HEAT EXCHANGE IN A PLASMA CHEMICAL REACTOR WITH MULTIJET
MIXING CHAMBER

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The article presents the results of the investigation of the heat exchange in a
multijet plasma chemical reactor in dependence on the hydrodynamic conditions and
design dimensions of the conical mixing chamber.

The most widely used reactors in plasma chemical technology are reactors with a multijet mixing chamber. This is so because of the axisymmetric feed of the raw material, the simplicity of varying the performance of the reactor, of changing the number and unit power of plasmotrons connected to the mixing chamber. The almost uniform temperature profile in the reactor channel at the initial sections makes it possible to solve relatively simple problems of predicting processes of conversion.

A comparison of the thermal characteristics [1] of different mixing chambers confirms the substantial influence of the reactor geometry on heat exchange and the lower heat losses from the plasma stream through the channel walls when a conical mixing chamber is used. However, the presented results do not make it possible to carry out quantitative evaluations of the influence of the shape of the reactor on heat exchange. In this connection it is important to study the dependences of the thermal fluxes to the channel walls on the design dimensions of the mixing chamber and on the operating regimes of the reactor; this will make it possible to choose the optimum design of the mixing chamber and operating regime of the reactor.

The experiments were carried out with a plasma chemical reactor (Fig. 1) consisting of the conical mixing chamber and a cylindrical water-cooled channel assembled from separate sections 0.07 to 0.19 m long. To reduce the mutual thermal influence between sections, asbestos interlayers $(1-2) \cdot 10^{-3}$ m thick were inserted. All the elements of the plasma chemical reactor were made of stainless steel, and the channel wall was $2.5 \cdot 10^{-3}$ m thick. Electric arc plasmotrons with eddy stabilization of the arc with an overall power of up to 50 kW were arranged 120° apart over the lateral surface of the mixing chamber. We used chambers
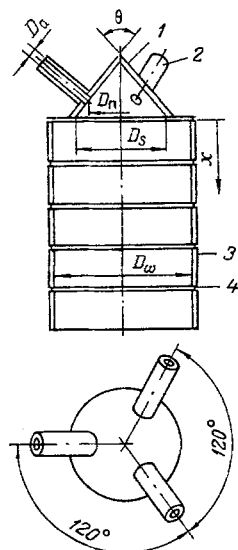

Fig. 1. Diagram of a three-jet plasma chemical reactor: 1) mixing chamber; 2) plasmotron; 3) channel section; 4) heat insulating interlayer.

TABLE 1. Values of the Criteria and Simplexes in the Experiments

Variable	Mean	Min.	Max.
St	0.076	0.0057	0.19
H/H_{298}	7.1	2.6	15
Re	1450	610	2800
Pr	0.67	0.53	0.73
St_x	0.071	0.028	0.30
$1/(1+\theta)$	0.40	0.32	0.49
D_s/D_w	0.84	0.70	1
D_p/D_s	0.62	0.37	0.80
$1/(1+x/D_w)$	0.34	0.15	1
Re_0	900	580	1380
Pr_0	0.55	0.53	0.57
H_0/H_{298}	15	12	18

with different diameters of the base D_s, different angles at the apex of the cone θ, and different diameters D_p on which the plasmotrons were arranged. The air flow rate was determined from the pressure gradient on the diaphragm measured by a reference manometer. The flow of cooling water in the elements of the plasmotrons, the mixing chamber, and in the channel section was measured by rotameters. For determining the water temperature we used thermocouples group KhK whose indications were registered by a multipoint electronic potentiometer. We envisaged the possibility of checking the thermocouple indications with a scale division of 0.1°K. The overall error of calorimetering did not exceed ±15%.

The mean mass temperature of the heat transfer agent was calculated from the thermal balance. An approximate calculation of the wall temperature showed that with temperature heads of about 2000°K it may be taken equal to the temperature of the cooling water, which is in agreement with the data of [2]. The thermal flux was found by measuring the flow rate and the temperature of the cooling water. The initial data were generalized in the form of simplexes: D_s/D_w, D_a/D_s, and D_p/D_s, i.e., the relative diameters of the mixing chamber, of the anode channel and of the mixing chamber at the place of inlet of the plasma jet, respectively; $1/(1 + \theta)$, i.e., the angle at the apex of the mixing chamber, $1/(1 + x/D_w)$, i.e., the relative channel length, H/H_{298}, i.e., the enthalpy factor. In the equation of local heat exchange the Reynolds and Prandtl numbers were determined in each section according to the channel diameter at the mean arithmetic temperature of the gas stream at the inlet and outlet. In this case the Stanton number characterizes the local heat transfer. In the equation of zonal heat exchange the numbers Re_0 and Pr_0 were calculated at the mean mass temperature of the plasma at the edge of the anode channels, and the number St_x was referred to the overall heat loss by the plasma stream in the mixing chamber and in a channel section of length x. The region of the experimental data is shown in Table 1.

There is an exceedingly large number of expressions of criterial dependences of heat transfer, and in the general case the best form cannot be chosen a priori. This is so, firstly, because it is impossible to obtain an analytical solution of the problem of heat transfer in a plasma chemical reactor with a multijet mixing chamber, and secondly it has to do with the influence of the applied criteria and simplexes on the form of the approximating expression. In the present work we used an exponential dependence in which the exponent is a linear function of the independent criteria and simplexes. This form of equation was chosen because it is conveniently linearized relative to the unknown coefficients. To solve the stated problem, we used the known method of Doolittle [3], i.e., stepwise multiple regression, which makes it possible to include successively in the equation the terms exerting the greatest influence on the dependent variable. As a result we obtain a sequence of regression equations with an increasing number of terms characterized by a decreasing standard error of the evaluation.

The expression for the zonal Stanton criterion obtained on a computer has the form

$$St_x = 0.096 \left(\frac{1}{1+\theta}\right)^{0.000084 Re_0 - \frac{0.25}{1+x/D_w}} \left(\frac{D_s}{D_w}\right)^{-\frac{3.9}{1+x/D_w}} \left(\frac{D_p}{D_s}\right)^{\frac{0.3}{1+x/D_w}} \left(\frac{D_a}{D_s}\right)^{\frac{0.26}{1+x/D_w}} Pr^{4.5-6\frac{D_s}{D_w}} \left(\frac{1}{1+x/D_w}\right)^{1.7\frac{D_s}{D_w}-0.76}. \tag{1}$$

The standard error of the evaluation is equal to 6% with a correlation coefficient 0.964. When the simplexes D_s/D_w and D_p/D_s are increased and D_a/D_s is decreased, heat transfer is reduced. With increasing angle θ the plasma jets become of a more confused nature, the turbulence of the flow in the mixing chamber and in the channel decreases, and the intensity of heat transfer decreases. However, when the lengths are great, the effect of the shape of
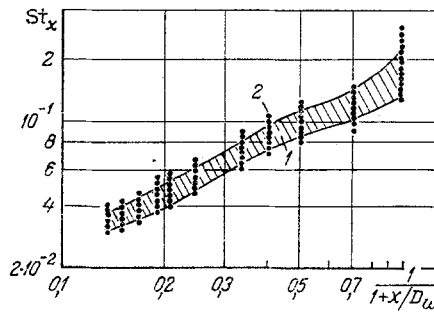
Fig. 2   Fig. 3

Fig. 2. Dependence of the zonal Stanton criterion of a
plasma chemical reactor on the relative channel length: 1)
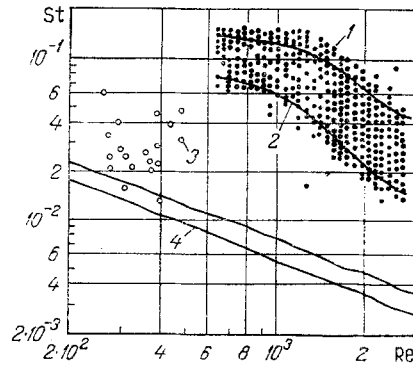range of calculated values; 2) experimental data.

Fig. 3. Dependence of the local Stanton criterion on the
hydrodynamic flow regime: 1) experimental value; 2) range
of the calculated values; 3) data of [3]; 4) calculation by
the equation $Nu = 0.15 Re^{0.33} Pr^{0.43} Gr^{0.1} (Pr/Pr_w)^{0.25}$ [4].

the mixing chamber becomes less palpable. It can be seen from Fig. 2 that the range of the
experimental data is satisfactorily described in Eq. (1). Local heat transfer in the reac-
tor channel is described by the relation

$$St = 0.0041 Re^{-0.16 + \frac{0.067H}{H_{298}}} Pr^{0.68-0.006Re} \left(\frac{H}{H_{298}} \right)^{2.9Pr - 0.0017Re} \qquad (2)$$

Here the standard error of the evaluation is equal to 17%, and the correlation coefficient
is 0.685. The larger standard error in this case is due to the fact that the equation gener-
alizes the results for all mixing chambers but does not take into account the differences in
chambers that manifest themselves particularly strongly at the initial section of the chan-
nel. To calculate St by the criterial equation $Nu(Re, Pr, Gr, \ldots)$, presented in [4] for
laminar flow, we used the known identity $St = Nu/(RePr)$. It can be seen that for the same
Reynolds numbers, heat transfer with steady flow and with flow at the initial channel sec-
tion differs by one order of magnitude (Fig. 3).

A comparison of different mixing chambers in respect of the efficiency of the plasma
jet, determined as the ratio of the enthalpy of the flow at the outlet from the mixing cham-
ber to the initial enthalpy, leads to the expression

$$\eta = 0.79 \left(\frac{1}{1+\theta} \right)^{-0.13} \left(\frac{D_s}{D_w} \right)^{-0.096} \left(\frac{D_p}{D_s} \right)^{0.053} Re_0^{-0.0019} Pr_0^{0.14} \left(\frac{H_0}{H_{298}} \right)^{-0.045} \qquad (3)$$

with a standard error of 20% with a correlation coefficient 0.733. An increase of θ and D_p
leads to an increase of η of the mixing chamber to 96% whereas with small angles and diame-
ters the efficiency drops to 77%.

The obtained results permit the conclusion that if heat losses to the walls of a plasma
reactor are to be reduced, conical mixing chambers with large angle θ should be used, and
the plasmotrons should be situated far from the reactor axis.

NOTATION

c_p, heat capacity; D_a, diameter of the anode channel; D_p, diameter of the mixing cham-
ber at the place of inlet of plasma jets; D_s, diameter of the base of the mixing chamber, D_w,
channel diameter; H, entahlpy; x, length of the channel; λ, thermal conductivity; μ, viscos-
ity; ρ, density; θ, angle at the apex of the mixing chamber, rad; μ, efficiency, w, flow vel-
ocity; q, heat flux density. Criteria: $Re = wD\rho/\mu$: Reynolds number; $Pr = c_p\mu/\lambda$: Prandtl
number; $St = q/[w\rho(H - H_w)]$: Stanton number. Subscripts: 0) state at the inlet to the mix-
ing chamber; w) channel wall.

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CALCULATION OF PHASE TRANSITION DYNAMICS UPON LASER

IRRADIATION OF SEMICONDUCTORS

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Approximate expressions are obtained for calculations of the time characteristics of fusion and recrystallization, recrystallization rate, and depth to which the material fuses upon laser annealing of semiconductors. The expressions obtained may be used for selection of processing regimes.

Impulsive processing of semiconductor materials by laser radiation has recently come to be employed in a number of technological applications [1].

Since the fundamental processes which occur in such a situation are assumed to be rapid fusion of a surface layer of the semiconductor and subsequent recrystallization, in order to monitor the phenomena of defect removal, redistributions, and segregation of impurity atoms, and ultimately, the electrophysical properties of this layer, it is necessary to evaluate the parameters of the phase transition: time characteristics of fusion and recrystallization, recrystallization rate, and the depth to which the material fuses. Determination of these parameters experimentally or by numerical methods for solving the thermal conductivity equation using a computer is quite complex and cumbersome.

When the optical radiation absorption coefficients of the material are high, [2, 3] indicated the possibility of calculating these quantities with approximate expressions obtained from time-dependent thermal balance equations using scaling coefficients for more accurate matching of calculated values with those obtained by numerical methods and experimentally.

The present study will utilize a numerical solution of the thermal conductivity equation with consideration of phase transitions and temperature dependence of optical and thermophysical properties to study approximate expressions for the evaluation of laser annealing parameters in a number of semiconductor materials.

It will be assumed that the optical energy is instantaneously transferred to the specimen lattice in the form of heat and is then redistributed through the material by thermal conductivity. Diffusion of hot charge carriers will not be considered.

A one-dimensional thermal flux will be considered, i.e., the dimensions of the irradiated region will be assumed significantly larger than the effective penetration depth of heat into the specimen: $d \gg (2\lambda\tau/\rho c)^{1/2}$, where τ is the time interval over which the phase transitions are accomplished.

With consideration of the above assumptions, we write the thermal conductivity equation

$$c\rho \frac{\partial t}{\partial \tau} = q(x, \tau) + \frac{\partial}{\partial x}\left(\lambda(t)\frac{\partial t}{\partial x}\right). \tag{1}$$