ENTHALPY MEASUREMENT IN A LOW-DENSITY HIGH-TEMPERATURE INFRASONIC FLOW

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UDC 533.9.07

Enthalpy measurement in a high-temperature nonequilibrium gas flow within an hf-plasmotron is considered. Results obtained by two different enthalpy measurement methods are compared, and their good agreement is shown.

High-frequency (hf) plasmotrons [1] are used in studies of nonequilibrium heat exchange in a high-temperature flow. The gas temperature in such devices reaches $T = 5\cdot10^3-10^4$°K at pressures of $P \approx 10^3-10^4$ Pa. The most suitable flow regime for such studies is infrasonic ($M \sim 0.2-0.3$), in connection with which the quite nontrivial problem of measuring characteristics of such flows arises. The present study will consider some methods of measuring the most important characteristic of such flows, the braking enthalpy, H_0.

It has been shown that for such flows (in contrast to hypersonic ones) the conventional expressions for calculation of heat exchange in the thin boundary layer unexpectedly prove to be applicable at least to Reynolds numbers $Re \gtrsim 10$, which makes it possible to use the conventional calorimetric method of enthalpy measurement [3].

Independent enthalpy measurements can also be performed with a special enthalpy meter [3], the construction and gas dynamics of which will be described below. For the experiments performed both methods give similar results.

The calorimetric method of braking enthalpy determination reduces to measurement of a thermal flux

$$q = \alpha(H_0 - h_w),\ H_0 = h_0 + \frac{1}{2}u_0^2 \quad (1)$$

for known values of α and h_w. This method gives good results in dense gases, but under rarefied nonequilibrium flow conditions it requires special justification for two major reasons.

The enthalpy of a dissociated gas is equal to $h = c_pT + h_f$, where h_f is related to the energy of atom (nitrogen and oxygen) formation and internal degrees of freedom (molecular oscillations, etc.).

For an equilibrium flow the quantity $h_f = h_f(p, T)$ can be calculated, but is not known beforehand for the nonequilibrium flow typical of an hf plasmotron. Moreover, in the cases of a frozen boundary layer [4]:

$$h_w = c_pT_w + h_{f_0}(1 + \mathrm{Le}^{-2/3}z)^{-1},\ z = k_w\rho_w\alpha^{-1}. \quad (2)$$

In the temperature range $T_0 = 5-10\cdot10^3$°K the ratio $h_{f_0}/H_0 \approx 0.3-0.7$ (in an air flow), so that generally speaking, possible arbitrariness in values of h_{f_0} may introduce significant error into the H_0 determination. This can be avoided only by eliminating the effect of k_w on the thermal flux value, i.e., at $z \gg 1$.

To calculate heat exchange at the critical point of a hemisphere in an infrasonic flow a good approximation is given by the expression [4]

$$\alpha = 0{,}71\left(\frac{\rho_\delta\mu_\delta}{\rho_w\mu_w}\right)\sqrt{\rho_w\mu_w\beta}\,\mathrm{Pr}^{-2/3}, \quad (3)$$

where $\beta = 1.5\,u_0/R$ is the velocity gradient on the sphere. Therefore, the quantity $z \sim p^{1/2}$ increases together with the pressure.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 1, pp. 5-9, January, 1988. Original article submitted August 7, 1986.

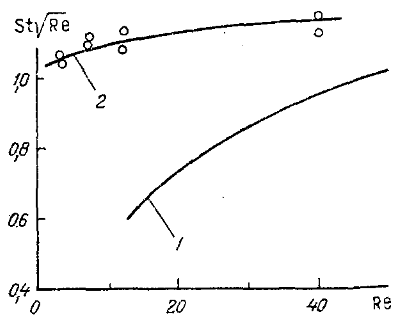

Fig. 1

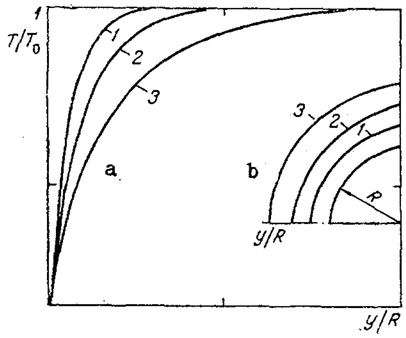

Fig. 2

Fig. 1. Quantity St$\sqrt{\text{Re}}$ vs Re for supersonic (curve 1) and infrasonic (curve 2) flow regimes.

Fig. 2. Temperature profiles T/T_0 vs distance from sphere y/R at critical point (a) and boundary layer thickness (b) for various Reynolds numbers: 1) Re = 40; 2) 12.5; 3) 3.5.

For a copper calorimeter various sources indicate $k_w \gtrsim 7$ m/sec, and for the experimental conditions ($p_0 = 2\cdot10^3$ Pa, $u_0 = 500$ m/sec, $T_w = 300$°K, $R = 1.25\cdot10^{-2}$ m) the contribution of the term with h_f to the quantity H_0 does not exceed $\Delta H_0/H_0 \sim h_{f_0}/h_0$ z $\lesssim 0.2$ and vanishes with further increase in k_w.

The second question which needs to be considered is the applicability of Eq. (3) for the small Reynolds numbers Re ∿ 10-50 realized under the indicated experimental conditions. Results known for hypersonic velocities [5] indicate significant (up to 40%, curve 1, Fig. 1) deviation of the quantity St $\text{Re}^{1/2}$ from the constant corresponding to an asymptotically thin boundary layer at large Reynolds numbers, for which Eq. (3) was obtained.

However, experiments in which Re was varied by changing sphere radius (Fig. 1, curve 2) show that in an infrasonic flow M ∿ 0.2 and low temperature factor $T_w/T_0 \sim 0.05$, at least in the range Re ≈ 10-100, The Reynolds number does not affect the value of the complex St $\text{Re}^{1/2}$, which remains the same as for an asymptotically thin boundary layer at the critical point of the hemisphere, despite the marked relative thickness of the latter. In Fig. 2a the solid lines show corresponding temperature profiles for $T_w/T_0 = 0.05$, with velocity profiles practically coinciding with the temperature profiles (curves 1, 2, 3 correspond to Re = 40, 12.5, 3.5). Figure 2b shows corresponding boundary-layer thicknesses.

The value of the flow velocity u_0 required for determining the heat-exchange coefficient can be found by measurements with a U-shaped manometer filled with dibutyl phthalate (ρ = 1046 kg/m³), from the difference between total and static pressures $\Delta p = p_0 - p_{st}$. Because of the low numbers Re ∿ 10-50 for a headpiece with rounding radius $R = 1.25\cdot10^{-2}$ m, we must introduce into this expression a correction factor γ, $\Delta p = 1/2\ \gamma\rho u^2$, where according to the data of [6], γ = 1-1.5.

Since the viscosity of air $\frac{\mu_\delta}{\mu_w} \sim \left(\frac{T_\delta}{T_w}\right)^{0,7}$, the coefficient $\left(\frac{\rho_\delta\mu_\delta}{\rho_w\mu_w}\right) \sim \left(\frac{T_\delta}{T_w}\right)^{0,1}$ does not introduce noticeable error into the value of α. Writing α in the form

$$\alpha \sim \sqrt{\rho_w\mu_w u_0} \sim (\rho_w\mu_w)^{\frac{1}{2}}\left(\frac{2\Delta p}{\gamma\rho_\delta}\right)^{\frac{1}{4}} \sim (\rho_w\mu_w)^{\frac{1}{2}}\,\rho_\delta^{-\frac{1}{4}}\left(\frac{\Delta p}{\gamma}\right)^{\frac{1}{4}}, \tag{4}$$

it can be concluded that inaccuracy in determining γ and Δp of the order of 30-40% leads only to insignificant (7-10%) error in the heat-exchange coefficient, and thus, in the calculated enthalpy H_0.

The enthalpy meter consists of a flow calorimeter in the form of a cylindrical copper tube (1, Fig. 3a), the lateral surface of which is insulated from the effect of the high temperature flow by thermal insulator 2 and copper screen 3.

The principle of operation of such a meter involves measuring the mass of gas m passing through the inner channel, its mean heat content H_b in the output section b, and the heat Q transferred to the calorimeter. The measured enthalpy of the external flow will then equal $H_0 = Q/m + H_b$.

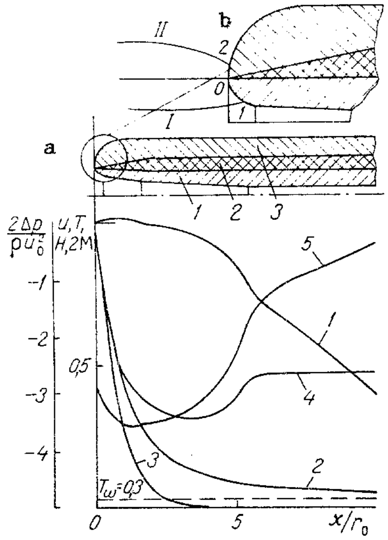

Fig. 3

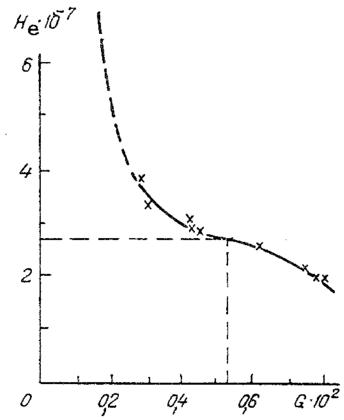

Fig. 4

Fig. 3. Dimensionless pressure (1), temperature (2), total enthalpy (3), velocity (4), and Mach number (5) on flow axis in enthalpy meter channel vs distance x/r_0 from entrance to meter.

Fig. 4. Enthalpy H (kJ/kg) measured by enthalpy meter vs gas flow rate through enthalpy meter channel G (g/sec).

The low gas flow rate in the channel (of the order of 0.005 g/sec) allows determining the gas mass m from the pressure differential in the sampling chamber before and after the experiment.

The profile of the initial segment of the input channel is determined by preliminary thermal calculations from the condition of a fourfold reduction in flow velocity ahead of the enthalpy meter input section. To clarify the enthalpy meter's operating regime a calculation was performed for the flow of a chemically nonequilibrium gas in a channel of variable section in the Poiseuille formulation (as in [7]). Calculation results for a cold wall with catalycity k_w = 20 m/sec for input orifice diameter 8 mm and flow parameters $p_0 = 1.5 \cdot 10^3$ Pa, u_0 = 400 m/sec are shown in Fig. 3a. The digits 1, 2, 3, 4, 5 are dependences on coordinate x/r_0 of pressure, temperature, total gas enthalpy, velocity, and Mach number of the jet axis.

It is evident that under the experimental conditions ($Re_d = \rho_0 u_0 r_0/\mu_0 \approx 3$) the thermal and chemical components of gas heat content are fully transferred to the enthalpy meter even in the initial segment of the input channel. Consequently, $H_b \approx c_p T_k \ll c_p T_0$, since calorimeter heating does not exceed $\Delta T \lesssim 50°K$. The Mach number never reaches unity, which permits regulating the flow rate.

However, the small distance at which enthalpy relaxation occurs significantly increases the sensitivity of the measurement results to the position of the braking point (1, 0, 2 at Fig. 3b) of the flow line dividing the flows I and II (entering the enthalpy meter (I) and flowing around it (II)). The optimal case will be the arrival (at some flow rate G = G*) of this line at the point 0. Then the flows I and II will be completely separated, and the most proper determination of H_0 can be made. As can easily be seen, shift of the braking point to the calorimeter (point 1, Fig. 3b) or the thermal insulator (point 2, Fig. 3b) leads to elevation or reduction of H_0 due to heating of the calorimeter in the segment 1–0 by flow II, or heat loss from flow I to the segment 2–0 of the insulator.

The corresponding experimental curve $H_e(G)$ is shown in Fig. 4. This curve has an inflection point at $G = 0.53 \cdot 10^{-2}$ g/sec with minimum slope. It is logical to assume that this point corresponds to arrival of the separating line at point 0 of Fig. 3b, since it is the segment with vertical tangent to the enthalpy meter contour which will correspond to the greater change in flow rate for least deviation of the braking point, and consequently, the smallest deviation of the measured quantity H_0.

To compare H_0 measurement results experiments were performed with two hf plasmotron operating regimes. The enthalpy meter produced results of H_1 = 27, H_2 = 38 MJ/kg, while a calorimeter at the critical point of the hemispherical model gave H_1 = 26.5 and H_2 = 35 MJ/kg.

The closeness of these results (deviation of not more than 5%) can be considered evidence of the reliability of both enthalpy measurement methods for rarefied infrasonic high temperature flows.

NOTATION

p, gas pressure; T, gas temperature; h, gas enthalpy; H, total enthalpy; ρ, gas density; u, gas velocity; c_p, specific heat of external degrees of freedom; k_w, constant for catalytic recombination of atoms on surface; α, heat-exchange coefficient; R, radius of spherical model; Le, Lewis–Semenov number; Re, Reynolds number; r, radius of enthalpy meter channel; w, subscript indicating values on body surface; 0, subscript indicating value in incident flow, as well as initial radius of enthalpy meter channel.

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USE OF THE IMPROVED THIN-WALL METHOD IN INVESTIGATING HEAT TRANSFER IN A HYPERSONIC WIND TUNNEL

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UDC 536.24.08:533.6.011.55

The authors determine unsteady heat fluxes on a thin-walled model, taking account of two time derivatives of the measured temperature.

A very sensitive method of thermal measurement in investigating heat transfer on models in wind tunnels is the method of microthermocouple measurements on thin-walled models, a method that has found rather wide use [1-3]. Thanks to the use of high-sensitivity measuring equipment [4] and the developed technology of microthermocouple installation [2] high spatial and temporal resolution of temperature fields in the test regions has been achieved [5, 6]. The density of location of microthermocouples on models of wall thickness 0.05-0.1 mm is 7 items per mm, the equipment sensitivity is $1 \cdot 10^{-6}$ V, and the time resolution is $1 \cdot 10^{-4}$ sec.

The data reduction of microthermocouple measurements on thin-walled models is ordinarily performed using the theory of regular regimes [7], or using a general relation connecting the time-dependent heat fluxes q(τ) acting on the model with the rate of change of temperature T(τ) of its internal surface

$$q(\tau) = \rho c \delta \frac{dT(\tau)}{d\tau}. \tag{1}$$

To reduce the error of the approximation (1), we consider relations for calculating unsteady heat fluxes in which we take into account not only the first derivatives of the measured

*Deceased.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 1, pp. 9-13, January, 1988. Original article submitted July 13, 1984.

0022-0841/88/5401-0004$12.50