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INTERPHASE HEAT TRANSFER BETWEEN LOW-TEMPERATURE PLASMA AND DISPERSE MATERIALS IN A PLASMA REACTOR

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Data on heat transfer of plasma flows in a cylindrical channel of a reactor with a three-jet mixing chamber are analyzed. Experimental results are also presented on interphase heat transfer between plasma flows and disperse particles, and two possible methods of generalization of the results are shown.

Development of process facilities for chemical plasma treatment of materials and dispersed solutions requires the solution of some problems concerned with heat and mass transfer in the "plasma flow—treated material—walls of the reactor channel" system.

One of the main problems that may arise in choice of the type and in development of designs of chemical plasma reactors is the creation of conditions for the best mixing and heat transfer between the initial raw material and the heat transfer agent, a plasma-forming gas. The importance of these two conditions is primarily determined by the necessity that equilibrium, which ensures heat transfer and physicochemical transformations, be established as quickly as possible and that the yields of the end products approach the thermodynamically possible yields in the limit. In the presence of chemical conversions the same conditions are also necessary for kinetic reasons, since chemical reactions can take place over the entire cross-section of the reactor only if the mixture becomes homogeneous as quickly as possible.

Consideration of the existing schemes and types of plasma reactors shows that direct-flow plasma reactors with transverse discharge of treated materials and plasma reactors with a three-jet mixing chamber, the so-called plasma modules, are most popular at present. In this case the material to be treated is fed along the axis of the reactor and the mixing chamber can be cylindrical or conical. The main characteristic of the flow of plasma jets and flows in channels of such plasma devices intended for both homogeneous and heterogeneous processes is that mixing and heat transfer occur in a section of substantially undeveloped flow, where the greatest temperature drops arise.

Theoretical and experimental studies of mixing and heat transfer of plasma jets in axisymmetric channels of plasma devices are analyzed in monographs [1, 2]. The following formula can be recommended for calculation of heat transfer in a flow of an air plasma jet in a cylindrical channel:

$$\mathrm{St} = 0.446\,\mathrm{Re}^{-0.53}\,\mathrm{Pr}^{-0.67} \tag{1}$$

where the mean mass temperature is used as the characteristic temperature. Relation (1) differs slightly from the relation

$$\mathrm{St} = 0.332\,\mathrm{Re}_x^{-0.5}\,\mathrm{Pr}^{-0.67}\,, \tag{2}$$

obtained for laminar flow of a high-temperature gas with constant physical properties. With high flow rates of the plasma-forming gas corresponding to turbulent flow, the following formula can be recommended for the starting length of the channel at $x/D < 6-8$:

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$$St = 0.85\, Re_x^{-0.46}\, Pr^{-0.6}\,, \tag{3}$$

and at $x/D > 6-8$:

$$St = 0.037\, Re^{-0.22}\, Pr^{-0.6}\,. \tag{4}$$

These results exceed the known theoretical relations for turbulent flow, which can be explained by the effect of tangential swirling of the gas in the discharge chamber of the plasma generator, the presence of radiation, the high nonuniformity of temperature and velocity profiles, as well as by delivery of a cold gas to be mixed with the plasma jet.

Results of studies of mixing and heat transfer processes in plasma reactors with a multijet mixing chamber are given in [1, 3-5]. Spectral studies of the temperature distribution at the outlets of mixing chambers of various types (cylindrical, conical, and tangential) were carried out to infer the structure of a plasma jet that is formed in these chambers. Comparison of the obtained data has revealed that the temperature profiles are nonuniform in conical and tangential mixing chambers: in the former a distinct maximum is observed on the axis of the plasma jet with a substantial temperature gradient toward the walls; in the latter, a dip is observed in the temperature profile followed by a rise along the relative radius r_x/r with a maximum in the range of r/r_{max} from 0.4 to 0.6. Then, the temperature is found to fall again. The temperature profile that is formed in a cylindrical mixing chamber with radial injection of plasma jets is uniform in the section 0.8 r_x/r and then starts to fall abruptly in the region very close to the wall.

Results of studies of variants of the schemes for mixing three plasma jets have shown that the structure of the plasma flow in the reactor can be controlled by changing the geometry of the mixing chamber, the means of injection of the plasma jets into it, and the characteristics of the design, and operation parameters of electric-arc plasma generators.

The same factors affect heat transfer of the plasma flows in the reactor channels. In Fig. 1 one can see the results of generalization of experimental data on heat transfer of a plasma air flow in three-jet mixing chambers of various types and in cylindrical reactor channels coaxial with the chambers. The following relations are obtained:

- for a cylindrical mixing chamber with radial injection of plasma jets

$$St = 10.7\, Re_x^{-0.86}\, Pr^{-0.67}\,, \tag{5}$$

- for a cylindrical mixing chamber with tangential injection of plasma jets

$$St = 15.55\, Re_x^{-1.04}\, Pr^{-0.67}\,, \tag{6}$$

- for conical mixing chamber with radial injection of plasma jets

$$St = 1.012\, Re_x^{-0.66}\, Pr^{-0.67}\,. \tag{7}$$

It should be noted that formula (7) generalizes the results of studies of heat transfer in reactors with mixing chambers in which the angle of injection of plasma jets is equal to 60°, 45°, and 30°.

For comparison, in Fig. 1 we also presented relation (2) for laminar flow of a high-temperature gas with constant physical properties

$$St = 0.332\, Re_x^{-0.5}\, Pr^{-0.67}\,.$$

Thus, it is evident that changes in the angle of injection of plasma jets into the mixing chamber and, accordingly, changes in the angular opening of the cone do not have a marked effect on heat transfer in the cylindrical channel itself. It is the case, in spite of the fact that, as was shown by spectral studies, the structure of plasma flows is different in the three cases compared. At an injection angle of 60°, the plasma flow is formed at

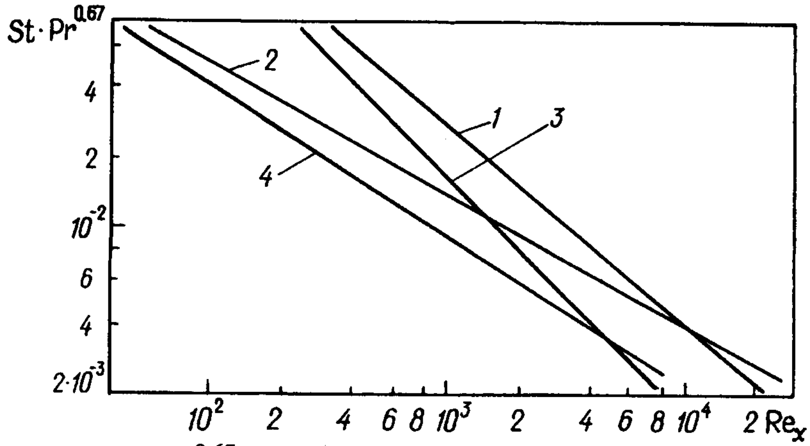

Fig. 1. Plot of $St \cdot Pr^{0.67}$ versus Re_x: 1) cylindrical mixing chamber with radial injection of plasma jets, 2) laminar flow in stabilized section, 3) cylindrical mixing chamber with tangential injection of plasma jets, 4) conical mixing chamber with radial injection of plasma jets.

the outlet of the mixing chamber, i.e., mixing is completed. At an injection angle of 30°, the flow consists of three joined jets, and mixing is completed only in length $x/D > 6.0$.

An increase in the power of the plasma flow to 600 kW, i.e., about a 5–6-fold increase, also does not have any significant effect on heat transfer, or, in any case, the results are within the experimental measurement error, whose relative error is ±30%.

The properties of the plasma-forming gas are more important. This can be explained by the great differences in the heat capacities and thermal conductivities of hydrogen and some hydrogen-containing gases from those properties of other gases in the temperature range 2000–4500 K [6]. This fact has a substantial effect on heat transfer between a high-temperature hydrogen jet and the wall of a cylindrical channel and, probably, on heat transfer of such hydrogen-containing gases as H_2S, H_2O, HCl, and NH_3, for which so far there are no results on heat transfer. In [6] heat transfer is taken into consideration by inclusion of the mean mass thermal conductivity of hydrogen and its thermal conductivity at the wall in dimensionless equations. A generalized relation is obtained in the form

$$St = 1.35 \cdot 10^3 \, Re^{-1.28} \, Pr^{-0.67} \, (\lambda_b/\lambda_w)^{-0.86} . \tag{8}$$

Summarizing the present analysis of the material on heat transfer of plasma jets and flows in the channels of reactor devices, it should noted that the information that characterizes these processes is rather complete, because of which they can be modeled quite reliably. However, there is little information on heat transfer in these channels with various lining materials and, accordingly, there are no results for the operation of reactors with various configurations, although, as a rule, these factors lead to increase in the heat utilization factor in the reactor facilities.

Another problem is interphase heat transfer between the plasma flow and particles of a disperse material or drops of a dispersed solution, and this heat transfer is one of the limiting factors that determine the efficiency of technological plasma processes.

Analysis of the available reported data on heat transfer between disperse particles and plasma jets and flows is contained in [1, 7, 8]. In most of the presented relations for interphase heat transfer, physical parameters are taken at the main flow temperature. Therefore, at substantial temperature gradients in the boundary layer of a particle, Nu_p can be lower than two. For the case of a plasma flow around single fixed particles in the starting length, where temperatures of the flow and particles differ greatly. Katta and Gauvin [7] have proposed a formula that includes changes in the thermophysical properties of the boundary layer.

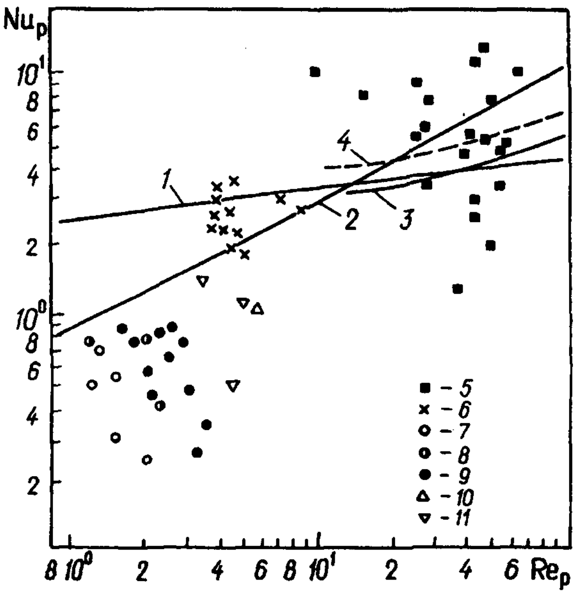

Fig. 2. Plot of Nu_p versus Re_p for heat transfer between gas flow and disperse particles: 1) $Nu_p = 2 + 0.6\, Re_p^{0.5} Pr^{0.33}$; 2) $Nu_p = 1.5\, Re_p^{0.5} Pr^{0.33}$, 3) $Nu_p = 2 + 0.6\, Re_p^{0.5}$, 4) $Nu_p = 2 + 0.4\, Re_p^{0.5}$; experimental data; 5) calcium carbonate (particle size is 90–630 μm), 6) neodymium oxalate (50 μm); 7-11) phosphorite (80, 110, 130, 175, and 200 μm).

$$Nu_p = 2\frac{\lambda_p}{\lambda_g} + 0.6\, Re^{0.5}\, Pr^{0.33} \left[\frac{\rho_g \mu_g}{\rho_w \mu_w}\right]^{0.2}, \tag{9}$$

Klubnikin et al. [8] obtained a similar relation

$$Nu_p = 2\frac{q d_p c_p}{\Delta H \lambda_g} = 2\frac{\lambda_p}{\lambda_g} + 0.5\, Re^{0.5}\, Pr^{0.4} \left[\frac{\rho_g \mu_g}{\rho_w \mu_w}\right]^{0.2}. \tag{10}$$

Subscripts g, p, and w mean that the physical parameters are taken at the temperatures of the gas, particle surface, and wall, respectively.

When a set of particles moves in a plasma flow, the conditions of heat transfer change, because the particles interact with themselves and with the wall of the channel, are polydisperse, and have a nonspherical surface, and also because the hydrodynamic conditions vary along the axis and in the cross-section of plasma flow. Moreover, heat transfer is affected by changes in the direction of motion of radially and axially fed particles, a nonuniform cross-section distribution of the particles, and changes in the compositions of the gas and condensed phases. In spite of all these, it can be suggested that there is analogy between heat transfer to a single fixed spherical particle and to a particle that moves in a dust-laden flow. In this connection, it can be suggested that dimensionless equations (9) and (10) can be used for description of the integral effect of interphase heat transfer in a dust-laden flow. Comparison of experimental results with the known dimensionless relations (Fig. 2) shows that for various materials (phosphorite, neodymium oxalate, and calcium carbonate) and plasma-forming gases (air and hydrogen), Nu and Re differ by 1.5–2 orders of magnitude. This scatter can be explained by differences in the properties and concentrations of the disperse materials and in the thermophysical properties of the plasma-forming gases.

Further processing of experimental data can be carried out by two methods [9, 1]. In one case where the mean mass temperature is used for calculation of thermal properties and it is taken into consideration that the thermal conductivities of some gases and mixtures (for example, hydrogen), change substantially in the temperature range studied, the ratio of thermal conductivities (gas–hydrogen) at the mean mass temperature of the gas in the measured section and at the temperature of the surface of the solid phase is used as a dimensionless number. The

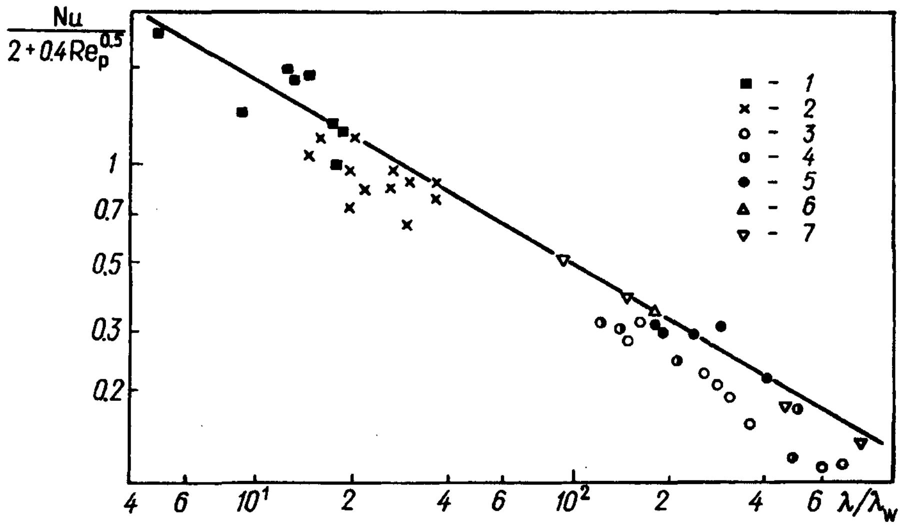

Fig. 3. Effect of ratio of thermal conductivities of gas at mean mass temperature and at surface temperature of solid phase on interphase heat transfer: 1) calcium carbonate, 2) neodymium oxalate, 3-7) phosphorite (particle size as in 7-11 in Fig. 2).

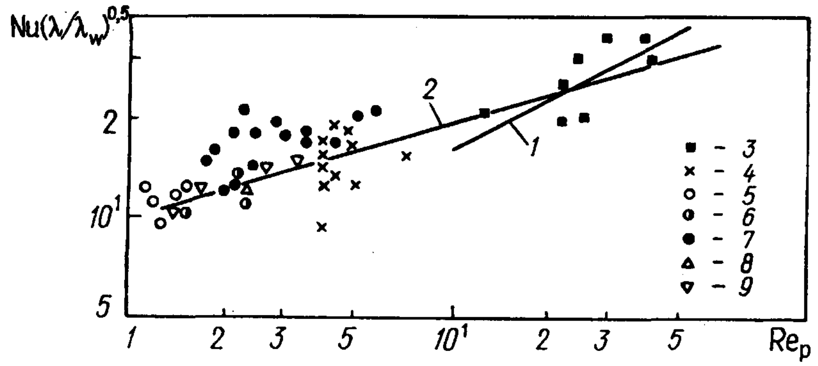

Fig. 4. Effect of Re_p on interphase heat transfer between plasma flow and disperse particles: 1) $Nu_p = [\lambda_w/\lambda]^{0.5}(2 + 5.2Re_p^{0.5}$, 2) $Nu_p = [\lambda_w/\lambda]^{0.5}(2 + 9.8Re_p^{0.5})$, 3) calcium carbonate, 4) neodymium oxalate, 5-9) phosphorite (particle size as in 7-11 in Fig. 2).

effect of the thermal conductivity ratio on heat transfer is shown in Fig. 3 under the condition that the characteristic temperature was calculated from the formula [9]

$$T = T_w + 0.19\,(T_g - T_w)\,. \tag{11}$$

With the effect of thermal conductivity in the boundary layer taken into consideration, the characteristic of heat transfer is shown in Fig. 4 and can be expressed by a dimensionless equation of the form

$$\mathrm{Nu} = \left[\frac{\lambda_w}{\lambda_g}\right]^{0.6} \cdot (2 + 9.8\,\mathrm{Re}_p^{0.5})\,. \tag{12}$$

As was shown in [9], in this case the exponent at Re coincides with the exponent at Re in the case of heat transfer between a fixed sphere and a plasma flow and the difference between the factors at the number Re_p is substantial, but partly compensated by the thermal conductivity ratio. Another procedure that can be used for processing of experimental data relates the Nusselt number Nu to the volume concentration of disperse particles in the plasma flow [1]

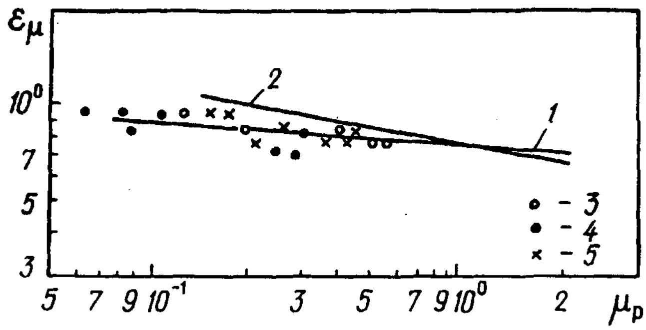

Fig. 5. Effect of concentration of disperse material (μ_p) on heat transfer of dust-laden plasma flow to chamber walls (coefficient ε_μ) at $D = 0.1$ m, $d_p = 0.05$–0.08 mm: 1) $\varepsilon_\mu = 0.81\mu_p^{-0.02}$ for conical chamber, 2) $\varepsilon_\mu = 0.7\mu_p^{-0.08}$ for cylindrical mixing chamber with radial injections of jets, 4) phosphorite in cylindrical chamber with tangential injection, 5) calcium carbonate in cylindrical chamber with radial injection.

$$\beta = \frac{G_p}{G_g} \frac{\rho_g}{\rho_p} \frac{\nu_g}{\nu_p} \frac{D^2}{d_p^2}. \tag{13}$$

In this case for calculation of intercomponent heat transfer of a set of particles that move in a plasma flow, the formula is suggested

$$\mathrm{Nu} = 2\frac{\lambda_s}{\lambda_g} + 0.78\,\mathrm{Re}_p^{0.5}\,\mathrm{Pr}^{0.33}\left[\frac{\rho_g \mu_g}{\rho_s \mu_s}\right]^{0.2} \varepsilon_\beta, \tag{14}$$

where ε_β is a correction for the effect of the volume concentration. At $\beta < 4\cdot 10^{-4}$, $\varepsilon_\beta = 1$ and at $\beta > 4\cdot 10^{-4}$, the correction is estimated from the expression

$$\varepsilon_\beta = 7.82\cdot 10^{-8}\beta^{-2.1}. \tag{15}$$

In Fig. 5 one can see the curve $\varepsilon_\mu = \mathrm{Nu}/\mathrm{Nu}_0 = f(\beta)$, in which new data on heat transfer of neodymium oxalate particles are presented. The same experimental data processed in [10] allowed those authors to express the effect of the dependence of the relative flow mass concentration on the heat flux from the plasma to the walls of mixing chambers of various types in the form $\varepsilon_\mu = f(\mu_\beta)$. Here ε_μ is the ratio of the heat fluxes to the walls of a mixing chamber with disperse material fed into a plasma jet and without it.

In the range of relative mass concentrations of the raw material between 0.8 and 2.8 kg/kg, experimental data are approximated by the relations:

- for a cylindrical mixing chamber with radial and tangential injections of jets

$$\varepsilon_\mu = 0.75\mu_p^{-0.08}, \tag{16}$$

- and for a conical mixing chamber with radial injection of jets

$$\varepsilon_\mu = 0.81\mu_p^{-0.02}. \tag{17}$$

Analysis of the present relations shows that in a cylindrical mixing chamber the effect of the material concentration on heat transfer between the material and the wall is more important than in a conical chamber. Meanwhile, the type of injection of plasma jets into a cylindrical mixing chamber does not have a significant effect on heat transfer of a dust-laden plasma flow, which can be explained by the fact that the structure of the boundary layer that is formed in mixing of stabilized (tangentially swirled) gas-jet in plasma generators is similar in both cases [1].

Experimental data on interphase heat transfer are generalized by the dimensionless relation suggested in [10]

$$\mathrm{Nu} = 2\frac{\lambda_s}{\lambda_g} + 0.78\,\mathrm{Re}_p^{0.5}\,\mathrm{Pr}^{0.33}\left[\frac{\rho_g \mu_g}{\rho_s \mu_s}\right]^{0.2} \varepsilon_\beta\,\varepsilon_\mu\,, \tag{18}$$

Thus, it is confirmed that formula (14) can be used for calculation of interphase heat transfer between disperse particles and a plasma flow that is formed in a three-jet mixing chamber.

Relations (14)-(18) are used for calculation of the modes of treatment of disperse materials in plasma reactors with the various types of mixing chambers and for modeling high-power plasma reactors.

In conclusion it should be noted that different available publications use almost similar approaches to estimation of interphase heat transfer between plasma flows and disperse particles. However, we think that the number of experimental data, especially on heat transfer with account of chemical conversions, is still insufficient for higher statistical significance of the present dimensionless relations. Unfortunately, this problem does not attract adequate attention of researchers in plasma technology.

NOTATION

x, distance along length of reactor channel; r, D, radius and diameter of reactor channel; d_p, particle diameter; G_g, gas flow rate; G_p, disperse material flow rate; v_g, velocity of plasma jet; v_p, particle velocity; T, temperature; Re, Pr, Nu, St, Reynolds, Prandtl, Nusselt, and Stanton numbers, respectively; λ_g, λ_b, λ_w, thermal conductivity of the plasma-forming gas flow based on mean mass temperature, on temperature in initial cross-section, and on temperature of the reactor wall, respectively; λ_p, thermal conductivity of particle; c_p, ρ_p, heat capacity and density of particle, respectively; ρ_g, ρ_w, flux density of plasma-forming at mean mass temperature and wall temperature, respectively; μ_g, μ_w, viscosity of plasma-forming gas at mean mass temperature and wall temperature, respectively; q, density of heat flux to particles; ΔH, difference of enthalpies of plasma flow and particle; β, volume concentration of particles; ε_β, correction for effect of volume concentration; ε_μ, ratio of heat fluxes into reactor wall with and without disperse material; ρ_s, density of plasma-forming gas flow at temperature of particle surface; μ_s, viscosity of plasma-forming gas flow at temperature of particle surface. Subscripts: g, p, w, x, s, refer to plasma-forming gas, particle, wall of reactor channel, instantaneous coordinate along reactor axis, and particle surface, respectively; β, refers to initial cross-section of flow.

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