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STUDYING UNSTABLE REGIMES OF JET INTERACTION WITH APPROACHING FLOWS

V. V. Kondrashov and R. I. Soloukhin*

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We present and clarify results from numerical experiments pertaining to the description of unstable flow regimes where supersonic jets are propagated into an oncoming gas flow.

Problems of propagation in media and the interactions between these media and supersonic gas jets are of considerable interest. Here, results of studies into the nonsteady (unstable) regimes of flow in the oppositely directed interaction of an underexpanded heated supersonic jet with a flow have not been systematically organized and they are frequently contradictory [1-3]. This is associated with the considerable difficulties involved in deriving information regarding specific details of the flow in an instrumental study of the spatial pulsating flows which can frequently be obtained during the course of numerical experiments with a computer, and these difficulties arise also as a consequence of the great sensitivity of the flows in the case of unstable regimes to minor variations in the determining parameters.

Even the initial attempts to utilize profiled subsonic nozzles for purposes of generating sonic jets streamlining a surface turned into the direction of the flow gave evidence of an extremely complex interaction between the parameters defining the flow of the gas within the nozzle and the streamlining [by an external flow] of a body with a notched nozzle in its nose section [1, 4].

At the beginning of the 1960s researchers demonstrated that a flow is nonsteady if the total pressure across the jet is small and if the characteristic dimension of the jet is small in comparison with the dimensions of the body. The oncoming jet in this case is regarded as a gasdynamic analog of a needle or a cone, mounted on the forward section of a body, and the results of investigations into the latter, both here and abroad [5], were applied to this approaching stream. Unstable interaction regimes (UIR) of a jet with a flow in this case is characterized by the conditions under which the separated region is formed at the surface and by the mutual disposition of the deformed bow shock and the body.

The forces assumed in [6] for the development of an analytical model of oncoming jet interaction with a flow demonstrated the importance of making provision for the regimes under which a jet is discharged out of a nozzle, and the related UIR. Results from studies into these interaction regimes, making provision for the extent to which the calculations for the jet are incomplete, have been generalized in [7], where an attempt was also undertaken to construct a model to determine the parameters in the region of the detached flow. The accumulated data from these experimental studies showed that the UIR are determined also by the conditions of flow for the jet layer near the point at which the detached region closes. In this case, the very presence of a mass source within the flow becomes significant.

*Deceased.

A. V. Lykov Institute of Heat and Mass Exchange, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 4, pp. 539-545, October, 1989. Original article submitted May 16, 1988.

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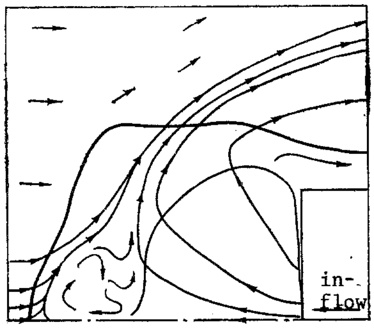

Fig. 1

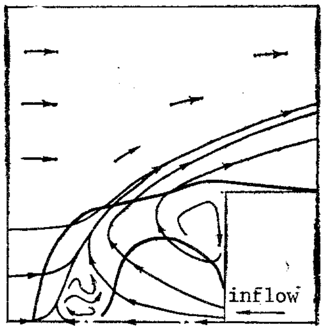

Fig. 2

Fig. 1. Flow patterns with formation of a central vortex zone as the heated sonic jet is discharged into an oncoming supersonic flow. The developed interaction regime: $M_\infty = 6$; $M_a = 1$, $R_m/R_a = 4.8$; $P_a^*/P_{0\infty}' = 13$; $V_a = 1352$ m/sec.

Fig. 2. Flow pattern with formation of a central vortex zone with a heated sonic jet discharged into an oncoming supersonic flow. Developed interaction regime: $M_\infty = 10$; $M_a = 1$; $R_m/R_a = 4.8$; $P_a^*/P_{0\infty}' = 4$; $V_a = 662$ m/sec.

Analysis of the flow patterns enabled us to isolate five basic diagrams of oncoming interaction for a supersonic jet source and a flow, and these were taken from [3]. Application of the concept of a jet source made it possible to isolate two fundamental elements governing the structure of a perturbed flow region: the actual body and the source contained within the body. As a consequence, in studying the UIR it is possible to identify unstable regimes that are characteristic exclusively of the source, as well as those which arise as a consequence of perturbation interference within the flow, generated both by the body and the source. Among the latter we include the pulsating flow regimes that arise under conditions of nozzle operating regime variations and exhibit various pulsation mechanisms [6, 7].

For the given jet source and for the given flow a fully defined flow configuration is characteristic. We have reference here, primarily, to the shape of the surface separating the external medium from the source, governed by the dynamic equilibrium between the two regions of opposing flow deceleration. Experimental data [6-9] provide information basically with regard to flows in which the boundary of separation closes about the source and intersects the surface of the body in which the source is contained. In the area in which these surfaces intersect, conditions for UIR are formed.

In this case, the most unfavorable case is the one in which the shape of the body provides for the flow of gas into a volume bounded by the separation surface. Primarily, this might occur when the bow shock formed on the streamlining of the boundary of separation by the flow impinges directly on the surface of the body. The small angles of intersection may be acceptable in this case if we eliminate the accumulation of a gas mass at the boundary of the jet. With this in mind, we should also limit ourselves to small angles where the jet layer is attached to the body (8-22° [6]).

As the gas is pumped into the container, with the gas accumulating at the edges of the jet, we can distinguish the development of two UIR processes. When the pressure in the jet at the outlet section of the nozzle is small (in comparison with the maximum pressure at the boundary separating the media) the rise in pressure which occurs in this case at the boundary may be accompanied by a change in the regime under which the jet is discharged, with subsequent development of the UIR described in [1, 6, 7]. If the pressure at the outlet section of the nozzle is greater by a factor of more than two than the characteristic pressure at the boundary separating the media, we generally have discharge of the underexpanded supersonic jet of gas into a flow with an extensive region of detached flow at the boundary of the jet. The accumulation of a mass of gas in this region is accompanied by the formation of a powerful vortex whose inside surface deforms the boundary of the jet. The UIR which arises in this case is described in [10] in terms of the results from a numerical study of the interaction between the sonic jet source and a hypersonic flow by the large-particle method. These studies indicated that such a UIR is characteristic, generally speaking, of supersonic jet sources, because of inadequate drainage of the mass out of the gas cavern into the gasdynamic wake. If the shape of the body surface is properly chosen, it is possible to eliminate the accumulation of the gas mass in the region of the detached flow.

In practical applications it is necessary to ensure a suitable value for the gas-flow rate in achieving the gasdynamic flow pattern being considered here. In this connection, we make use of supersonic nozzles, annular nozzles, and the incoming gas is heated. We thus establish conditions for the development of UIR, associated with the unique features involved in the deceleration of the supersonic flow by means of a deformed obstacle that is formed by the boundary of separation between the media.

The use of a supersonic nozzle, all other conditions being equal, leads primarily to a reduction of the pressure at the outlet section from the nozzle to the jet and to a corresponding change in the spatial distribution of the parameters both within the jet and in the deceleration region, or in the region of flow compression at the forward section of the jet obstacle, where the development of unstable phenomena becomes possible near the boundary of separation. Accumulation of a gas mass in the central jet deceleration region may be a consequence thereof. In the absence of mass drainage, this may lead to the deformation of the boundary of separation, accompanied by changes in the force effect of the external flow on the jet obstacle, tending to reducing that quantity. The removal of the mass and the return to the original state will be accompanied by the development of transitional processes and instability phenomena in other regions of the flow.

Pulsations of the parameters near the central point of flow intersection also facilitates the development of Rayleigh—Taylor and Helmholtz instabilities. In the research carried out by Vasil'kov and Murzinov [3] it was demonstrated that with certain parameters of the supersonic source we may find that no stable position exists for the boundary separating the media. This assumption was confirmed through numerical experimentation [11].

Numerical studies into the interaction of supersonic jets with an approaching flow were conducted by means of the Belotserkovskii—Davydov "large particle" method. The modification involved derivation of a completely conservative outline of the method whose applicability to the solution of the jet problems being considered here is shown in [12-15]. A complete system of nonsteady gas-dynamics equation was solved (the Euler equations for the calculation of axisymmetric flows), for which the stationary solution, if it exists and is hydrodynamically stable, was derived by determination. Sufficiently precise modeling of the time processes in this method also yield the possibility of studying the dynamics of nonstationary interaction phenomena [12, 13]. The solution algorithm and the method of specifying the boundary conditions do not differ from those generally employed [10-12].

We examined the opposing interaction of two media, consisting of an air mixture of gases (the injection of the air into the air flow). To calculate the pressure and the temperature on the basis of the density and the internal energy, we utilized explicit approximations of the thermodynamic functions of the air, taken from [16]. The symmetry axis of the flow coincided with that of the cylinder at whose end surface was located coaxially the sonic nozzle to supply the air into the approaching flow.

As the heated sound jets were discharged into the flow near the point of flow intersection a central vortex zone is created. The values of the specific flow rate and the specific total energy in the jet may be smaller than the corresponding values for the approaching flow.

The appearance of the central vortex zone is accompanied by a change in the geometry of the closing discontinuity in the jet and in the surface separating the media near the axis of flow symmetry. The latter, in the majority of cases, is slightly bulged in the direction of the external flow. The heating of the injected gas intensifies this bulging, deforming the central portion in such a manner that the pressure losses in this portion of the discontinuity are diminished and an axial jet is developed with near-sonic parameters, eliminating the possibility of any further bending of the surface of separation.

The vortex zone is maintained through $M = 6$ (Fig. 1) as well as with the reduction in the jet discharge velocity (from 1352 to 662 m/sec). In this case, the magnitude of the total jet energy is reduced to values of less than 50% of the total energy of the flow; the excess of total jet pressure is assumed to be equal to $\Pi = 13$.

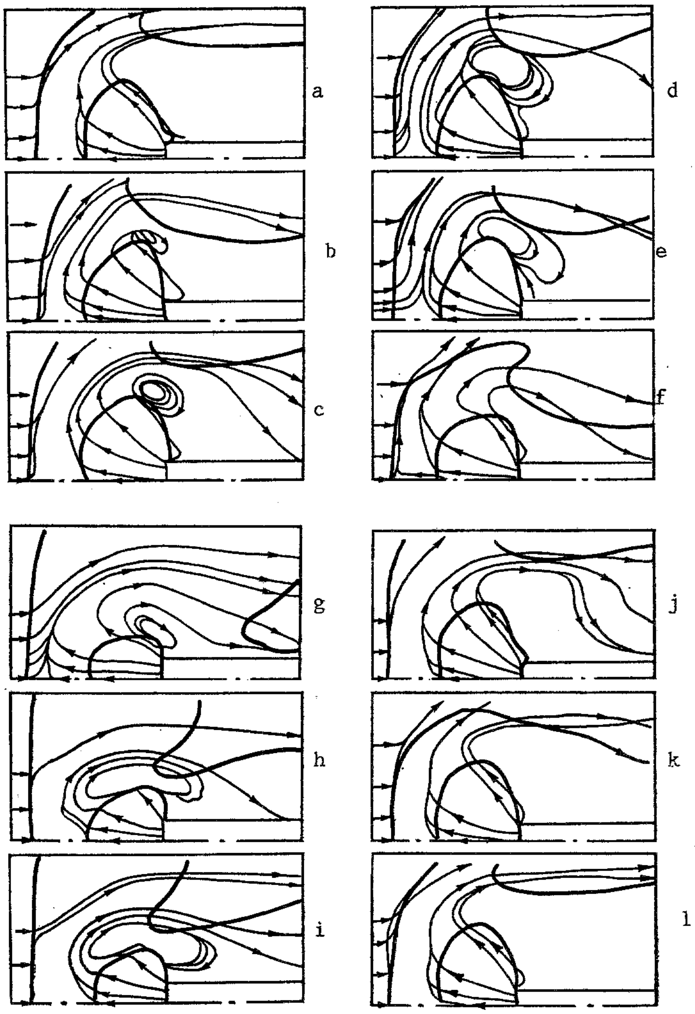

Fig. 3. Vector flow field, streamlines, and calculated datum lines for the Mach number equal to unity.

When the velocity of the external flow is increased to M = 10 (here the velocity of the sonic jet is 662 m/sec) the vortex zone is maintained during the subsequent reduction in the excess of the total pressure from 15 to 4 (Fig. 2). The total energy of the jet amounted to about 15% of the value for the approaching flow.

The central vortex zone, its appearance and its destruction, can all serve to explain the origin of flow pulsations accompanied by nonsymmetric deformations of the surface of media separation. In the course of the experiments these pulsations were recorded for the regimes of developed flow interaction as the jet was injected with a Mach number equal to the Mach number of the approaching stream, when the total energies of the flows are similar to each other. In particular, results are presented in [8] for the visual and instrumental observations of flow pulsations in the case of streams with Mach numbers of M = 4, for which no explanations exist.

It was demonstrated in [7] that the flow being considered here is extremely sensitive to coaxiality of the flows when the total jet pressure excesses are small. This may serve to explain the appearance of asymmetric pulsations. However, when rigorous axisymmetry of the flow is maintained in the regime of developed interaction we observe asymmetric pulsations in the boundary of separation for the media "in the form of acoustic waves" [7] when a jet of air with M = 1.5 and 2 is injected into a flow with M = 2.04.

In numerical modeling the flow pattern for the central vortex zone is stationary. No pulsations of the parameters were observed. It is probable that the presence of perturbations in the approaching flow, the vibrations of the jet-forming device, and the instability of the flow in the vicinity of the central portion of the closing discontinuity in the jet and in the surface of medium separation lead to a disruption of the vortex zone under the conditions of the experiment, driving it downstream, which makes itself evident in the form of high-frequency asymmetric pulsations.

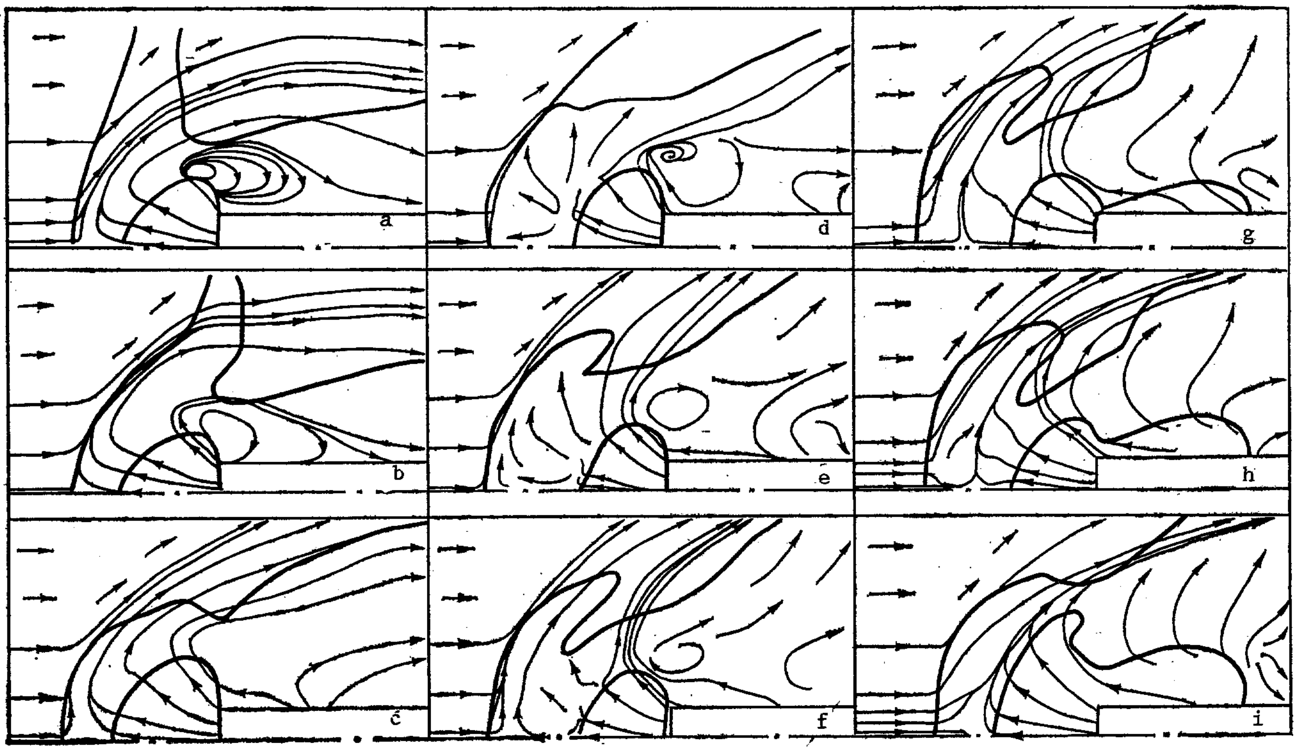

Fig. 4. Vector flow field, streamlines, and calculated datum lines for a Mach number equal to unity.

The development of instability phenomena may also occur in the region of jet-flow closure (reverse flow) at the surface of the body or at the axis of flow symmetry. The deflection of the "fluid body" contour defined by the surface of medium separation beyond the limits of some low-resistance body defined by the parameters of the external flow and the shape of the leading surface of the jet obstacle will increase as the mass of the gas increases, the latter having been ejected into the detached region out of the reverse flow and drawn into the vortex motion. Conditions arise for the appearance of flow-rate pulsations [3, 10]. Figures 3 and 4 show flow-field patterns with streamlines, taken from [10], for the sound source in hypersonic flow (M = 24). It is possible to observe that the pulsations of the flow within a single cycle are determined by the features encountered in the closure of the vortex detached region.

Figure 3a-c shows how the formation of the closed vortex zone takes place as the injection products are propelled into that zone out of the subsonic reverse jet flow. Here we also observe the displacement of the shock wave front, with the formation of an extensive gas "pillow" behind the front.

Figure 3d-f shows the instant at which the gas "pillow" behind the front is destroyed and the onset of the deformation of the supersonic cell of the underexpanded opposing jet through the action of that mass of gas accumulated by this time in the detached region and participating in the vortex motion.

Figure 3g-i shows the process by which the vortex deforms the jet. If the unevenness of the jet causes the nozzle to operate in an underexpansion regime, no restructuring of the jet is observed, and we note restoration of the configuration for the region of the supersonic flow and the propulsion of the vortex downstream (Fig. 3j-m).

When the jet discharge regime under the conditions of Fig. 3 changes, we have a concentrated injection of a mass of gas in the form of a "gas needle" to a considerable distance upstream. The limitations of this region made it impossible to carry out any corrective calculations of the flow under these conditions.

It was noted that the vortex formed at the boundary of the jet (Fig. 3g-i) can be destroyed more rapidly if a vortex motion is set up in the region in which the flows meet, so as to block its forward motion. Figure 4 shows a fragment of the flow pattern that exists immediately following the instant of time corresponding to Fig. 3f. The instant of greatest jet cell deformation here coincides with the departure of the shock wave forward and with the formation of unstable vortex motion (Fig. 4a-c) in the gas "pillow" interacting with the flow behind the forward shock wave (Fig. 4d-f). The destruction of the gas "pillow" and of the vortex occurs simultaneously (Fig. 4g-i).

In physical units the computation integral amounts to $2.2 \cdot 10^{-7}$ sec, which made it possible to resolve the pulsation processes over time. The gas was pumped into the vortex region in $0.9 \cdot 10^{-3}$ sec, the compression of the cell lasted about $3 \cdot 10^{-3}$ sec, and the expulsion of the vortex lasted about $(1.5\text{-}2) \cdot 10^{-3}$ sec. The duration of the total cycle varied from 3 to 4.5 msec, which yields an average pulsatoin frequency of about 270 Hz.

These studies of the unstable supersonic jet interaction regimes involving counterflow currents thus demonstrate that in practical applications it is necessary not only to provide for matched body shape and the wave structure of the jet source, but also to be concerned with the formation of the jets which ensure the stable deceleration of the supersonic flow. Let us note that our studies of the quantitative relationships governing the interactions of the supersonic jets with the flows enabled us to establish general characteristics of the flow for supersonic gas streams, based on solutions of the mathematical problem of the streamlining of a supersonic jet source by means of the supersonic flow [3, 17].

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