value, m^3; W_2, probability of impact of the potential active center of a macromolecule with the active center of a metal substrate; n_M, density of active centers of the metal substrate, m^{-3}; n_p, density of potential active centers, m^{-3}; $n_{0,p}$, maximum possible density of potential active centers, m^{-3}; t_{opt} and T_{opt}, time and temperature for compound formation corresponding to maximum adhesional strength, sec and K; $\tau_{r,0}$ constant, sec; U_r, effective activation energy of relaxational mobility of macromolecules, $J \cdot mole^{-1}$.

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HEAT TRANSFER BETWEEN A STATIONARY GRANULAR PACKING AND A DESCENDING FLOW OF DUSTY GAS

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The transfer of heat from a stationary granular bed (packing) to a gas–particle flow has been investigated experimentally. A correlation is obtained for calculating the heat-transfer coefficient in the system.

In our view, the use of gas suspensions in apparatus with a stationary granular packing is very promising for a number of processes accompanied by a strong heating effect (catalytic processes, fuel processing, waste-heat recovery, etc.). For these systems the published information concerning external heat transfer (from the packing to the gas suspension) is extremely sparse [1, 2].

The heat transfer experiments were carried out on an apparatus with an open gas–particle flow system. The advantages as compared with other systems (semiclosed and closed) are explained in detail in [3]. The principal element of the apparatus was a column of square cross section containing the packing, which was supported on wire grids attached to the column base. In all the experiments we used only monodisperse packing. In some cases this took the form of smooth steel balls, and in others the form of round porcelain granules with a slightly rough surface. As the particles added to the gas flow we used three narrow fractions of sand and electrical corundum 12 (GOST 3647-71) of polyfractional composition. The prin-

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TABLE 1. Characteristics of the Dispersed Components

No.	Material	d_p, mm	ρ_p, kg/m^3
1	Sand	0,150	2540
2	Sand	0,250	2540
3	Sand	0,700	2650
4	Corundum	0,125	3760

TABLE 2. Characteristics of the System Investigated

Series No.	Packing	d_V, mm	d_R, mm	ε	Φ	d, mm	Dispersed component from Table 1
		150 × 150 mm column					
1	Steel balls	25,4	25,4	0,421	1,0	10,74	2
2	" "	25,4	25,4	0,421	1,0	10,74	4
		80 × 80 mm column					
3	Steel balls	15,3	15,4	0,451	1,0	7,136	1
4	" "	15,3	15,4	0,451	1,0	7,136	2
5	«	15,3	15,4	0,451	1,0	7,136	3
6	«	15,3	15,4	0,451	1,0	7,136	4
7	«	11,4	11,4	0,410	1,0	4,712	1
8	«	11,4	11,4	0,410	1.0	4,712	2
9	Porcelain granules	6,26	15,4	0,382	0,9	2,196	1
10	The same	6,26	15,4	0,382	0,9	2,196	4
11	«	6,26	11,4	0,382	0,9	2,289	1
12	«	6,26	11,4	0,392	0,9	2,289	4

cipal characteristics of the dispersed component and the packing are given in Tables 1 and 2.

The particles were introduced into the air flow from a feed hopper which, when fully loaded, held enough material for at least a 5-min experiment.

The dusty gas flowed through the packing from top to bottom. The apparatus was designed to ensure the equalization of the air and particle temperatures and a uniform particle distribution over the column cross section ahead of the entrance to the packing.

The separate measurement of the throughput of particles, which after passing through the column were collected by means of a cyclone and cloth filter, and the air flow rate, measured with an orifice plate, made it possible to determine the particle concentration in the flow K with a relatively high degree of accuracy (±1.5%).

The external heat transfer coefficient was determined by local modeling of the heat transfer in the steady temperature field regime, which was obtained using calorimeters fitted with built-in electric heaters. In all the experiments we used calorimeters in the shape of a hollow sphere with outside diameter equal to 11.4, 15.4, or 25.4 mm (see Table 2). The body of the calorimeter was made of machined copper; a Chromel–Copel thermocouple was attached to its surface with silver solder. The body contained a heater consisting of a ceramic insulator closely wound with Nichrome wire 0.1 or 0.15 mm in diameter. The wire diameter was so chosen that the electrical resistance of the coil exceeded that of the leads by a factor of not less than 50. The calorimeter circuit included a dc source and a class 0.1 wattmeter.

The temperature of the air and the dusty gas were measured at several points, including two in the packing (upstream and downstream of the calorimeter), likewise with Chromel–Copel thermocouples. The cold junctions of the thermocouples (including the calorimeter thermocouple) were connected to the terminals of a multipoint self-balancing potentiometer with a temperature recording error of not more than ±0.2°C.

In order to avoid encumbering the intergranular space the thermocouple leads in the packing and the calorimeter heater leads were passed through holes drilled in the balls or granules and led out through sleeves in the column walls.

Obviously, with this method of modeling the heat transfer in the packing, apart from the heat given up by the calorimeter directly to the flow, there is an additional source of heat transfer associated with the difference between the temperatures of the calorimeter body and the surrounding "cold" packing and, moreover, with the presence in the calorimeter of a built-in electric heater, whose coil temperature exceeded the temperature of the leads by several hundred degrees. In this connection, it became necessary to isolate from the overall heat transfer coefficient α_{exp}, calculated on the basis of the experimental data from the expression

$$\alpha_{exp} = \frac{q}{\pi d_c^2 (t_c - t_{am})}, \quad (1)$$

the convective component α, which corresponds to the true heat transfer coefficient in industrial apparatus with a granular bed. For this purpose we introduced the following corrections into α_{exp}: for the heat transfer through the contact spots between the calorimeter and the adjacent balls or granules ($\Delta\alpha_c$); for the heat losses through the ends and the leads of the electric heater ($\Delta\alpha_h$); and for the calorimeter emission ($\Delta\alpha_r$). The corrections $\Delta\alpha_c$ and $\Delta\alpha_h$ were determined in auxiliary experiments, and $\Delta\alpha_r$ by calculation.

Bearing in mind the fact that each of the corrections is a function of temperature, in order to make the procedure for taking them into account simpler and more reliable we tried to maintain the temperature of the calorimeter surface and that of the ambient medium (gas, gas suspension, "cold" packing) at the constant levels t_c = 37°C, t_{am} = 17°C, respectively, in both the main and the auxiliary experiments.

We also note that determining the exact value of the correction $\Delta\alpha_c$ is a complicated matter. Accordingly, we were particularly careful to reduce the fraction of the total heat-transfer coefficient that it represents. This was achieved by using so-called facing granules in the immediate vicinity of the calorimeter. In shape and size these were the same as the rest of the "cold" packing but had a lower thermal conductivity since they were made of wood (beech).

The experiments carried out to estimate the correction $\Delta\alpha_c$ were performed on a column with an atmosphere of still air (without blowing). The correction was determined as the difference in the values of the calorimeter heat-transfer coefficient obtained with and without contact between the calorimeter and the facing granules (in the latter case the calorimeter was introduced above the packing). In both cases we used the regular cooling regime method for a body not having built-in heater [4]. Accordingly, before the experiment the calorimeter was heated in an electric oven to t_c = 60°C. This heating of the calorimeter was quite sufficient to enable it, once placed in the column, to enter the regular cooling regime by the time its temperature had fallen to the value t_c = 37°C at which the heat transfer rate was recorded and, moreover, was also acceptable from the standpoint that the accumulated heat released during the cooling process in the packing raised the temperature of the surrounding material only slightly above the level t_{am} = 17°C characteristic, as already noted, of the main experiments.

While it remained constant within each series of experiments, the value of $\Delta\alpha_c$ was varied from series to series over the interval from 9.7 W/(m²·K) (series 7 and 8) to 32.4 W/(m²·K) (series 9 and 10).

In determining the correction $\Delta\alpha_h$ we exposed each calorimeter to a stream of air in an empty column, with and without a built-in heater. The packing granules through which the leads were led out in the main experiments were left threaded on the calorimeter leads (in both cases) and on the heater leads (in the first case). The approach stream velocity was varied from 1 to 100 m/sec, which made it possible to cover the entire interval of values of the heat-transfer coefficient obtained in the main experiments. When the heater was present in the calorimeter, the heat-transfer coefficient was determined by the steady-state thermal regime method, and when no heater was present by the regular cooling regime method. In the first case it was represented in the form of the function $\alpha_1 = f_1(Re)$, and in the second in the form $-\alpha_2 = f_2(Re)$. As the correction we took the difference $\Delta\alpha_h = (\alpha_1 - \alpha_2)_{Re=idem}$. Within each series of experiments its relative value $\varphi = (\Delta\alpha_h/\alpha_2)\cdot 100\%$ differed only slightly from a constant and amounted to 10-13% for d_c = 25.4 mm, 15-19% for d_c = 15.4 mm, and 19-23% for d_c = 11.4 mm.

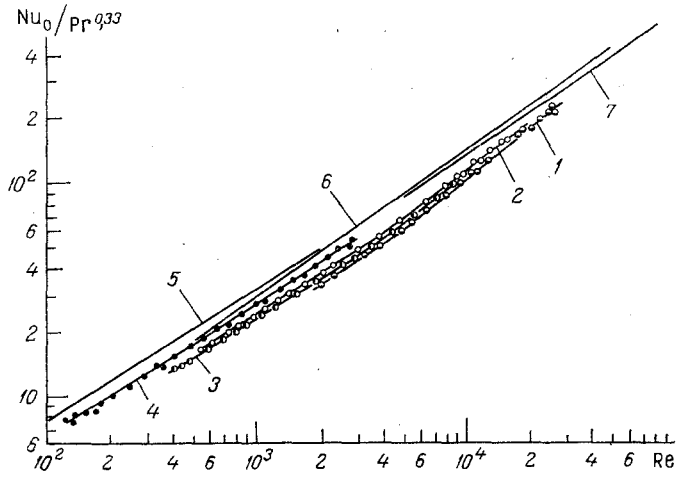

Fig. 1. Heat transfer between a granular packing and a clean air flow: 1, 2, 3) steel balls d_V = 25.4, 15.3, and 11.4 mm respectively; 4) porcelain granules d_V = 6.26 mm; 5) $Nu_0 = 0.395\ Re^{0.64}Pr^{0.33}$ [10]; 6) $Nu_0 = 0.23\ Re^{0.7}Pr^{0.33}$ [7]; 7) $Nu_0 = 0.287\ Re^{0.67}Pr^{0.33}$ [9].

The correction $\Delta\alpha_r$ was calculated from the expression for the radiative heat transfer between two gray surfaces, one of which is located in a closed space bounded by the other [5]:

$$\Delta\alpha_r = \varepsilon_t C_0 [(T_c/100)^4 - (T_{fg}/100)^4]/(T_c - T_{fg}), \quad (2)$$

where $\varepsilon_t = \left[\frac{1}{\varepsilon_c} + \frac{F_c}{F_{fg}}\left(\frac{1}{\varepsilon_{fg}} - 1\right)\right]^{-1}$, and the subscripts "c" and "fg" correspond to the calorimeter and the facing granules of the packing. In all the series of experiments the calculated value of $\Delta\alpha_r$ = 1.24 W/(m²·K). In the calculations it was assumed that: F_c/F_{fg} = 0.3, C_0 = 5.67 W/(m²·K), ε_c = 0.202 (dull copper) [5], and ε_{fg} = 0.95 (beechwood) [6].

In the course of the experiments it was established that with decrease in the calorimeter diameter and the gas flow velocity and, moreover, with increase in the temperature difference between the calorimeter and the "cold" packing the overall fraction of the above-mentioned heat losses increases and may reach a large value (in our experiments up to 0.375·α_{exp}). Accordingly, on the accuracy with which the heat losses are taken into account there also depends the accuracy of determination of the unknown coefficient α. However, in the known investigations [7-11], in which the heat transfer between a granular packing and a gas stream (in our case a gas suspension) was studied by electrically heating a single ball, insufficient attention was paid to this question. Because of the effect considered and, moreover, in connection with the fact that, below, in constructing the relation describing the heat transfer from the granular packing to the gas suspension as the unknown variable we have taken the ratio Nu/Nu_0 (by analogy with the heat transfer to a gas suspension in other kinds of devices, e.g., tubes and annular channels [3, 12, 13]) it became necessary to improve the accuracy of the expression for calculating Nu_0. For this purpose, in addition to the experiments with a gas suspension, we carried out experiments with clean air, the results of which are reproduced in Fig. 1.

It is important to stress that in all our investigations in analyzing the experimental data the structure of the packing and the nature of the flow in it were considered from the standpoint of the so-called "capillary" model of a granular bed which, together with other approaches to the solution of this question, is examined in detail in [10, 11]. Preference was given to this model because the ideas on which it is based make it possible, as follows from [10, 11], to describe the heat transfer from the packing to a pure gas flow by means of a simple expression of the form:

$$Nu_0 = f(Re, Pr), \quad (3)$$

in which the effect of the porosity of the packing ε, the packing shape factor Φ, and moreover the confining walls of the apparatus can be taken theoretically into account, with an accuracy sufficient for practical purposes, in constructing the parameters d and U entering

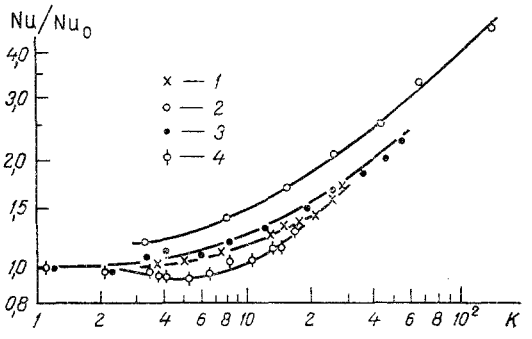

Fig. 2

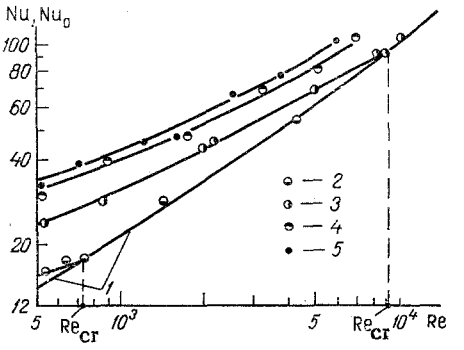

Fig. 3

Fig. 2. Effect of concentration of the ratio Nu/Nu_0: 1) series of experiments No. 1, Re = 2300; 2) series No. 3, Re = 560; 3) series No. 4, Re = 865; 4) series No. 5, Re = 310 (see Table 2).

Fig. 3. Effect of Reynolds number Re on the heat-transfer rate: 1) heat transfer with clean air in series of experiments Nos. 3-6 (Table 2) ($Nu_0 = 0.2931 \times Re^{0.622(1+2.4\cdot10^{-6}Re)}$); heat transfer with gas suspension: 2) series No. 5 (K = 8.6 kg/kg); 3, 4, 5) series No. 6 (K = 7.7, 17.7, and 21.2 kg/kg).

into the complexes $Nu_0 = \alpha_0 d/\lambda$ and $Re = Ud\rho/\mu$. In our work these parameters were calculated from the expressions recommended in [10]:

$$d = \frac{2}{3}\,\frac{\varepsilon\Phi d_V}{\left[(1-\varepsilon)+\dfrac{\Phi}{2n}\right]}. \tag{4}$$

$$U = G/(F\varepsilon\rho), \tag{5}$$

where

$$\Phi = \frac{6}{(S_g/V_g)\,d_V}, \quad n = \frac{D}{d_V}, \quad d_V = \left(\frac{6}{\pi}V_g\right)^{1/3}.$$

The results presented in Fig. 1 confirm the validity of using the "capillary" model for describing the heat transfer between continua and the surface of a granular packing. Most significant in this respect were the experiments using procelain granules (series Nos. 9-12, Table 2). In fact, in these experiments the size and shape of the calorimeter differed considerably from the size and shape of the other elements of the packing. Nonetheless, curve 4, which corresponds to these experiments, was found to lie only 10-15% above curve 2, which approximates the data obtained in the experiments with steel balls having practically the same diameter as the calorimeter (d_V = 15.3 mm; d_C = 15.4 mm). In our view, so small a difference between the curves in question, like curves 1-3, is attributable not to the defects of the model but to the obvious difference in the structure of the bed in the vicinity of the calorimeter in the two cases considered and, moreover, to the error in measuring the parameters ε, Φ, and d_V in the experiments.

At the same time, it should be stressed that the values of Nu_0 obtained in our experiments were 20-50% lower than those calculated from the known relations proposed in [7, 9, 10] (curves 5-7). This is evidently a consequence of our fuller and more careful estimation of the calorimeter heat losses. It should be added that the experimental points plotted in Fig. 1, which were obtained for $d_V = d_C$ on the interval $400 < Re < 26{,}000$ with an error of ±5.1%, are approximated by the single relation

$$Nu_0 = 0.32Re^{0.619(1+3.3\cdot10^{-6}Re)}\,Pr^{1/3}. \tag{6}$$

We now turn to the examination of the data obtained in the experiments on the heat transfer between a descending gas suspension and a granular bed.

In order to explore the effect on the heat transfer of one of the principal parameters of the dusty gas flow — the flow-rate particle concentration K — some of the experiments in series 1 and 3-5 (Table 2) were carried out at the same Re. The experimental data were

analyzed on the basis of the relation

$$\mathrm{Nu}/\mathrm{Nu}_0 = f(K). \tag{7}$$

The results of this analysis are presented in Fig. 2, from which it follows that the influence of the particle concentration on the heat transfer rate is different for small and large values of K. When $K \gtrsim 9$ in all the series an increase in concentration leads to a monotonic increase in heat transfer, at a relatively high rate. At low concentrations (K = 0-5) a slight increase in heat transfer is usually observed, and in individual cases even a fall ($1 > (\mathrm{Nu}/\mathrm{Nu}_0) > 0.94$) characteristic of experiments with a very high degree of crowding of the particles ($d/d_p \lesssim 10$-12). We note that a similar kind of heat transfer deterioration, though more substantial and over a broader range of variation of the particle concentration ($1 > (\mathrm{Nu}/\mathrm{Nu}_0) > 0.65$), was previously observed in investigating the heat transfer between gas suspension flows and the walls of tubes and annular channels [3, 12].

In addition to the parameters K and d/d_p, the motion of the gas, characterized by the Reynolds number Re, has an appreciable influence on Nu. The graphic representation of this effect (Fig. 3) was made possible by the fact that from the large number of experiments on gas suspensions carried out within the framework of our investigation (nearly 400 experimental points) we were able to isolate those in which the condition K = idem when Re ≠ idem was satisfied. According to the figure, the particles can have a positive effect on the heat-transfer coefficient only up to certain values of the Reynolds number (we have denoted them by Re_{cr}) which, in their turn, depend on the parameters K and d/d_p. A similar situation also arises when analyzing the experimental data relating to the heat transfer between a gas suspension and tube walls [3, 14]. When $\mathrm{Re} > \mathrm{Re}_{cr}$ for the system we investigated, with an accuracy sufficient for practical purposes it may be assumed that $(\mathrm{Nu}/\mathrm{Nu}_0) = 1$.

In connection with the analogy observed between heat transfer to a gas suspension in a granular packing and in tubes, expressed as the qualitatively identical effect of the principal parameters of the process on the ratio $(\mathrm{Nu}/\mathrm{Nu}_0)$ and, moreover, taking into account the fact that in the case of tubes the most successful relation (from the standpoint of simplicity and the accuracy of description of a considerable volume of experimental data) is, in our view, the relation

$$\mathrm{Nu}/\mathrm{Nu}_0 = C(K\delta_v/d_p)^n, \tag{8}$$

proposed in [3, 13], after modification the latter was tested in relation to the generalization of the data obtained in our investigation. We recall that in [3, 13] the quantity δ_v in Eq. (8) represents the thickness of the viscous gas sublayer and in those studies was calculated from the known (see, for example, [15]) expression

$$\delta_v \approx 65d/\mathrm{Re}^{0.9}. \tag{9}$$

The coefficient C and the exponent n in (8) were determined on the basis of the experimental data.

Expression (9) and hence Eq. (8) itself are meaningful only in the case of developed turbulent motion of the tube flow. In order to extend Eq. (8) to our case, as indeed to the case of the known regimes of motion of gas suspensions in tubes, instead of the concept of a viscous sublayer it is proposed to introduce the effective thickness of the temperature boundary layer, which it is natural to define as

$$\delta_t = d/\mathrm{Nu}_0. \tag{10}$$

As a rule, the value of Nu_0 required for its calculation is known or can be found experimentally.

Obviously, replacing δ_v by δ_t in expression (8) (this also constitutes its modification) does not affect the accuracy of the generalization if

$$\delta_v/\delta_t = \mathrm{const}. \tag{11}$$

It is easy to show that for a gas suspension in developed turbulent tube flow this relation is satisfied to within ±15% on the range of Reynolds numbers ($6000 < \mathrm{Re} < 90{,}000$) currently investigated. In fact, in the case in question after determining Nu_0 from the known expression [16]

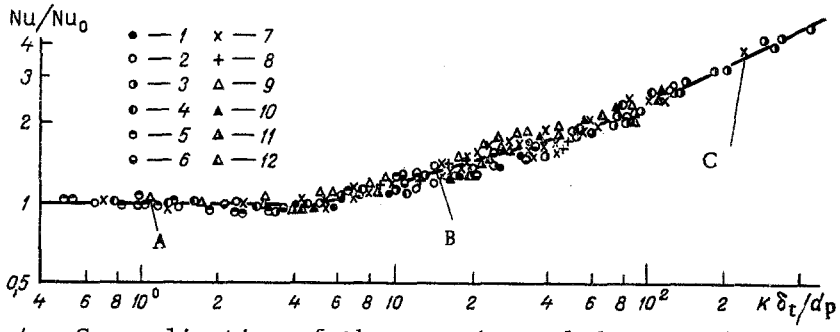

Fig. 4. Generalization of the experimental data on the heat transfer between a descending gas suspension and the surface of a granular packing: 1-12) series of experiments Nos. 1-12 respectively; A) $(Nu/Nu_0) = 1$; B) $(Nu/Nu_0) = 0.68\ (K\cdot\delta_t/d_p)^{0.25}$; C) $(Nu/Nu_0) = 0.28\ (K\cdot\delta_t/d_p)^{0.465}$.

$$Nu_0 = 0{,}022Re^{0.8}\,Pr^{0.43}, \tag{12}$$

and δ_v from relation (9) and taking into account the fact that for different gases the value of the Prandtl number is practically the same, for the Re interval in question we can write

$$\delta_v/\delta_t = k_1\,Re^{-0.1} \approx \text{const}. \tag{13}$$

For comparison, we recall that the experimental data so far accumulated on the heat transfer of gas suspensions in tubes (for an extensive list of these data see [3]) are generalized by expression (8) with a mean-square error of ±20%.

The testing of a relation of the form $(Nu/Nu_0) = f\ (K\delta_t/d_p)$ for generalizing the data on the heat transfer between a gas suspension and the surface of a granular packing is illustrated in Fig. 4. In the generalization process the value of Nu_0 was determined from curves 1-4 in Fig. 1.

In approximating the data obtained the region of variation of the complex $K\delta_t/d_p$ was divided into three intervals (in the case of tubes in [3, 13] the region of variation of the complex $K\delta_v/d_p$ was also divided into three parts), in each of which the quantity Nu/Nu_0 could be described by means of an expression of the form:

$$Nu/Nu_0 = C_1\,(K\delta_t/d_p)^m. \tag{14}$$

It was found that on the interval $0 < (K\delta_t/d_p) < 4.7$ $C_1 = 1.0$, $m = 0$; when $4.7 \le (K\delta_t/d_p) < 60$ $C_1 = 0.68$; $m = 0.25$; and when $60 \le (K\delta_t/d_p) < 435$ $C_1 = 0.28$; $m = 0.465$.

With a mean-square error of ±8.7%, Eq. (14) holds good over the following ranges of variation of the variables: $125 < Re < 23{,}300$; $10.2 < d/d_p < 86$; $0 \le K < 143$; $1638 < \rho_p/\rho < 3270$.

In conclusion, we note that if Nu_0 is determined not from curves 1-4 in Fig. 1 but from expression (6), which is more convenient in practice, the accuracy of the calculations based on expression (14) will be somewhat reduced.

NOTATION

a, thermal diffusivity of the gas, m^2/sec; C_0, emissivity of an absolutely blackbody, $W/(m^2\cdot K^4)$; d, equivalent diameter of the packing "channels" or the tube diameter, m; d_V, packing diameter, m; d_c, diameter of the calorimeter, m; d_p, mean particle diameter, m; D, diameter of the apparatus (column), m; F, cross-sectional area of the apparatus (column), m^2; F_c/F_{fg}, ratio of the area of the calorimeter surface to the corresponding area of the facing granules, m^2; G, gas flow rate, kg/sec; K, flow-rate concentration of the dispersed flow component, kg/sec; q, power of the electric calorimeter heater, W; S_g, surface area of a packing element, m^2; t_c and t_{am}, temperatures of the calorimeter surface and the ambient medium, °C; V_g, volume of a packing element, m^3; α_0 and α, heat-transfer coefficients of the gas and the gas suspension, $W/(m^2\cdot K)$; ε, porosity of the packing; ε_c and ε_{fg}, emissivities of the calorimeter and the facing granules; λ, thermal conductivity of the gas, $W/(m\cdot K)$; μ, dynamic viscosity coefficient, Pa·sec; ρ_p and ρ, densities of the particle material and the gas, kg/m^3; and Φ, packing shape factor. Dimen-

sionless numbers: Nusselt number – $Nu_0 = \alpha_0 d/\lambda$ (for a gas), $Nu = \alpha d/\lambda$ (for a gas suspension); Prandtl number – $Pr = \mu/(\rho a)$; Reynolds number – $Re = Gd/(F\varepsilon\mu)$.

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