We substitute for D and ν taken at the mean temperature of the diffusion boundary layer [7] into (1) to get the best agreement with exact calculations (Fig. 4). However, (1) then loses its asymptotic significance and thus the original physical significance. Therefore, that substitution may be considered only as a procedure for empirically correcting (1) that does not reflect physical regularities in mass transfer under nonisothermal conditions.

NOTATION

A and a, coefficients in (8); c, reagent concentration; $\bar{c} = c/c_\infty$; c_p, specific heat of liquid; D, diffusion coefficient; $\bar{D} = D/D_0$, f, g, h, dimensionless hydrodynamic functions from (5); j, reagent mass flux density; K, mass-transfer coefficient; L, linear scale; p, pressure; Pr, Prandtl number; Sc, Schmidt number; T and t, temperature; U, velocity scale, $\mathbf{u} = \mathbf{v}/U$; $\mathbf{v}$, velocity vector; x, y, z, cartesian coordinates; ξ, η, ζ, dimensionless cartesian coordinates; θ, dimensionless temperature; Θ, temperature scale; λ, thermal conductivity; μ, viscosity; ν, kinematic viscosity; $\bar{\nu} = \nu/\nu_0$; ρ, density; ω, angular velocity. Subscripts: w, values at the wall (disk surface), ∞, values deep in the liquid, and 0 to values at the standard temperature T_0.

LITERATURE CITED

1. W. M. Keys, Convective Heat and Mass Transfer [Russian translation], Moscow (1972).
2. Yu. V. Pleskov and V. Yu. Filinovskii, Rotating Disk Electrodes [in Russian], Moscow (1972).
3. J. Batchelor, Introduction to Liquid Dynamics [Russian translation], Moscow (1973).
4. V. G. Levich, Physicochemical Hydrodynamics [in Russian], Moscow (1959).
5. D. P. Gregory and A. C. Riddiford, J. Chem. Soc., 52, 3756-3764 (1956).
6. D. T. Porter, M. Donimirska, and R. Wall, Corr. Sci., 8, 833-843 (1968).
7. V. S. Pakhomov, A. G. Parshin, and Ya. M. Kolotyrkin, Élektrokhimiya, 18, No. 2, 176-184 (1982).
8. V. G. Levich, V. S. Markin, and Yu. G. Chirkov, Élektrokhimiya, 1, No. 12, 1416-1421 (1965).
9. R. Bird, W. Stuart, and E. Lightfoot, Transport Phenomena [Russian translation], Moscow (1974).
10. D. Perry, Chemical Engineer's Handbook [Russian translation], Leningrad (1969).

HEAT TRANSFER IN A PLASMOCHEMICAL REACTOR

M. V. Lyakin, A. L. Suris, and V. M. Postnikov

UDC 536.24

An empirical method is proposed for calculating heat transfer in the channel in a plasmochemical reactor when the reagents are input via a system of holes in the wall.

There is an extensive class of plasmochemical reactors in which the raw material is introduced via a system of holes in the cylindrical wall (Fig. 1). The heat transfer then occurs in an unstabilized flow section and is complicated by the jet mixing, the reaction, the recirculation in the mixing chamber, and the considerable temperature differences.

Measurements have been made on heat transfer here [1] for various geometrical and other parameters and in the presence of exothermic reactions. The quantities characterizing the heat transfer are: the Stanton number St, Reynolds number Re for a plasma flow, ratio between the flow rates of the energy carrier M_1 and the raw material M_2, the ratio of the enthalpy H_1 in the plasma jet reckoned from 0 K to the enthalpy in the products at the wall temperature H_w, the ratio of the length of the heat-transfer section ℓ to the channel diameter d_p, and the ratio of the total area of the holes f_2 for the raw material to the area f_1 of the reaction channel. One corrects for the reaction heat as regards the transfer via the observed relationship by means of the energy criterion proposed by Suris and Shorin [2, 3]:

Moscow Chemical Engineering Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 1, pp. 71-74, January, 1989. Original article submitted August 3, 1987.

TABLE 1. Values of Coefficients in (1)

Coefficients	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
On the assumption that H_w is the enthalpy of the products at the wall temperature	0,212	−0,496	−0,039	−0,011	0,068	2,008	−2,777	−1,484	1,182
On the assumption that H_w is the enthalpy of the plasma flow at the wall temperature	1,754	−0,739	−0,102	−0,002	0,007	0,479	−1,406	−1,753	0,940

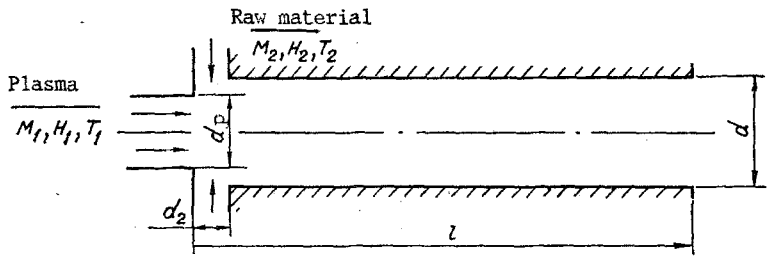

Fig. 1. The reactor.

of the reaction channel. One corrects for the reaction heat as regards the transfer via the observed relationship by means of the energy criterion proposed by Suris and Shorin [2, 3]:

$$K_{en} = \frac{N}{M_2 Q_{ch}},$$

where N is the power represented by the plasma flow and the heated reagents, while Q_{ch} is the heat from the complete conversion of the raw material to products at the standard temperature (positive for exothermic). A disadvantage of the [1] relation is that it was derived for narrow ranges in M_2/M_1 (0 − 3) and H_1/H_w (15 − 45).

There are however various plasmochemical processes in which M_2/M_1 can exceed ten, e.g., on injecting a chloride stream into a hydrogen or nitrogen plasma, and also, it is common to use a reactor with a lined channel, which reduces the enthalpy factor. We have therefore made measurements on the transfer in a reactor providing for reagent input as transverse jets entering via holes in the cylindrical wall; which has been used over a wide range in the parameters.

Figure 2 shows the apparatus. We used a dc plasmotron with self-adjusting arc length. The gas was helium, with the mixing gas argon or air. We corrected for the reaction heat as affecting the heat transfer on the basis that the data were processed with the incorporation of the [1] results, in which the transfer occurred with exothermic reactions (methane burning in an air plasma) and with endothermic ones ($CH_4 + CO_2 \rightarrow CO + H_2$). The study was designed to give a method of calculating the transfer in the mixing chamber applicable to a parameter range wider than that in [1].

The heat transfer in the channel was examined by calorimetry on the water-cooled sections; the diameters and lengths were varied, as was M_1 (the plasma gas flow rate) and the flow of gas for mixing, in addition to the jet power. The calorimetry on the latter section of the reaction channel was not incorporated in the processing because there are uncontrolled axial heat leaks through the flange there. The data were fitted by computer by means of a standard stepwise regression program in accordance with

$$\mathrm{St} \equiv \frac{Qd/(4l)}{N + N_{ch} - N_w} = a_0 \mathrm{Re}^m (1+\varphi)^p \left(1 + \frac{M_2}{M_1}\right)^r \times \left(1 + \frac{d}{d_p}\right)^k \left(1 + \frac{f_2}{f_1}\right)^y \psi^t \left(\frac{H_1}{H_w}\right)^s, \qquad (1)$$

in which

$$m = a_1 + a_2\varphi + a_3\frac{M_2}{M_1} + 0{,}050\frac{N}{N_p} - 0{,}040\frac{d}{d_p} - 0{,}670\frac{f_2}{f_1},\quad p =$$
$$= 10{,}800 + a_4\frac{M_2}{M_1} - 1{,}300\psi + 2{,}500\frac{d}{d_p} + 200\frac{f_2}{f_1},\qquad r = a_5 + a_6\varphi -$$
$$- 0{,}300\psi,\quad y = 6{,}800 - 185\varphi - 2{,}400\frac{d}{d_p},\qquad k = -5{,}400\varphi + 2{,}600,\quad s =$$
$$= a_7 + a_8\varphi - 0{,}140\frac{d}{d_p},\ t = 0{,}350 + 4{,}200\varphi \text{ for } \varphi = \frac{1}{1 + l/d};\ \psi = \frac{1}{1 + 1/K_{en}};$$

Q is the heat flux to the wall and N_w the thermal power in the flow at the wall temperature.

The reaction heat was derived from

$$N_{ch} = M_2 Q_{ch}\,\gamma_c, \tag{2}$$

in which γ_c is the degree of raw material conversion under equilibrium conditions corresponding to known K_{en}.

As it is often difficult to calculate H_w (the product enthalpy at the wall temperature), we derived an empirical relationship analogous to (1) on the assumption that H_w is the enthalpy of the plasma flow at the wall temperature. Table 1 gives values of a_0-a_8 here.

The curves describe the measurements with ±15% error for the following ranges: Re = 350-5500; M_2/M_1 = 0-37; l/d = 2-20; d/d_p = 1-3.33; H_1/H_w = 4-80(3.5-10)*, where the * is on the assumption that H_w is the enthalpy of the plasma flow at the wall temperature.

Figure 3 compares values of the Stanton number calculated from (1) and by the [1] method with the measured values for l/d = 3.3 with M_2/M_1 = 0-37, H_1/H_w = 4-80. The [1] method gives

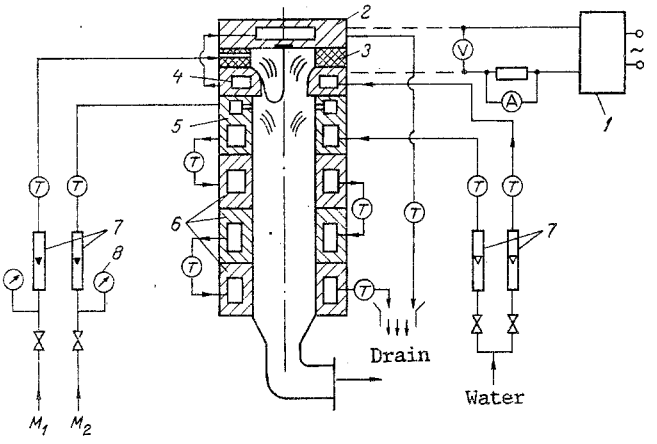

Fig. 2. The apparatus: 1) dc source; 2) cathode; 3) vortex chamber; 4) anode; 5) mixing chamber; 6) calorimetric section; 7) rotameters; 8) pressure gauges; T differential thermocouples.

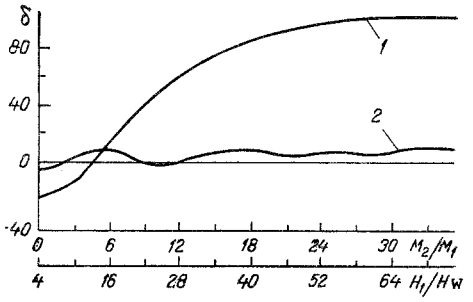

Fig. 3. Theoretical and observed values for St with l/d = 3.3; 1) $\delta = (1 - St'/St_{exp}) \times 100\%$; 2) $\delta = (1 - St/St_{exp}) \times 100\%$; St' calculated by the method given in [1]; St calculated from (1); St_{exp} being the experimental value.

good agreement with experiment only in a narrow range in M_2/M_1 set by the region used. As M_2/M_1 increases, so does the discrepancy, which attains about 100% for $M_2/M_1 = 37$ (curve 1). From (1), one can obtain satisfactory agreement between the measurements and calculations on the Stanton number over a wide range in the mass ratio (curve 2).

LITERATURE CITED

1. L. S. Aslanyan, A. L. Suris, and S. N. Shorin, Khim. Mashinostr., Vol. 1, 42-45 (1974).
2. A. L. Suris and S. N. Shorin, Khim. Vys. Énerg., 5, No. 3, 204-210 (1971).
3. A. L. Suris, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk., Issue 3, No. 13, 61-66 (1977).

METHOD FOR DETERMINING THE GAS–DYNAMIC CHARACTERISTICS OF A NONEQUILIBRIUM HYPERSONIC FLOW OF NITROGEN BASED ON EXPERIMENTAL DATA ON THE STAGNATION PARAMETERS

V. N. Komarov and O. Yu. Polyanskii

UDC 533.6.011.55

A method is developed for determining the pressure, temperature, density, velocity head, Mach number, and other gas–dynamic parameters of a nonequilibrium flow of nitrogen in a hypersonic nozzle. The method is based on experimental data on the stagnation parameters T_0, p_0, and p_0' and the gas–kinetic model adopted for nitrogen.

1. A method for determining the gas–dynamic quantities in the working part of gas–dynamic setups (GSs), based on the experimental data on the stagnation parameters of the gas T_0, p_0, and p'_0, as well as the known thermodynamic model of the given working gas, has been theoretically substantiated and is widely employed for operating regimes of GSs, in which the behavior of the working gases corresponds to the behavior of a perfect or equilibrium gas [1-5].

Thus, the gas–dynamic characteristics for the case of a perfect gas are determined from the relations [1]

$$\frac{p_0'}{p_0} = \left[\frac{(\gamma+1)M^2}{2+(\gamma-1)M^2}\right]^{\frac{\gamma}{\gamma-1}} \left(\frac{\gamma+1}{2\gamma M^2-(\gamma-1)}\right)^{\frac{1}{\gamma-1}},$$

$$\frac{q}{p_0'} = \frac{\gamma}{\gamma+1}\left[\frac{4\gamma}{(\gamma+1)^2}\right]^{\frac{1}{\gamma-1}} \left(1-\frac{\gamma-1}{2\gamma M^2}\right)^{\frac{1}{\gamma-1}}, \quad q=\frac{\rho u^2}{2}, \tag{1}$$

$$\frac{T}{T_0} = \left(1+\frac{\gamma-1}{2}M^2\right)^{-1}, \quad \frac{p}{p_0} = \left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma}{\gamma-1}}.$$

In the case of an equilibrium gas the method developed in [1-5] also permits finding quite simply the gas–dynamic characteristics, using some tabulated functions that depend on T_0, p_0, M, and the composition of the gas.

In reality, in high-enthalpy GSs the gas flow is a nonequilibrium flow. The gas–dynamic characteristics are not only functions of p_0, T_0, M, and γ, but they also depend on the shape and dimensions of the nozzle and on the kinetic model and composition of the gas.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 1, pp. 74-80, January, 1989. Original article submitted June 3, 1987.

0022-0841/89/5601-0058 $12.50