HEATING OF A BLUNT BODY BY A PLASMA JET

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The results are presented on an experimental study of heat exchange with a high temperature gas jet in the region of the stagnation point of a blunt axially symmetric body. A generalized dependence for the heat flux is obtained.

Formulas for the intensity of heat exchange with a jet of dissociated and ionized gas of a blunt body in the region of the stagnation point were obtained in [1-4] from a theoretical analysis.

The results of the calculations are compared with heat-flux measurements in shock tubes in a number of works [5-10]. The results of measurements in shock tubes do not agree with each other in several cases [4, 6].

It is interesting to compare the calculated heat-flux values and the experimental data obtained in shock tubes with the results of measurements of the intensity of heat exchange in a stationary high temperature gas jet, a plasma jet, obtained with an electric arc heater.

A description of the electric arc gas heater, its characteristics, and the parameters of the plasma jet (nitrogen was heated) are presented in [10, 11]. A heater with cooled copper electrodes 100 mm long each, with turbulent compressed gas discharge was used. The diameter of the channel in the cathode and anode was 15 mm. The fractional contamination of electrode material in the heated gas discharge did not exceed 0.1%. Methods used to measure heat fluxes, the exponential and cooled calorimeter methods, were examined in the same articles. It follows from an analysis of methodical and instrumental errors that the error in measuring heat fluxes by the exponential method is equal to 15%. In using the cooled calorimeter method it is 20%. The parameters of the gas jet (enthalpy and stagnation pressure) were measured with an error of 10-12%. An analysis of the application of the exponential method to the cases considered was given in [12]. In contrast to [10] Textolite cylinders were used as specimens, which were 20 mm in diameter with a spherical blunt end having as the calorimetric element a copper cylinder 3 mm in diameter and 5 mm long set in a Textolite socket in the area of the forward critical point. Conical specimens with spherical blunting were used to study the effect of the form of the body and the radius of curvature. The cone angle varied from 0 to 20° and the radius of curvature from 3 to 10 mm. In addition, specimens with flat faces were used. After working on the lathe the surface of the specimens was polished with fine grain emery paper.

The conical specimens were blown on by a gas jet with the following parameters: the enthalpy was (19,600 ± 2300) kJ/kg (T = 6650°K), the jet velocity was 300 m/sec. The given parameters corresponded to a power of 70 kW supplied to the discharge chamber and a nitrogen consumption of 2 g/sec. The diameter of the cylindrical nozzle in the anode was 15 mm.

A graphite nozzle was placed at the outlet from the anode to obtain a stagnation pressure higher than atmospheric in blowing on cylindrical specimens 20 mm in diameter with spherical blunting. A nozzle with a critical cross-section diameter of 4 mm with a widening section (the output cross-section diameter was 10 mm) and cylindrical elements 4 and 6 mm in diameter were used. The power consumed in the discharge chamber was measured in these experiments from 45 to 180 kW and the gas consumption from 1.3 to 6 g/sec, which corresponded to variations in enthalpy and stagnation pressure of 9900-20,200 kJ/kg and 1-4 bar, respectively. Contamination of the jet of heated gas by graphite was found within the limits of 0.15-0.5%. No change was noted in the nozzle cross-sectional area and the parameters in the course of one

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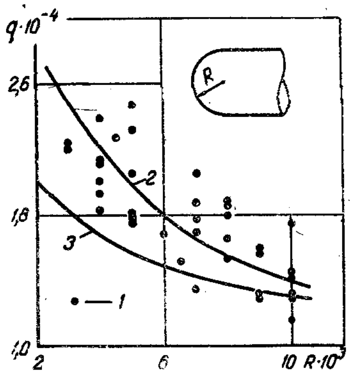

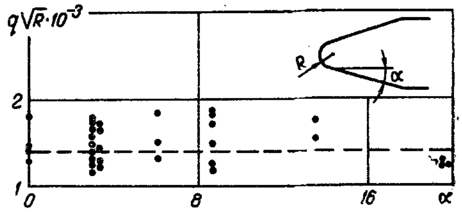

Fig. 1 Fig. 2

Fig. 1. Dependence of heat flux, kW/m^2, on radius, m: 1) experimental results for specimens with spherical blunting; 2) computed from Eq. (1); 3) results of experiments on cylindrical specimens with flat faces.

Fig. 2. Dependence of $q\sqrt{R}$, $kW \cdot m^{-3/2}$, on apex angle of cone, deg. Dashed line computed from Eq. (1).

experiment. All the specimens were mounted at a distance of 25 mm from the nozzle tip. In addition, in formulating the generalized dependence for the heat flux at the stagnation point use was made of the measurements of one of the above authors [10] on the heat-flux values in a range of change of the stagnation enthalpy of 6000-100,000 kJ/kg and stagnation pressures of 1-1.5 bar, as well as results of measuring heat fluxes using shock tubes.

The stagnation enthalpy was determined from the energetic balance of the heater and with an enthalpy pickup, and from the temperature measured by the spectroscopic method in [10]. The stagnation pressure was measured using a pickup with a graphite tip introduced into the jet, in conjunction with a standard manometer and an electrical pressure pickup. The equation used for calculating the heat flux in connection with the exponential method has the form

$$q = \delta c_p \rho dT/d\tau.$$

Since the nozzle diameter chosen for the jet was 4-10 mm, a test was made of the effect of the calorimetric element diameter on the results of the heat flux measurements. The diameter of the copper cylinder was 1.5, 3, and 5 mm. The average heat-flux values for several experiments, measured under one set of operating conditions of the instrument (gas enthalpy within the limits of 15,400-16,300 kJ/kg), were equal to 1.84, 2.02, and 1.85 kW/cm^2, respectively. The differences in the values obtained lie within the limits of the experimental error. Thus, a calorimeter diameter of 3 mm could be used for the heat-flux measurements.

The test conducted also confirmed that with rates of change with time of the calorimeter temperature in the range of 200-2200 deg/sec the inertia of the thermocouple–vibrator system of the oscillograph had essentially no effect on the results of the measurements. The rate of heating of the thermocouple junction in the plasma jet was an order of magnitude greater than the maximum heating rate of the specimen.

The measurements showed that the magnitude of the heat flux at the stagnation point decreases with an increase in the blunt radius R (Fig. 1). The results of the measurements agree with a calculation by the equation of Fey and Riddell for a dissociated gas jet (Fig. 1, curve 2)

$$q = 0.763 R^{-0.5} \Pr^{-0.6} (\rho\mu)_w^{0.1} (\rho\mu)_0^{0.4} \left[1 + (\mathrm{Le}^{0.52} - 1)\frac{h_D}{h_0}\right]\left[\frac{2(p_0 - p_\infty)}{\rho_0}\right]^{0.25} (h_0 - h_w), \quad (1)$$

which, with the calculation of the parameters for this series of experiments given above, takes the following form: $q = 1.38 \cdot 10^3/\sqrt{R}$. The heat-flux values measured have a lower scatter in the case of a flat face than for a cylinder with spherical blunting (Fig. 1, curve 3). The variation in heat fluxes also diminishes with an increase in the radius of curvature. For the flat face R is the radius of the face.

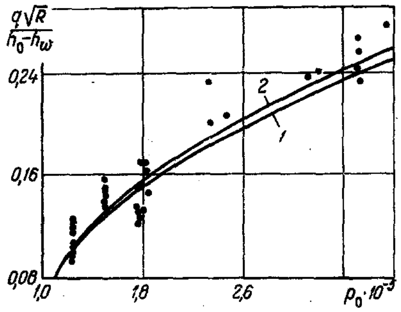

Fig. 3. Dependence of value of $q\sqrt{R}/(h_0 - h_w)$, $m^{-3/2}$ kg · sec^{-1}, on stagnation pressure, N/m^2 [1) calculation by Eq. (1); 2) calculation by Eq. (2); points) experiment].

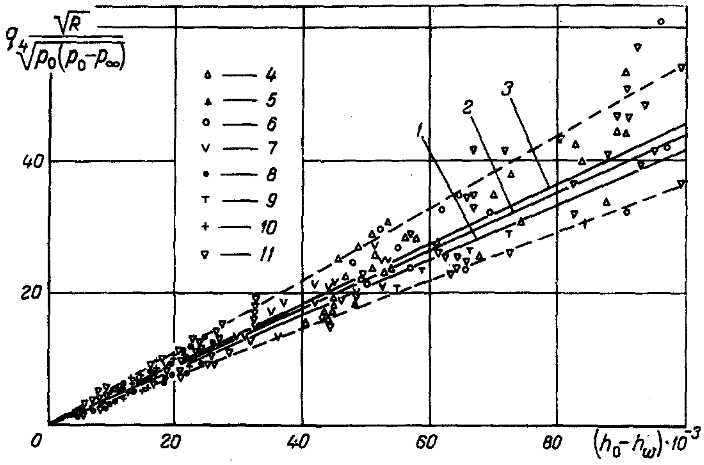

Fig. 4. Dependence of value of $qR^{0.5}p^{-0.25}(p_0 - p_\infty)^{-0.25}$, kW · $m^{-0.5}$ · $N^{-0.5}$, on variation in enthalpy $(h_0 - h_w)$, kJ /kg: 1) calculated by Eq. (3); 2) by Eq. (1); 3) generalized experimental relation (Eq. (2)); 4, 5, 6) data from [7]; [4) pickup made of aluminum; 5) of Nichrome; 6) of gold]; 7) [9]; 8) [5]; 9) [8]; 10) [10]; 11) results of present work. Dashed lines: deviation of ±20% from relation 3.

Temperature pulsation in a heated gas jet [14] was studied using a specially developed photoelectron adapter [13] for a type UM-2 monochromator, which we used to study heat transfer.

The measurements showed that the root mean square variation in the temperature was found within the limits from 90 to 350°K at different points along the radius for temperatures at the nozzle tip near the axis from 5800 to 6300°K. The range of frequencies studied was 0-2 kHz.

It follows from the data obtained on heat transfer (Figs. 1 and 4) that the effect of the given temperature pulsations on the intensity of heat transfer does not exceed the error in measuring the thermal fluxes. This result confirms the conclusions of [15] devoted to a study of the effect of pulsations of the parameters of an electric arc heater on the intensity of heat transfer in the stagnation point region.

Among the parameters determining the intensity of heat transfer at the stagnation point are the stagnation enthalpy and pressure. However, the properties of the gas, which also have an effect on the heat flux (Eq. (1)), are usually determined uniquely by the enthalpy and pressure. In connection with this for the given gas it is sufficient to study the dependence of the heat flux on the stagnation enthalpy and pressure.

An example of the dependence of the heat flux on the pressure is given in Fig. 3. The growth in heat flux with increased stagnation pressure gradually slows. The measured results agree with the calculation according to Eq. (1).

The dependence of the measured values of the complex, including the heat flux, on the enthalpy of the gas is presented in Fig. 4. The given dependence is practically linear over a wide range of enthalpy variation. The scatter of the measured heat-flux values (points 10 and 11) around the average curve 3 is mostly found within the limits ±20%. The experimental data is represented with the given error by the following relation:

$$q = 4.5 \cdot 10^{-4} R^{-0.5} p_0^{0.25} (p_0 - p_\infty)^{0.25} (h_0 - h_w). \quad (2)$$

Experimental results from [5, 7-9] obtained using shock tubes are also shown in Fig. 4. The stagnation pressure in [5] has a range of variation of 1-100 bar for a stagnation enthalpy change from 2600 to 32,000 kJ/kg. At higher values of the enthalpy (Fig. 4) obtained in shock tubes the stagnation pressure was from 2 to 7 bar [7]. The results of heat-flux measurements obtained in shock tubes agree with Eq. (2) found in the present work with an error of ±20%.

A comparison of the relation found with the equation of Avduevskii and Glebov [2]

$$q = 0{,}763 R^{-0{,}5} (0{,}75 + 2{,}73 \cdot 10^{-2} T_w) (\mathrm{Pr}_{eff})_w^{-0{,}6} (\mu\rho)_0^{0{,}185} (\mu\rho)_w^{0{,}315} [2 (p_0 - p_\infty)/\rho_0]^{-0{,}25} (h_0 - h_w), \quad (3)$$

obtained for an ionized gas jet (Fig. 4, curve 1) indicates the good agreement of the experimental results with the theoretical calculation. The results of a calculation by Eq. (1) for the dissociation region, extrapolated to the ionization region, are also given in Fig. 4 (curve 2). Thus, a calculation by Eq. (1) gives heat-flux values in agreement with experiment in the ionization region.

NOTATION

q	is the specific heat flux, kW/m^2;
p_0, p_∞	are the stagnation pressure and pressure far from the surface, N/m^2;
h_0, h_w	are the stagnation enthalpy and enthalpy at wall temperature, kJ/kg;
R	is the radius of curvature of spherical front surface of body, m;
δ	is the thickness of calorimetric element.

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