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EFFECTS OF PLASMA FLOW STRUCTURE ON HEAT TRANSFER WITH POWDER PARTICLES

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Measurements have been made on the heat transfer to granular material in a plasma reactor having a multijet mixing chamber. The temperature distribution over the cross section has been measured by a spectral method and by calorimetry. The granular-material flow rate affects the heat flux to the walls. The measurements are fitted to an equation in dimensionless parameters.

The performance in processing a granular material in a plasma device is dependent on the thermophysical parameters, the relation between the mass flow rates, and the organization of the mixing, being ultimately governed by the transfer; the data on this are scanty and conflicting.

To accelerate the transfer, various reactor designs have been tested, one of the most promising being a multijet mixing chamber (plasma module). Even in the simplest style, a three-jet chamber can produce a plasma flow with fairly uniform temperature and velocity profiles. One can also use any method of injecting the granular material and can raise the reactor power by increasing the total number of plasmotrons or the unit power of each and by combining the multijet chamber with one or more modular reactors. This improves the performance, increases the total power, and extends the applications.

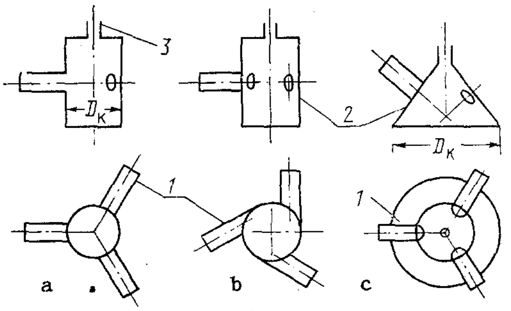

Fig. 1. Mixing chambers: a) cylindrical; b) tangential; c) canonical: 1) plasmotron; 2) mixing chamber; 3) inlet.

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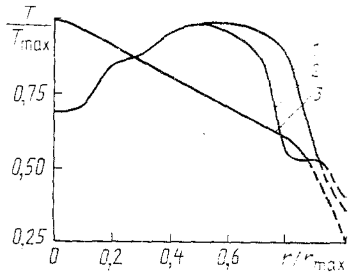

Fig. 2. Relative plasma-flow temperatures in mixing chambers referred to unit radius for T_{max} = 5000 K (±10%): 1 and 2) cylindrical with radial and tangential inputs correspondingly; 3) conical with radial input.

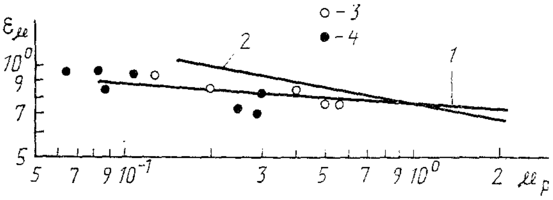

Fig. 3. Effects of grain concentration (phosphorite) on heat flux from plasma to chamber walls with D = 0.1 m, d_p = 0.08 mm: 1) $\varepsilon_\mu = 0.81 \cdot \mu_p^{-0.02}$ for canonical chamber; 2) $\varepsilon_\mu = 0.75\ \mu_p^{-0.08}$ for a cylindrical chamber; 3) cylindrical chamber (cerium oxalate); 4) cylindrical chamber with tangential input (phosphorite).

Measurements have been made [1] on plasma flow structure control in cylindrical and conical mixing chambers, which Fig. 1 shows involves changes in geometry, injection method, operating mode, and design features. The jets enter the chamber radially or tangentially. The geometry of a conical chamber may be varied via the cone angle. If the plasmotrons are perpendicular to the generator in the mixing chamber, the angles to the axis can be varied from 0 to 90°. At 0°, the axes of all three plasmotrons are parallel, while at 90° they are perpendicular, and all intermediate values correspond to different forms of the conical chamber.

We examined the flow structures by spectral methods and by means of an enthalpy sensor. The geometrical characteristics have been given [1-3], while the spectral methods (relative intensity technique) have been described in [4], and the enthalpy sensor has been described in [2]. The total input to the three plasmotrons varied from 100 to 200 kW, while the power at the inlet to the mixing chamber ranged from 70 to 120 kW, and in that section, the mean-mass enthalpy and temperature were correspondingly 10.0-16.0 kJ/g and 5000-5700 K, total air flow rate from 3.0 to 8.0 g/sec.

The temperature variation along the radius was recorded. We examined how the gas flow and power affected it, and in all cases found that the maximum spectral temperature was closely correlated with the mean-mass temperature as determined by calorimetery.

Figure 2 shows T/T_{max} as a function of r/r_{max} at the outlet from a cylindrical chamber with radial and tangential input and from a conical one with radial input. This confirms that the temperature distributions are nonequilibrium in the conical and tangential chambers, and it also provides a qualitative explanation for the finding [4, 5] of higher efficiency in the conical chamber relative to the cylindrical one because of the flow deformation (and effect on the temperature profile) in the multijet chamber. These data should be utilized in examining heat transfer to granular material. Profile 1 (Fig. 2) is the best, which occurs in a cylindrical chamber with radial jets, but the efficiency is lower because of increased heat loss to the wall.

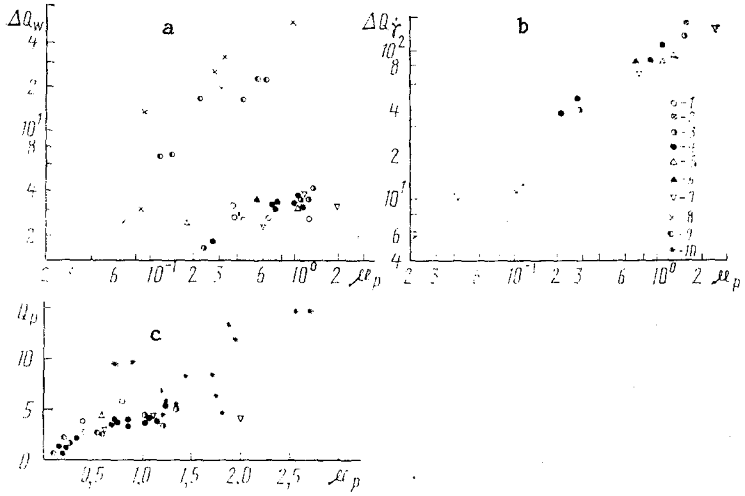

Fig. 4. a) Heat flux to mixing chamber walls; b) amount of heat leaving chamber with plasma flow; c) amount of heat transferred to granular material in mixing chamber, in each case as a function of the mass flow concentration: 1-7) [2] data; 8) $d_p = 0.13$ mm; 9) 0.08 mm for chamber with tangential input; 10) data for cylindrical chamver with radial cerium oxalate input ΔQ_w, $\Delta Q_{\gamma}\cdot$, Q_p, in kW.

The efficiency is higher in a conical chamber, and the maximum temperature occurs at the axis, which defines the best grain input zone. With input along the axis, the particles disperse along a cone, and the temperature tends to be equalized over the cross section, so the particles are under identical conditions.

Axial input to a tangential chamber is clearly undesirable, as the input should be displaced into the peak-temperature zone. In that case one shoul probably give preference to tangential input in a plane perpendicular to the axis of the reactor or at a certain angle to it.

We examined how granular materials affected the heat transfer in the various flow structures; in all cases, monodisperse or polydisperse powders reduced the mean mass temperature because of the heat uptake and thus reduced the heat flux to the wall, to an extent substantially dependent on the amount and concentration of the granular material. For equal power levels and concentrations, the amount of heat transmitted to the smaller grains was larger because of the greater contact surface.

The flow mass concentration was related to the heat flux from the plasma to the chamber walls as $\varepsilon_\mu = f(\mu_p)$ (Fig. 3), in which ε_μ is the ratio of the heat flux to the walls in a multijet chamber with granular input to that without it.

In the flow mass concentration range from 0.8 to 2.8 kg/kg, the data were fitted to the following: for a cylindrical chamber with radial and tangential jet input

$$\varepsilon_\mu = 0.75\mu_p^{-0.08}, \tag{1}$$

and for a conical one with radial jet input

$$\varepsilon_\mu = 0.810\mu_p^{-0.02}. \tag{2}$$

The effects of the concentration on the heat transfer to the wall in a cylindrical chamber are more marked than in a conical one. The mode of jet input to a cylindrical chmaber has no marked effect on the heat transfer from the particle-loaded flow, since the boundary layer in the two cases has similar structures, which arise from the mixing of the stabilized tangentially swirling gas jets [2].

The [2] method was used with the heat-balance equations for two modes of operation (with and without particle input) to determine the changes in heat flux to the walls of the mixing chamber and reactor, the amounts of heat leaving with the gases, and the amount of heat transferred to the granular material (Fig. 4, a-c correspondingly). The data obtained for phosphorite [2] have been supplemented with ones for dry rare-earth oxalates.

Figure 4c shows the amount of heat passed to the granular material in the mixing chamber (in the heating part) as the same for both types of material and is substantially dependent on μ_p, the ratio of the granular flow to the total gas flow.

The heat-transfer data were fitted to a proposed [2] formula in terms of dimensionless quantities:

$$\mathrm{Nu} = 2\frac{\lambda_s}{\lambda_g} + 0.78\mathrm{Re}_p^{0.5}\,\mathrm{Pr}^{0.33}\left(\frac{\rho_g\mu_g}{\rho_s\mu_s}\right)^{0.2}\varepsilon_\mu. \quad (3)$$

One can use (3) to calculate the heat transfer to a granular material from a plasma flow in a three-jet mixing chamber.

We have used (1)-(3) to calculate granular processing conditions for plasma reactors with various types of mixing chamber and to simulate high-power plasma reactors.

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