HEAT EXCHANGE IN A PLASMOCHEMICAL REACTOR

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Some aspects of heat exchange in a plasmochemical reactor are discussed. A criterional equation is obtained based on the results of experimental studies of heat exchange in a reactor.

Modern constructions of plasmotrons of different types make it possible to obtain for extended times steady plasma jets of various gases, where the temperature of the plasma jet and its enthalpy potential as a function of kind of stabilizing carrier gas and the thermal efficiency of the plasmotron can reach very high values.

The problem of the most effective use of the energy of the plasma jet in a plasmochemical reactor evidently consists in the selection of the most efficient system of mixing the raw material with the heat carrier and in the conditions of heat exchange with the walls. Unfortunately, there is at present no acceptable method of calculating the main parameters of the reactor. Problems concerning the process of introducing raw materials into the reactor, the shape and volume of the reactor, the sizes and location of openings for introducing raw materials etc., are examined experimentally in [1, 2]. However, these problems are solved individually for each concrete process (mainly for the synthesis of acetylene from methane) and independent of the processes of heat exchange in the reactor.

The most widely distributed plasmochemical reactors, for both laboratory and experimental–industrial purposes, are continuous flow reactors of ideal displacement for homogeneous systems. The principal difference in their construction from the usual chemical reactors of similar type lies in the use of forced cooling of the reactor walls necessitated by the very high temperatures introduced into the reactor by the plasma jet.

The problem can be simulated analytically by an examination of convective heat exchange in a pipe under conditions of variation in the chemical properties of the medium, which change under the influence of the temperature field that forms as a result of heat exchange between the cooled surface and the plasma stream.

The following system of differential equations [3] is used to obtain and analyze the corresponding criteria, taking into account the variation in the physical properties involved and the functions determining the dependence of these properties on temperature:

$$
\begin{gathered}
\operatorname{div}(\lambda \operatorname{grad} t) = cg\rho \frac{Dt}{d\tau}, \\
2\operatorname{div}(\mu\dot{S}) - \operatorname{grad}\left(p + \frac{2}{3}\mu \operatorname{div}\vec{w}\right) = \rho\frac{D\vec{w}}{d\tau}, \\
\frac{\partial\rho}{\partial\tau} + \operatorname{div}(\rho\vec{w}) = 0, \\
\lambda = \lambda(t);\ \mu = \mu(t);\ c = c(t);\ \rho = \rho(t).
\end{gathered}
\tag{1}
$$

After selection of the scales of the linear dimensions, temperatures, velocities, and corresponding physical properties the system of equations (1) can be reduced to a dimensionless form, from which are derived the principal criteria Nu, Pr, and Re related through the heat content to the temperature of the jet. Assuming further that the relative changes in physical properties are sufficiently well defined, then for a

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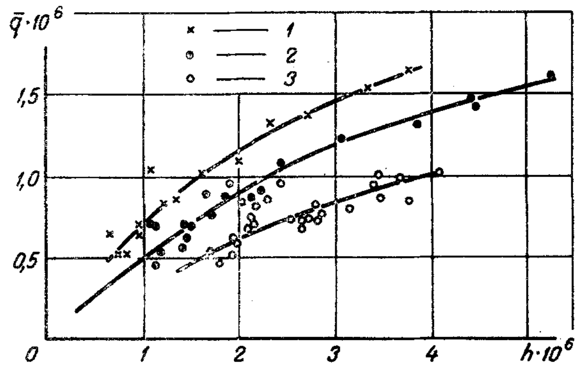

Fig. 1. Dependence of mean specific heat fluxes on the average mass enthalpy of the nitrogen plasma jet at different degrees of expansion of the channel f_0: 1) $f_0 = 0.267$; 2) 0.4; 3) 0.5.

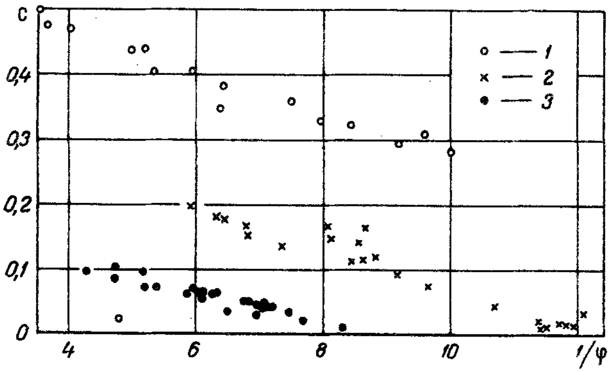

Fig. 2. Dependence of $C = Nu/Re^{0.8}Pr^{0.4}$ on the temperature factor $1/\varphi$ for different degrees of channel expansion f_0: 1) $f_0 = 0.267$; 2) 0.4; 3) 0.5.

strongly nonisothermal gas jet such as the medium in a plasmochemical reactor we obtain from [3] with sufficient approximation for the relative change in absolute temperature

$$Nu = \Phi(Pr;\ Re;\ X;\ \varphi),$$

where $X \equiv x/R_0$ and $\varphi = T_{wl}/T$ is the temperature factor.

Heat exchange from a nitrogen plasma jet to the water-cooled walls of a cylindrical reactor channel with abrupt expansion in a section of nonstabilized flow was studied experimentally.

In the range studied the nitrogen flow rate at the stabilization arc in the plasmotron varied from 0.5 to 2.5 g/sec, the electric power from 3 to 50 kW with variation in the current from 45 to 230 A, which made it possible to obtain average-mass temperatures at the reactor outlet of from 2000 to 6500°K.

A change in the density and viscosity of the plasma jet affects the conditions of its expansion in emerging from the plasmotron nozzle into the reactor. Therefore in addition to the parameters given above the change in efficiency of heat exchange with the reactor walls as a function of the degree of expansion of the jet $f_0 = d/D = F_0/F$ was studied, where d is the diameter of the plasmotron nozzle and D is the reactor diameter. In the experiments the flux of heat to the cooling walls of the reactor was determined in a stationary state, the onset of which was determined with differential thermocouples based on the establishment of a constant cooling water temperature for the given system. The treatment of the experimental data was based on the assumption of a one-dimensional flow model. The specific heat flux at the inner surface of the pipe, averaged over the length of the reactor, was determined from the formula

$$q = c_r G \Delta t / \pi d l. \tag{2}$$

The power carried into the reactor by the plasma jet was calculated from the enthalpy and flow rate of the plasma-generating gas in the absence of the addition of raw material gas to the reactor, or from the enthalpy and flow rate of the mixture of plasma-generating gas and raw material gas supplied at the reactor entrance

$$Q_{in} = 4,\ 18 h_{mx(g)} G_{mx(g)} \tag{3}$$

and the enthalpy of the gas emerging from the reactor

$$h_{out} = 0.239 Q_{eff.\,r} / G_{mx(g)}. \tag{3'}$$

For a more precise calculation of the temperature and enthalpy of the mixture at the reactor input nitrogen was also used as the raw material gas supplied to the reactor at the plane of the plasmotron nozzle.

The average temperature in the reactor $\bar{T}_r$ was determined as the logarithmic mean between the value of the average-mass temperature or the mixture temperature for only the stabilizing gas or for the mixture, respectively, and the value of the temperature of the gases emerging from the reactor: $T_{out} = f(h_{out})$ [6]. Because of the low thermal resistance of the walls of the copper chamber the temperature of the inner surface of the reactor was taken as equal to the temperature of the cooling water. Hence the effective value

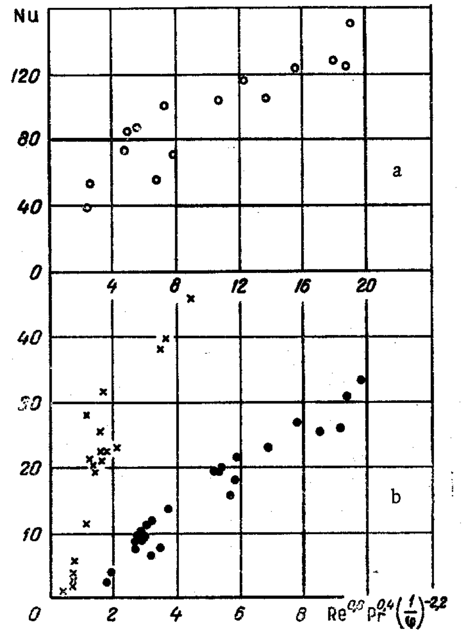

Fig. 3. Results of experimental study of heat exchange as a function of generalized criterional characteristics of flow for different degrees of expansion f_0: a) $f_0 = 0.267$; b) $f_0 = 0.4$ and 0.5 (notation corresponds to Fig. 2).

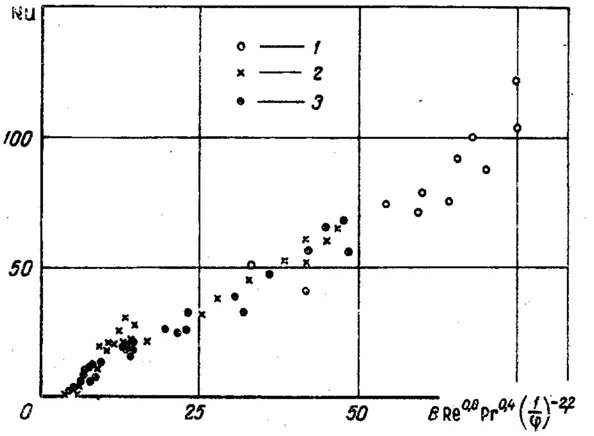

Fig. 4. Generalized heat-exchange characteristic at wall of cooled cylindrical reactor for different values of f_0 (notation corresponds to Fig. 2).

of the coefficient of heat exchange $\bar{\alpha} = \bar{q}/(T_r - T_w)$, where $\bar{q}$ is the average specific heat flux.

All the thermophysical characteristics, the density ρ_g, dynamic viscosity μ_g and heat conduction λ_g, and the changes in volume V_g and velocity W_g are related to the average reactor temperature $\bar{T}_r$ [4-6].

The dependence of the effective mean specific heat fluxes to the reactor walls $\bar{q}$ on the average-mass enthalpy h of the nitrogen plasma jet is presented in Fig. 1. It is evident that the specific heat flux $\bar{q}$ grows with an increase in h, while it also grows with a decrease in the degree of expansion of the jet f_0.

The experimental data were correlated using the criterional equation [3] for developed turbulent flow

$$Nu = C\,Re^{0.8}\,Pr^{0.4}. \tag{4}$$

It was established that, in the region of unstable flow, with the sudden expansion of the channel, the coefficient of heat exchange upon mixing of the plasma and cold jets in the plane of expansion, without taking into account the sources or sinks of energy in chemical conversions, essentially depends on the temperature factor $\varphi = T_W/T$ with variation of the latter from 0.05 to 0.5 (Fig. 2) and in the range of the parameters studied can be determined using the empirical equation

$$Nu = B\,Re^{0.8}\,Pr^{0.4}\,(1/\varphi)^{-2.2}. \tag{5}$$

The results of the experiment treated according to Eq. (5) in the form of the function Nu = f(Re, Pr, φ) for different degrees of channel expansion f_0 are presented in Fig. 3, where the coefficient B evidently characterizes the dependence of the coefficient of heat exchange on the degree of channel expansion. The increase in the coefficient of heat exchange with a decrease in f_0 is clearly seen.

A sufficiently good correlation of the experimental data obtained in the experiments on the heat exchange of a nitrogen plasma jet in a reactor, taking into account the degree of expansion f_0, was obtained after treatment of the results according to Eq. (5), where $B = 3.0 f_0 - 2.5$. The results of the correlation are presented in Fig. 4.

Thus, the dependence obtained in the region of Re numbers from 500 to 2000 is approximated well by an expression of the type (5) taking into account the degree of channel expansion f_0, allowing the heat-exchange coefficients to be determined from the hydrodynamic and thermophysical parameters of the plasma jet for any geometrical dimensions of the plasmotron nozzle and reactor channel (within the limits of the investigated region, L/D = 3-15).

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