Journal of Engineering Physics and Thermophysics, Vol. 73, No. 2, 2000

SPECIAL FEATURES OF HYPERSONIC FLOW OVER BLUNT BODIES WITH EXCITATION OF INTERNAL DEGREES OF FREEDOM IN THE GAS

G. A. Tarnavskii and S. I. Shpak

UDC 533.6

The special features of hypersonic gas flow over blunt bodies with excitation of additional degrees of freedom (vibrational or electronic) are studied using computer modeling based on numerical integration of the nonstationary system of complete Navier–Stokes equations. Calculations over a wide range of determining parameters indicated the existence of regions of weak and strong flow instabilities in gases with small effective adiabatic exponents for finite disturbances of the parameters in the incident flow.

Experimental investigations [1-4] have established the fact of the instability of fairly high-intensity shock waves in some gases (carbon dioxide, argon, xenon, and Freons 12 and 14), which manifests itself in the form of nonuniformities at the front of the forward shock and in the shock layer of the gas or even in destruction of the forepart of the shock wave, depending on the parameters of the incident flow and the shape of the surface of the body in the flow. All the problems that differ substantially in formulation [1-4] (motion of shock waves in channels and hypersonic flow over bodies with formation of a detached forward shock) are unified by the fact that the instabilities and destruction of the shocks are related to excitation of additional degrees of freedom in the working fluids, specifically, rotational and vibrational ones in high-molecular-weight gases and electronic ones in monatomic gases. Similar phenomena were also observed in [5, 6].

The physical mechanism of these processes, which leads to the instability of shocks in the flow field, is little understood. The interpretation of the appearance of the instability relies mainly on the version of "pumping" of the kinetic energy of the gas flow in a shock into internal degrees of freedom and of anomalous relaxation behind the shock front. This furnishes, to some extent, an explanation of the appearing energy disbalance and, correspondingly, the shock-free flow deceleration at certain values of the determining parameters. Actually, a correction to the equation of state is assumed, as, for example, in [7], with account for collective interactions between the particles in an ionized plasma (or a high-molecular-weight gas with excited vibrational degrees of freedom that are locally concentrated in space, for example, behind the shock front). This version of the process seems fairly reasonable, and the current work aims at studying the mechanical-mathematical aspect of the manifestation of the anomaly of the gasdynamic structures (specifically, the instability of the shocks) based on computer modeling of continuum flows using a program complex that has been well tried-out on a wide class of problems and a special technology for organizing and tracking the calculations [8, 9].

An extensive series of computational experiments was performed as follows. Consideration was given to supersonic flow of a viscous heat-conducting gas over the spherical blunt forepart of a body. In the region bounded by the surface of the heat-insulated body, the forward shock (whose position and configuration were sought during the solution), and the outlet boundary, we integrated numerically the nonstationary system of Navier–Stokes equations in the traditional dimensionless form with the determining parameters M_∞, Re_∞, Pr,

Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 2, pp. 354-357, March–April, 2000. Original article submitted February 10, 1999; revision submitted September 8, 1999.

1062-0125/00/7302-0345$25.00

and γ. The parameters Re_∞ and Pr were fixed ($Re_\infty = 10^4$ and $Pr = 0.72$) over the entire experimental series, and M_∞ and γ were varied over the ranges $2 \leq M_\infty \leq 50$ and $1.01 \leq \gamma \leq 1.4$. This system was closed by a quasi-equilibrium equation of state written in the form of the equation of state for a perfect gas with a variable γ.

The question of the variation of γ was determined in accordance with the following considerations. It is well known that γ in a perfect gas is related to the number f of excited degrees of freedom of the gas molecules (atoms) as $\gamma = (f+2)/f = 1 + 2/f$. For a monatomic gas with only the translational degrees of freedom excited, $f = 3$, and, correspondingly, $\gamma = 1.667$. In air, which consists mainly of diatomic molecules, at not too high temperatures two rotational degrees of freedom, are excited in addition to the translational degrees of freedom, $f = 5$ and $\gamma = 1.4$. For high-molecular-weight compounds, a temperature rise entails excitation of additional vibrational degrees of freedom (these being electronic in monatomic gases). By averaging over N ensembles of molecular (atomic) groups that consist of n_i particles with number f_i of excited degrees of freedom, we determine the "effective" adiabatic exponent, $f_r = \sum_{i=1}^{N} n_i f_i / \sum_{i=1}^{N} n_i$, $\gamma_{eff} = 1 + 2/f_r$ with continuous variation in the range from 1 for $f \to \infty$ to 5/3 for $f = 3$. In the integrated system of equations we used precisely γ_{eff} (subsequently, the subscript eff is omitted for brevity).

All the computational experiments were broken down into groups. Each group was characterized by a single fixed value of M_∞ and variation of γ. The calculation in a group started with the value $\gamma_1 = 1.667$ and was carried out until the solution (stationary, quasistationary, or nonstationary) was obtained. Next, the calculation was performed with a decreased value $\gamma = \gamma_2$ using the results of the previous calculation as the initial gasdynamic fields of the nonstationary problem. This mathematical formulation of the initial data complies with the physical condition of sudden flight of a body into a gas medium with different properties or of a certain degree of disturbance of the parameters in the flow field. The calculation step $\delta\gamma = (\gamma_i - \gamma_{i-1})$ in a group is decreased with γ_i to retain the same degree of pressure disturbance in a normal shock. Then, the value of M_∞ was changed and the cycle of calculations with variation of γ was repeated.

Completion of the calculation in a group was determined by the achievement of one of three goals. A stationary solution of the nonstationary system of Navier–Stokes equations, if it existed, was obtained using the method of transition to a steady state. The solution convergence that provides an accuracy of the transition to a steady state $\varepsilon = 10^{-3}$ was determined by two criteria: a "near" criterion $|(f^{n+1} - f^n)/\tau f^n| < \varepsilon$ on successive time layers n and $n+1$ and a "distant" criterion $|(f^{n+N} - f^n)/\tau f^n| < \varepsilon$ on time layers that are spaced appreciably with the interval N. The second criterion was used for sorting out steady-state solutions from so-called "creeping" solutions, where, with the fulfillment of the first criterion, a solution can markedly change with time ("pseudotransition to a steady state"). In this computational series, in the capacity of f we selected the density ρ as the quantity that reaches a steady state most slowly, and N was taken to be equal to 50–100, depending on the situation (see [10] for details). Steady-state quasiperiodic and self-oscillatory modes were controlled on a large time interval that contained 10-15 periods (quasiperiods) of oscillations of the solution about a certain "mean" line whose degree of transition to a steady state was controlled by two criteria that are similar to the above ones for stationary situations (see [10]). Unsteady modes that lead to intense oscillations of the solution were interpreted as incompatible with the problem formulation ("the external boundary is unstable and cannot be a steady shock wave").

Figure 1 presents integrally the results of the entire cycle of computational experiments. On the (α, γ) plane, where $\alpha = 1/M_\infty$, the boundaries of a change in the flow modes are given. Curve 1 represents the boundary that separates the region of steady mode I from the region of quasiperiodic self-oscillatory modes II, and curve 2 additionally isolates the region of possible unsteady modes III (boundary 1 was marked starting with the appearance of 5%, in amplitude, density oscillations in the flow, and boundary 2 was marked starting with the appearance of about 50% oscillations of the numerical solution relative to a 10% disturbance of the initial parametric field). Additionally, the dashed curve in the figure marks the stability boundary, taken from [11], that separates the region where strong discontinuities are always (in a linear analysis) stable relative to

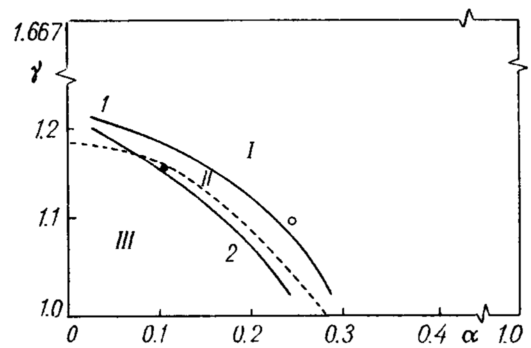

Fig. 1. Boundaries of a change in the flow mode.

small perturbations from the region where a linear analysis is "inappropriate and unsteady modes can appear." This result correlates well with the results of the current work.

Analyzing the position of the curves in the (α, γ) plane, it is possible to draw several conclusions. First, with increase in M_∞, the flow can be destabilized at higher γ, i.e., at earlier stages of excitation of additional degrees of freedom. Second, instabilities of shock waves and flows behind them manifest themselves only in high-velocity flows ($M_\infty > 3$), which is consistent with the conclusions of [1-4].

The figure plots two points from the experimental work [1]. The light point marks the position of a point of weak instability (small-amplitude disturbances), and the dark point marks the position of a point of strong instability (destruction of the forward shock). While there is a noticeable difference in the formulation of the physical and computational experiments, the results of both works are in good qualitative agreement. For further investigation of this problem, in numerical modeling, the equation of state of a perfect gas that closes the Navier–Stokes system should, obviously, be adjusted to another equation, for example, of the van der Waals type or of the type of [7].

NOTATION

$M = U/a$, Mach number; $Re = \rho UR/\mu$, Reynolds number; $Pr = \mu C_p/\chi$, Prandtl number; U, flow velocity; a, velocity of sound in the flow; ρ, gas density; R, characteristic dimension (radius of the spherical bluntness of the body in the flow); μ, dynamic viscosity; C_p, specific heat of the gas at constant pressure; χ, thermal diffusivity; γ, adiabatic exponent; f, number of excited degrees of freedom of the gas; $\delta\gamma$, step of the numerical calculation with respect to γ. Subscripts: ∞, incident undisturbed flow; r, mean value; eff, effective value; i, number of the numerical calculation.

REFERENCES

1. A. S. Baryshnikov, A. P. Bedin, V. G. Maslennikov, and G. I. Mishin, *Pis'ma Zh. Tekh. Fiz.*, **5**, No. 5, 281-284 (1979).
2. A. P. Ryazin, *Pis'ma Zh. Tekh. Fiz.*, **6**, No. 9, 516-520 (1980).
3. V. G. Grigor'ev, G. I. Mishin, N. I. Yushchenkova, and O. V. Roshchin, *Pis'ma Zh. Tekh. Fiz.*, **12**, No. 4, 224-231 (1986).
4. A. P. Bedin, *Pis'ma Zh. Tekh. Fiz.*, **14**, No. 24, 2282-2285 (1988).
5. P. K. Tret'yakov, G. P. Grachev, A. I. Ivanchenko, et al., *Dokl. Ross. Akad. Nauk*, **336**, No. 4, 466-467 (1994).
6. P. K. Tret'yakov, A. F. Garanin, G. P. Grachev, et al., *Dokl. Ross. Akad. Nauk*, **351**, No. 3, 339-340 (1996).
7. G. I. Mishin, *Pis'ma Zh. Tekh. Fiz.*, **23**, No. 14, 81-88 (1997).
8. M. K. Lebedeva, A. E. Medvedev, and G. A. Tarnavskii, *Avtometriya*, No. 5, 76-83 (1994).

9. G. A. Tarnavskii, *Teplofiz. Aéromekhanika*, **2**, No. 2, 103-109 (1995).
10. V. M. Kovenya, G. A. Tarnavskii, and S. G. Chernyi, *Use of the Method of Splitting in Aerodynamics Problems* [in Russian], Novosibirsk (1990).
11. V. P. Fedosov, *Presence of the Regions of Instability of Flows with Shock Waves in a Perfect Gas*, Preprint No. 21 of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Academy of Sciences of the USSR [in Russian], Novosibirsk (1985).