SPECTROSCOPIC DETERMINATION OF ROTATIONAL TEMPERATURE IN RAREFIED HYPERSONIC FLOW BY GLOW-DISCHARGE EXCITATION OF LUMINESCENCE

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The use of the relative intensity method for measurement of the rotational temperature of nitrogen in a rarefied air flow by means of glow-discharge excitation of luminescence is described. Special features of measurement of the rotational temperature at low static pressure of the gas in the flow are noted. Profiles of the rotational temperature along the stagnation line in the case of transverse flow over a cylinder are obtained. The dependence of the measurement error on the temperature is discussed.

Measurement of the gas parameters in hypersonic low-density flows involves considerable difficulties. One of the most difficult parameters to determine is the static temperature. In recent years experiments have begun to use electron-beam excitation of the luminescence of nitrogen to measure the rotational temperature of nitrogen in hypersonic flows by the relative intensity method [1]. In some conditions the equality of the rotational and translational temperature is assumed. Available published data on the distribution of rotational temperature relate mainly to freely expanding jets [2, 3].

Below we give the results of measurement of the rotational temperature in a fully-formed hypersonic rarefied flow and near a model. The luminescence in the flow was excited by a glow discharge. Dried air was used as the working gas.

1. The rotational temperature of nitrogen in the case of electron-beam excitation is usually determined from the distribution of luminescence intensity in the R branch of the (0, 0) I band of the negative system [1-4]. The rotational temperature T_r is determined by using the relationship

$$\lg \frac{I_{K'}}{(K'+K''+1)\,G\nu^4} = \frac{BK'(K'+1)}{T_r} \tag{1.1}$$

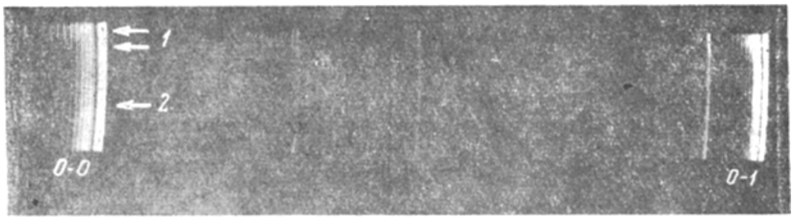

Fig. 1

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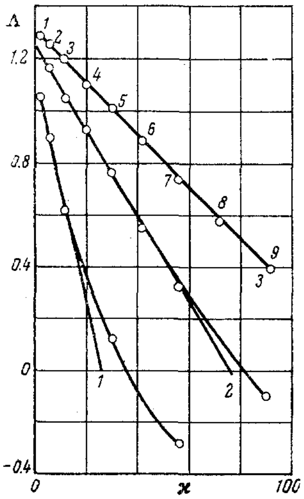

Fig. 2

Here K' and K" = K'−1 are the quantum numbers of the upper and lower rotational levels between which the radiative transition occurs, $I_{K'}$ is the relative intensity of the rotational line, ν is the line frequency, B = 125°K at temperatures ≤ 800°K, and the quantity G, which depends on K' and T_r, was introduced and tabulated by Muntz [1]. This relationship is suitable for determination of T_r in the negative-glow region of a glow discharge. The cathode for the production of a glow discharge in the working chamber of a low-density wind tunnel was a hypersonic nozzle insulated from the walls of the working chamber; the anode was placed in the working chamber outside the field of vision. The effect of the discharge on the gas flow parameters can be neglected [5]. The luminescence is concentrated mainly in the central part of the flow [6].

The luminescence spectrum was photographed on KN-4 film by means of an ISP-51 glass spectrograph with a focal length of 270 mm. The luminescence was projected onto the spectrograph slit with approximately sevenfold reduction. When the discharge current was a few tens of mA the required exposure was 1-1.5 h.

Figure 1 shows the spectrum of the air flow in front of a transverse cylinder. This spectrum was obtained by positioning the spectrograph so that its slit was oriented along the stagnation line. The parameters of the hypersonic flow were as follows: Mach number M_∞ = 5, stagnation temperature T_0 = 290°K, Reynolds number referred to radius of model R_∞ = 156. The bulk of the luminescence is concentrated in bands I of the negative system of the molecular nitrogen ion. Bands II of the positive system become appreciable in the spectrum with increase in exposure, but their intensity can be neglected. The luminescence spectrum, shown in Fig. 1, consists of two fairly distinct regions. Region 1 corresponds to the gas stagnation zone at the model, region 2 corresponds to the zone upstream of the model. The distribution of intensity between the rotational lines of the R branch in bands I of the negative system in regions 1 and 2 differs significantly. In region 2 the luminescence intensity is concentrated at the start of the R branch, i.e., in lines with low values of K', which is a consequence of the low free-stream gas temperature. On transition to region 1, to the gas stagnation zone, the temperature increases, and the intensity of lines with high K' increases.

2. The rotational temperature was determined from the gradient of the relationship

$$\Lambda = \Lambda(\varkappa) \qquad \left(\Lambda = \lg \frac{I_{K'}}{2K'G\nu^4}, \quad \varkappa = K'(K'+1)\right) \tag{2.1}$$

In the case of Boltzmann distribution of molecules over the rotational energy levels this graph is a straight line; Fig. 2 shows typical graphs for three experiments in the free-stream zone. We give the flow parameters and the obtained values of the rotational temperature for experiments 1, 2, and 3 shown in the figure

	M_∞	T_0, °K	R_∞	T_∞, °K	T_r, °K
1	7.6	291	495	23±2	30±7
2	4	291	40	70±3	75±8
3	5	673	46	112±6	115±12

Here T_∞ is the static temperature of the gas in the flow. The Reynolds number for 1 cm was calculated.

The figure shows that with temperature reduction the intensity is redistributed in favor of lines with lower K', and the gradient of the graph increases. At static temperature T_∞ = 112°K all the experimental points lie satisfactorily on a straight line, and the measured value of T_r agrees within the error of measurement with T_∞. With reduction in T_∞ the points corresponding to high values of K' begin to deviate upwards from a straight line, and T_r is above the value of T_∞ calculated on the basis of Pitot tube readings. A similar result is obtained when the luminescence of nitrogen is excited by a focused electron beam [2, 3].

The possible cause of nonequilibrium population of the rotational N_2^+ levels at low temperature is now being investigated. In particular, the excess of T_r over T_∞ in the stream has been attributed to rotational

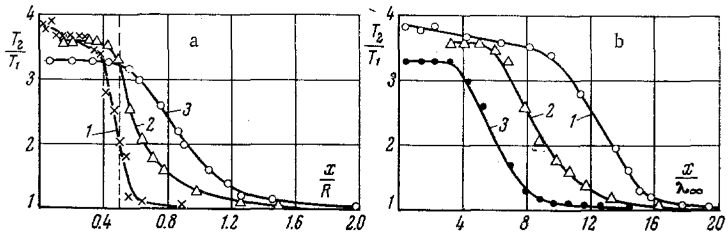

Fig. 3

relaxation [3, 7]. In several papers [10-12] the inadequacy of the dipole transition model in this case has been pointed out, and attempts to take the effect of gas density into account have been made [4, 10, 12]. The determination of T_r from the gradient of the linear part of the graph of $\Lambda = \Lambda(\varkappa)$ gives a value which differs significantly from the translational temperature (by 15-20% or more) at 20-30°K or lower [2].

3. An investigation of the gas temperature distribution near models in a rarefied flow is of great interest. We investigated the distribution of rotational temperature along the stagnation line in the case of flow over a transverse cylinder. The obtained profiles are shown in Fig. 3.

The distance x upstream from the model wall is expressed relative to R – the radius of the model (Fig. 3a) – and to λ_∞ – the mean free path of the molecule in the free stream (Fig. 3b). The local rotational temperature T_2 is compared with the free-stream rotational temperature T_1.

The experiment was conducted with $M_\infty = 4$ and $T_0 = 290$°K.

The number R_∞, referred to the radius of the model, was altered by using models of different radii and was 156, 78, and 39 (curves 1, 2, 3, respectively, in Fig. 3). The temperature T_r was measured at 0.7-mm intervals along the x axis. It is apparent that the profiles are distinctly smeared, and the degree of smearing increases with reduction of R_∞. For the flow regime corresponding to $R_\infty = 156$ the temperature drop on the shock approaches the continual Hugoniot-Rankine value $T_2/T_1 \approx 4$. With reduction in R_∞ the temperature drop decreases and does not attain the continual value. We can assume that at $R_\infty = 156$ the shock wave and the boundary layer are separated by a region of inviscid flow. The shock standoff distance, measured as the distance from the midpoint of the temperature profile to the model wall, is close to the continual value 0.51 R in this case.

The measured rotational temperature profiles for transverse flow over a cylinder agree with the profiles obtained by means of a free-molecular temperature probe [8], which probably indicates the equality of the rotational and translational temperatures in the shock zone in the investigated flow regimes.

4. For the flow regime corresponding to $R_\infty = 156$ the ratio of the mean free path λ_∞ to the thickness δ_T of the temperature jump is 0.16. This value agrees quite well with the experimental data of [8] and with the theoretical result ($\lambda_\infty/\delta_T = 0.19$) obtained from the bimodal Mott-Smith theory for Maxwellian molecules [9].

5. We consider the accuracy of rotational temperature measurement at low T_r. The expression for the relative error of measurement of T_r can be written formally as:

$$\frac{\Delta T_r}{T_r} = \frac{T_r}{B\,[K_2'(K_2'+1) - K_1'(K_1'+1)]}\left[\left(\frac{\Delta I_{K_1'}}{I_{K_1'}}\right)^2 + \left(\frac{\Delta I_{K_2'}}{I_{K_2'}}\right)^2 + \left(\frac{\Delta G_1}{G_1}\right)^2 + \left(\frac{\Delta G_2}{G_2}\right)^2\right]^{1/2} \quad (4.1)$$

Here the subscripts 1 and 2 correspond to the extreme points through which a straight line on a graph similar to that shown in Fig. 2 passes. We assume for simplicity that the straight line passes through the two extreme points, although in fact a set of points is used to obtain the line. It is apparent that $T_r^{-1}\Delta T_r$ is directly proportional to T_r, i.e., on reduction of T_r the relative error will decrease. In fact, the reverse occurs at low temperatures. As was mentioned above, with reduction of T_r the intensity of the luminescence is redistributed in favor of lines with low K' values, with the result that the error in determination of the intensities of lines with low K' increases significantly. In addition, on the graph of $\Lambda = \Lambda(\varkappa)$ the points corresponding to large K' deviate from a straight line. At $T_r = 30$°K the extreme point still lying on the straight line corresponds to K' = 3 (Fig. 2). Hence, at low temperatures T_r the term $[K_2'(K_2'+1) - K_1'(K_1'+1)]$ in the denominator of (4.1) plays a much greater part in the determination of the relative error. For instance, at T_r = 300°K lines from K' up to 21 are used for plotting the graph, and the value of this term is 460, whereas at T_r = 30°K lines from K' only up to 10 are used. Hence, the factor

$$\frac{T_r}{B\left[K_2'(K_2'+1)-K_1'(K_1'+1)\right]}$$

is 0.52 and 2.4. Thus, with the same error in measurement of the line intensity $I_{K'}^{-1}$, $\Delta I_{K'}$, and in the choice of G the total error in the determination of T_r is not reduced by a factor of 10, but is increased by a factor of almost 5.

It should be noted that at low temperatures the value of the correction G becomes much greater. Hence, when the straight line is drawn through a small number of experimental points the error in the choice of G can lead to a large error in the determination of T_r. It is obvious also that the reduction per se of the number of experimental points through which the straight line is drawn leads to an increase in the error in the determination of the gradient of this line, i.e., to an increase in the error in the determination of T_r.

Thus, at room temperature the error in the determination of the rotational temperature from the intensity distribution in the R-branch of the (0, 0) band is ~3% [1, 3], whereas at low temperatures it can reach several tens per cent.

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