SUPERSONIC ANNULAR JET

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The flow in supersonic annular jets has been investigated experimentally. Schemes for shock interaction during reconstruction from an open to a closed base region are determined. The fundamental parameters characterizing the structure of the separation flow are extracted.

When a compact cluster of nozzles is arranged around the circumference of the base section, the escaping jet in certain modes is similar to an annular jet. Moreover, the possibility of using special annular nozzles in a number of cases is not excluded. Annular nozzles have a number of advantages over Laval nozzles (for example, less loss of thrust during overexpansion, convenience of the configuration in the root part). In practice, radically shortened annular nozzles are expedient; hence, the thrust determination of such nozzles is associated with a study of the separation flow behind the endface of the central body. Also of interest is an investigation of the flow modes in annular jets during pressure changes in the external medium.

In recent years, there has been a number of publications in which are contained results of investigations of flows in annular nozzles and jets. Numerical computations of the flow in annular nozzles are presented in [1]. The flow in an annular nozzle with a central body has been computed by using a difference scheme [2] and the method of characteristics [3].

Approximate methods of computing annular jets have also been developed. The method of the separating streamline has been used to compute the base pressure at the endface of an annular nozzle. A computation of the separation flow in annular nozzles [4], performed on the basis of integral methods, was carried out by starting from quasi-one-dimensional models for flows with open and closed base regions. A solution for inviscid main and ejected streams [5] has been obtained for a nozzle with a central body having mass supply in the base region. The supersonic stream parameters in the jet were determined by the method of characteristics, and the parameters of the additional stream, by using one-dimensional theory.

There are approximate computations and experimental investigations of the base pressure for annular imcompressible fluid jets. Then, low-speed annular jets have been investigated in application to air cushion apparatus. A number of publications is devoted to turbulent mixing of coaxial jets: free, in a channel, in the presence of secondary flows, solid particles, and chemical reactions.

Great attention has been paid to a study of the flow in the base region of multinozzle configurations. The base pressure has been computed on the basis of the method of the separating streamline for a number of jets escaping into the "cutoff" mode of the base region [6]. Numerical computations have been performed for several cases of jet escape from a four-nozzle module into a supersonic co-flow [7]. The influence of the number of nozzles and their arrangement on the magnitude of the base pressure and on the thrust characteristics has been studied experimentally for a nozzle cluster. Data about the flow parameters directly in the separation zone and about the nature of compression shock interaction as the annular jet flow modes changes are of interest.

Represented below are results of experimental investigations of the flow in supersonic annular jets. These investigations permitted studying the flow modes on simpler models compared to an annular nozzle cluster on the one hand, and obtaining some additional data for the construction of computational schemes, on the other. Annular jets formed by plane nozzles in radial flow have been tested with the design Mach numbers $M_j = 1.35$; 2; 3.1 and 3.6, inner edge diameter 87.6 mm and outer (D) diameter 110 mm, and a

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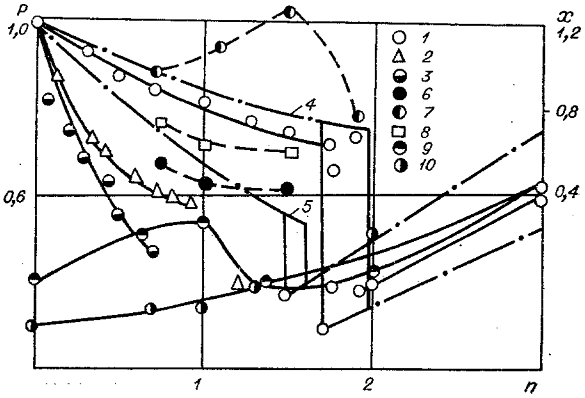

Fig. 1

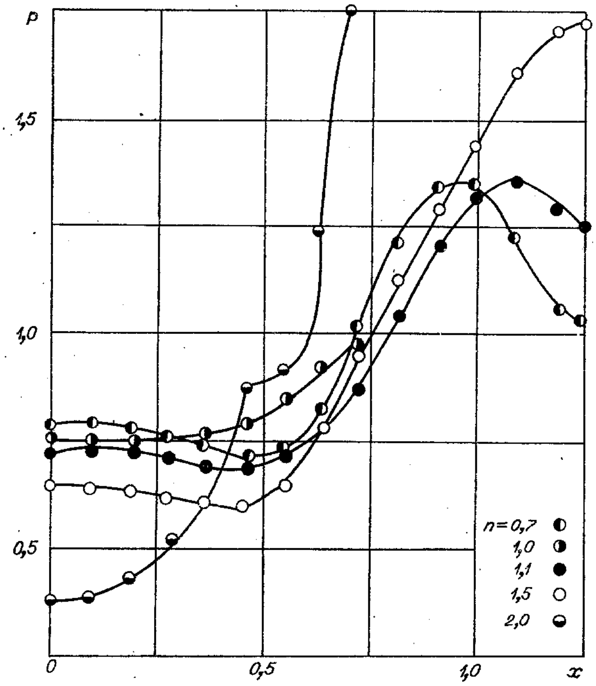

Fig. 2

36.5% ratio between the annulus area to the total nozzle area. A nozzle with M=2.5 and an inner edge diameter 101.8 mm was also tested. The plane end face of the annular nozzle was drained in radius with a $\Delta D = 0.045$ step. The pressure was measured in the annular jet by using total and static pressure probes with a 1.2 mm outer diameter, which were mounted on an automatic traversing gear.

SEPARATION FLOW

The pressure distribution over the radius of the central part of the nozzle was kept approximately constant. The dependence of the relative base pressure $P = P_i/P_\infty$ (P_i is the measured pressure, and P_∞ is the pressure in the surrounding space) on the degree of off-design of the emerging jet $n = P_a/P_\infty$ (P_a is the static pressure at the exit edge of the nozzle) for nozzles with M=2, 3.1, 3.6 (curves 1-3, respectively) is represented in Fig. 1. An increase in the degree of off-design results in a diminution in the base pressure, where the pressure curve is located below for high values of M. A pressure rise was observed for a nozzle with $M_j = 1.35$ for a 0.1-0.2 off-design. For each M_j a definite value of the off-design n° exists for which a passage from a reduction to a rise in pressure, the critical mode, is realized. This value of n° will be less, the greater the number M_j of the emerging jet. A diminution in the pressure corresponds to an open base region, and an increase, to a closed region. Measurements of the total pressure showed that closure of the base region occurs upon extension of the supersonic part to the site of the jet interaction; hence the base pressure is lowered by a jump and reaches the minimal value. Prior to closure the velocity

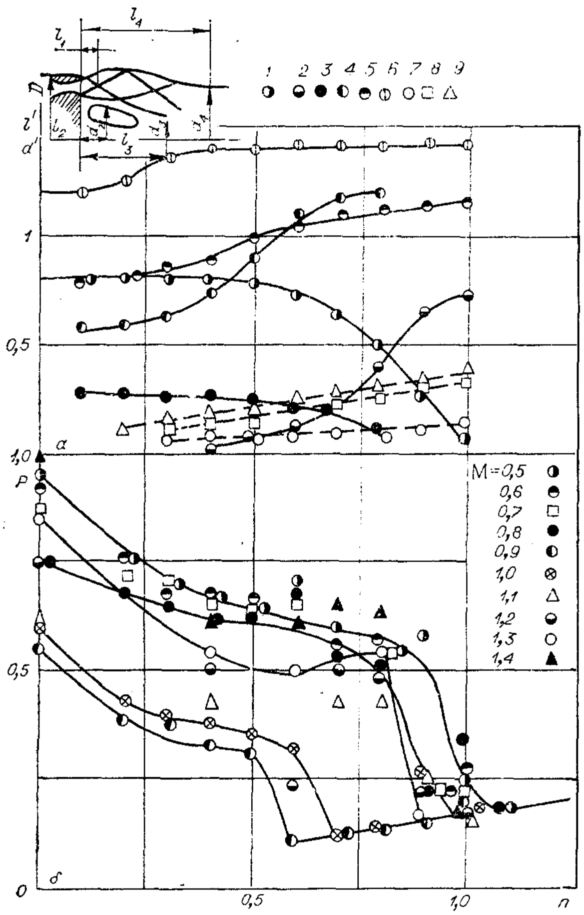

Fig. 3

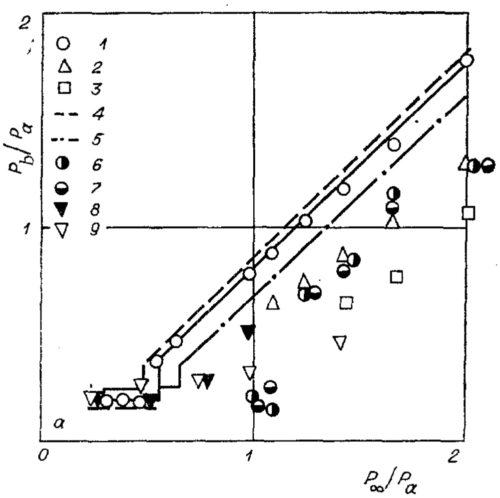

Fig. 4

along the jet axis is subsonic, after closure the base region is surrounded by a supersonic stream in which the pressure is independent of the pressure of the external medium and grows in proportion to the pressure in the prechamber.

Presented in the graph in addition to the experimental results is a computational two-parameter dependence of the relative base pressure ($M_j = 2$ and 3, curves 4 and 5) on the degree of off-design and the Mach number in the exit section of the nozzle, where the stream is taken uniform and parallel to the axis [4]. For a nozzle with $M_j = 2$ the computed values are located above the experimental values in the open base region mode and below in the closed mode. A nonmonotonic change in the base pressure in the closed base region is obtained in the computations as a function of M_j, which is explained by the opposite influence of the rarefaction wave intensity incident on the nearby wake, and the quantity M_j.

Sharp fluctuations in the jet structure have been observed by means of high-speed moving pictures of the flow during passage through the critical mode, and intense discharge fluctuations in the base pressure at a low frequency have hence been realized ($\Delta P \approx 0.4$, frequency ~ 20 Hz). The pressure values and the values of n differ by 10-20% upon approaching n° from the greater or lesser off-designs. The hysteresis is associated with the prehistory of the mode change during passage from one stable position to another. The possibility of the origination of quasistationary fluctuations is indicated in the computations [4] and an approximate estimate of the hysteresis domain is given. Let us note that it is necessary to go over to the "through" numerical methods of computing an inviscid flow in order to investigate it in detail and to determine n° ex-

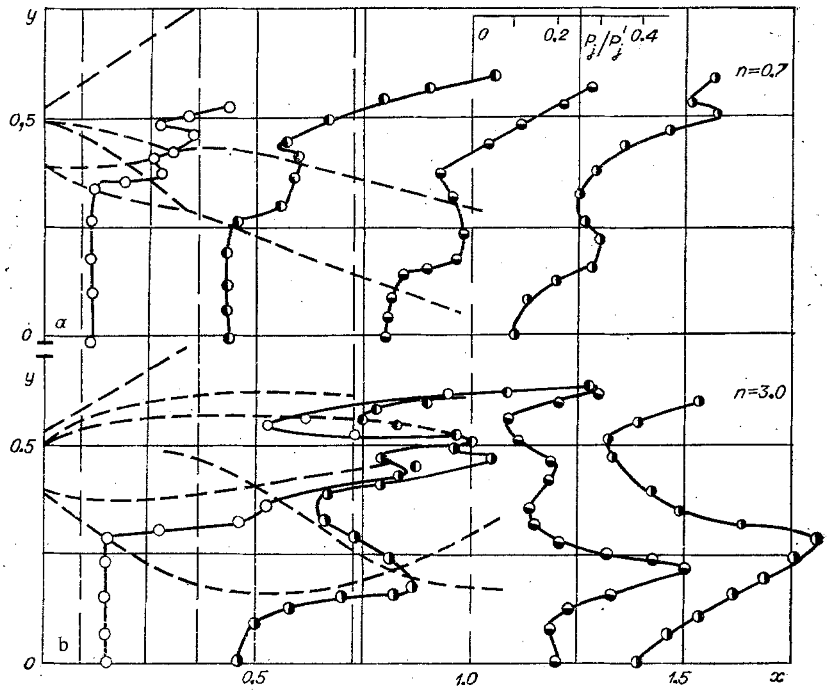

Fig. 5

actly. The pressure fluctuations during flow reconstruction were observed in experiments with multinozzle configurations and with disk nozzles [8]. It is interesting to note that the acoustic radiation of an annular jet, including the discrete component in the pressure fluctuation spectrum also, is reduced during the reconstruction [9].

The static pressure distribution along the wake axis of a model with $M_j = 2$ is given in Fig. 2. The maximum static pressure shifts downstream as the off-design increases, and upstream after reconstruction ($n^0 \approx 1.8$), the pressure hence rises sharply. The minimum value of the static pressure on the wake axis corresponds to the maximum velocity of the reverse flow. The static pressure near the base section rises as a result of deceleration of the reverse flow.

The stagnation point on the wake axis was determined on the basis of measurements of the static and total pressures of the reverse streams. The displacements of the minimum and maximum static pressure points and the stagnation point as the off-design of the jet varies from $M_j = 2$ are shown in Fig. 1 (curves 6-8, respectively). As the off-design increases the stagnation point approaches the nozzle end face.

Relative dimensions of the jet and the separation zone are determined from photographs of the flow (Fig. 3a, $M_j = 3.6$; $l' = l/D$; $d' = d/D$). The data obtained indicate that toroidal circulation flow, terminating in a contraction recalling a nozzle throat, is formed in the separation zone of an annular jet. The contraction formed by the first cell (d'_2, l'_2, curves 1 and 2) differs little from the diameter of the central body for low off-design values. An increase in the off-design above n = 0.4 realizes a diminution in the first contraction and its shift downstream, where this process occurs especially intensively in the neighborhood of the critical mode. A change in the degree of off-design exerts an analogous influence on the quantities d'_3 and l'_3 (curves 3 and 4); however, flow reconstruction occurs for an off-design $n \approx 0.8$ and the second cell vanishes. The external throat of the jet (d'_4, l'_4, curves 5 and 6) broadens and recedes from the base section as the off-design grows.

The behavior of the inner and outer boundaries of the annular jet is different as the degree of off-design changes. If the governing factor for the inner boundary is the flow mode with an open or closed base region, then the outer boundary changes analogously to a jet emerging from a Laval nozzle, the boundaries stand off from the axis as the external pressure is reduced, and the length of the cell increases.

SHOCK INTERACTION

The main distinction between a supersonic annular jet and a solid circular jet is the existence of two escape modes: with an open and closed base region, as well as the pressure difference on its outer and

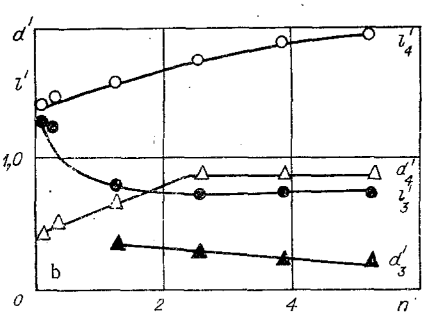

Fig. 6

inner surfaces. These factors realize a flow scheme with systems of compression and rarefaction waves which are different at the outer and inner parts of the jet. Since the magnitude of the off-design is given with respect to the external pressure, modes are possible when the flow in the jet will be overexpanded relative to the outer stream and underexpanded relative to the inner. For concrete escape conditions dependent on the Mach number and the degree of off-design, flow reconstruction relative to the external pressure can occur for both over- and underexpanded jets. At the same time, reconstruction will always set in for an underexpanded jet relative to the internal pressure.

The shape of an annular nozzle also plays an important part in the organization of the flow scheme. Thus, for example, a nozzle with $M_j = 2.5$ has an exit slot almost twice as narrow as the rest of the nozzle. In this case, it is necessary to have a large off-design to extend the supersonic section to the axis. If the characteristics standing off from the outer edge of the nozzle intersect on the jet axis behind the sonic point, then external perturbations cannot affect the separation flow. Hence, the off-design given with respect to P_∞ cannot determine the flow in an annular jet uniquely; however, for a given nozzle shape it is an objective indicator of the process.

An annular jet and the compression shocks formed therein are curved considerably towards the axis of symmetry. This is related to the pressure difference on the outer and inner jet surfaces, to the curvature of the characteristics in an axisymmetric flow, and to the change in the degree of stream expansion along the slot of the annular nozzle. Separation of the jet from the nozzle walls occurs for a considerable overexpansion of an annular jet ($n < 0.3$) because of compression shock interaction with the boundary layer, and the jet diameter becomes somewhat less than for a jet with separation-free flow.

External hanging shocks form a Mach wave configuration in the critical mode for a jet with $M_j = 2$. This case recalls the structure of a single cylindrical jet for large off-design values when only the first cell, terminating in a normal or bridge-shaped shock behind which the jet is turbulized strongly and the flow continues at a subsonic velocity, remains out of the cellular structure. As the off-deisgn grows, the Mach disk stands off from the nozzle, the outer and inner hanging shocks first intersect regularly for $n = 2.5$, and then a Mach interaction of the reflected external shocks occurs.

The external and internal hanging shocks in the critical mode first intersect regularly at a distance 1.3D from the nozzle for a jet with $M_j = 3.1$ and then (at approximately 0.1D) Mach interaction of the reflected external shocks is realized.

As the pressure increases, the cell size grows and the number of cells diminishes. For example, if a jet with $M_j = 3.6$ consists of three cells for $n < 0.5$ then it consists of two for $n = 0.8$. The jet instantaneously is reconstructed between the off-designs 0.8 and 0.9 in such a way that only the first, considerably enlarged, cell is seen, which is elongated sharply and is expanded inward. The internal and external hanging shocks in the critical mode of a jet with $M_j = 3.6$ first interact regularly, and then the external reflected shocks reach the jet axis without the formation of a Mach disk. As the jet Mach number increases, the slope of the internal hanging shock to the axis of symmetry diminishes and for $M_j = 3.6$ the internal shock is almost parallel to the axis.

Upon approaching the critical mode, the expansion wave starts to interact with the near wake, which results in a sharp diminution in the pressure in the separation zone. The dead-water zone is surrounded just by the first cellular jet in the postcritical mode for all the nozzles tested although the flow structure is distinct depending on the jet parameters. The degree of nozzle expansion exerts great influence on the jet structure. According to photographs of jets with $M_j = 3.1$ and 3.6, it is seen that the base region is closed in the first case and open in the second for the same pressure in the prechamber ($P_0 = 45$ gage atm).

The dependence of the relative distance between the nozzle exit and the point of shock interaction in the jet l'_1($M_j = 2$; 3.1 and 3.6, curves 7-9) on the degree of off-design in represented in Fig. 3a. This distance increases linearly as the off-design rises, just as for a circular jet, and the growth of the quantity l'_1 grows more intensively in a nozzle with a high escape velocity. Let us notethat in the case of supplying gas to the central portion of an annular nozzle, the total pressure of the injected gas plays a governing role in the formation of the jet contours, for example, as the total pressure doubles, the distance between the nozzle edge and the point of shock intersection is halved [5].

The fundamental nozzle and jet parameters governing the flow mode have been extracted as a result of tests. It is shown that reconstruction from an open to a closed base region is realized during interaction between supersonic sections of the jet, the base pressure is hence reduced by a jump and reaches a minimal value. Intense discharge fluctuations in the pressure at a low frequency are realized during the reconstruction; at the same time the acoustic radiation of the jet and the discrete component in the pressure pulsation spectrum are reduced [9].

FLOW IN A CO-STREAM

Investigations on jets escaping into a co-stream have been performed on models consisting of a cylinder (110 mm diameter and 300 mm length) and a conical forward part with a 21° half-angle. The model was fastened on a side plate whose leading and trailing edges had a wedge taper. The plate was located at a 1.5 caliber distance from the bottom section.

The jets were tested in a wind tunnel with 600×600 mm working section at $M = 0.5$-1.4, 2, and 3 free-stream Mach numbers. The Reynolds numbers computed by means of the free-stream parameters and referred to the model diameter varied between $1.3 \cdot 10^6$ and $3 \cdot 10^6$.

Annular nozzles with $M_j = 2$, 3.1, and 3.6 were mounted in the base part of the model. As the free-stream velocity grew, the static pressure in the working section was reduced, hence the appropriate pressure in the receiver of the jet model was determined in order to conserve a constant off-design value for each number M.

Considering the dependence of the base pressure, measured at the central point of the nozzle end face, on the degree of off-design of a jet with $M_j = 3.6$ escaping in a sub- and transonic co-flow, some general regularities about the change in base pressure and about the origin of a critical flow mode (see Fig. 3b) can be extracted. For a co-stream velocity of $M = 0.5$-0.8 the critical mode sets in at a greater off-design than for escape into a submerged space, while for $M = 0.9$ the off-design is less ($n = 0.6$). The structure of a supersonic jet escaping from a nozzle into a subsonic co-flow is mainly analogous to the structure of a jet escaping into a submerged space.

At a low supersonic external stream velocity, the pressure increase in the prechamber first causes a diminution in the base pressure, the base pressure rises for $n = 0.6$-0.8 and the transition to the critical mode is again associated with a pressure reduction. An external compression shock is formed upon the escape of a jet into a supersonic stream ahead of an expanding jet, just as ahead of a solid body, but the pressure on the contact surface separating the jet from the external stream is variable. The pressure rise noted is determined by the pressure growth behind the external compression shock since the base region is open and the rise in external pressure affects the magnitude of the base pressure. In the case of escape into a submerged space after the closure of the base region, the external pressure does not exert influence on the magnitude of the base pressure and it is determined just by the escaping jet parameters. The magnitudes of P in the critical mode and in the closed base region mode are located on one line passing through the origin for all off-designs independently on the co-stream velocity ($M = 0.5$-3).

In the case of escape into a co-flow, the annular jet has some singularities as compared with a circular solitary jet. For a circular jet ($M_j > M$) the minimal magnitude of the base pressure is realized in the escape of an overexpanded jet and corresponds approximately to the nozzle "starting" mode. As has been shown above, the minimal value of the base pressure for an annular jet ($M_j > M$) is reached before reconstruction of the flow from an open to a closed base region, which can correspond to both an overexpanded and underexpanded jet.

Let us examine the flow reconstruction occurring in the sub- and transonic velocity region in an example of the escape of an annular jet with $M_j = 3.6$ for an off-design close to the critical value ($M = 0.8$). An increase in the co-stream velocity from $M = 0.5$ to $M = 0.8$ causes no substantial changes in the structure: the length of the first cell and the diameter of the wake throat in the region of the first and second cells remain practically constant. Passage from $M = 0.8$ to 0.9 involves reconstruction of the jet, the base region is closed; the jet is overexpanded relative to the external stream and underexpanded relative to the internal stream. The compression shock standing off from the outer nozzle edge passes over a jet expanded strongly within the first cell, regularly intersects first the internal hanging shock and then the external shock from the opposite edge, and reaches the jet boundary.

The growth in velocity from $M = 1.1$ to $M = 1.2$ is associated with repeated reconstruction of the jet structure, the base region is open. This is accompanied by the appearance of a second cell and a diminution in the size of the first (mainly because of an increase in the throat diameter). The flow obtained recalls the structure of an annular jet at M=0.5 with the sole difference that the first cell is shortened somewhat and the section of the annular jet is compressed.

Closure of the base region in the transonic velocity range for almost critical off-designs can be explained as follows. A local supersonic zone bounded by a compression shock in the area of the jet throat originates near the nozzle edge for a transonic external stream velocity. In this zone the pressure is below the pressure in the free stream, hence the degree of off-design realizable becomes greater than the given value and reaches the critical value. This results in closure of the base region for values of n less than for the escape into a submerged space. A rise in the external stream velocity is accompanied by the passage to a completely supersonic flow picture with supersonic velocity behind the closing shock. A compression shock arises in front of the first jet cell, and the pressure grows on the surface of separation; therefore, for a given off-design the value of n realizable will be less than the critical and the base region is opened.

Investigations of an annular jet escaping into a supersonic co-flow were performed on a model mounted on a side plate, which ordinarily results in the appearance of flow perturbations in the base region, especially in cases of submersion of the holder in the separation zone formed as a result of interaction between the strongly underexpanded jet and the supersonic free stream [10]. The relative holder thickness in the experiments was less than 1/5, the jet escaped either overexpanded or slightly underexpanded; in the case of separation zone formation on the cylinder it would not reach the holder but the perturbed section of the free-stream would interact with the surface of the supersonic annular jet. This resulted in a deflection of the annular jet by a one degree order of magnitude and exerted no essential influence on the flow in the separation zone and on the data of the pressure measurements in sections outside the perturbed area.

As in the escape into a submerged space, the pressure distribution over the nozzle end face varies insignificantly. The values of the base pressure for a jet escaping into a supersonic co-stream with $M_j=2$ and 3 are presented in Fig. 1 (curves 9 and 10). In the first case, a local maximum in the quantity P is realized for the open base region mode. The following flow picture can be constructed by comparing the behavior of the pressure curve with the photographs of the stream. For the flow around a model without a jet, the external stream is turned into a rarefaction wave up to a value of the base pressure corresponding to M=2. As the degree of off-design grows, the escaping jet first is a source of additional mass in the base region, then the jet is separated near the critical section up to starting of the nozzle, and the static pressure at the exit becomes greater than the design value for a given number M_j. These factors produce an increase in the base pressure.

The dependence $P_b/P_a = f(P_\infty/P_a)$, constructed for the escape into a submerged space and in a co-stream (M=0; $M_j=2$; 3.1 and 3.6; computation M=0, $M_j=2$ and 3 [4]; M=0.5 and 0.7; $M_j=3.6$; M=2 and 3; $M_j=2$, curves 1-9, respectively) is represented in Fig. 4. In the open-base-region mode, these dependences differ slightly from the linear, and the slope is almost one for all the curves. In the critical mode the quantity P_b/P_a is reduced by a jump and in the closed base region is kept constant.

The total pressures and flow contours are represented by Toepler photographs (dashes) in Fig. 5 for supersonic jet flow (M=3, $M_j=2$). The magnitude of the pressure measured by a total head tube P_j is referred to the pressure behind a normal shock in the design jet P'_j. The inner jet boundary agrees with the pressure measurement data, the constant pressure section at the center of the jet corresponds to circulation flow. As the degree of off-design grows, the maximum pressure zone in the jet approaches the axis. Reconstruction of the flow is accompanied by a substantial diminution in the size of the circulation zone, where the total pressure in the central part of the jet grows in the closed-base-region mode and the jet boundaries expand.

An escaping annular jet is narrowed and the least jet section can be called the throat by analogy with the near wake, where a compression shock originates during flow around this throat. An increase in the off-design expands the jet and the throat, the shock approaches the nozzle, the pressure on the outer boundary of the first cell grows, and flow reconstruction occurs later than for the escape into a submerged space. After flow reconstruction, the pressure increase in the model prechamber is not only associated with diminution in the angle of external flow rotation, but also with the emergence of the annular jet outside the nozzle, accompanied by the formation of a compression shock. But the dead-water region in the closed-base region mode is surrounded by a supersonic stream and the magnitude of the base pressure is independent of the pressure on the outer jet boundary. In this case, in order to determine the escape parameters the base pressure is determined constant independently of whether the annular jet escapes into a submerged space or into a co-stream.

The characteristic dimensions of the circulation zone (Fig. 6, M = 3, M_j = 3.6, the notation is the same as in Fig. 3a) are determined from the flow photographs. An increase in the degree of off-design of an underexpanded jet causes a diminution in the circulation zone the throat diameter of the total jet; and the distance to it hence grow. After the formation of a Mach wave configuration, the hanging shock diminishes the slope to the axis and the Mach disk recedes from the nozzle. Investigations of the structure of cylindrical underexpanded turbulent jets showed that a supersonic co-flow exerts substantial influence on the jet, resulting in "degeneration" of the central shock and diminution of the size of the initial section [11].

It has been established as a result of tests with jets in a subsonic co-stream that for almost-critical off-designs, a closed base region is realized. This is explained by the origination of a local supersonic zone near the nozzle edge. The dependences $P_b/P_a = f(P_\infty/P_a)$ in the open-base-region mode differ slightly from the linear, and the slope of the curves is almost one; the values of P_b/P_a remain constant in the closed-base-region mode.

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