FLOW OF A SUPERSONIC LOW-DENSITY JET OF NITROGEN AND NITROGEN – HYDROGEN MIXTURE OVER A BLUNT BODY

A. A. Bochkarev, V. A. Kosinov,
V. G. Prikhod'ko, and A. K. Rebrov

UDC 533.6.011.8

This paper gives the results of electron-beam measurements of the rotational temperature of nitrogen and its concentration in front of a spherically blunt cylinder situated on the axis of a supersonic rarefied jet of nitrogen and nitrogen–hydrogen mixture.

Investigations of the stagnation temperature in supersonic jets of a mixture of gases of different molecular mass with adiabatic probes showed higher stagnation temperatures than the theoretical limit for pure gases [1]. These results can be attributed to acceleration of heavy molecules by the light ones and subsequent barodiffusive separation of the components in the shock wave and the compressed layer in front of the body. An increase in the concentration of the heavy component in the frontal region has been shown experimentally in the case of an argon–helium mixture [2]. The theoretical calculation of a supersonic flow of gas mixture over a body is fairly difficult, since barodiffusive effects appear in the transition regime between continuum flow and free-molecule flow. As an attempt at a theoretical analysis we can mention the calculation of a flow of a binary mixture of monatomic gases over a cylinder by the Monte Carlo method [3].

Electron-beam diagnostics of rarefied gases can be used to investigate the flow of a mixture of the molecular gases nitrogen and hydrogen over bodies. One of the advantages of this mixture is that the temperature of the rotational degrees of freedom of the heavy molecule can be measured.

The experiments were conducted in a low-density wind tunnel fitted with the equipment required for electron-beam diagnostics. The experimental apparatus is described in [4]. A diagram of the test section is shown in Fig. 1.

A 15-keV electron beam 5 passed through the brass model 6 to meet the jet and fell on the collector 1, mounted in the forechamber of the nozzle 2. The model was a hemisphere-cylinder of diameter D=32 mm with an axial channel for passage of the electron beam. The diameter of the exit opening was 3 mm. The channel had five diaphragms 7 to increase its hydraulic resistance and thus reduce the effect of the hole on the flow in front of the body. In the experiments we used a sonic nozzle with critical diameter $d^* = 9$ mm. The model, the nozzle, and the collector were water-cooled. The temperature of the model was measured with a nichrome–constantan thermocouple and in the experiments was 12-15°C.

The analyzer for the gas radiation in the experiments was a monochromator with its entrance slit 4 perpendicular to the electron beam. The radiation detector was an FÉU-70 photomultiplier mounted in a case cooled with liquid nitrogen. The condenser 3 focused the beam image on the monochromator entrance slit at a reduction of 1:2. The maximum width of the entrance slit in the experiments was 0.2 mm. Thus, the measurements related to a region formed by a cylinder with a diameter equal to that of the electron beam (≈ 1.5 mm) and a height of 0.4 mm. The detection system could be moved along the beam. The accuracy of determination of the coordinate of the measurement point was ± 0.1 mm.

The nitrogen concentration was determined from the measured partial densities of the components. The electron-beam method of gas-density measurement, based on the relationship between the electron-

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 50-55, November-December, 1972. Original article submitted October 7, 1971.

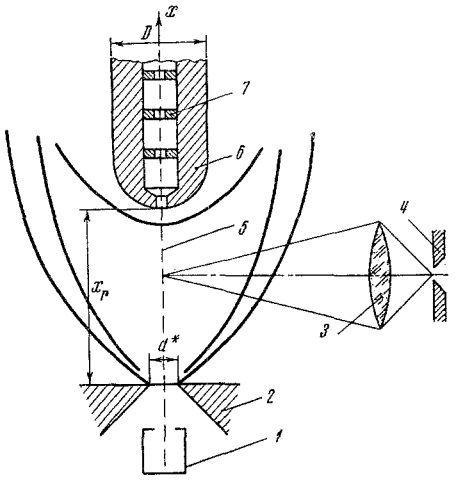

Fig. 1

TABLE 1

f_0	p_0	p_k	Re_0	x_r
1.0	1.33	$2\cdot10^{-3}$	386	54
1.0	1.33	$2\cdot10^{-3}$	386	27
0.2	1.83	$3\cdot10^{-3}$	343	54
0.2	1.83	$5\cdot10^{-3}$	343	27
0.1	2.03	$5\cdot10^{-3}$	337	27

excited luminescence of the gas and the density, has been described in many papers [5-7]. The nitrogen density was determined from the intensity of the 0−0 vibrational band of the positive nitrogen ion N_2^+, which lies in the region 3914 ± 20 Å. To measure the hydrogen density we used the H_β 4861-Å line.

We first investigated the relationship between the intensity of emission in the selected spectral regions and the density (in the pressure range 0.050-0.600 mm Hg at room temperature) and the mole fraction of nitrogen in the mixture (f = 0.05-0.4). The results of this methodological work reduce to the following:

1) when the H_β line is used to measure hydrogen density in a nitrogen−hydrogen mixture a correction must be made for the emission of nitrogen in this spectral region. The correction amounts to 30% of the hydrogen emission in the case of equal fractions of the components;

2) when a nitrogen−hydrogen mixture is excited by an electron beam the nitrogen luminescence is quenched as the hydrogen content increases. At concentration $f < 0.1$ this quenching must be corrected for by calibration according to the density in the mixture;

3) in the investigated ranges of concentration and pressure the hydrogen luminescence intensity in the electron beam is independent of the hydrogen content of the mixture and depends only on the total particle density in the mixture.

The rotational temperature of nitrogen was determined from the distribution of intensity in the lines of the vibrational structure of the 0−0 band of the R branch of the N_2^+ ion. The method of measurement, devised and described by Muntz [5], is based on the relationship

$$\log \frac{I(K', K'')}{(K' + K'' + 1)\, G\, (\nu/\nu_0)^4} = -\frac{\theta_R}{T_R} (K')(K' + 1) + \text{const} \qquad (1)$$

which is valid in the case of equilibrium distribution of the molecules over the rotational terms. Here I(K', K") is the reduced rotational line intensity; θ_R is the characteristic rotational temperature of the molecule; G is a function which depends on T_R and K'; ν is the wave number; K' and K" are the quantum numbers of the upper and lower rotational levels. The value of $G(\nu/\nu_0)^4$ was calculated by Muntz [5] for T_R = 75-1000°K and K' = 3-21. The graph in coordinates

$$\log \frac{I(K', K'')}{(K' + K'' + 1)\, G\, (\nu/\nu_0)^4} = f(T_R, K')$$

is a straight line whose gradient is inversely proportional to the rotational temperature T_R. At $T_R \approx 300$°K the rotational spectrum of the R branch consists of 21 lines. When the temperature is reduced the number of observed lines decreases, and the graph begins to deviate from a straight line. At present there is no definitive explanation of this deviation; the most probable mechanism is deviation from equilibrium in the gas and nonequilibrium excitation of the higher rotational levels by secondary electrons [5, 8, 9]. In this case the temperature cannot be determined definitely. In the present work the temperature was determined mainly from the rotational lines with K' from 3 to 9-12, which are the most highly populated.

The zone of the viscous front of the shock wave is a significantly nonequilibrium region, since any point of this zone is accessible to molecules from either side of the shock wave. Relationship (1) cannot be represented by a single straight line. In the treatment of the results of these experiments it was approximated by two intersecting straight lines (for the lower and upper quantum levels). The gas appears to be a two-temperature mixture. Temperature stratification characterizes nonequilibrium.

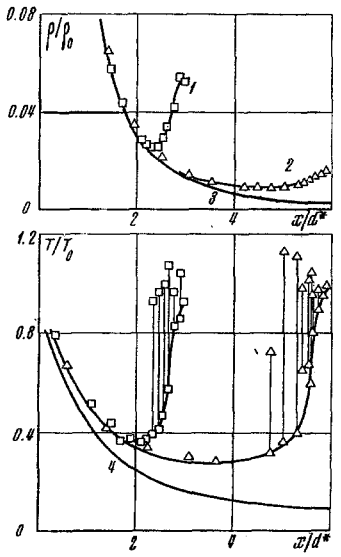

Fig. 2

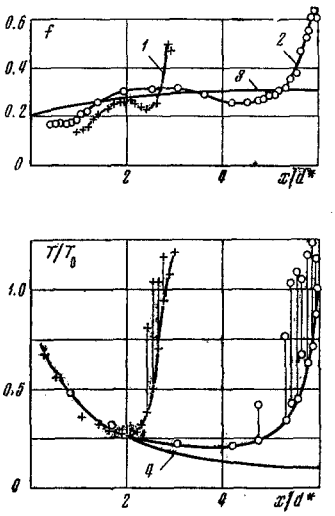

Fig. 3

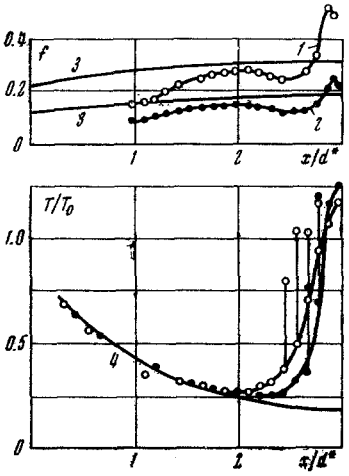

Fig. 4

The experiments were conducted with pure nitrogen and with nitrogen–hydrogen mixtures at stagnation temperature 290°K. The experimental conditions are given in Table 1, where f_0 is the concentration in the forechamber, equal to $n(N_2)/[n(N_2)+n(H_2)]$, where n is the number of particles per unit volume, p_0 is the stagnation pressure, p_c is the pressure in the working chamber, Re_0 is the Reynolds number, calculated from the stagnation parameters, and x_r is the distance from the nozzle to the frontal point of the body.

Figure 2 shows the results of density and temperature measurements in a jet of pure nitrogen. Curves 1 and 2 correspond to distances from the jet to the body $x_r = 27$ and 54 mm. The graph shows that the nitrogen density decreases at first owing to expansion of the jet, and coincides with the theoretical curve 3 obtained for isentropic expansion by the method of characteristics [10]. The reduction is followed by an increase in density in the shock wave in front of the body. In the experiment with $x_r = 54$ mm the shock wave is more diffuse due to the greater rarefaction, the density increase is more gradual, and the density disturbances propagate further upstream than in the case of smaller x_r. From the points with maximum density gradient we determined the standoff distances Δ of the shock wave from the body. For $x_r = 54$ and 27 mm we obtained $\Delta = 3.6$ and 3.15 mm, respectively. On the assumption of isentropic expansion the Mach numbers at the points with maximum density gradient are $M = 6.6$ and 4.53. Relative to the radius of the body (radius of spherical nose) Δ takes the following values: $\Delta/R = 0.22$ and 0.2. For $Re_0 \approx 400$ in a homogeneous flow of pure nitrogen with $M = 4.2$, using x-ray diagnostics of the rarefied gas, Russell [11] obtained a value $\Delta/R = 0.23$. In an experiment with a large distance between the nozzle and the body the density increase in the shock wave was given by $\rho_2/\rho_1 = 5.3$ (ρ_2 is the measured density of nitrogen in front of the body, ρ_1 is the density calculated from the isentropic formula for $M = 6.6$). The density increase is in good agreement with the theoretical value for a plane shock wave with free-stream $M = 6.6$: $(\rho_2/\rho_1)_T = 5.4$.

The density increase when the body was at a distance of 27 mm from the nozzle was given by $\rho_2/\rho_1 = 3.3$ (the value of ρ_1 was calculated for $M = 4.53$). This density increase is much less than the theoretical value. According to the Rankine-Hugoniot relations, $(\rho_2/\rho_1)_T = 4.8$. The great reduction of ρ_2/ρ_1 can be attributed to the fact that the density in front of a body with diameter D = 32 mm, situated at a distance of 27 mm from a nozzle with $d^* = 9$ mm, is more strongly affected by nonunidimensionality of the flow.

The shock wave standoff distances determined from the density and temperature distribution obtained from the first rotational levels agreed with one another. The values of T_r/T_0 (T_r is the temperature close to the frontal point of the body) were 0.98 for $x_r = 54$ mm and 0.95 for the smaller distance. The theoretical value for both cases $(T_2/T_0)_T = 0.97$ (T_2 is the temperature behind the shock wave). The recovery factor $r = (T_r - T_0)/(T_0 - T_1)$, where T_1 is the temperature in the flow in front of the shock wave, was 0.97 for $x_r = 54$

mm and 0.92 for $x_r = 27$ mm. The temperatures in the jet were above the isentropic values for the translational temperature (curve 4). A probable explanation of this fact is incomplete relaxation in the jet [12, 13], but then the temperature difference should decrease with increase in p_0. In these experiments we did not observe any appreciable change in the temperature difference with increase in p_0 from 1.33 to 8.8 mm Hg.

An analysis of the populations of the rotational levels, not given in this paper, showed that the significant loss of equilibrium arising in the shock wave decreases with approach to the body surface, and at the surface itself becomes insignificant.

Fig. 3 shows the results of experiments in a mixture with $f_0 = 0.2$. Curves 1 and 2 correspond to $x_r = 27$ and 54 mm. The results for the nitrogen concentration (top graph) for $x/d^* = 2$-3 are in good agreement with Sherman's calculation [14]. At smaller distances from the nozzle the agreement is poorer, probably due to noncoaxiality of the beam and jet. The concentration in the immediate vicinity of the nozzle could not be measured, since the density of the mixture here is greater than 0.6 mm Hg and electron-beam diagnostics cannot be used in this region. The reduction of concentration at $x/d^* = 2.5$ for $x_r = 27$ mm and $x/d^* = 4.5$ for $x_r = 54$ mm is due to enrichment of the leading edge of the shock wave with the light component. The smallness of this reduction can be attributed to the fairly considerable rarefaction of the flow; concentration diffusion reduces the separation.

Owing to the separation in the shock wave there is a considerable increase in concentration of the heavy component in front of the body. The concentration ratio $f_r/f_0 = 3.15$ for the experiment with $x_r = 54$ mm and $f_r/f_0 = 2.5$ for $x_r = 27$ mm. The thickness of the shock waves in the mixture is 2-2.5 times greater, due to barodiffusive effects, than in pure nitrogen. At the large distance from the nozzle the shock region is approximately 2.5 times broader than at the small distance.

The profiles of the rotational temperature in the mixture are similar to the profiles in the pure gas. The differences are as follows:

1) the rotational temperature in the jet is the same as the translational temperature (curve 4) calculated on the assumption of isentropic expansion. The probable reason for this is the more rapid translational and rotational relaxation in the mixture, even though viscous effects in the jet are the same for the pure gas and for mixtures (the Reynolds number, calculated from the critical parameters, is the same for all regimes). An increase in pressure p_0 in the case of the mixture leads to a small reduction of temperature;

2) the values of T_r/T_0 obtained for a mixture are higher than for the pure gas: $T_r/T_0 = 1.12$ for the large distance and $T_r/T_0 = 1.17$ for the small distance. The temperature recovery factor $r = 1.15$ and 1.23, respectively, whereas the theoretical limit for diatomic gases in free-molecule flow past a body is 1.17. The measured value obtained with a stagnation-temperature adiabatic probe for $f_0 = 0.2$, $p_0 = 2.2$ mm Hg, $x_r = 6d^*$ was $r = 1.13$.

Figure 4 shows the results of measurement of the concentration and rotational temperature of nitrogen in the case of flow of a supersonic jet of nitrogen–hydrogen mixture over a body. Curves 1 and 2 are for a mixture with $f_0 = 0.2$ and 0.1, and curves 3 and 4 are, respectively, the theoretical values of the concentration [14] and temperature in the case of isentropic expansion of the gas [10]. The nitrogen concentration in a mixture with $f_0 = 0.1$ behaves in a similar manner to the concentration in a mixture with $f_0 = 0.2$. The concentration increase is given by $f_r/f_0 = 2.3$. The thickness of the shock wave is approximately the same, but the profile of the rotational temperature of nitrogen in a mixture with $f_0 = 0.1$ is a little narrower than in a mixture with $f_0 = 0.2$. This may be due to the fact that in the case with $f_0 = 0.1$ concentration diffusion is of less importance.

The rotational temperatures of nitrogen on the axis of a jet in a mixture with $f_0 = 0.1$ and 0.2 are the same. The increase in temperature in the 10% mixture is given by $T_r/T_0 = 1.25$, and the recovery factor $r = 1.33$. The temperature recovery factor in the mixture with $f_0 = 0.1$ is higher than in the mixture with $f_0 = 0.2$, which agrees with the results of measurements of the recovery temperature T_r with an adiabatic probe, but its numerical value, obtained from measurements of the rotational temperature, is smaller. This disagreement is due to the nonadiabaticity of the body in these experiments.

The reported experimental results show that:

1) the rotational temperature of nitrogen in a mixture with hydrogen is closer to equilibrium with the translational temperature than in pure nitrogen. The presence of the lighter hydrogen molecules accelerates relaxation processes;

2) the observed and previously discussed increase in the temperature recovery factor at the frontal point of the blunt body is due to the presence of gas heated to a temperature above stagnation temperature at the surface of the body. The heating of the gas is due to stagnation of the mixture in the shock wave and compressed layer, which occurs simultaneously with barodiffusive separation of the components.

LITERATURE CITED

1. G. Maise and J. B. Fenn, "Recovery factor measurements in gas mixtures," Phys. Fluids, 7, No. 7 (1964).
2. V. H. Reis and J. B. Fenn, "Separation of gas mixtures in supersonic jets," J. Chem Phys., 39, No. 12 (1963).
3. G. A. Bird, "The structure of rarefied gas flows past simple aerodynamic shapes," J. Fluid Mech., 36, No. 3.
4. A. A. Bochkarev, V. A. Kosinov, V. G. Prikhod'ko, and A. K. Rebrov, "Structure of a supersonic jet of argon–helium mixture in a vacuum," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 5 (1970).
5. E. P. Muntz, "Static temperature measurements in a flowing gas," Phys. Fluids, 5, No. 1 (1962).
6. D. E. Rothe, "Electron beam studies of the diffusive separation of helium–argon mixtures," Phys. Fluids, 9, No. 9 (1966).
7. D. I. Sebacher, R. W. Guy, and L. P. Lee, "Diffusive separation in free jets on nitrogen and helium mixtures," in: Rarefied Gas Dynamics, Vol. 2, Academic Press (1969).
8. B. L. Maguire, "Density effects on rotational temperature measurements in nitrogen using the electron beam excitation technique," in: Rarefied Gas Dynamics, Vol. 2, Academic Press (1969).
9. P. V. Marrone, "Rotational temperature and density measurements in underexpanded jets and shock waves using an electron beam probe," UTIAS Rept No. 113, Univ. Toronto Inst. Aerosp. Studies (1966).
10. V. A. Zhokhov and A. A. Khomutskii, Atlas of Supersonic Flows of a Freely Expanding Ideal Gas Issuing from an Axisymmetric Nozzle [in Russian], Tr. TsAGI, No. 1224 (1970).
11. D. A. Russell, "Density disturbance ahead of a sphere in rarefied supersonic flow," Phys. Fluids, 11, No. 8 (1968).
12. D. R. Miller and R. P. Andres, "Rotational relaxation of molecular nitrogen," J. Chem. Phys., 46, No. 9 (1967).
13. D. Tirumalesa, "Rotational relaxation in hypersonic low-density flows, AIAA J., 6, 765 (1968).
14. F. S. Sherman, "Hydrodynamical theory of diffusive separation of mixtures in a free jet," Phys. Fluids, 8, No. 5 (1965).