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HEAT EXCHANGE OF DYNAMIC POWDER BEDS WITH A HEAT-TRANSFER SURFACE.
II. A DUST-LADEN GAS FLOW

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Heat exchange of a dust-laden gas flow with the wall of a cylindrical channel in laminar and laminar-to-turbulent transitional regimes of gaseous-phase motion is studied experimentally. Corundum with a particle size of 40 μm was used as the solid phase while air was used as the carrier gas. Experimental values of the heat-transfer coefficient are obtained and approximate dependences for the Nu number are proposed.

Heat exchange of a gas-suspension flow that is turbulent in the gaseous phase with a channel wall has been studied sufficiently; in the literature [1, 2], criterial equations are given that enable us to calculate heat-transfer coefficients, for example,

$$\mathrm{Nu}_{\mathrm{fl}} \approx 0.023\,\mathrm{Re}_{\mathrm{fl}}^{0.8}\,\mathrm{Pr}_{\mathrm{fl}}^{0.4} = \mathrm{Nu}\,(1+\mu)^{0.8}\,(1-\beta)^{0.12}\left(\frac{1 + C_{\mathrm{sol}}\,\mu C^{-1}}{1+\mu}\right)^{0.4}, \tag{1}$$

where μ and β are the dimensionless parameters

$$\mu = \frac{G_{\mathrm{sol}}}{G} = \frac{\beta}{1-\beta}\,\frac{\rho_{\mathrm{sol}}V_{\mathrm{sol}}}{\rho V}\,, \quad \beta = \frac{F_{\mathrm{sol}}}{F_{\mathrm{syst}}} = \frac{F_{\mathrm{sol}}}{F_{\mathrm{sol}} + F} = \frac{\mu}{\dfrac{\rho_{\mathrm{sol}}V_{\mathrm{sol}}}{\rho V} + \mu}\,. \tag{2}$$

However, for regimes of motion of a dust-laden gas flow that are laminar and transitional as far as the gaseous phase is concerned, no data on heat transfer are found in literature sources. At the same time, in chemical technology, there are exothermic processes in a gas-solid system whose characteristic period is such that, in a chemical reactor with a vertical dust-laden gas flow of length of the order of several meters used as the reaction zone, the laminar regime of gaseous-phase flow will be realized.

Therefore, to measure the intensity of the heat exchange of a dust-laden gas flow that moves in the indicated regime with a tube wall, we developed an experimental laboratory setup, whose diagram is given in Fig. 1. In it, a dust-laden gas flow moves from the bottom upward along vertical tube 1 of inside diameter 9 mm and length 900 mm. In bin 2, the gas is separated from the powder, and it is removed from the setup through filter 3. Along vertical tube 4 of inside diameter 25 mm the powder arrives under gravity at ejector unit 5, where the dust-laden gas flow is formed.

The dust-laden gas flow is heated from the wall of tube 1, which is thermostated using electric heaters U_1, ..., U_4 connected along with wall thermocouples TC_1, ..., TC_4 to systems of atomatic temperature control, which enables us to maintain a uniform temperature distribution on the surface of tube 1 accurate to ±5°C. Chromel–Copel thermocouples T_1, ..., T_5 of diameter 200 μm are intended to measure the flow temperature.

We used aluminum oxide (corundum) with an average particle size of 40 μm as the solid phase and air as the carrier gas. The experiments were conducted at a pressure of 1–1.2 atm.

In the first series of experiments, we obtained a characteristic of the ejector unit: the flow rate of the solid phase as a function of the flow rate of the carrier gas. Results of the experiments are given in Table 1.

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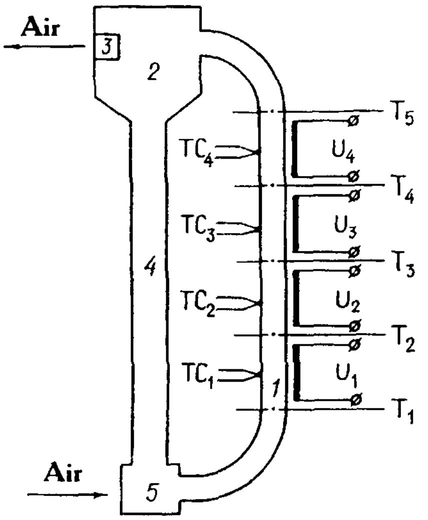

Fig. 1. Schematic diagram of the laboratory setup.

TABLE 1. Flow Rates of the Powder G_s as Functions of the Flow Rate of the Air G with an Increase and a Decrease in the Flow Rate of the Air G

G	Decrease in G			Increase in G		
	G_s	μ	β	G_s	μ	b
0.64	8.3	13.0	0.0041	8.4	13.1	0.0041
0.48	8.3	17.3	0.0054	8.0	16.7	0.0052
0.36	8.0	22.2	0.0070	7.5	20.8	0.0065
0.23	6.5	28.3	0.0088	5.9	25.7	0.0080
0.18	6.3	33.0	0.0109	5.6	31.1	0.0097
0.18	23.5	130.6	0.0396	22.0	122.2	0.0371
0.16	25.0	156.3	0.0470	21.0	131.2	0.0400
0.15	24.0	160.0	0.0480	20.0	133.3	0.0404

According to [1], the physical features of dust-laden gas flows are most completely reflected by the true bulk concentration β. In [1], the following tentative boundaries of the basic flows are proposed: $0 < \beta < 0.00035$ are slightly dusty flows; $0.00035 < \beta < 0.03$ are gas-suspension flows; $0.03 < \beta < 0.3$ are fluid flows; $0.3 < \beta < \beta_{\lim}$ are flows in a dense phase.

From the data of Table 1 we can infer that, at flow rates of the air of over 0.18 $g \cdot sec^{-1}$, there is a gas-suspension flow, and at $G < 0.18$ $g \cdot sec^{-1}$, there is a fluid flow. The boundary between the regimes is independent of the direction of a change in the air flow rate. At $G > 0.18$ $g \cdot sec^{-1}$, the flow rate of the solid phase depends weakly on the gas flow rate.

In experiments on investigating the heat transfer, we varied the flow rate of the carrier gas and maintained the temperature of the wall of the heat-transfer segment constant and equal to approximately 150°C.

The heat-transfer coefficient α was calculated from the temperature difference between the readings of thermocouples T_1 and T_5, which was 25–35 K, using the logarithmic-mean temperature difference. The wall temperature was found by averaging the readings of thermocouples TC_1, ..., TC_4.

Results of experiments for different flow rates of the carrier gas and the solid phase are given in Table 2, in which lines 1-4 correspond to the fluid regime of flow while lines 5-18 correspond to gas-suspension flow. In the fluid regime, the heat-transfer coefficient is higher by approximately a factor of 1.5 than in the gas-suspension flow and amounts to 160–170 $W \cdot m^2 \cdot K^{-1}$.

The values of α for μ = 160–170 differ significantly from the results of V. S. Nosov given in [1]. Possibly, this is explained by the fact that, in our experiments, a piston regime of disperse-system motion is realized in the heat-exchange tube. In powder "plugs," for small ($\approx$ 1000) values of Re, the particles are in a constrained state;

TABLE 2. Heat-Transfer Coefficient as a Function of the Flow Rate of the Carrier Gas.

No. of line	G	G_s	μ	β	V	Re	Pe(D/L)	α	Nu
1	0.15	25	167	0.042	2.24	1018	7.21	165	48.5
2	0.15	25	167	0.041	2.31	1017	7.20	165	49.4
3	0.17	29	170	0.044	2.47	1139	8.07	163	48.9
4	0.18	31	171	0.045	2.62	1220	8.65	173	51.6
5	0.17	5.6	31.1	0.0083	2.64	1211	8.58	102	30.3
6	0.19	6.3	29.2	0.0075	2.93	1297	9.18	117	31.2
7	0.20	6.3	30.9	0.0079	3.17	1328	9.37	113	32.3
8	0.19	5.6	29.2	0.0073	3.01	1254	8.84	103	29.3
9	0.28	6.6	23.9	0.0064	4.07	1882	13.3	118	35.4
10	0.26	5.9	22.4	0.0058	4.00	1726	12.2	104	29.7
11	0.36	8.0	22.2	0.0061	5.20	2387	16.9	135	39.2
12	0.36	7.5	20.8	0.0058	5.14	2490	17.6	111	33.9
13	0.47	8.3	17.7	0.0051	6.45	3114	26.0	136	39.6
14	0.47	7.9	16.9	0.0048	6.44	3117	22.0	123	36.0
15	0.53	8.0	15.2	0.0043	7.27	3662	26.0	115	35.2
16	0.60	8.2	13.7	0.0040	8.03	4126	29.2	116	35.2
17	0.61	8.3	13.6	0.0045	7.32	4193	29.8	121	36.8
18	0.65	8.3	12.8	0.0039	8.14	4341	30.72	134	39.5

this leads to deterioration of radial mixing and hence of heat transfer. The values of α obtained for $\mu = 160-170$ are in qualitative agreement with the results of A. P. Litvak for the piston regime [1], where the heat-transfer coefficient was 90 and 145 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for different powders.

In the gas-suspension flow, in regimes that are laminar and transitional as far as the gas is concerned, the heat-transfer coefficient varies weakly in the investigated range of the gas and powder flow rates and is 100–140 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$.

The error of indirect measurement of α did not exceed 10%; the main contribution to it is made by the averaging of the tube-wall temperature over the readings of thermocouples $\mathrm{TC}_1, \ldots, \mathrm{TC}_4$. The average temperature of the wall was determined to an accuracy of ±5 K.

We should note that the heat-transfer coefficients obtained in calculation by formula (1) are more than twice the values of α given in Table 2 for similar flow regimes. This demonstrates the impossibility of using formula (1) to calculate the heat transfer in a dust-laden gas flow that is laminar in the gaseous phase.

The results were processed using the least-squares method, and approximate dependences of Nu on the experimental parameters were obtained. We performed a four-factor regression analysis and established the dependence of Nu on such variables as $1 + C_s\mu C^{-1}$ and $\mathrm{Pe}DL^{-1}$. No dependence of Nu on Re and $\rho_s\rho^{-1}$ was revealed: the coefficients of these terms in the regression equation differ little from zero with a confidence level of 95%. This is apparently due to the fact that the indicated variables varied weakly in the experiments.

The approximate dependences have the following form:

$$\frac{\mathrm{Nu}_{\mathrm{fl}}}{\mathrm{Nu}} = a\left(1 + \frac{C_s\mu}{C}\right)^b \left(\mathrm{Pe}\frac{D}{L}\right)^c K, \tag{3}$$

where $K = (TT_w^{-1})^{0.45}$ for $\mathrm{Re} > 2400$ and $K = 1$ for $\mathrm{Re} < 2400$. The factor $(TT_w^{-1})^{0.45}$ is introduced to allow for flow nonisothermicity in the region that is transitional to the turbulent region.

The coefficients a, b, and c in relationship (3), the variances δ_0^2 that characterize the deviation of the experimental points from the approximating curve, and the variances of the coefficients a, b, and c for different ranges of Re and μ are given in Table 3. The maximum error of the approximations proposed does not exceed 12%.

TABLE 3. Coefficients a, b, and c in Eq. (3) and Variances δ_0^2, δ_a^2, δ_b^2, and δ_c^2 for Different Ranges of Re and μ

Re	μ	a	b	c	$\delta_0^2 \cdot 10^3$	$\delta_a^2 \cdot 10^3$	δ_b^2	δ_c^2
1200–2400	10–30	1.94	0.45	0.58	1.19	1.69	0.001	0.001
2400–4200	10–30	3.27	0.45	0.41	3.75	127	0.001	0.001
900–4200	10–30 166–172	1.55	0.45	0.64	3.95	15.7	0.015	0.001

In conclusion, we should note that when a chemical reactor with powdered material as one of the reagents is employed it is possible to use a solid phase as thermal capacity and to perform synthesis in a steady-state thermal regime virtually under adiabatic conditions, for example, in gravitational fall of the powder in a tube of rather large diameter. In this case, the heat released in the reaction zone is completely absorbed by the powdered component, and then, outside the reactor now, the powder is cooled to the required temperature in one of the devices described above and is supplied to the synthesis zone again.

It also seems very promising to use a dust-laden gas flow as the reaction zone for performing a highly exothermic gaseous-phase process. In this system, the powder acts as an inert heat-transfer agent that absorbs the heat of the reaction. The coefficient of heat transfer from the gas to the powder particles is determined by the distance between the particles in the dust-laden gas flow and can attain values of the order of 1000 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$. In this case, owing to the high α the Frank-Kamenetskii parameter [3]

$$\delta = \frac{Q}{\alpha} \frac{E}{RT^2} D k_0 \exp\left(-\frac{E}{RT}\right)$$

turns out to be smaller than its critical value even for reactions with a rather high activation energy E, and the synthesis takes place in a steady-state thermal regime without changing to combustion and explosion.

NOTATION

G_s, flow rate of the powder, $\mathrm{g \cdot sec^{-1}}$; G, flow rate of the air, $\mathrm{g \cdot sec^{-1}}$; ρ_s, solid-phase density, $\mathrm{kg \cdot m^{-3}}$; ρ, gas density, $\mathrm{kg \cdot m^{-3}}$; V_s, velocity of powder motion, $\mathrm{m \cdot sec^{-1}}$; V, velocity of gas motion, $\mathrm{m \cdot sec^{-1}}$; μ, flow-rate (flow) concentration; β, true bulk concentration of the solid component; β_{lim}, limiting true bulk concentration of the solid component; F_s, volume of the solid component, $\mathrm{m^3}$; F, volume of the gas, $\mathrm{m^3}$; F_{syst}, volume of the system; $\mathrm{Nu_{fl}} = \alpha_{\mathrm{fl}} D \lambda_{\mathrm{fl}}^{-1}$, Nusselt number for the dust-laden gas flow; $\mathrm{Pr_{fl}} = \eta_{\mathrm{fl}} \alpha_{\mathrm{fl}}^{-1} \rho_{\mathrm{fl}}^{-1}$, Prandtl number for the dust-laden gas flow; $\mathrm{Re_{fl}} = \rho_{\mathrm{fl}} V_{\mathrm{fl}} D \eta_{\mathrm{fl}}^{-1}$, Reynolds number for the dust-laden gas flow; C_s, heat capacity of the solid component; η_{fl}, viscosity of the dust-laden gas flow, Pa·sec; a_{fl}, thermal diffusivity of the dust-laden gas flow, $\mathrm{m^2 \cdot sec^{-1}}$; λ_{fl}, thermal conductivity of the dust-laden gas flow, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$; α_{fl}, heat-transfer coefficient of the dust-laden gas flow, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$; D, channel diameter, m; L, channel length, m; α, heat-transfer coefficient, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$; P, pressure, atm; $\mathrm{Nu} = \alpha D \lambda^{-1}$, Nusselt number for the gas flow; $\mathrm{Pr} = \eta a^{-1} \rho^{-1}$, Prandtl number for the gas; $\mathrm{Re} = V D \rho \eta^{-1}$, Reynolds number for the gas flow; $\mathrm{Pe} = V D a^{-1}$, Péclet number for the gas flow; η, gas viscosity, Pa·sec; α, thermal diffusivity of the gas, $\mathrm{m^2 \cdot sec^{-1}}$; T_w, wall temperature °C; δ, Frank-Kamenetskii parameter; Q, thermal effect of the reaction, $\mathrm{J \cdot m^{-3}}$; E, activation energy, $\mathrm{J \cdot mole^{-1} \cdot K^{-1}}$; R, universal gas constant; k_0, preexponential factor, $\mathrm{sec^{-1}}$.

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