle was kept approximately constant.

The dependence of the relative base pressure P, measured at the central point of the nozzle face, on the Mach number of the wake for the nozzle with M_j = 3.6 is presented in Fig. 1 ($n = P_a/P_\infty$, n is the nonrated factor, P_a is the static pressure at the exit rim of the nozzle, and n = 0, 0.4, 0.6, 0.7, 0.8, 0.9, and 1.0 are denoted by 1-7, respectively).

Three types of flow can be distinguished. The first type corresponds to low nonrated factors (n < 0.5). An increase in the Mach number to 0.9 is accompanied by a decrease in pressure, while a further increase in the velocity causes an increase in pressure. The pressure at the central part of the nozzle varies similarly to the base pressure (n = 0), with an increase in the nonrated factor leading to a decrease in the pressure. Reorganization is not observed for this type of flow.

The second type corresponds to the discharge of an overexpanded jet with restoration of the pressure in a system of Mach waves or regular waves (n = 0.6-0.8). An increase in the wake velocity from M = 0.8 to 0.9 brings about the reorganization of the flow from an open to a closed base region, which is accompanied by a sharp reduction in the base pressure. The closing of the base region lasts until M = 1.1, while with a further increase in the velocity a second reorganization of the jet from a closed to an open base region with an increase in the base pressure is observed. In the mode of a closed base region the values of P are about the same for all nonrated factors.

The third type of flow, close to rated flow (n = 0.9-1.0), is characterized by little variation in the base pressure in the range of Mach numbers studied. This is explained by the fact that when n ≥ 0.9 the base region is closed and the base pressure is determined by the parameters of the discharging jet.

The reorganization of the flow which takes place in the region of subsonic and transonic velocities is examined from photographs of the flow of an annular jet with M_j = 3.6 and with nonrated factors close to the critical value (n = 0.8). An increase in the wake velocity from M = 0.5 to M = 0.8 does not cause marked changes in the structure: the length of the first cell and the diameters of the separation zone in the region of the first and second cells remain almost constant. The transition from M = 0.8 to M = 0.9 involves the reorganization of the jet — the base region closes; the jet is overexpanded with respect to the outer stream and underexpanded with respect to the inner stream. The shock wave issuing from the outer rim of the nozzle passes along the expanded first cell, regularly intersecting first with the suspended shock wave and then with the outer shock wave from the opposite rim.

The increase in the Mach number from 1.1 to 1.2 is connected with the second reorganization of the jet: the base region opens, the first cell decreases, and a second cell appears. The structure of the jet resembles the flow at M = 0.5 with the difference that the first cell is somewhat shortened and the outer boundaries of the jet are constricted.

Along with the study of the flow structure a study was made of the pressure pulsations at the face of the annular nozzle. Studies of the pulsations relating to nonstationary flow in the base region were described in [4, 5], while pulsations at the face of an annular nozzle during discharge into a flooded space were described in [6, 7].

In the course of the experiments the pressure pulsations were measured at the center of the face part of the nozzle and at a distance of 0.5 diameter in the plane of the nozzle cut using an induction pickup mounted on a pylon. The recording channel was calibrated with a pulsator of the resonance type and with a microphone, amplifier, and recorder of the Brül and Kier Co.

Only systematic errors of the second kind were allowed for in estimating the error of these measurements. The estimate of the rms error (the systematic errors were assumed to be distributed according to the normal law) in the determination of the rms value of the spectral level of the process analyzed is as follows: error of pressure pickup due to nonlinearity ±1%, of station ±3.6%, of amplifier ±8%, of magnetic recorder ±1.5%, of analyzer ±10%, of recorder ±11%. The relative rms error of the amplitude measurements for the entire recording-measuring channel is ±15.4% with a reliability of 70%. The error in the frequency determination is composed of the errors of the station (±3%), of the analyzer (±1%), and of the recorder (±2%) and equals ±3.7% (the error of the pickup and the magnetic recorder is negligibly small).

As was shown in [6], during discharge into a flooded space the pressure pulsations at the face of an annular nozzle depend on the modes of flow in the jet. A characteristic property of annular jets is the sharp reduction in the level of the pulsations at the face of the nozzle during reorganization of the flow from an open to a closed base region. In the mode of an overexpanded jet increases in the nonrated factor and in the Mach number lead to a monotonic reduction in the frequency of the discrete component in the spectrum of pressure pulsations. The disappearance of the discrete component in the critical mode is displayed. In this mode a single sharply expanded annular cell is formed before the merging of the jet and then a Mach or regular interaction of the waves develops, the entire jet does not have a definite periodic structure, and it does not oscillate as a single unit, as a consequence of which a resonance process does not occur.

In the case of flow in a wake in a channel the walls of the tube strongly affect the stability of the jet because of the reflection of sound waves. Therefore, the results of studies of pulsations in a wake in a channel cannot be directly carried over to the case of discharge into an unbounded wake. At the same time there are some general relationships inherent both to a jet in a channel and to a jet in a free wake.

In the analysis of the dependence of the total level B of pressure pulsations on the Mach number of the wake one can distinguish three groups of curves for specific values of the nonrated factor (Fig. 2; here $B = 20 \log [(\overline{q^2})^{1/2}/B_0]$, where $(\overline{q^2})^{1/2}$ is the rms value of the pressure pulsations and $B_0 = 2 \cdot 10^{-5}$ Pa [8]). The results of tests for a nozzle with $M_j = 3.6$ are presented in the graph (n = 0.4, 0.6, 0.7, 0.8, 0.9, 1.0 are denoted by 1-6, respectively). For n < 0.5 the level of pressure pulsations varies little up to M = 0.8 and then decreases somewhat. For n = 0.6-0.8 the value of B is sharply reduced during the transition from M = 0.8 to M = 0.9 and increases again with a jump in the transition from M = 1.1 to M = 1.2. For M = 0.9-1.1 the base region is closed and, consequently, surrounded by the supersonic annular jet and radiation penetrates to the face of the nozzle only from the section of the jet before the sonic point. In addition, after the reorganiza-

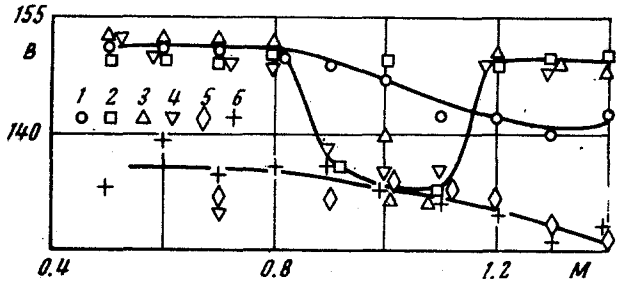

Fig. 2

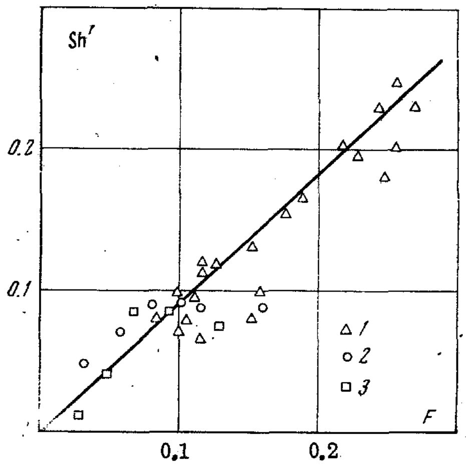

Fig. 3

tion the inner surface of the jet, which is the main source of radiation in the direction of the base cut, is sharply decreased. In this case, as in the discharge into a flooded space [6], the pressure pulsations in the mode of a closed region are smaller than in the case of an open region. In the vicinity of the rated discharge n = 0.9-1.0 the sonic pressure is small, since the base region is closed in the entire range of wake velocities studied.

The continuous spectrum of pressure pulsations at the nozzle face depends on the acoustic radiation of the jet [6], on the instability of the flow in the base separation zone [4, 5], and on pressure pulsations in the oncoming stream. The noise radiation of the jet arises mainly in the zones with the highest turbulence. A reduction in the maximum turbulence in the jet is an effective means of reducing the noise. The highest degree of turbulence is reached in the zone of tangential discontinuity of the axial velocity between the jet and the wake. As the wake velocity increases the velocity of the discharging jet relative to the surrounding jet decreases, which causes a decrease in the degree of turbulence in the viscous layer and a decrease in the noise. A reduction in the noise of a low-velocity jet in a wake was obtained in [9].

In experiments with annular jets an increase in the wake velocity up to sonic velocity is accompanied by a reduction in the broad maximum and its displacement into the region of low frequencies. Waves emitted by supersonic boundary vortices [10] are one of the main noise sources of supersonic jets. For high-velocity jets one must allow for the Doppler coefficient $(1 - M_e \cos \theta)$, which is equal to $(1 + M_e)$ in the case of the transmission of disturbances upstream. Here M_e is the Mach number of the boundary disturbances, and θ is the angle between the direction of the radiation and the direction of the jet. In the presence of a subsonic wake the frequencies vary in proportion to $(1 - M)$, since this coefficient determines the variation in the wave velocity relative to the nozzle.

A discrete component was observed in the spectrum of pressure pulsations. The tests of a jet in a tube showed that two types of discrete component are realized: the first is induced acoustic inverse coupling and the second is resonance ejector excitation. For the first type the velocity of propagation of disturbances upstream decreases in proportion to the increase in the wake velocity, and the period t of the oscillations must increase.

The period t of the resonance system is comprised of the time of passage of the disturbances from the nozzle to the effective source and the time of passage of the sound wave back to the nozzle. In the case of discharge into a flooded space $t = l/ku_i + l/a$, in a wake $t' = l/[u + k(u_i - u)] + l/(a - u)$, where k is the coefficient of convection of vortices at the boundary of the supersonic boundary layer; l is the distance from the nozzle cut to the effective source of radiation of a discrete tone; u_i and u are the velocities of the jet and wake, respectively, and a is the speed of sound [11].

The ratio of the frequency of a discrete tone during discharge into a wake to the corresponding frequency for zero wake velocity is

$$\frac{f'}{f} = \frac{t}{t'} = \frac{[u + k\,(u_i - u)]\,(a - u)\,(a - ku_i)}{kua\,[a + k\,(u_i - u)]}$$

Using the empirical equation [12] $f = a/k_1 d(P_0/P_\infty - 1.89)^{-1/2}$, we obtain

$$\mathrm{Sh} = \frac{F}{k_1} = \frac{[M + k\,(M' - M)]\,(1 - M)\,(1 - kM')}{k_1 kM\,[1 + k\,(M' - M)]}\,(P_0\,/\,P_\infty - 1.89)^{1/2}$$

Here $M' = u_i/a$, d is the diameter of the critical cross section of a round nozzle, which for annular nozzles is equivalent with respect to the area of the critical cross section to the diameter of the round nozzle, and P_0 is the pressure in the forechamber.

The dependence of Sh on F is presented in Fig. 3 for the results of flight tests [11] (1 is the flight tests where the second harmonic was measured, and therefore the value of Sh given on the graph is equal to half the measured value) and for the discrete component in the pulsation spectra of annular nozzles (2 and 3 are $M_j = 3.6$ and $n = 0.4$ and 0.6, respectively). The data of the flight tests are described by a linear dependence coinciding with the calculated dependence for $k_1 = 1.1$. The results of the experiments with annular jets approach the linear dependence in the section of a decrease in frequency M = 0.7-0.9.

LITERATURE CITED

1. M. G. Lebedev and G. F. Telenin, "Study of the interaction of a supersonic jet with an acoustic field," Izv. Akad. Nauk SSSR, Mekh. Zhidk. i Gaza, No. 4 (1970).
2. M. A. Beheim, "Flow in the base region of axisymmetric and two-dimensional configurations," NASA, TR R-77.77 (1960).
3. A. Heyser, F. Maurer, and E. Oberdoerffer, "Experimental investigation on effect of tail surfaces and angle of attack on base pressure in supersonic flow," in: The Fluid Dynamic Aspects of Ballistics, AGARD Conference Proceedings, No. 10 (1966), pp. 263-290.
4. Yu. A. Panov, A. I. Shvets, and A. M. Khazen, "Study of oscillations in base pressure behind a cone in a supersonic stream," Izv. Akad. Nauk SSSR, Mekh. Zhidk. i Gaza, No. 6 (1966).
5. A. I. Shvets, Yu. A. Panov, A. M. Khazen, and V. A. Novikova, "Effect of the Mach number on oscillations in base pressure," Vestn. Mosk. Gos. Univ., Ser. Matem. Mekh., No. 1 (1968).
6. V. A. Lyutyi, L. V. Novikov, and A. I. Shvets, "Pressure pulsations in annular nozzles," Izv. Akad. Nauk SSSR, Mekh. Zhidk. i Gaza, No. 5 (1973).
7. A. I. Shvets, "A discrete component in the pulsation spectra of annular jets," in: Abstracts of Reports of Eighth All-Union Acoustics Conference [in Russian], Vol. 2, Moscow (1973).
8. Aviation Acoustics [in Russian], Mashinostroenie, Moscow (1973).
9. G. M. Corcos, "Some effects of sound-reduction devices on a turbulent jet," J. Aero-Space Sci., 26, No. 10 (1959).
10. Random Oscillations [Russian translation], Mir (1967).
11. J. A. Hay and E. G. Rose, "In-flight shock cell noise," J. Sound and Vibr., 11, No. 4 (1969).
12. A. A. Powell, "On the mechanism of choked jet noise," Proc. Phys. Soc., Ser. B, 66, No. 408 (1953).