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:

\[ St = 0.446 \text{Re}^{-0.53} \text{Pr}^{-0.67} \]  

(1)

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

\[ St = 0.332 \text{Re}_x^{-0.5} \text{Pr}^{-0.67} , \]

(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 \( x/D < 6-8 \):

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 $r/r_{\text{max}}$ 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 $60^\circ$, $45^\circ$, and $30^\circ$.

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

$$St = 0.332 Re_x^{-0.5} Pr^{-0.67}. \tag{2}$$

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 $60^\circ$, the plasma flow is formed at