HEAT EXCHANGE BETWEEN PLASMA JET AND OBSTACLE UNDER UNSTEADY CONDITIONS

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A method and the corresponding detectors for measuring large, varying heat fluxes have been studied. The heat fluxes from a plasma jet to a blunt object near the stagnation point have been measured under unsteady conditions.

For an arbitrary time variation of the heat flux at a surface, the temperature field of a semi-infinite object is given by the integral [1]

\[ T(x,t) = T_0 + \frac{1}{V \lambda \rho c_p} \int_0^t \frac{q(l)}{\sqrt{\pi(l-t)}} e^{-x^2/4a(l-t)} \, dl. \]  

(1)

Partitioning the time interval under consideration into \( k \) subintervals, and assuming that the heat flux is constant over each such subinterval, we find the following equation for the heat flux [1]:

\[ q_k = \Phi_{x,k}^{-1} \left[ \frac{\lambda}{2 \pi V \Delta F_0} \int (T(x,t_k) - T_0) - \sum_{s=1}^{k-1} \Phi_s q_{s,r} \right] , \]  

(2)

where

\[ \Phi_{x,s} = V k - s + 1 \text{ erfc} \frac{1}{2 \sqrt{\Delta F_0} (k - s + 1)} - V k - s \text{ erfc} \frac{1}{2 \sqrt{\Delta F_0} (k - s)} . \]

To determine the time dependence of the heat flux in Eq. (2) we must measure the temperature at some point of the object at a distance \( x \) from the surface. Calculations show that for measurement of heat fluxes on the order of 1 kW/cm² the solution in (2) is stable for \( \Delta F_0 x > 0.5 - 1 \) [2]. When a thermocouple is placed 1-2 mm from the surface, the first value of the heat flux can be found at a time 0.005-0.01 sec after the beginning of the process. This time interval is the minimum value of the time intervals into which the curve \( T = f(t) \) can be partitioned in order to find a stable solution.

The detectors used in this method are long copper rods with heat-insulated lateral surfaces. The temperature at the rear end of the rod is monitored by a thermocouple. Near the front end of the rod, between the rod and the insulation, is an annular contact 0.5-1 mm wide; over the remainder there is an air-filled gap.

Comparison of the method of a semi-infinite object with the method of [3] shows (see Fig. 1 of [4]) that the two give approximately the same results. To determine the heat fluxes by the second method it is necessary to measure the rod temperature at four points along its length. For a constant value of the heat flux, the method of a semi-infinite object agrees within the measurement error (10%-15%) with the exponential method for measuring heat fluxes (Fig. 2 of [4]). Finally, the test of the method reported below also confirms its suitability for measurements (Fig. 2).

To test the applicability of the one-dimensional theory [Eq. (2)] in the case of cylindrical detectors, we carried out a numerical calculation of the temperature fields for a detector model. We treated versions of the detector with textolite and copper protective sleeves. For version a (Fig. 1) the heat flux was assumed to be 0.7 or 3 kW/cm², corresponding to concrete experiments; for version b it was \( q = 0.55 \) kW/cm², and the width...
of the contact between the detector and the sleeve was 1 or 0.4 mm. On the basis of preliminary calculations we chose a length of 10 mm for the detector; this is sufficient for simulation of a semiinfinite object over a time interval of 0.2–0.3 sec.

In accordance with the explicit calculation scheme (whose applicability for a problem of this type was checked beforehand through a comparison with the analytic solution for a semiinfinite object), the temperature at the interior points of the model detector (Fig. 1) was determined from

\[
t_{i,m,k+1} = [1 - 2 (\Delta F_{\alpha} + \Delta F_{\beta})] t_{i,m,h} + \Delta F_{\alpha} \left( 1 - \frac{\Delta r}{2r_i} \right) t_{i-1,m,h} + \Delta F_{\beta} \left( 1 + \frac{\Delta r}{2r_i} \right) t_{i+1,m,h} + \Delta F_{z} (t_{i,m-1,h} + t_{i,m+1,h}).
\]

The step along the z direction was chosen to be 0.2 mm, and we chose \(\Delta r = 0.5\) mm; then the step \(\Delta t\) can be assumed to be \(10^{-1}\) sec on the basis of the stability condition \(0 \leq [1 - 2(\alpha/\Delta r)^2 + \alpha A_{\tau}/(\Delta z)^2] \leq 1\). We assumed ideal thermal contact at the contact between the detector and the sleeve; at the other surfaces, except the front end, we assumed there was no heat transfer.

Analysis of the temperature fields found shows that in the detector there are radial temperature gradients, which have essentially no effect on the temperature at the axis of the detector in the cases considered (Fig. 2). Reconstruction of the heat flux on the basis of the temperature at the axis at a distance of 1 mm from the end, by means of the method of a semiinfinite object, yields values approximately the same as the original fluxes. In particular, for the case shown in Fig. 2 the heat flux in the numerical calculation was assumed to be 3 kW/cm², which is in good agreement with the calculated values of \(q\) (points 9). It also follows from this chart that there are no significant radial heat fluxes in the detectors used, so that they are suitable for measurements.

Measurement of the heat fluxes in the initial stage of the heating of a blunt object near the stagnation point in a plasma jet [2, 4] showed that the heat fluxes usually increase from zero to a steady-state value (Figs. 2 and 3), which is governed by the properties of the gas flow and by the shape of the object [5]:

\[
q = 4.5 \times 10^{-4} R^{-0.5} P_0^{0.25} (P_0 - P_m)^{0.25} (h_b - h_w).
\]

In some cases the heat fluxes were constant, beginning with the first value found. The behavior of the heat flux does not depend on the nature of the gas [6] (air or argon) or the properties of the gas flow [6] (Figs. 2 and 3). The heat flux is the same if the detector is in a coaxial arrangement with the nozzle before the appearance of the plasma jet or if the detector is inserted into the jet after the apparatus has been turned on [6].

This analysis of the temperature fields in the detector showed that the observed increase in \(q\) during the initial stage cannot be attributed to heat fluxes across the contact between the detector and the protective sleeve. The change in the heat flux was caused by external factors.

The problem of the flow of a gas with constant properties around a blunt object, with unsteady heat exchange, can be formulated as follows [7]:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial f}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 f}{\partial \eta^2} + \frac{1}{2} \left( 1 - f^2 \right) = 0, \quad \frac{\partial \theta}{\partial \tau_w} = \text{Pr} \frac{\partial \theta}{\partial \eta} + \frac{\partial \theta}{\partial \eta^2}.
\]

Neglecting the second term of the energy equation near the stagnation point, where the velocity components vanish, we reduce the heat-transfer problem to a heat-conduction problem in order to study the nature of the