TRANSVERSE TEMPERATURE FIELDS IN NONEQUILIBRIUM RAREFIED GAS FLOWS BEHIND CYLINDRICAL CHANNELS

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Experimental investigations of the transverse temperature distribution are performed in a broad range of Knudsen numbers.

The transverse temperature characterizing the molecule velocity distribution in directions perpendicular to the mass motion of the gas must be known in solving a number of practical problems [1] associated with the utilization of nonequilibrium rarefied flows. Information obtained experimentally by using sources possessing a simple but at the same time extensively utilized geometry in practice is needed to approve the numerical experiments and analytical methods of computing parameters in a nonequilibrium gas flow field. One such kind of source is cylindrical channels with different ℓ/d ratio.

All the results cited in this paper refer to carbon dioxide gas. Its utilization as the object of investigation is due to the necessity to maintain a high vacuum in the working chamber for large gas flow rates ($\sim 10^{20}$ moles/sec). Effective application of cryogenic evacuation facilities is possible in the vacuum chamber varied between $1.3 \cdot 10^{-2}$ and $1.5 \cdot 10^{-1}$ Pa. A dissipation mode was hence realized in the experiments; consequently there were no compression shocks in the rarified flows.

Known methods of determining the transverse temperature $T_\perp$ [2-5] are complicated as a rule and require simplified model representations due to the presence of a specific kind of source of the nozzle–skimmer type.

The method used to obtain data on the $T_\perp$ distribution is sufficiently simple for its practical realization in experiment. Description of the apparatus and methodology of determining $T_\perp$ is elucidated in [6]. In addition to [6], it should be noted that the transverse temperature was determined on the basis of direct measurements of the pressure P_d in the nozzle static pressure tank and the local value of the density n in the gas flow domain under investigation. It is assumed that the molecule velocity distribution function in a gas flow field is anisotropic [7]

$$f = n\left[\left(\frac{m}{2\pi kT_\perp}\right)\exp\left(-\frac{mv_\perp^2}{2kT_\perp}\right)\right]\left[\left(\frac{m}{2\pi kT_\parallel}\right)^{1/2}\exp\left(\frac{-m(v_\parallel - u)^2}{2kT_\parallel}\right)\right],$$

where $T_\perp$ and $T_\parallel$ are the transverse and longitudinal temperatures, respectively.

If the streamline and flow mode in the nozzle are characterized by the number Kn > 1, then the transverse temperature was computed from the simple formula

$$T_\perp = \frac{P_d^2}{k^2 n^2 T_d}. \quad (1)$$

The error in determining $T_\perp$ was 10-50% depending on the magnitude of P_d and n. The temperature T_d corresponded to room temperature during the experiment. The local value of the density n was measured by using an electron-beam method. Recording of the radiation was performed here in the 289-nm section of the spectrum [8].

The correctness of the method of determining $T_\perp$ was confirmed by experiments in a free CO_2 jet formed by a hole with $\ell/d = 4.1 \cdot 10^{-2}$ and $P_0 d_{ef} = 6.76$ Pa·m.

The effective diameter here is $d_{ef} = gd$, where the mass flow rate coefficient g was found in conformity with the measured value of the gas flow rate. Comparisons were made with available data on the $T_\perp$ distribution in N_2 and CO_2 jets [5, 9].

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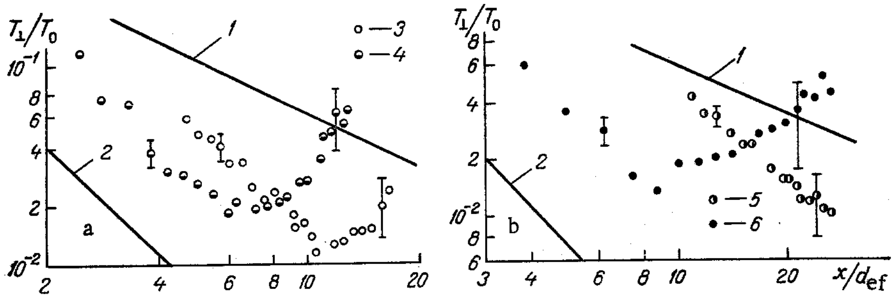

Fig. 1. Change in $T_{\perp}$ along the stream axis behind cylindrical channels (a – ℓ/d = 5.02; b – 24.26): 1) isentrope; 2) effusion efflux; 3) Kn = $1.57 \cdot 10^{-3}$; 4) $4.23 \cdot 10^{-3}$; 5) $5.55 \cdot 10^{-4}$; 6) $4.13 \cdot 10^{-3}$.

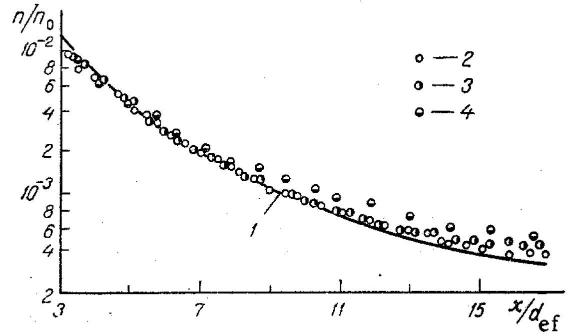

Fig. 2. Density distribution along the stream axis behind a short channel (ℓ/d = 5.02): 1) isentrope; 2) Kn = $1.57 \cdot 10^{-3}$; 3) $4.23 \cdot 10^{-3}$; 4) $4.90 \cdot 10^{-2}$.

The transverse temperature distribution along the stream x axis behind single channels is represented in Fig. 1. The origin of the coordinate system is in the plane of the channel output exit and is superposed with its geometric center. The gas efflux was stationary and the gas temperature in the source chamber corresponded to room temperature. The mean free path λ in the source chamber, calculated by means of a formula for the dynamic viscosity coefficient for solid spherical molecules, was used to determine the Knudsen number Kn_0

It should be noted that for low numbers Kn_0, starting with the efflux mode with slip, in a coordinate system referred to d_{ef}, the distribution of the relative density n/n_0 along the x axis behind the channel in a definite flow domain corresponds to an isentropic nature of the change n in a free jet formed by a sonic nozzle (curve 1 in Fig. 2). Consequently, the case of isentropic expansion of the gas in a free jet (curve 1 in Fig. 1) was also examined in analyzing the results on the distribution of the other parameter $T_{\perp}$. By analogy with free jets, the deviation of the experimental data from curve 1 corresponds to the case of a nonequilibrium gas state. Curve 2 in Fig. 1 characterizes the change in temperature for effusion efflux from the hole.

As is seen from Fig. 1, domains of decrease, minimal values, and growth of $T_{\perp}$ are remarked with distance from the source exit. The presence of domains of diminution in $T_{\perp}$ is due to spoilage of the equilibrium in the translational degrees of freedom. Existence of growth domains is a result of stream molecule interaction with molecules of the surrounding rarefied space. An estimate of the influence of the pressure change in the vacuum chamber on the quantity $T_{\perp}$ at the stream periphery indicates this. Thus, as the pressure increases 9% the transverse temperature grows ~14% in the domain x/d_{ef} = 16.3.

Therefore, a diminution in the mutual molecule collision frequency on one hand and the action of the gas of the surrounding space on the stream, on the other, results in an ambiguous change in $T_{\perp}$ and the existence of a domain of the minimum.

The diminution and growth of $T_{\perp}$ in the domain under investigation can be characterized by a power-law dependence of the form

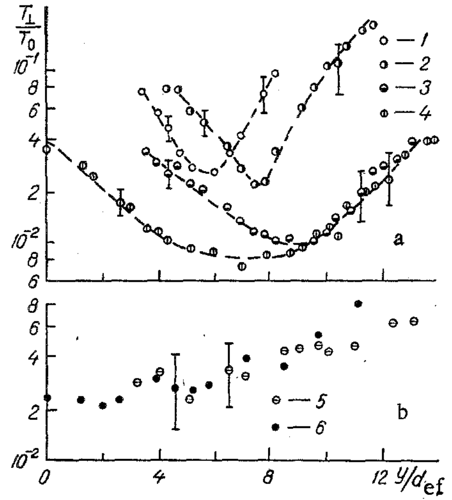

Fig. 3

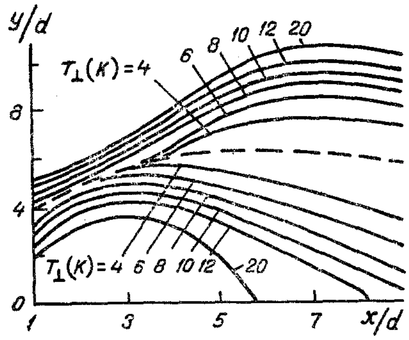

Fig. 4

Fig. 3. Distribution of $T_\perp$ in planes transverse to the stream axis behind a channel with $\ell/d = 24.26$ for Kn ≈ 5.6·10^{-4} (a) and Kn ≈ 4.1 (b): 1) $x/d_{ef} = 2.1$; 2) 3.9; 3) 7.94; 4) 10.7; 5) 12.1; 6) 16.3.

Fig. 4. Lines of constant values of $T_\perp(K)$ in gas stream behind a long channel ($\ell/d = 24.26$; Kn ≈ $5.6 \cdot 10^{-4}$).

$$\frac{T_\perp}{T_0} = A_1 (x/d_{ef})^{B_1}. \quad (2)$$

The coordinate of the imaginary source x_s that approximates the free jet far field ($x_s/d_{ef} = 0.4$ for CO_2) [10] must be taken into account when studying the distribution of $T_\perp$ along the free jet axis near the plane of the nozzle output exit. Consequently, the dependence

$$\frac{T_\perp}{T_0} = A_2 (x/d_{ef} - 0.4)^{B_2} \quad (3)$$

was used when analyzing the nature of the change in $T_\perp$ along the x axis for channels.

The relationships (2) and (3) describe the $T_\perp$ distribution in tests with identical accuracy.

The values of the exponent B_2 for the domain of diminution of $T_\perp$ for different channels differ insignificantly, and are identical for different channels for the very same Kn_0. Thus, for instance, for short ($\ell/d = 5.02$) and long ($\ell/d = 24.26$) channels the exponent is $B_2 = -1.7$ for $Kn_0 \approx 4.2$. As the number Kn_0 diminishes for cylindrical channels, the tendency for a decrease in B_2 follows in connection with the growth of the number of collisions.

The value of B_2 is less than 2 in absolute value, which holds for the spherically symmetric case during effusion gas efflux from a hole. The reason is, firstly, the possible influence of the source geometry on the $T_\perp$ distribution, and secondly, the sufficiently high density of the number of intermolecular collisions per path length between x and ∞ in the gas jet formed by the nozzle according to [11] with the trial Maxwell molecule

$$\Sigma(x, \infty) = \frac{\gamma^2 - 1}{\pi\gamma} \mathrm{Re}_a \frac{d_a}{2x} \quad (4)$$

and the stiff spherical molecule

$$\Sigma(x, \infty) = \frac{4}{\pi\gamma} \frac{\mathrm{Re}_a}{\gamma M_a} \left(\frac{d_a}{2x}\right)^{\nu}. \quad (5)$$

When estimating the quantity $\Sigma(x, \infty)$ the number $Re = 4mN/(\pi d_{ef}\eta_a)$ was computed together with the Reynolds number Re_a at the channel exit. The magnitude of the dynamic viscosity η_a was selected at a temperature that holds for the Mach number $M = 1$. It is assumed that the Mach number at the channel exit is $M_a = 1$. If the effective diameter d_{ef} is considered as the channel output diameter d_a in (4) and (5), then $\Sigma(x, \infty) = 5$ for the Maxwell model of a molecule for $x/d_{ef} = 10$ (short channel), while $\Sigma(x, \infty) = 4$ for a model of solid spheres. Therefore, the quantity of collisions between molecules for such an estimate is sufficient to build up equilibrium in the translational degrees of freedom since the main energy exchange in the translational relaxation process occurs after 1-2 collisions [11].

It should be noted that as $T_\perp$ increases the value of $T_\perp$ should approach the vacuum chamber wall temperature equal to the room temperature in the long run as x/d_{ef} grows (growth domain). However, the power-law relationships (2) and (3) do not yield an asymptotic approximation of $T_\perp$ to the wall temperature. Consequently, the change in $T_\perp$ according to the power-law dependence occurs in a bounded domain outside whose limits the nature of the change in $T_\perp$ should be different and correspond to the requirements of a gradual approach to the chamber wall temperature.

It has been noted as a result of comparing the transverse temperature distribution for sources of different geometry for the identical number Kn that for the domain of $T_\perp$ diminution the tendency for its growth is traced at a fixed coordinate on the stream axis as ℓ/d increases. The greater the ℓ/d the less intensively does the growth of the transverse temperature occur behind the section of its minimal values.

To clarify the spatial nature of the change in $T_\perp$, its distribution must be known in planes transverse to the stream axis (along the y axis). Such information was obtained for a long channel for small Knudsen numbers (Fig. 3).

The transverse temperature first diminished to a certain minimal value with distance from the stream axis to its periphery (Fig. 3), and then started to grow. The minimal value of $T_\perp$ in the transverse planes shifted to the stream periphery as x/d increased and then again approached the x axis. As the coordinate of the transverse section under consideration x/d_{ef} grows, the numerical value of $T_\perp$ diminishes in the section of the minimum.

The diminution of $T_\perp$ in a plane transverse to the stream axis as y/d_{ef} grows (Fig. 3a) occurs if the coordinate of the section under consideration is in the section of x/d_{ef} corresponding to the domain of decrease in $T_\perp$ along the stream axis. As a result of the tendency of molecules in the stream to arrive at thermodynamic equilibrium with the surrounding medium, the domain of the minimum in the transverse section will approach the stream axis ($x/d_{ef} = 10.7$) as x/d_{ef} grows, and will emerge on it in the long run. With the approach to the section of minimal values of $T_\perp$ along x/d_{ef} behind which its growth occurs, the nature of the change in $T_\perp$ varies in the corresponding transverse planes. No domain of $T_\perp$ diminution exists; conversely, its growth is noted as the coordinate y/d_{ef} increases (Fig. 3b).

Therefore, in the initial section connected to the domain of $T_\perp$ diminution for $Kn < 10^{-2}$, the influence of the surrounding gas on the parameter distribution is negligible. However, as the gas stream expands its rarefaction increases and the fraction of molecules from surrounding space that penetrate into it grows. Because of interaction between the molecules of the carbon dioxide gas stream under investigation with the gas of the surrounding space, dissipation occurs of the energy of the molecule directional motion, which indeed results in growth of the transverse temperature.

On the basis of the test data obtained for a long channel, a qualitative distribution is given in Fig. 4 for the constant values of $T_\perp$. This pattern yields a graphic representation of the transverse temperature field in a rarefied CO_2 gas stream. A most significant gradient is observed near the channel output section. The line of minimal values of $T_\perp$ (the dashed line in Fig. 4) demarcates the domain of diminution and growth of the transverse temperatures.

It is seen from a comparison of the nature of the change in transverse temperature (see Fig. 1a) with the density distribution for the same values of the number Kn_0 (Fig. 2) that $T_\perp$ is more "responsive" to the presence of nonequilibrium in the gas flow field than to the density. In fact, the deviation of the distribution curve for $T_\perp$ from the corresponding isentropic nature of the change in temperature is observed in that flow domain where the density distribution conforms well enough to the isentropic nature of gas expansion.

NOTATION

ℓ, d are the channel length and diameter; d_a, diameter at the source exit; m, molecular mass; $v_\parallel$, $v_\perp$, longitudinal and transverse components of the molecule thermal velocity; $T_\parallel$, $T_\perp$, longitudinal and transverse temperatures; u, mass flow rate; Kn, Kn_0, Knudsen numbers; T_d, temperature in the tank space; P_0, T_0, pressure and temperature in the source chamber; A_1, A_2, B_1, B_2, coefficients and exponents in relationships (2) and (3); $\Sigma(x, \infty)$, number of mutual molecule collisions; k, Boltzmann constant; γ, adiabatic index; n_0, density in the source chamber.

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PARTICLE TEMPERATURE FLUCTUATIONS IN A TURBULENT STREAM

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The question of temperature fluctuations of particles suspended in a turbulent stream of a radiating and scattering medium is analyzed.

Investigation of the fluctuation characteristics of phases [1] is important in the study of the heat transfer of two-phase turbulent streams. The purpose of the present report is investigation of the influence of radiation on turbulent particle temperature fluctuations.

The following assumptions were made: turbulence is homogeneous and isotropic, the particle sizes are sufficiently small and their heat conductivity is sufficiently large so that the temperature field within would remain homogeneous.

We write the particle energy equation in the form

$$\rho_p V_p c_p \frac{dT_p}{dt} = \frac{\mathrm{Nu}\varkappa_f}{d} s(T_f - T_p) + \frac{s}{4}\int_0^\infty k_a^\lambda(r)(G_\lambda - 4\pi I_{b\lambda})\,d\lambda. \quad (1)$$

The spectral coefficient of particle absorption is computed according to the theory of Mie [2].

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