HEAT TRANSFER AT THE NOSE OF A BLUNT BODY IN A RAREFIED SUPERSONIC FLOW OF A NITROGEN – HYDROGEN MIXTURE

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

UDC 533.6.011.8

The temperature-recovery factor and specific heat flux have been measured at the nose of a spherically blunted body in a low-density supersonic stream of a nitrogen–hydrogen mixture. The experiments were carried out in the transition flow regime from continuous to free-molecular flow. The measurements show that the values of the recovery factor and heat flux in the mixture are larger than in the pure gases.

Gradient flows of gas mixtures are characterized by flow nonequilibrium with respect to the translational degrees of freedom, as is exhibited, in particular, by a change in the local composition of the mixture due to diffusion separation of the components. The role of diffusion processes is particularly significant in rarefied gases, because the diffusion rate in this case can become comparable with the flow velocity. For a mixture composed of light and heavy particles, barodiffusion is the predominant separating factor. For supersonic flow past blunt bodies diffusion influences the structure of the bow shock and the compressed layer ahead of the body. The high-pressure zone (nose region) is depleted of heavy particles due to the pressure gradient along the streamlines and due to the curvature of the streamlines near the stagnation point. Concentrational diffusion and thermal diffusion diminish the separation effect. The translationally nonequilibrium gas interacts with the nose surface of the blunt body. If the components of the mixture have the same static temperature and translation velocity in the freestream, an increase in the concentration of the heavy component in the stagnation zone increases the total flow enthalpy in that zone relative to the undisturbed region. This fact is responsible for the singular features of the heat-transfer process for bodies immersed in a flow of rarefied gas mixtures.

The adiabatic stagnation temperature in a mixture of gases with different molecular masses has been measured in [1]. Most of the measurements were carried out in a supersonic stream of a mixture of argon and helium. The measurement recovery temperatures at the nose of a blunt body turn out to be considerably higher than the stagnation temperature and higher than the limiting value for free-molecular flow of a pure gas past bodies. The composition and temperature on the stagnation line have been investigated in [2].

The objective of the present study is to determine the characteristic differences between the heat transfer in the flow of a gas mixture past bodies under conditions such that separation of the components takes place and the heat transfer in a pure gas. In the experiments we measured the recovery temperature and specific heat flux at the nose of a spherically blunted body for various initial concentrations and stagnation pressures of a mixture and a pure gas.

The measurements were carried out in the low-density wind tunnel described in [3]. The recovery temperature T_r was measured with an adiabatic stagnation-temperature sensor on a spherical model 8 mm in diameter, similar to the one described in [1]. The nose temperature was measured with a Nichrome–Constantan thermocouple, which was separated from the copper sphere by a heat-insulating spacer. The sphere was heated with a shielded heater to prevent heat-conduction losses; its surface temperature was monitored with a second Nichrome–Constantan thermocouple, whose hot junction was placed in the immediate vicinity of the nose. The temperature obtained for identical readings of both thermocouples was adopted as the stagnation temperature.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 88-91, November-December, 1973. Original article submitted February 20, 1973.

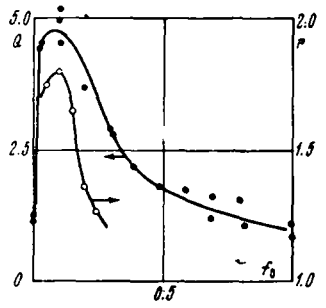

Fig. 1

The specific heat fluxes at the nose were measured by a nonstationary method based on the solution of the second boundary-value problem for the heat-conduction equation

$$\frac{\partial T}{\partial \tau} = a^2 \frac{\partial^2 T}{\partial x^2} \qquad (x \geqslant 0, \tau \geqslant 0) \tag{1}$$

for a half-space.

Here T is the temperature, τ is the time, x is the coordinate, and a is the thermal diffusivity. The boundary conditions are

$$T(x, 0) = T_w, \quad T(0, \tau) = \varphi(\tau)$$

where $\varphi(\tau)$ is the surface temperature of the sphere at the critical point and is measured with a thin-film resistance thermometer. The procedure for these measurements is described in [4]. The thermometer was a platinum film with a thickness of $\approx 0.5\ \mu$ and an area of 0.5×1.5 mm. The sphere was made of 3S-5 molybdenum glass and had a diameter of 32 mm. The contacts were formed by platinum wires 0.3 mm in diameter fused into the glass and polished until flush with the surface. A shutter was set up in front of the sphere, intercepting the flow. At a certain time taken as the initial time the shutter was opened and the readings of the resistance thermometer recorded. The records were interpreted by precalibrations of the sensor and the obtained values of the temperature $\varphi(\tau)$ at the nose in the following expression for calculation of the specific heat flux [4]:

$$q = \frac{\lambda}{\sqrt{\pi a \Delta\tau}}\left[2t_n + \sum_{i=1}^{n-1} t_{n-i}\left(2\sqrt{i-1} - 4\sqrt{i} + 2\sqrt{i+1}\right)\right] \tag{2}$$

which is an approximate arithmetic expression for the exact solution of Eq. (1) in quadratures; in Eq. (2) n is the number of subintervals into which the experimental dependence $\varphi(\tau)$ is partitioned, $\Delta\tau$ is the subinterval length, λ and a are the thermal conductivity and thermal diffusivity of the glass, and

$$t_n = \varphi_n(\varphi) - T_w$$

The sensors were placed on the axis of the supersonic jet from a sonic nozzle. The diameter of the critical section of the nozzle was d = 2.25 and 9 mm in the experiments to measure T_r and q, respectively, and the distance between the nozzle and the sphere was $l = 3d$.

In the processing of the results the freestream parameters, designated by the subscript ∞, were calculated from the conditions for isentropic expansion [5]. The freestream Mach number M_∞ was interpreted as the value of that quantity with allowance for the shock standoff distance [6]. Under the given experimental conditions $M_\infty = 4.53$.

The experimental values of the temperature-recovery factor $r = (T_r - T_\infty)/(T_0 - T_\infty)$ and the ratio of the specific heat fluxes at the nose $Q = q_\Sigma/q_\Sigma^\circ$, measured and determined for a gas mixture with an equivalent thermal conductivity but not subjected to diffusion separation, are given in Fig. 1. The subscript Σ indicates the gas mixture. The data refer to constant values of the Reynolds number with respect to the stagnation parameters and sensor diameter ($Re_0 \approx 372$). The stagnation temperature was maintained at room temperature. The temperature was measured with a pressure $p_0 \approx 1.1$ mm Hg in the prechamber. For the heat flux measurements (in the range $f_0 = 0$ to 1, where f_0 is the mole fraction of the heavy component) the pressure in the prechamber was varied from 2.5 to 1.32 mm Hg. The subscript 0 refers to the values of the quantities in the prechamber, and the subscript w to their values at the model.

The values of r are far above the limiting value r = 1.17 for diatomic gases under free-molecular conditions. The maximum value r = 1.77 is obtained for $f_0 \approx 0.07$. The measured dependence $q_\Sigma(f_0)$ is analogous to the dependence $r(f_0)$. We assume that the Prandtl number remains the same for flows of pure N_2, pure H_2, or a mixture of the two past the body. Inasmuch as the values of the specific heat ratio γ, M, and Re remain invariant in the given experiments to measure q_Σ, the following relation must be satisfied in the presumed absence of barodiffusion processes:

$$q_{N_2} / \lambda_{N_2} = q_{H_2} / \lambda_{H_2} = q_\Sigma^0 / \lambda_\Sigma$$

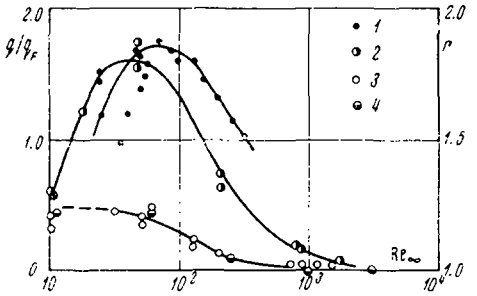

Fig. 2

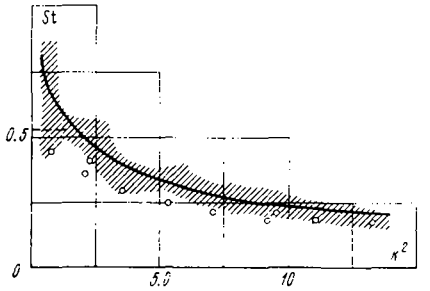

Fig. 3

In the absence of diffusion processes the heat flux in the mixture must be $q_\Sigma^0 = q_{N_2}\lambda_\Sigma/\lambda_{N_2}$. The dependence $Q = q_\Sigma/q_\Sigma^0$ plotted in Fig. 1 indicates the heating effect of diffusion separation. The r and Q maxima occur at identical values of f_0.

Figure 2 gives the results of the recovery factor and heat flux measurements in a mixture with f_0 = 0.1 (points 1 and 2) and the heat flux measurements in pure N_2 and pure H_2 (points 3 and 4) with variation of the stagnation pressure, in the form of dependences $r(Re_\infty)$ and $q/q_F(Re_\infty)$. The Reynolds number Re_∞ was calculated with respect to the sensor diameter, and q_F is the free-molecular specific heat flux calculated according to [7] for an accommodation coefficient $\alpha = 1$, $M_\infty = 4.53$, and $T_w/T_0 = 1$.

The measurement results for nitrogen and hydrogen indicate a smooth decrease of q/q_F as Re_∞ is increased. This behavior is attributable to the reduction of the recovery factor from the extreme value r = 1.17 under free-molecular conditions to a value $r \approx 0.9$ in the continuous-flow regime. The recovery factor measurements for the mixture indicate the occurrence of a maximum at $Re_\infty \approx 75$. This behavior of r corresponds to the curve with a maximum for q/q_F in the mixture. A comparison of the q/q_F curves for the mixture and the pure components enables us to determine the range of Reynolds numbers $10 < Re_\infty < 2000$ in which diffusion separation significantly affects the heat transfer. The merging of points 2, 3, and 4 for $Re_\infty < 10$ corresponds to a value of $q/q_F = 0.5$ under free-molecular conditions. This value clearly implies that the true thermal accommodation coefficient for molecules on the surface of the model is $\alpha \approx 0.5$.

The values of the Stanton number St calculated according to the expression

$$St = q_\Sigma / \rho_{\infty\Sigma} U_{\infty\Sigma} c_{p\Sigma} (T_{r\Sigma} - T_w)$$

for $f_0 = 0.1$ (ρ, U, and c_p are the density, velocity, and specific heat at constant pressure) are given in Fig. 3 as a function of $k^2 = Re_\infty/M_\infty^2 \gamma c$ for comparison with the data of [4], where

$$c = \mu T_\infty / \mu_\infty T,$$
$$T = (T_0 + T_w)/2$$

and μ is the dynamic viscosity coefficient.

The hatched region encompasses the experimental points given in [4] for T_w/T_0 = 0.1 to 0.43, M_∞ = 3 to 24, and the solid curve represents the calculated value [8] (theory of a thin shock layer) for $\alpha = 1$, $T_w/T_0 = 0$, and $M_\infty = \infty$. The dashed line on the left next to the ordinate axis indicates the value of the number St for free-molecular conditions with $M_\infty = 4.53$, $T_w/T_0 = 1$, and $\alpha = 0.5$.

Taking the measurement error into account, we infer from Fig. 3 that there is no fundamental difference between the heat-transfer mechanism for a body in flows of pure gases or their mixtures when a flow zone with an appreciable translational nonequilibrium is present in front of the body. The experimentally observed heating effect of barodiffusion separation of the mixture is accounted for by the Stanton number, provided that the recovery temperature is taken as the reference variable.

The satisfactory agreement of the data compared here confirms the conclusion [4] that St is independent of T_w/T_0 for $k^2 = 1$ to 10 and $T_w/T_0 = 1$.

The authors are grateful to I. F. Zavarzina and P. G. Itin for assistance.

LITERATURE CITED

1. G. Maise and J. B. Fenn, "Recovery factor measurements in gas mixtures," Phys. Fluids, 7, No. 7 (1964).
2. A. A. Bochkarev, V. A. Kosinov, V. G. Prikhod'ko, and A. K. Rebrov, "Flow of a supersonic jet of nitrogen and a low-density nitrogen–hydrogen mixture past a blunt body," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 6 (1972).
3. A. A. Bochkarev, V. A. Kosinov, V. G. Prikhod'ko, A. K. Rebrov, "Structure of a supersonic jet of an argon–helium mixture in a vacuum," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 5 (1970).
4. I. F. Zavarzina, "Experimental investigations of local heat fluxes on a sphere and the spherical nose of an axisymmetrical body," Izv. Akad. Nauk. SSSR, Mekhan. Zhidk. i Gaza, No. 4 (1970).
5. V. A. Zhokhov and A. A. Khomutskii, Atlas of Supersonic Flows of a Freely Expanding Ideal Gas Flowing from an Axisymmetrical Nozzle [in Russian], TsAGI, Moscow (1970).
6. D. A. Russell, "Density disturbance ahead of a sphere in rarefied supersonic flow," Phys. Fluids, 11, No. 8 (1968).
7. W. D. Hayes and R. F. Probstein (eds.), Hypersonic Flow Theory (2nd ed.), Academic Press, New York (1967).
8. N. K. Cheng, "Hypersonic shock layer theory of the stagnation region at low Reynolds number," Proc. Heat Transfer and Fluid Mechanics Inst., Stanford Univ. Press, Stanford, Calif. (1961), pp. 161-175.