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EXPERIMENTAL-STATISTICAL INVESTIGATION OF HEAT EXCHANGE IN A CYLINDRICAL MIXING CHAMBER OF A THREE-JET PLASMA REACTOR

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Results of experimental investigation of the heat exchange in a plasma module which incorporates a mixing chamber and three plasmatrons operating on it are generalized by the methods of physical modeling with the use of regression analysis. It is shown that the heat exchange in such a system is determined by the processes occurring in arc heaters. The most substantial influence is exerted by convection and radiation.

Introduction. One promising trend in the application of a thermal plasma is associated with the use of reactors in which several electric-arc plasmatrons (EAPs) operate on a single multiarc mixing chamber (MMC) [1, 2]. This method makes it possible to obtain flat profiles of temperature and velocity of the heat-transfer agent in the channel of a plasmachemical reactor (PRC), which increases the degree of processing the dispersed raw material introduced into the reactor. Use is usually made of three-jet mixing chambers that allow the formation of quite uniform distributions of parameters over the cross section of the reactor.

An analysis of the existing experimental data on the plasmachemical reactors that are used to process dispersed inorganic materials and solutions [1–5] shows that a crucial influence on the heat exchange in them is exerted by the initial unstabilized portion of the gas flow. The heat-exchange process here is complicated by the presence of significant axial gradients of velocity and temperature and by the presence of radial ones in the boundary region, turbulization of the gas by an arc in plasmatrons, by the disturbing action of the reagent jets on the flux in the reactor channel, and by the occurrence of separating flows at the sites of uneven introduction of plasma jets into the mixing chamber.

Under such conditions, theoretical determination of heat transfer in plasmachemical reactors by the methods of mathematical modeling is difficult. Therefore, one often has to resort to using experimental data and to obtain on their basis formulas to describe the regularities of a phenomenon. Sometimes experimental dependences are assigned the form of simple empirical expressions reflecting the interrelationship between the initial physical quantities. However, the most convenient and substantiated form of description will be a presentation and corresponding processing of experimental results using dimensionless similarity numbers that are generalized variables whose form is determined by the methods of the theory of similarity and dimensions.

But, indeed, the application of the theory of similarity to electric-arc discharges and plasma devices (multiarc mixing chambers, plasma reactors, hardening systems) also involves a number of difficulties. They are due to both the variety of the processes occurring in the discharge or a device and the wide temperature

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range. The great body of initial data characterizing this variety generates a great number of their combinations in the form of dimensionless numbers and similarity numbers the total quantity of which is, in principle, not limited by anything. True, the number of determining criteria that are independent of each other and called fundamental [6] is always smaller than the total number of all independent (with account taken of the conditions of unambiguity) initial variables and parameters. However, identification of a set of such criteria using physical modeling is a matter of certain intuition under these conditions. This task can be facilitated by the methods of statistical processing of the experiment and of regression analysis in generalized variables [7].

Generalization of experimental data on the heat transfer in a plasmachemical reactor has until recently been performed with a method that is traditional for this kind of heat-exchange apparatus, in which it is permissible that the processes in the arcs do not exert a direct influence on the processes in the reaction space of the apparatus. The level of enthalpy at the inlet to the chamber and the reactor is assigned in advance and is not related to the parameters of the arcs in the plasmatrons. Meanwhile, taking account of the influence of plasmatrons would probably make it possible to consider the physical processes occurring in these objects (located one after another) in a certain interrelationship. This approach could improve the accuracy of generalization or simplify the calculational procedure, all other things being equal. To obtain this kind of generalized dependence, it is necessary to conduct experiments in which it is obligatory to have a simultaneous fixation of parameters in both the reactors and the plasmatrons.

In connection with the above, we set ourselves the task of adapting the method of physical modeling of arc discharges to statistical generalization of the parameters of heat transfer in a plasmachemical reactor with the example of experimental data on the heat exchange of the plasma jets with the walls of the plasma module, i.e., a cylindrical multiarc mixing chamber (CMMC) with three plasmatrons. Adaptation implies taking account of the prehistory of the flow.

1. Problems of Physical Modeling of Plasma Reactors. The main problems inherent in physical modeling of arc discharges are considered in [7]. The initial set of independent variables in the regression method of obtaining generalized volt-ampere characteristics (VACs) of the arc in different plasmatrons included the following basic similarity numbers that take into account one or another process of transfer of the energy of Joule dissipation: $\pi_{\text{conv}} = Gd\sigma_0 h_0/I^2$, convective transfer, $\pi_{\text{cond}} = \sigma_0\lambda_0 T_0 d^2/I^2$, conductive transfer, $\pi_{\text{rad}} = \sigma_0 Q_0 d^4/I^2$, transfer by radiation, and $\pi_{\text{turb}} = \sigma_0\rho_0 h_0^{1.5} d^3/I^2$, turbulent transfer.

To generalize experimental data on the heat exchange in reactor devices with multiarc mixing chambers, as a rule, we used an approach based on an analogy with high-temperature heat exchange between the gas flow and the wall of the tube. At the same time, the Nusselt number Nu or the Stanton number St [1, 8] is used as a generalized function, and the Reynolds number Re and the Prandtl number Pr are used as the main independent variables. In [8], dissociation was taken into account using the enthalpy factor. We note that a distinction is also drawn between generalization of data on heat exchange for the internal problem (with respect to the temperature in a given cross section and the diameter of the tube) and for the external problem (with respect to the temperature at the entrance to the tube and the distance from the entrance, i.e., as in the case of external flow about a plate). In the former case it is necessary to determine the temperature change along the tube and to use it to select the parameters of thermophysical properties. In the latter case the calculation becomes simpler, since the temperature change is not taken into account. Correction factors for the initial portion are also introduced.

The positive aspect of this approach is that the obtained expressions possess a certain universality, since they are suitable for calculation of heat exchange irrespective of the method of heating the working body (electric-arc body or any other one). However, this leads, first, to calculation involving intermediate stages, multistage calculations, and parameters that are not recorded in the experiment, which increases the computational error. Second, under conditions of industrial production, heating to temperatures above 2000–2500 K is always in some way problematic for methods other than electric-arc ones. Therefore, the advantage of universality of the obtained expressions remains unclaimed.

In this connection, one can propose a new approach that considers a plasmachemical reactor as a single system consisting of one or several electric-arc plasmatrons, a mixing chamber, and a reactor channel (RC). The heat exchange in the multiarc mixing chamber and in the reactor channel of the plasmachemical reactor is assumed to depend among other things also on the processes occurring in electric-arc heaters. The system electric-arc plasmatron–multiarc mixing chamber–reactor channel "remembers" this sufficiently well, and in relatively short devices the processes in the heaters must be of prime importance for the entire system, including the reactor channel.

Taking into account the above, it is expedient to introduce criteria, which were used earlier in generalizing experiments on the heat exchange in electric-arc plasmatrons with a longitudinally blown arc, into the initial hypothetical system of criteria to describe heat exchange in plasmachemical reactors. This is first of all not only such a generalized argument as $\pi_{\text{conv},d} = \sigma_0 h_0 G d / I^2$, but also the criterion $\pi_{\text{rad},d} = \sigma_0 Q_0 d^4 / I^2$. It is expedient to apply the Stanton number $\text{St} = q_{\text{w}} \pi D_{\text{r.c}}^2 / 4G(h - h_{\text{w}})$ or $\overline{\eta} = (1 - \eta)/\eta$ [9]. The latter quantity is an analog of the St number for its low values and is called a generalized thermal efficiency.

2. Use of Correlation and Regression Analyses. Processing of experimental data is an important stage of investigations. We have used the Statistica for Windows computer program of statistical processing (StatSoft Company) which makes it possible to carry out correlation and regression analyses [10]. The problems of regression analysis are: (a) obtaining the best point and interval estimates of the known parameters of regression, (b) checking the hypotheses relative to these parameters, (c) checking the adequacy of the model assumed, and (d) checking the set of corresponding assumptions. The magnitude of the linear dependence between two variables is measured using a simple correlation coefficient, whereas the magnitude of the linear dependence of one variable on several variables is determined by a multiple correlation coefficient. Approximations of the functional relations by exponential expressions are the most widespread.

The level of influence of a certain argument in the regression equation can quantitatively be evaluated by the magnitude of the standardized coefficients and by the partial value of the ratio of Fisher variances.

To analyze the dominant mechanisms exerting a primary influence on the heat exchange in a multiarc mixing chamber we applied the generalized exponential expression analogous to [11, 12]:

$$\pi_{\text{dep}} = C \prod_i \pi_{\text{ind},i}^{B_i} \,. \tag{1}$$

Linearization of relation (1) is carried out using decimal logarithms. The initial set of independent variables includes those variables that reflect different mechanisms of heat exchange.

In selecting the dominant similarity numbers for description of heat exchange in a multiarc mixing chamber, we used the program of multiple linear regression with a procedure of "forward" step testing [10]. It successively chooses the independent parameters (regressors) that ensure the maximum value of the determination coefficient R^2; when several regressors are introduced into the model one refines their relative contribution. The selection is completed when, upon introduction of the next regressor, the Fisher criterion F turns out to be lower than the threshold characterizing the F-distribution for a given confidential probability (one usually prescribes F = 4.0, which is close to the F-distribution in a wide range of the number of the degrees of freedom in the case of a 95% probability of the event that the value of F will exceed the tabulated value).

Determination of the relative contribution of individual regressors in the case of their strong correlation is realized by shifting the regression coefficients using the subprogram of ridge regression that ensures such a shift (the regularization coefficient $\alpha = 0.1$ was used). In the case of ordinary (not ridge) regression, the program selects only the most significant variables; the indicator of their relative contribution also includes the influence of processes that are strongly correlated with the selected ones and are not among the dominant processes. Here one obtains more compact and accurate characteristics than in the case of ridge regression.

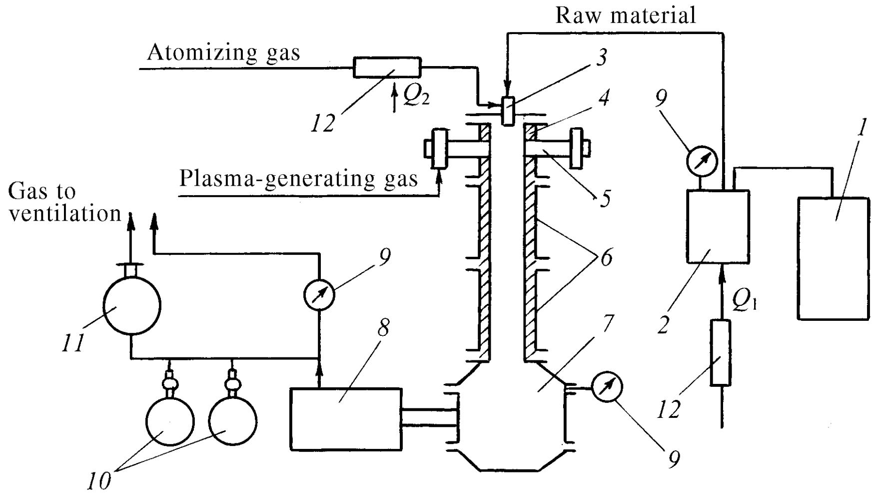

Fig. 1. Schematic diagram of the experimental setup for treatment of dispersed solutions based on a three-jet plasmachemical reactor: 1, 2) vessel with raw material; 3) burner; 4) mixing chamber; 5) plasmatrons; 6) reactor channel; 7) bin; 8) filter for collection of dispersed products of treatment; 9) manometer; 10) vacuumized flasks; 11) system of sampling of waste gases for analysis; 12) units of control of the raw-material temperature.

3. Experimental Setup. Experimental investigations were carried out on a specially prepared semi-commercial plasma unit with a power of 150 kW; the unit was assembled on a three-jet straight-thought plasmachemical reactor. The reactor was equipped with three d.c. electric-arc plasmatrons with a rod cathode (PDS-3) which were installed on a cylindrical multiarc mixing chamber with an air-atomizing burner and made it possible to treat commercial dispersed materials and dispersed solutions [1, 5]. The schematic diagram of the unit is shown in Fig. 1.

In the reactor, we obtained the parameters varying in the following ranges: the mass-mean temperature of the plasma at the inlet to the cylindrical multiarc mixing chamber varied within 3900–5800 K and the total flow rate of the gas through the reactor, including the flow rate of the plasma-generating and burner air, varied within 8.5–13.1 g/sec.

The cylindrical multiarc mixing chamber was cooled by water with a flow rate of 5 ± 2 kg/sec. We used constant diameters of the cylindrical multiarc mixing chamber (50 mm) and the reactor channel (65 mm) and the length of the cylindrical multiarc mixing chamber $X_{\mathrm{m.c}}$ = 110 mm; variation of the values of the geometric simplexes ($X_{\mathrm{m.c}}/D_{\mathrm{m.c}}$, $D_{\mathrm{m.c}}/D_{\mathrm{r.c}}$, $d/D_{\mathrm{m.c}}$) was insignificant in the experiments and was attained by changing (0 to 3 mm) the thickness of the skull layer of oxide products of treatment of the raw material on the walls of the cylindrical multiarc mixing chamber. In some cases the influence of this factor was disregarded.

4. Statistical Generalization of the Parameters of Heat Exchange of the Plasma Flow in the Cylindrical Multiarc Mixing Chamber of a Plasmachemical Reactor. Analysis of experimental data and generalization of the parameters of heat exchange of the plasma flow in the straight-through plasmachemical reactor with a cylindrical multiarc mixing chamber were carried out using the above-described statistical procedure. A sample of 38 experiments was considered [5]. Tables 1–7 and Fig. 2 give results of the statistical investigation.

$$\bar{\eta} = 35.4 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.933} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.639} \left(\frac{G_{3\mathrm{pl}}}{G_{3\mathrm{pl}} + G_{\mathrm{g.d}}} \right)^{2.070} . \qquad (2)$$

TABLE 1. Regression Parameters for the Generalized Efficiency of a Plasma Module (multiarc mixing chamber with three plasmatrons) (ordinary regression)

Parameters	Variables	β	Error of β	*B*	Error of *B*	Student quantile	Probability level
Air	c	–	–	1.549	0.185	8.36	0.000
$R = 0.868$ $R^2 = 0.753$	π'_{conv}	1.976	0.293	0.933	0.138	6.75	0.000
SE = 0.056	π_{rad}	1.255	0.293	0.639	0.149	4.29	0.000
$F_{(3.34)} = 34.5$ $d_{DW} = 1.59$	$G_{3pl}/(G_{3pl} + G_{g.d})$	0.230	0.086	2.070	0.773	2.68	0.011

TABLE 2. Correlation Matrix for the Generalized Efficiency of a Plasma Module (multiarc mixing chamber with three plasmatrons)

Generalized variables	π'_{conv}	π_{cond}	π_{rad}	π_{turb}	$X_{m.c}/D_{m.c}$	$G_{3pl}/(G_{3pl} + G_{g.d})$	$d/D_{m.c}$	$\bar{\eta}$
π'_{conv}	1.00	–0.96	–0.96	–0.96	0.11	–0.06	–0.10	0.76
π_{cond}	–0.96	1.00	1.00	1.00	–0.11	0.02	0.10	–0.63
π_{rad}	–0.96	1.00	1.00	1.00	–0.11	0.02	0.10	–0.63
π_{turb}	–0.96	1.00	1.00	1.00	–0.11	0.02	0.10	–0.63
$X_{m.c}/D_{m.c}$	0.11	–0.11	–0.11	–0.11	1.00	0.16	–1.00	0.18
$G_{3pl}/(G_{3pl} + G_{g.d})$	–0.06	0.02	0.02	0.02	0.16	1.00	–0.15	0.14
$d/D_{m.c}$	–0.10	0.10	0.10	0.10	–1.00	-0.15	1.00	–0.16
$\bar{\eta}$	0.76	–0.63	–0.63	–0.63	0.18	0.14	–0.16	1.00

TABLE 3. Regression Parameters for the Generalized Efficiency of Plasmatrons (ordinary regression)

Parameters	Variables	β	Error of β	*B*	Error of *B*	Student quantile	Probability level
Air	c	–	–	1.459	0.222	6.57	0.000
$R = 0.858$ $R^2 = 0.737$	π'_{conv}	1.704	0.302	0.935	0.166	5.64	0.000
SE = 0.067	π_{rad}	0.947	0.302	0.561	0.179	3.14	0.004
$F_{(3.34)} = 31.7$ $d_{DW} = 1.74$	$G_{3pl}/(G_{3pl} + G_{g.d})$	0.242	0.089	2.531	0.926	2.73	0.010

TABLE 4. Correlation Matrix for the Generalized Efficiency of Plasmatrons

Generalized variables	π'_{conv}	π_{cond}	π_{rad}	π_{turb}	$X_{m.c}/D_{m.c}$	$G_{3pl}/(G_{3pl} + G_{g.d})$	$d/D_{m.c}$	$\bar{\eta}_{pl}$
π'_{conv}	1.00	–0.96	–0.96	–0.96	0.11	–0.06	–0.10	0.79
π_{cond}	–0.96	1.00	1.00	1.00	–0.11	0.02	0.10	–0.68
π_{rad}	–0.96	1.00	1.00	1.00	–0.11	0.02	0.10	–0.68
π_{turb}	–0.96	1.00	1.00	1.00	–0.11	0.02	0.10	–0.68
$X_{m.c}/D_{m.c}$	0.11	–0.11	–0.11	–0.11	1.00	0.16	–1.00	0.26
$G_{3pl}/(G_{3pl} + G_{g.d})$	–0.06	0.02	0.02	0.02	0.16	1.00	–0.15	0.17
$d/D_{m.c}$	–0.10	0.10	0.10	0.10	–1.00	–0.15	1.00	–0.25
$\bar{\eta}_{pl}$	0.79	–0.68	–0.68	–0.68	0.26	0.17	–0.25	1.00

TABLE 5. Regression Parameters for the Generalized Efficiency of a Mixing Chamber (ordinary regression)

Parameters	Variables	β	Error of β	B	Error of B	Student quantile	Probability level
Air	c	–	–	0.186	0.220	0.85	0.403
$R = 0.561$ $R^2 = 0.315$	π'_{conv}	1.678	0.477	0.598	0.170	3.52	0.001
SE = 0.069 $F_{(3.34)} = 8.043$ $d_{DW} = 1.52$	π_{rad}	1.335	0.477	0.514	0.183	2.80	0.008

TABLE 6. Regression Parameters for the Stanton Number that Refers to the Plasma Module (multijet mixing chamber with three plasmatrons) (ordinary regression)

Parameters	Variables	β	Error of β	B	Error of B	Student quantile	Probability level
Air	c	–	–	0.204	0.181	1.13	0.268
$R = 0.854$ $R^2 = 0.730$	π'_{conv}	1.849	0.306	0.818	0.135	6.04	0.000
SE = 0.054	π_{rad}	1.122	0.306	0.535	0.146	3.67	0.001
$F_{(3.34)} = 30.64$ $d_{DW} = 1.567$	$G_{3pl}/(G_{3pl} + G_{g.d})$	0.240	0.090	2.022	0.756	2.67	0.011

TABLE 7. Regression Parameters for the Stanton Number that Refers to the Mixing Chamber (ordinary regression)

Parameters	Variables	β	Error of β	B	Error of B	Student quantile	Probability level
Air	c	–	–	–0.540	0.167	–3.24	0.003
$R = 0.578$ $R^2 = 0.334$	π'_{conv}	1.733	0.470	0.475	0.129	3.69	0.001
SE = 0.052 $F_{(2.35)} = 8.78$ $d_{DW} = 1.356$	π_{rad}	1.381	0.470	0.408	0.139	2.94	0.006

As the dependent variable in (1) we used the magnitudes of the generalized thermal efficiency $\bar{\eta}$ of the plasma module (multiarc mixing chamber with three plasmatrons), the generalized efficiency of the mixing chamber separately and the generalized efficiency of the plasmatrons themselves, and the Stanton number for the first two of these three cases.

The corresponding generalized formulas following from the data of the tables are written after each table with regression parameters for the generalized efficiency or the St number. In the expressions for the Stanton number in individual additional calculated variants we used the diameter of the anode of a plasmatron d or the diameter of the mixing chamber $D_{m.c}$ and not the diameter of the reactor $D_{r.c}$.

If the Stanton numbers are calculated from the diameter of the anode of the plasmatron d and from the diameter of the mixing chamber $D_{m.c}$, the formulas corresponding to expression (5) will have the form

$$\bar{\eta}_{pl} = 28.77 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.935} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.561} \left(\frac{G_{3pl}}{G_{3pl} + G_{gd}} \right)^{2.351} . \quad (3)$$

$$\bar{\eta}_{m.c} = 1.535 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.598} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.514} . \quad (4)$$

$$\mathrm{St} = \frac{q_{\mathrm{w}} \pi D_{\mathrm{r.c}}^2}{4G\,(h - h_{\mathrm{w}})} = 1.6 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.818} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.535} \left(\frac{G_{3\mathrm{pl}}}{G_{3\mathrm{pl}} + G_{\mathrm{g.d}}} \right)^{2.022} . \tag{5}$$

$$\mathrm{St} = \frac{q_{\mathrm{w}} \pi d^2}{4G\,(h - h_{\mathrm{w}})} = 0.495 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.825} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.557} \left(\frac{G_{3\mathrm{pl}}}{G_{3\mathrm{pl}} + G_{\mathrm{g.d}}} \right)^{1.961} , \quad R = 0.856 , \tag{6}$$

$$\mathrm{St} = \frac{q_{\mathrm{w}} \pi D_{\mathrm{m.c}}^2}{4G\,(h - h_{\mathrm{w}})} = 0.974 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.841} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.560} \left(\frac{G_{3\mathrm{pl}}}{G_{3\mathrm{pl}} + G_{\mathrm{g.d}}} \right)^{2.057} , \quad R = 0.841 . \tag{7}$$

$$\mathrm{St}_{\mathrm{m.c}} = \frac{q_{\mathrm{w.m.c}} \pi D_{\mathrm{m.c}}^2}{4G\,(h - h_{\mathrm{w}})} = 0.288 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.475} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.408} . \tag{8}$$

In calculating the independent variable from the plasmatron-anode diameter d, we obtain the following dependence instead of (8):

$$\mathrm{St}_{\mathrm{m.c}} = \frac{q_{\mathrm{w.m.c}} \pi d^2}{4G\,(h - h_{\mathrm{w}})} = 0.092 \left(\frac{I^2}{G d \sigma_0 h_0} \right)^{0.299} \left(\frac{\sigma_0 Q_0 d^4}{I^2} \right)^{0.259} \left(\frac{G_{3\mathrm{pl}}}{G_{3\mathrm{pl}} + G_{\mathrm{g.d}}} \right)^{3.023} , \quad R = 0.785 . \tag{9}$$

Returning to the procedure of obtaining generalized formulas, we note that we included first of all the already mentioned π_{cond}, π_{conv}, π_{rad}, and π_{turb} [7] or the inverse combinations $\pi'_{\mathrm{conv}} = I^2 G d \sigma_0 h_0$ and $\pi'_{\mathrm{rad}} = I^2 \sigma_0 Q_0 d^4$ into the initial set of the assumed significant independent variables. The parametric criteria $X_{\mathrm{m.c}}/D_{\mathrm{m.c}}$ (ratio of the length of the cylindrical multiarc mixing chamber to its diameter), $G_{3\mathrm{p1}}/(G_{3\mathrm{p1}} + G_{\mathrm{g.d}})$ (ratio of the total mass flow rate of the plasma-generating gas to the total flow rate of the gas), and $d/D_{\mathrm{m.c}}$ (ratio of the diameters of the plasmatron nozzle and the cylindrical multiarc mixing chamber) were used additionally. The characteristic properties appearing in the similarity numbers were determined according to the method of [7] that takes into account the dependence of plasma properties on temperature.

Since the processes of heat exchange occurring in the plasma module are interrelated, some of the independent variables that represent them turn out to be strongly correlated, which can be seen, for example, in the correlation matrix for the generalized efficiency of a plasma module (Fig. 2). Here, the relative role of individual variables is refined by shifting the regression coefficients (see Section 2). However, judging from the coefficient of multiple correlation between the regressors and the dependent variable, better "quality" in most of the calculated cases is provided by the ordinary form of regression and not by the ridge form.

Tables 1, 3 and 5–7 give the generalized arguments whose influence goes beyond the errors and the values of the coefficient of multiple correlation R, the determinant (determination coefficient) R^2, the regression ratio of Fisher variances F, and the standard error of regression SE. The relative role of individual variables is mainly reflected by the magnitude of the standardized coefficient β. Their values show that the convective mechanism and radiation exert the strongest influence on the intensity of heat exchange between the plasma and the plasma-module walls. Thus, for π_{rad} we found the values $\beta = 1.255$ in the case of regression for the generalized efficiency of a plasma module, $\beta = 0.947$ in the case of regression for the generalized efficiency of plasmatrons, and $\beta = 1.122$ in the case of regression for the Stanton number referring to the plasma module. This confirms the assumption that in describing of the heat exchange in three-jet electric-

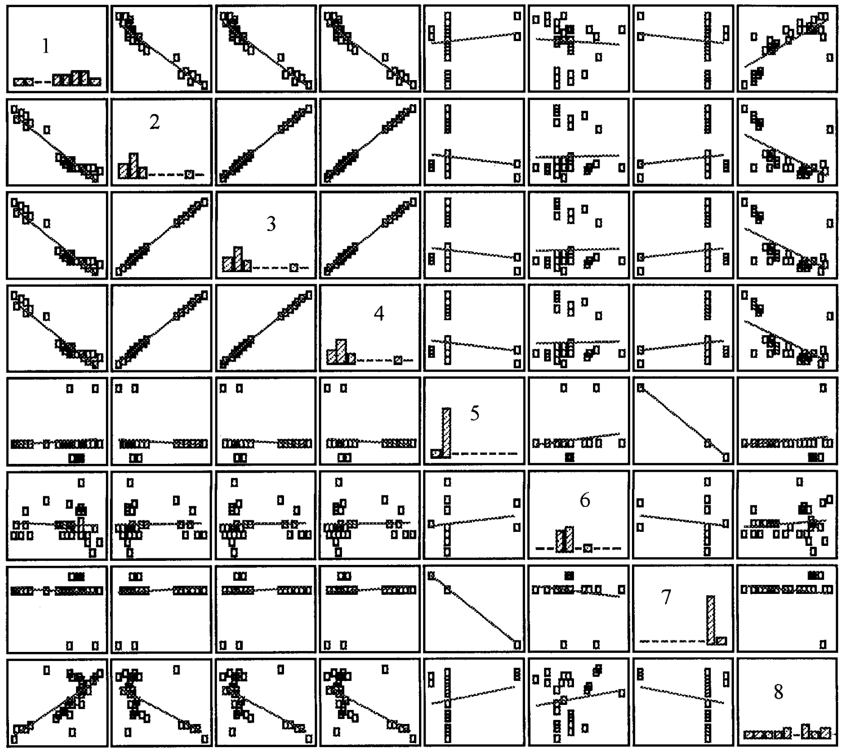

Fig. 2. Matrix of the graphs of dispersion of experimental points for different pairs of variables for regression of the generalized efficiency of a plasma module (multijet mixing chamber with three plasmatrons): lines, graphs of the linear probability dependence, rectangles, experimental points, and diagonal of the matrix, distribution diagrams of random quantities. The notation of the variables is as follows: 1) π'_{conv}, 2) π_{cond}, 3) π_{rad}, 4) π_{turb}, 5) $X_{\text{m.c}}/D_{\text{m.c}}$, 6) $G_{3\text{pl}}/(G_{3\text{pl}} + G_{\text{g.d}})$, 7) $d/D_{\text{m.c}}$, and 8) $(1 - \eta)/\eta$ (generalized efficiency).

arc plasma modules and in reactors based on them one must take into account not only the convective mechanism of transfer of the Joule-dissipation energy but the radiative mechanism as well.

Furthermore, the relative concentration of the plasma-generating gas in the total mass of the gas introduced into the multiarc mixing chamber through plasmatrons and burners, i.e., $G_{3\text{p1}}/(G_{3\text{p1}} + G_{\text{g.d}})$, turned out to be one more independent variable that also has a significant effect on the heat transfer in this plasma module.

On the whole, we should also note that the "quality" of regression generalizations obtained for the generalized thermal efficiencies and the Stanton number of this plasma module is quite acceptable, since the coefficients of multiple correlation are moderately high while the remaining parameters of regression generalizations (ratio of Fisher variances, Student quantiles for the coefficients of the equation, and Durbin–Watson criterion for the residuals d_{DW} [10]) are statistically valid. In particular, in the case of regression for the generalized efficiency of the plasma module (Table 1) $R = 0.868$, in the case of regression for the generalized efficiency of plasmatrons (Table 3) $R = 0.858$, and in the case of regression for the Stanton number referring to the plasma module (Table 6) $R = 0.854$.

In Table 8 and the corresponding criterial formulas following it, we give results of a regression analysis of the generalized volt-ampere characteristic for the plasmatrons which are used in this plasma module (sample of 114 points). The function $Ud\sigma_0/I$ is used as π_{dep} [11, 12]. As is seen, generalization of the volt-

TABLE 8. Regression Parameters for the Generalized Volt-Ampere Characteristic of an Arc in Linear Plasmatrons with a Rod Cathode that Operate with Air

Parameters	Variables	β	Error of β	*B*	Error of *B*	Student quantile	Probability level
			Ordinary regression				
$R = 0.966$	c	–	–	0.537	0.069	7.74	0.000
$R^2 = 0.933$	π_{conv}	0.710	0.082	0.464	0.053	8.68	0.000
SE = 0.040 $F_{(2.111)} = 766.77$ $d_{DW} = 0.71$	π_{rad}	0.264	0.082	0.187	0.058	3.23	0.002
			Ridge regression				
$R = 0.945$	c	–	–	0.960	0.099	9.72	0.000
$R^2 = 0.894$	π_{conv}	0.458	0.064	0.299	0.042	7.13	0.000
SE = 0.050 $F_{(3.110)} = 307.94$	π_{rad}	0.240	0.077	0.170	0.054	3.12	0.002
$d_{DW} = 0.84$	π_{cond}	0.240	0.077	0.170	0.054	3.12	0.002

ampere characteristic is rather good in this case (R = 0.966 for a nonridge regression) and agrees with the results (obtained earlier [11, 12]) of large-scale generalizations for linear plasmatrons with a longitudinally blown arc and a rod cathode operating with air. The determined values of the coefficients β = 0.710 for convection and β = 0.264 for radiation point to the similar hierarchy (convection ranks first and radiation ranks second) of the mechanisms of energy transfer that determine both the heat transfer in the plasma module (see Table 1) and the volt-ampere characteristic of the plasmatrons.

$$\frac{Ud\sigma_0}{I} = 3.44\left(\frac{I^2}{Gd\sigma_0 h_0}\right)^{-0.464}\left(\frac{\sigma_0 Q_0 d^4}{I^2}\right)^{0.187}, \quad \text{ordinary regression}, \tag{10}$$

$$\frac{Ud\sigma_0}{I} = 9.12\left(\frac{I^2}{Gd\sigma_0 h_0}\right)^{-0.299}\left(\frac{I^2}{\lambda_0 d^2\sigma_0 T_0}\right)^{-0.170}\left(\frac{\sigma_0 Q_0 d^4}{I^2}\right)^{0.187}, \quad \text{ridge regression}. \tag{11}$$

Conclusions. With the example of experimental data on the heat exchange of plasma jets and the flow of an air plasma with water-cooled walls of a plasma module, i.e., a cylindrical mixing chamber (with a diameter of 0.05 m and a total length of 0.11 m) with three d.c. plasmatrons operating on it, we have established the possibility of adapting the method of physical modeling of arc discharges to statistical generalization of the parameters of high-temperature heat transfer in a straight-through multijet plasmachemical reactor.

As a result of the investigations, we have obtained the corresponding criterial regression equations for the generalized thermal efficiencies and the Stanton number of the plasma module and the plasmatrons characterized by the coefficient of multiple correlation R = 0.841–0.868. The coefficient of multiple regression for the volt-ampere characteristic attains R = 0.966.

Analysis of the obtained regression equations (including that of the values of the standardized coefficients β) shows that the strongest influence on the intensity of heat exchange between the plasma and the walls of the plasma module is exerted by convection and radiation. This substantiates the hypothesis of the necessity of taking simultaneous account of these mechanisms in describing heat exchange in three-jet plasma reactors.

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NOTATION

T, temperature; σ, electrical conductivity; h, enthalpy; λ, thermal conductivity; Q, volume emissivity; ρ, density; G, flow rate of the gas; d, diameter of the anode of the plasmatron; D and X, diameter and length of the plasma device respectively; U, voltage; I, current strength; q, density of the heat flux to the reactor wall; η, thermal efficiency; $\overline{\eta} = (1 - \eta)/\eta$, generalized thermal efficiency; C, constant; $c = \ln C$; B, exponent; β, standardized correlation coefficient; R, coefficient of multiple correlation; R^2, determination coefficient; SE, standard error of regression; F, Fisher criterion (variance ratio); d_{DW}, Durbin–Watson criterion for the residuals of regression; π, generalized variables. Subscripts: 0, determining value; w, wall; dep and ind, dependent and independent variables respectively; conv, cond, rad, and turb, convective, conductive, radiant, and turbulent heat transfer respectively; pl and 3pl, one or three plasmatrons respectively; g.d, cold (injected through the nozzle) gas; m.c, mixing chamber; r.c, reactor channel; d, diameter of the anode of the plasmatron.

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