HEAT TRANSFER IN THE CASE OF A PLASMA JET FLOWING INTO A CYLINDER

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The heat transfer from a plasma jet to the walls of a cylinder is studied experimentally. It is shown that the heat transfer rate from the plasma jet to the cylinder walls is described by relation (2) obtained previously for a gas jet flowing into a cylinder.

When the energy of a low-temperature plasma jet is used for industrial purposes, it is essential to know the coefficient of heat transfer between the plasma jet and the wall of so-called plasma-jet reactors. A plasma-jet reactor is an extension of plasmatron design.

Results of Heat-Transfer-Coefficient Measurements

T, °C	G, m^3/hr	$\bar{t}$, °C	w, m/sec	α, W/m^2 · deg	Re	St × 3600
6400	5.3	3200	0.265	4.45	110	830
10600	5.3	5300	0.395	4.42	66	860
4500	8.4	2250	0.390	6.34	187	735
7100	8.1	3550	0.440	4.80	158	586
7800	8.1	3900	0.489	5.21	147	634
5960	7.8	2980	0.366	5.16	170	650
9800	5.3	4900	0.392	4.47	67	850
11400	5.2	5700	0.450	4.16	60	786
6700	8.3	3350	0.463	5.68	172	646

Two types of plasma-jet reactors are currently employed [1, 2]: reactors in the form of a narrow tube, with a diameter equal to the plasmatron channel, and large-diameter reactors with recirculation of the products in the high temperature zone. The reagents are supplied to the plasma usually at the outlet of the plasma jet from the plasmatron. In each of these reactor types, there form two zones in which the plasma-chemical process takes place. In the first (reaction) zone, the reagents are kept at a high temperature over a period of time defined by the thermodynamics and kinetics of the processes. In the second (quenching) zone, the reagents are subjected to rapid cooling at a rate that ensures conservation of the necessary reaction products obtained at high temperatures. Quenching can be achieved by spraying with a gas or liquid jet in heat exchangers with fluidized beds consisting of inert materials, with the aid of Laval nozzles or similar devices. In such quenching systems, cooling rates can be as high as 10^8 deg/sec.

In practice, it is often difficult to draw a geometrical boundary between the reaction and quenching zone in a plasma-jet reactor. For example, it can happen that over the cross section of the device, reactions will take place in the region of the axis, whereas quenching will occur in the region at the walls. In the case of small-diameter reactors, the zone directly adjacent to the plasmatron may be regarded as the reaction zone, while further downstream, it may become the quenching zone; in the case of a recirculation reactor, the region of the jet will be the reaction zone, while the remaining volume will be the quenching zone. In the simplest reactor configuration, a narrow tube, the quenching rates are on the order of 10^6 deg/sec [3]. On the other hand, the quenching rate is determined by the rate of heat transfer from the plasma jet (which extends over the reactor cross section) to the wall. In spite of the fact that experiments aimed at determining the heat transfer coefficients are being persistently conducted, there are still insufficient data for obtaining a complete picture of the heat transfer associated with the flow of a plasma into a cylinder. In [4], an empirical relation is given for evaluating the heat transfer rate from a plasma flow to the tube wall, where the tube is an extension of the plasma channel. The mean value of the heat transfer coefficient obtained from this relation is roughly 1500 W/m^2 · degree. This value is compatible with the values that correspond to the plasmatron channel [5].

Data concerning the heat transfer between a plasma jet and the walls of a circulation-type plasma-jet reactor are very scarce. It is known that for a gas jet flowing into a closed cylinder, the heat transfer rate is greatly intensified [6].

The empirical relation

$$\mathrm{St} = 4.9\,\mathrm{Re}^{-0.25}\,\frac{D}{H}\left(\frac{d}{D}\right)^{0.25}\left(\frac{D}{\delta}\right)^{0.35} \qquad (1)$$

was previously obtained for the following ranges: $200 < \mathrm{Re} < 10\,000$; $5 < H/D < 15$; $15 < D/d < 50$; $1 < D/\delta < 10$, where $\mathrm{Re} = wD/\nu$; w) scale velocity; d) jet diameter; D) cylinder diameter; H) cylinder height; δ) diameter of the defining slit in the cylinder. The mean value of the flow temperatures at the inlet and outlet of the cylinder was taken as the characteristic temperature.

However, the applicability of relation (1) to the evaluation of the heat transfer associated with the flow of a plasma jet into a cylindrical chamber remained questionable. Hence, it was decided to perform special heat-transfer-coefficient measurements for this case. Investigations were performed with the experimental equipment shown in the figure. An 18-mm-diameter argon plasma jet was made to flow into a cylindrical chamber measuring 300 mm in diameter and having a 1000-mm-tall cylindrical part ($H/D = 3.3$; $D/d = 13$; $\delta/D = 1$). The argon temperatures at the cylinder inlet were from 7000° to 12 000° K. Because of these relatively high temperatures, it was possible to assume certain specific heat transfer characteristics, such as an appreciable influence of free convection as a result of the substantial difference in the jet and gas-volume densities. The jet temperature at the inlet of the cylindrical chamber was calculated from the measured heat balance of the plasmatron. The heat balance was determined with reference to the cooling water; the measurements included the temperature difference of the inlet and outlet water and the flow rate. The thermal capacity of the jet was equal to the difference between the electric power supply and the heat removed by the water.

In addition, the vertical temperature distribution in the cylinder was measured with tungsten-molybdenum and chromel-alumel thermocouples. It should be noted that temperatures were measured only at levels where these thermocouples could operate without risking damage. The temperature between the origin of the jet and the level with T > 2000° C was extrapolated rather than measured directly.

The heat transfer coefficient was measured in the conventional way. The heat flux removed by the cooling water was measured and was referred to the heat transfer surface of the cylinder and to the thermal head. The mean logarithmic value of the thermal head was calculated from the measured temperatures of the plasma jet at the plasmatron outlet, the gas at the reactor outlet, and the wall temperatures.

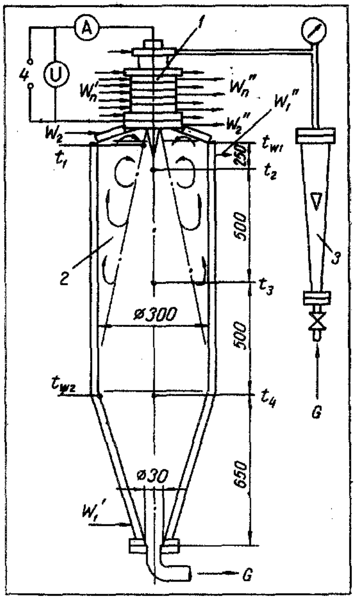
Preliminary test results are given in the table, together with the values of the criteria employed for describing the heat transfer process associated with the flow of a gas jet into a cylinder. The representation of the obtained results in dimensionless form is somewhat difficult by the doubtfulness of the appraisal of the characteristic temperature of the medium. An attempt was made to take the arithmetic mean of the inlet and outlet temperatures of a cylindrical chamber as the characteristic temperature. This temperature is practically equal to half the jet temperature at the plasmatron outlet.

The values of the thermophysical parameters for argon were taken from [7]. The results obtained were compared with expression (1). The results made it evident that by introducing the Prandtl number into (1), the experimental data can be satisfactorily approximated by the following relation:

$$\mathrm{St} = 5.7\mathrm{Re}^{-0.25}\mathrm{Pr}^{0.43}\left(\frac{D}{H}\right)\left(\frac{d}{D}\right)^{0.25}; \qquad (2)$$

for 60 < Re < 200, the ratio δ/D was unity. In this case, the scatter of the points did not exceed ±10%, which is acceptable for obtaining qualitative estimates of the heat transfer coefficient.

The heat transfer measurements performed for a plasma jet flowing into a cylinder lead to the preliminary conclusion that the heat transfer rate (α) is of the same order of magnitude as in the case of a gas jet. In the presence of large temperature gradients in the gas flow (large density differences), the influence of radiant transfer and free convection is only slight and need not be taken into account.



Schematic diagram of the experimental equipment: 1) plasmatron; 2) cylindrical chamber; 3) rotameter; 4) electric power source; t_1) radial temperature (tungsten-molybdenum thermocouple); t_w) wall temperature; t_{2-4}) gas temperature at the axis; W_n', W_n'') heat content of the cooling water at the inlet and outlet, respectively; A) ammeter; U) voltmeter.

NOTATION

α) heat transfer coefficient, in W/m^2 · degree; Pr) Prandtl number; Re = wd/ν) Reynolds number; ν) kinematic viscosity coefficient, in m^2/sec; c_p) heat capacity of the gas, in J/kg • degree; St = $\alpha/c_p\gamma w$) Stanton number; D, H, d, δ) geometrical parameters, in m; G) gas flow rate, in m^3/hr; γ) gas density, in kg/m^3; w) scale velocity of the gas at the characteristic temperature, in m/sec; T) initial jet temperature; t) characteristic temperature.

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