Journal of Applied Mechanics and Technical Physics, Vol. 42, No. 5, pp. 757–764, 2001

FLOW REGIMES FORMED BY A COUNTERFLOW JET IN A SUPERSONIC FLOW

V. M. Fomin,[1] A. A. Maslov,[1] A. P. Shashkin,[1]
T. A. Korotaeva,[1] and N. D. Malmuth[2]

UDC 532.526

Results on the effect of the dynamic pressure, Mach number, and temperature of a jet injected from a body upstream in a free supersonic flow on the formation of flow regimes are presented. Flow regimes that ensure the greatest decrease in the drag of the body are given, the mechanism of formation of the LPM flow structure is described, and an approximate criterion is found, which allows determination of the range of existence of various modes of jet penetration into the flow.

Unconventional methods of controlling the total aerodynamic characteristics of flying vehicles are of considerable interest now. Some authors (see, e.g., [1–11]) consider methods of changing the flow structure upstream of the body, which affects the forces and moments acting on the vehicle. The problems of efficiency and possibility of technical implementation of these methods, however, often remain unsolved.

One of the realistic methods of acting on the flow may be a jet injected upstream from the body. The counterflow jet forms various flow structures, which strongly depend on free-stream parameters and jet parameters such as the pressure, Mach number at the nozzle exit, and temperature. The flow structure also depends on the body geometry and the ratio of nozzle-exit and bluntness diameters.

Some experimental papers [3–9] deal with the action of counterflow jets on the flow structure. It is shown there that the jet injected from the forebody is the reason for pressure redistribution on the side surface and changes significantly the aerodynamic characteristics of the flying vehicle.

Yudintsev and Chirkashenko [4] studied possible regimes of penetration of a supersonic "cold" jet into the free stream. Plasma counterflow sonic jets were considered in [3, 5–8]. Exhaustion of supersonic jets into a supersonic flow was usually considered [3–7]. It was noted that, depending on the governing parameters, the depth of jet penetration into the free stream may be small [short penetration mode (SPM)] or large [long penetration mode (LPM)]. The SPM structure is fairly well examined [9], but the LPM structure is not defined rather clearly. For this reason, flow regimes that are actually SPM are referred to in some papers as LPM.

There are two hypotheses that explain the decrease in the drag of the body with an escaping jet:

1. High-frequency disturbances arising in the jet, including those due to instability in the shear layer, destroy the bow shock, and thus decrease the resistance to the escaping jet [6].

2. The main role in the events that occur in the flow belongs to mass-flow-rate processes, which form a new gas-dynamic structure around the body [8].

The calculations, which are in satisfactory agreement with experimental data, allow us to conclude that the second hypothesis is preferable.

In the present work, we made an attempt to summarize scattered experimental data by means of numerical simulation, to indicate flow regimes that influence the drag of the body most effectively, to describe the mechanism of formation of the LPM flow structure, and to find an approximate criterion that allows one to determine the range of existence of different flow modes.

---

[1]Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. [2]Rockwell Research Center, Thousand Oaks, California, U.S.A. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 42, No. 5, pp. 27–36, September–October, 2001. Original article submitted May 28, 2001.

0021-8944/01/4205-0757 $25.00

The study was performed within the framework of the inviscid gas model by the finite-volume method. An implicit central-difference scheme of the second order of approximation was used. A shock-capturing technique was used to solve a time-dependent unsteady problem. The preliminary solution without the jet was used as the initial data. Free-stream conditions were imposed at the external domain boundaries, and the condition that the second derivatives of flow parameters along the flow-velocity direction are equal to zero was imposed at the output boundary of the computational domain. The no-slip conditions were set on the body. At the jet output, the parameters were determined by solving a one-dimensional isentropic problem of gas exhaustion from a vessel with known parameters (the Mach number at the exit, the stagnation temperature, and the stagnation pressure were assumed to be known).

Flow Structure in Different Flow Modes. If the specific momentum of the jet does not exceed the specific momentum of the flow between the bow shock wave and the body, then SPM jet exhaustion occurs. A detailed description of the pattern of such a flow can be found in [9], where it is noted that the SPM jet acts in the region between the bluntness and the shock wave. It displaces the bow shock wave and, being entrained by the counterflow, forms a rather rarefied backflow zone above the side surface of the vehicle (Fig. 1).

If the specific momentum of the jet is greater than the specific momentum of the incoming stream, a supersonic flow with a stable multibarrel structure (LPM) is formed. In this regime, the jet is extended outside the limits of the bow shock wave. A backflow zone is formed upstream of the bluntness. A toroidal vortex arises with weakly changing pressure inside the backflow zone. Within the inviscid approximation used in the present paper, this vortex is purely dynamic; the reason for its formation is that a part of the jet flows along the side surface of the body and the other part, flowing down the butt-end face, passes into the backflow region. The calculations show that, for such a flow regime to be stable, the point of reattachment of the backflow part of the jet should be located on the blunted portion of the body. The reattachment point is shifted along the butt-end face with time. When it passes to the side surface, the pressure outside the jet decreases. This decreases the recirculation zone, and hence, the reattachment point returns to the butt-end face. Oscillations of the reattachment-point position near the butt-end face edge usually lead to periodic variations of the jet structure and its length. If the jet becomes strongly underexpanded, the flow may pass to the short penetration mode.

Figure 2 shows the LPM flow structure obtained by numerical simulation. The field of isobars for one computational variant is plotted. The LPM pattern obtained by analysis of the behavior of streamlines in the numerical solution is shown in Fig. 3.

Drag of a Blunted Body in SPM and LPM Jets. The effect of dynamic pressure in the jet on the flow regime and drag of the body was studied for fixed parameters of the exhausted jet, such as the Mach number at the nozzle exit, temperature, and ratio of nozzle-exit and butt-end face diameters.

The calculations were performed for a cone–cylinder configuration. The cone with an apex half-angle $\theta_c = 10^\circ$ has a bluntness in the form of a flat butt-end face of diameter d. The exit orifice of the nozzle of diameter d_j is located at the butt-end face. The free-stream Mach number is $\mathrm{M}_\infty = 2.04$, the angle of attack is $\alpha = 0$, $\bar{d} = d/d_j = 3.08$, and the Mach number at the nozzle exit $\mathrm{M}_a = 3.8$; the relative dynamic pressure of the jet was varied within the range $3 \leqslant P = p_{0j}/p'_{0f} < 90$, where p'_{0f} is the free-stream stagnation pressure behind the shock and p_{0j} is the stagnation pressure in the jet. The stagnation temperature in the jet was assumed to be equal to the free-stream stagnation temperature.

Solving the problem of penetration of a counterflow jet into a supersonic flow around a blunted body allowed obtaining two main flow modes (SPM and LPM) and transitional regimes in which oscillating (unstable) penetration modes are possible.

Figure 4 shows the length of the counterflow jet L/d (L is the jet length and d is the butt-end face diameter) as a function of P. The calculation results are in good agreement with the experimental data of [10]. The same figure shows the calculated results of the relative drag of the blunted cone model $C_d/C_{d,c}$ (C_d and $C_{d,c}$ are the values of the blunted cone drag with and without the jet, respectively). The calculations take into account the reactive component of the jet. It is seen that the counterflow jet decreases the cone drag. In the SPM → LPM transitional mode (region II), the decrease in drag is about 30% as compared to the cone without the jet. In region II, the cone and the streamsurface upstream of it form a surface close to the minimum drag surface; thereby, the minimum of the total drag (the sum of the wave drag and the reverse thrust of the jet) is reached. An increase in dynamic pressure leads to jet extension, the shape of the minimum drag streamsurface is violated, and the drag of the body increases. With further increase in dynamic pressure, the jet becomes strongly underexpanded. The LPM structure is destroyed, and the SPM structure is formed (region V). In region V, the total drag of the body may be greater

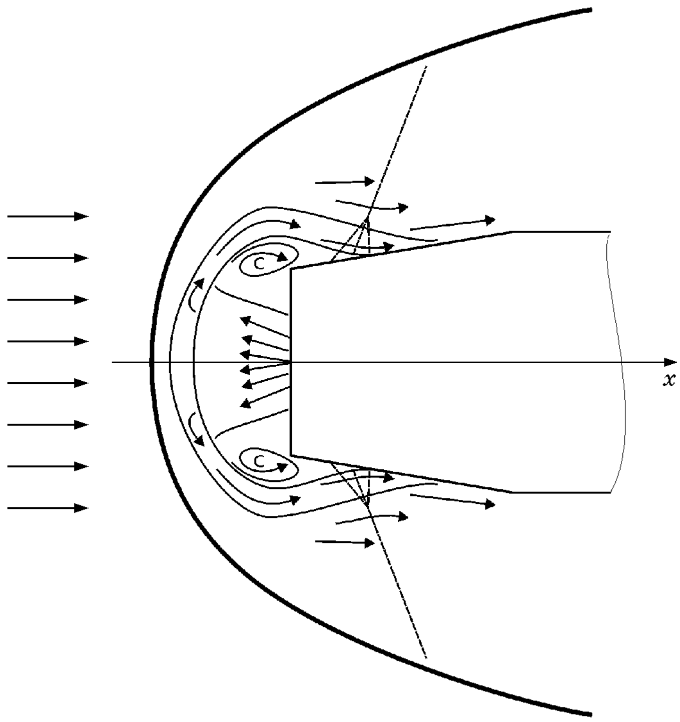

Fig. 1. SPM flow pattern.

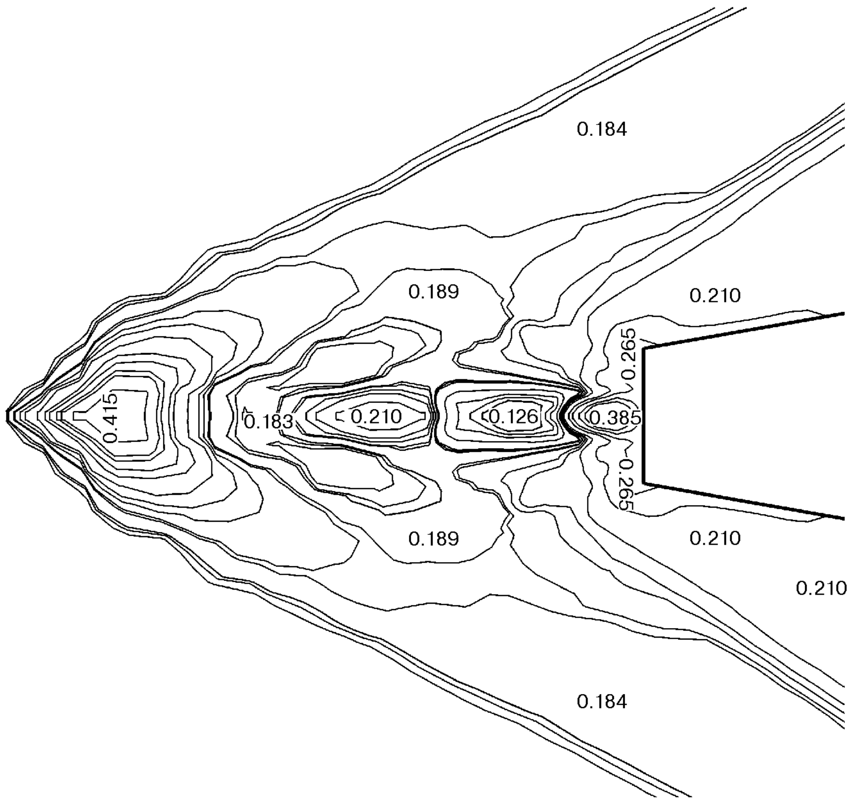

Fig. 2. LPM isobars p/p_{∞}.

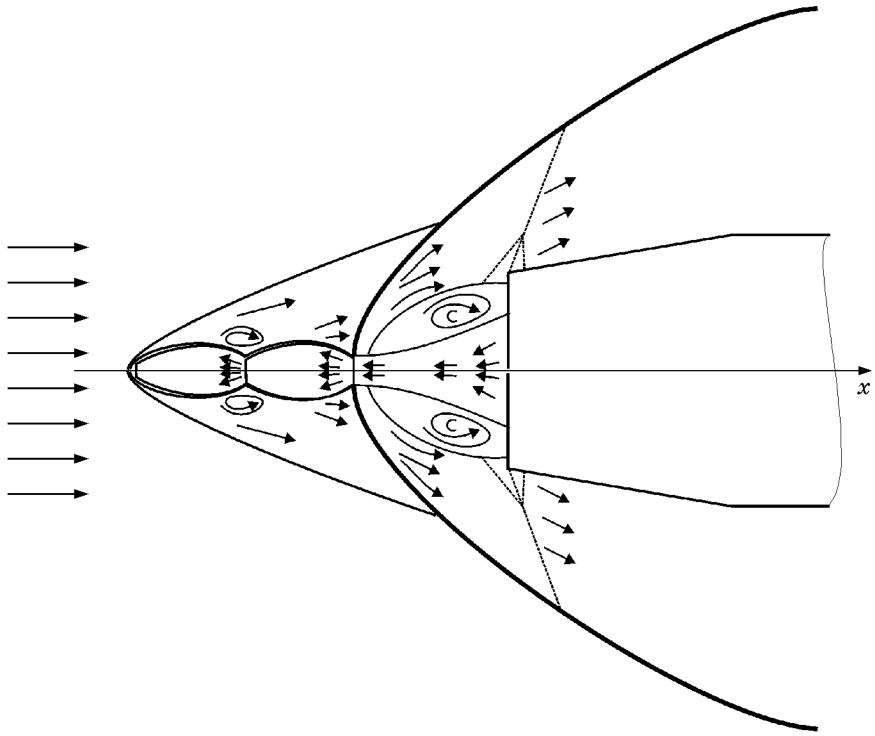

Fig. 3. LPM flow pattern.

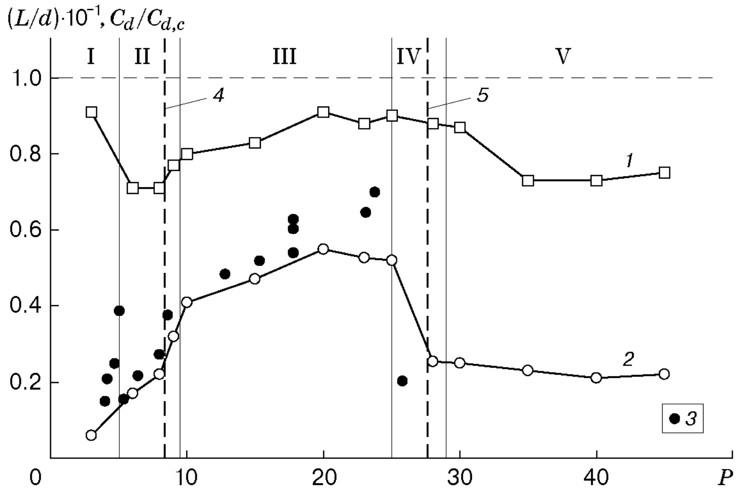

Fig. 4. Drag of a blunted cone with a jet injected upstream (curve 1) and jet-penetration depths (curve 2 and points 3) as functions of the parameter P: curves 1 and 2 refer to calculation, points 3 to experiment, and curves 4 and 5 refer to $P_{\min}$ and $P_{\max}$, respectively [calculation by (7)]; region I refers to SPM, region II to SPM → LPM transitional mode, region III to LPM, region IV to LPM → SPM transitional mode, and region V to SPM.

than the drag of the body without the jet. The backflow zone passes to the side surface, the pressure in the region of flow reattachment is high, though the forebody is in a rarefied region. The reactive component of the jet is also large. In this case, the decrease in cone drag in region V is explained by the fact that the backflow reattachment zone for this model with a short cylindrical part is located on the body cylinder.

Effect of the Mach Number at the Nozzle Exit. *Jet with* $\mathrm{M}_a > 1$ *at the Nozzle Exit.* If the counterflow jet at the nozzle exit is supersonic and weakly underexpanded or weakly overexpanded, a multibarrel periodic structure may be formed.

In the case of exhaustion of a weakly underexpanded jet, its cross-sectional area insignificantly increases, the Mach number increases, and the pressure in the jet decreases to values lower than in the flow; as a result, the jet starts to shrink. This leads to an increase in the specific momentum of the jet, and the jet moves forward, upstream of the bow shock wave.

If the jet is strongly underexpanded, a significant increase in its cross-sectional area decreases the specific momentum and decelerates the jet; as a result, a normal shock arises upstream of the jet. The momentum of the jet decreases even more behind the normal shock, and the flow passes to the short penetration mode.

If the supersonic jet is weakly overexpanded, its cross-sectional area decreases, the specific momentum increases, and the long penetration mode is observed.

In strongly overexpanded jets, a normal shock arises at the nozzle exit; for this reason, the specific momentum decreases, and the short penetration mode is formed.

Jet with $\mathrm{M}_a = 1$ *at the Nozzle Exit.* For jets with a sonic exhaust velocity at the nozzle exit, similar to the Laval nozzle flows, two solutions are possible:

1. The weakly underexpanded jet starts to expand, and the Mach number becomes greater than unity. Then, the flow development follows the scenario for a supersonic jet, which may result in the transition to the long penetration mode.

2. A normal shock wave arises in the strongly underexpanded or overexpanded jet, the Mach number becomes lower than unity, and the short penetration mode is formed.

Jet with $\mathrm{M}_a < 1$ *at the Nozzle Exit.* Theoretically, acceleration of an initially subsonic jet to a supersonic velocity is possible, if the streamlines form the Laval nozzle in air [12]. The calculations performed in the present work support this fact. The long penetration mode was obtained for convergent jets. In this case, the streamlines converge at the nozzle exit, and the Mach number increases to the critical value $\mathrm{M} = 1$, then the streamlines go apart, the jet expands and is accelerated to a supersonic velocity, and processes typical of a supersonic jet are developed. In calculations, this solution was observed only for high temperatures of the jet.

Thus, multibarrel periodic structures were observed in calculations, if there were conditions for jet transition to a supersonic mode, and the jet was weakly overexpanded integrally over its length. In addition, a backflow region should be located upstream of the bluntness, which stabilizes the LPM structure as a whole.

Effect of Jet Temperature. *Hot Jets.* The distinctive feature of hot jets is that they have a greater momentum at a fixed value of the Mach number at the nozzle exit. In addition, cooling down, hot jets become narrower, which leads to an increase in the specific momentum. Figure 5 shows the pressure fields for different temperatures of the exhausted jet. The calculations show that the depth of penetration of hot-gas jets is much greater than the depth of penetration of "cold" jets.

Plasma Jet in a Hypersonic Flow. The calculation results for low Mach numbers ($\mathrm{M}_\infty = 2$) for "cold" and hot jets are in good agreement with the experimental data of [8, 10]. In this case, apparently, the influence of physicochemical processes in the jet is insignificant. For $\mathrm{M}_\infty = 6$, the calculation results, where the exhaustion of a hot jet of a perfect gas was simulated [11], and experiments with exhaustion of a plasma jet [7] are only in qualitative agreement.

The calculations were performed for a circular cone with a half-angle $\theta_c = 15^\circ$ and bluntness in the form of a flat butt-end face with a nozzle-exit orifice of diameter d_j. The free-stream Mach number was $\mathrm{M}_\infty = 6$, $\alpha = 0$, $\bar{d} = d/d_j = 3.5$, $\mathrm{M}_a = 2.5$, $1.3 \leqslant P < 21.5$, and the relative stagnation temperature was $T = T_{0j}/T_{0f} = 15$. The calculations showed that LPM can also exist for these parameters.

For a hypersonic free-stream velocity, however, the shock wave is close to the body surface, the pressure and temperature are high, and vibrational degrees of freedom are excited. In this case, the internal structure of the jet and the processes that affect the physicochemical properties of the flow play an important role. Possibly, the neglect of these factors is responsible for the fact that the length of the LPM jet in the experiment of [7] is greater than in calculations with hot jets [11], where the depth of penetration into the counterflow does not exceed the butt-end face diameter.

At the same time, the features of SPM and LPM formation are the same as those for jets with lower values of M_∞. Figure 6 shows the drag and penetration depth as functions of P. The cone drag is calculated taking into account the reactive force of the jet. Figure 6 shows the drag of a blunted cone without the counterflow jet ($C_{d,t}$) and with the jet ($C_{d,j}$), and also the drag of a sharp cone with a half-angle 15° ($C_{d,c}$). All dependences are normalized to the drag of a sharp cone with a half-angle $\theta_c = 15^\circ$. LPM implies a significant decrease in the drag of the body. Nevertheless, the penetration depth of the jet and its effect on drag in a hypersonic flow are smaller than at lower Mach numbers.

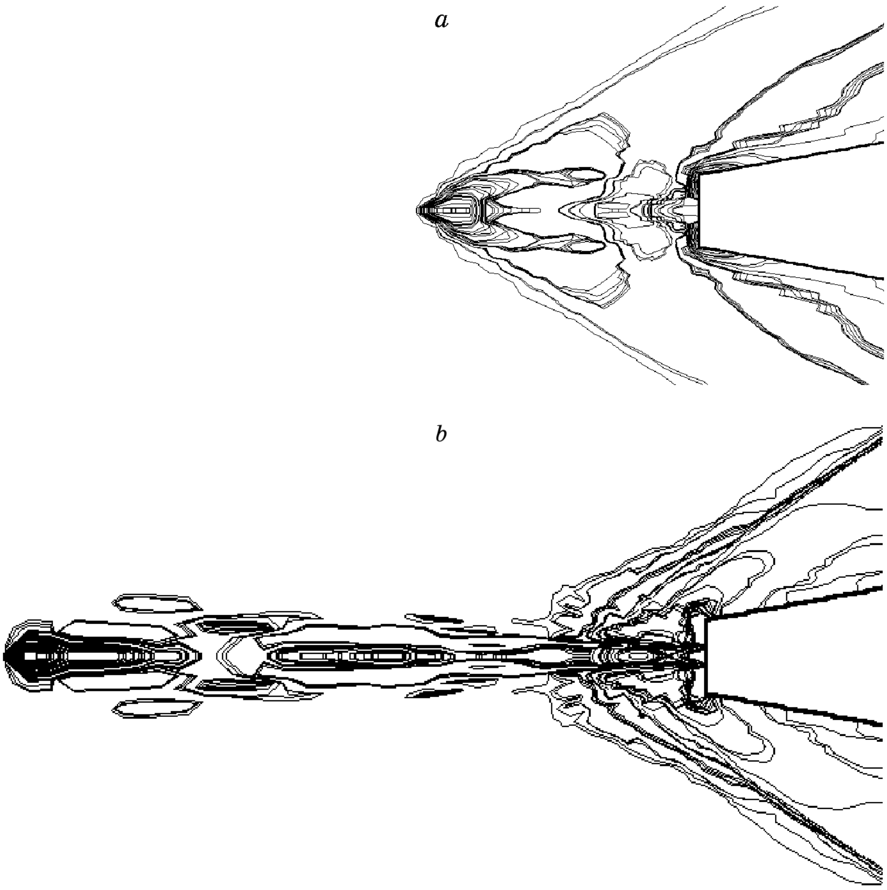

Fig. 5. Effect of temperature on the penetration depth and jet structure ($M_\infty = 2.04$, $M_a = 3.8$, and $P = 26.6$): isobars for $T_j = 300$ K (a) and 5000 K (b).

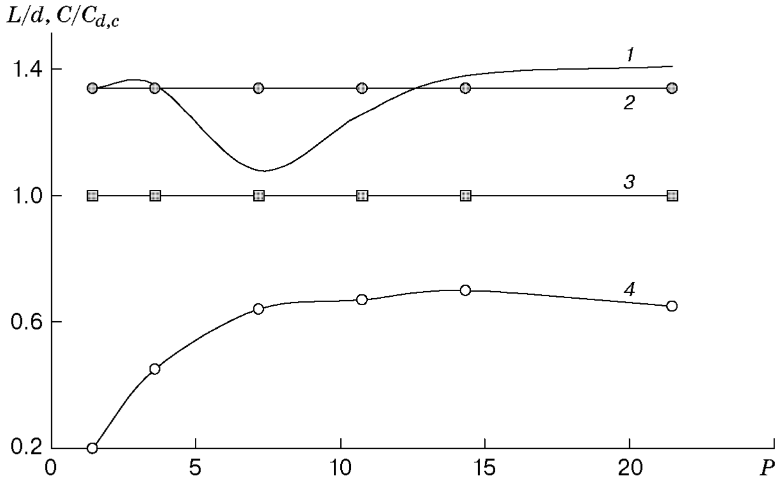

Fig. 6. Drag of a blunted cone with an upstream injected jet and penetration length as functions of the parameter P: 1) $C_{d,j}/C_{d,c}$; 2) $C_{d,t}/C_{d,c}$; 3) $C_{d,c}/C_{d,c}$; 4) L/d.

Approximate Criterion for Determination of the Penetration Mode. Interaction of a counterflow jet and a supersonic flow is a complex phenomenon. To obtain an approximate estimate of the penetration process, a model problem is analyzed. The basic assumptions of this model are as follows: the jet exhausted from the nozzle is surrounded by a toroidal vortex, the flow is inviscid, the jet boundary may be identified, the jet flow is weakly underexpanded or weakly overexpanded, and the angle of inclination of the velocity vector of the jet at the nozzle exit is small. It is assumed in the estimates that the Mach number in the jet equals the Mach number at the nozzle exit ($\mathrm{M}_a > 1$).

Bodies with a flat butt-end face are considered, for which the ratio of the bluntness diameter to the jet diameter is 3–5, are considered.

For the jet to leave the nozzle and pass beyond the shock wave, the following condition should be satisfied [4]:

$$0.3 < n = p_a/p_\infty < 1.5. \tag{1}$$

Here n is the nozzle-pressure ratio, p_a is the static pressure at the nozzle exit, and p_∞ is the free-stream static pressure. Otherwise, a normal shock arises in the jet, and p_{0j} should be replaced by p'_{0j}. Designating the mean pressures in the jet and at its boundary as $\tilde{p}_j$ and $\tilde{p}_n$, we can rewrite condition (1), making it more rigorous:

$$0.3 < \tilde{n} = \tilde{p}_j/\tilde{p}_n < 1.0. \tag{2}$$

We determine the mean pressures $\tilde{p}_j$ and $\tilde{p}_n$. The mean pressure in the jet is

$$\tilde{p}_j = p_{0j}/[\varphi(T)(1 + \mathrm{M}_a^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}], \tag{3}$$

where T is the static temperature, $\varphi(T)$ is the dependence of the jet area on temperature, and γ is the ratio of specific heats. Assuming that there is an isobaric input (output) of heat in the jet, we obtain [13]

$$\varphi(T) = (1 + T_a/T_2)/2. \tag{4}$$

Hereinafter the subscript 2 refers to parameters behind the shock wave. To determine the mean pressure at the jet boundary $\tilde{p}_n$, we assume that:

1) The pressure behind the bow shock wave is

$$p_2 = p'_{0f}/(1 + \mathrm{M}_2^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}; \tag{5}$$

2) The pressure is almost constant near the bluntness ($dp/dx \approx 0$). The pressure on the body, except for the nozzle exit, equals the base pressure p_b, which follows from experiments and calculations;

3) The pressure p_n along the external boundary of the jet varies in accordance with the quadratic law within the range p_2–p_b. Then, the mean pressure along the external boundary of the jet is

$$\tilde{p}_n = \int_0^1 p_n\,dt = \frac{p_2 - 2p_b}{3}. \tag{6}$$

Finally, using Eqs. (1)–(6) and passing from the static pressure to the stagnation pressure, we obtain the following expression for the parameter P:

$$P = \frac{\tilde{n}}{2}\,\frac{1 + T_a/T_2}{3 - (\tilde{n}/n)(1 + T_a/T_2)}\,\frac{(1 + \mathrm{M}_a^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}}{(1 + \mathrm{M}_2^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}}. \tag{7}$$

Substituting the values $\tilde{n} = 0.3$ or $\tilde{n} = 1$ into Eq. (7), we can obtain, respectively, the minimum or maximum value of the parameter P at which LPM formation is possible.

We classify three main modes of jet penetration into the free stream: $\mathrm{SPM}_{\min}$ ($P < P_{\min}$), $\mathrm{SPM}_{\max}$ ($P > P_{\max}$), and LPM ($P_{\min} < P < P_{\max}$).

In accordance with criterion (7), test conditions in a hypersonic flow [7] were chosen. The existence of numerically predicted flow modes was confirmed. This criterion is also valid for other experiments, including those with "cold" jets. The dashed vertical lines in Fig. 4 indicate the boundaries of existence of the main flow modes determined by Eq. (7). This allows us to argue that the main role in the mechanism of formation of flow modes belongs to gas-dynamic processes, at least, for "cold" jet or jets exhausted into a flow with a moderate Mach number.

Thus, the numerical solution of the problem of penetration of a counterflow jet into a supersonic flow around a blunted body shows that there are two basic modes: SPM and LPM. LPM may be obtained in the case of a supersonic or sonic velocity of the jet exhausted into a supersonic incoming flow. The formation of a multibarrel periodic structure is also possible for a transonic velocity of jet exhaustion into a supersonic incoming flow, but the jet should be convergent and hot.

Counterflow jets in all exhaustion modes may affect the drag of the body. Most effective regimes from the viewpoint of decreasing the drag of bodies are regions of SPM → LPM transitional regimes and LPM with a comparatively small depth of jet penetration into the incoming flow.

This work was supported by the Rockwell Research Center (U.S.A.) (Contract No. B8S413840).

REFERENCES

1. P. K. Tretyakov, V. M. Fomin, and V. I. Yakovlev, "New principles of control of aerophysical processes research development," in: *Proc. of the Int. Conf. on the Methods Aerophys. Res.* (Novosibirsk, June 29–July 3, 1996), Part 2, Inst. Theor. and Appl. Mech., Sib. Div., Russ. Acad. of Sci., Novosibirsk (1996), pp. 210–220.
2. G. G. Chernyi, "The impact of electromagnetic energy addition to air near the flying body on its aerodynamic characteristics," in: *Proc. of the 2nd Workshop on Weakly Ionized Gases* (Norfolk, April 27–30, 1998), Norfolk (1998), pp. 1–20.
3. S. Leonov, "Experiments on influence of plasma jet lift and drag of wing," in: *Proc. of the 1st Workshop on Weakly Ionized Gases* (Colorado, June 9–13, 1997), Vol. 1, S. l. (1997), pp. J1–J24.
4. Yu. N. Yudintsev and V. F. Chirkashenko, "Regimes of interaction of a counterflow jet with a supersonic incoming flow," in: *Gas-Dynamics and Acoustics of Jet Flows* [in Russian], Inst. Theor. Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, Novosibirsk (1979), pp. 75–106.
5. Y. C. Ganiev, V. P. Gordeev, A. V. Krasilnikov, et al., "Aerodynamic drag reduction by plasma and hot-gas injection," *J. Thermophys. Heat Trans.*, **14**, No. 1, 10–17 (2000).
6. J. S. Shang, B. Ganguly, R. Umstattd, et al., "Developing a facility for magneto-aerodynamic experiments," AIAA Paper No. 0447 (2000).
7. V. M. Fomin, A. A. Maslov, N. D. Malmuth, et al., "Experimental investigation of counterflow plasma jet in front of blunted body for high Mach numbers flows flow," in: *Proc. of the 2nd Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications* (Moscow, April 5–7, 2000), Inst. of High Temperatures, Russian Acad. of Sci. (2000), pp. 112–116.
8. N. D. Malmuth, V. M. Fomin, A. A. Maslov, et al., "Influence of a counterflow plasma jet on supersonic blunt body pressures," AIAA Paper No. 4883 (1999).
9. P. J. Finley, "The flow of a jet from a body opposing a supersonic free stream," *J. Fluid Mech.*, **26**, No. 2, 337–368 (1966).
10. V. M. Fomin, N. D. Malmuth, A. A. Maslov, et al., "Numerical study of the effect of a cold jet opposing a supersonic flow on the total aerodynamic characteristics of a blunted body," *Dokl. Ross. Akad. Nauk*, **374**, No. 1, 55–57 (2000).
11. V. M. Fomin, A. A. Maslov, N. D. Malmuth, et al., "Numerical investigation of counterflow jet penetration in hypersonic flow," in: *Proc. of the 2nd Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications* (Moscow, April 5–7, 2000), Inst. of High Temperatures, Russian Acad. of Sci. (2000), pp. 116–121.
12. M. E. Deich, *Technical Gas-Dynamics* [in Russian], Gosenergoizdat, Moscow (1961).
13. G. G. Chernyi, *Gas Dynamics* [in Russian], Nauka, Moscow (1988).