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HEAT EXCHANGE OF DYNAMIC POWDER BEDS WITH A HEAT-TRANSFER SURFACE. I. A HELICAL SCREW CONVEYER AND A HORIZONTAL ROTATING CYLINDER

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Heat exchange of dynamic (mixing) beds of powders with heat-transfer surfaces in a tube with a helical conveyer and in a rotating smooth horizontal cylinder is studied by experimental methods. The heat-transfer coefficients as functions of the regime of powder motion are obtained.

In chemical technology, there are a number of highly exothermic processes that occur in a gas-solid system, for example, fluorination of gaseous hydrocarbons, halogen hydrocarbons, and other compounds by powdered higher fluorides of variable-valence metals (in particular, cobalt trifluoride), the fluoride-carbon interaction, etc. When a reactor for processes of this kind is constructed, removal of the released heat from the reaction zone becomes one of the major problems. In a reactor in the shape of a tube of diameter of the order of hundreds of millimeters with a fixed powder bed, through which a gas is blown, a non-steady-state thermal regime of the exothermic reaction is generally realized: a filtration-combustion wave is formed. In many cases, the wave regime of synthesis turns out to be suitable for industrial use [1, 2].

At the same time, use of a reactor with a fixed powder bed that operates in a steady-state thermal regime turns out to be inefficient [3] since these powder beds have a very low ($0.01-0.1\ W \cdot m^{-1} \cdot K^{-1}$) thermal conductivity [4]. To ensure a steady-state thermal regime for the interaction of a powder and a gas in a chemical reactor, we can use dynamic (mixing) powder beds, in which the intensity of heat transfer is much higher than in fixed beds [5]. Different types of dynamic powder beds used in industrial apparatuses are known: a fluidized bed, a vibrating-rotating bed, a dust-laden gas flow, and beds mixed by means of a helical screw conveyer and in a rotating horizontal cylinder with a degree of filling of less than 3.14 rad.

Heat transfer in beds of the first two types has been studied in sufficient detail [5, 6]. Data on the last three systems are limited, and therefore we performed experimental work on this problem.

In the first stage, we investigated the heat exchange of a powder with the wall of a tube along which the powder is moved using a flexible helical screw conveyer. In the few publications [7-10] on flexible-conveyer operation, the problems of calculating the apparatus capacity and the velocity of material motion as functions of the rotational speed, the conveyer diameter, and the lead of the helix are presented while heat-transfer processes are virtually not considered.

The basic element of the laboratory setup, a diagram of which is given in Fig. 1, is horizontal tube 1 with an inside diameter of 20 mm, in which a helical screw conveyer rotates. The tube is assembled from three separable sections; the length of each section is 300 mm. The temperature of the tube wall is maintained constant using electric heaters U_1, U_2, and U_3 and wall thermocouples TC_1, TC_2, and TC_3 that are connected to systems of automatic temperature control. The powder is supplied to the heat-transfer tube from bin 2 via unheated tube 3 with a radius of curvature of the order of 400 mm.

The flexible conveyer is rotated using a dc motor with a variable number of revolutions; the flow rate of the powder is varied by altering the rotational speed. The dimensions of the flexible conveyer were selected according to the recommendations of [10]: $D_{hel} = (0.75-0.90)D$; $\delta = (0.15-0.20)D_{hel}$; $s = (0.75-1.40)D_{hel}$.

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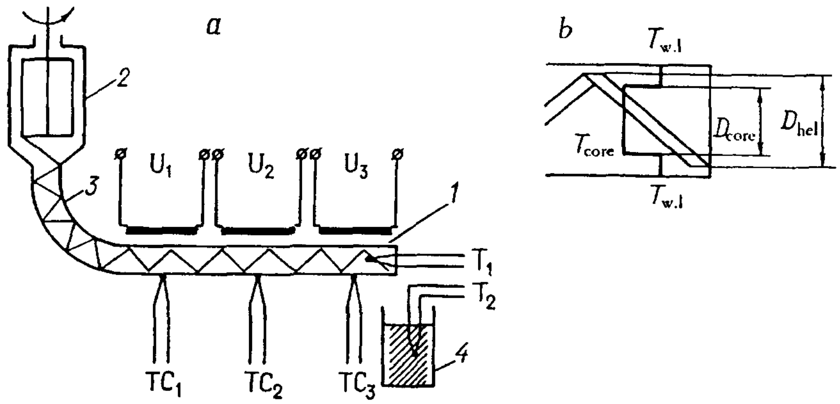

Fig. 1. Diagram of the laboratory setup (a) and the temperature distribution in a powder flow (b).

TABLE 1. Temperatures T_1, T_2, and $T_{w.l}$ and Heat-Transfer Coefficient α as Functions of the Flow Rate and the Linear Velocity of the Solid Phase

G_s	V_z	T_1	T_2	$T_{w.l}$	α	$\alpha_{w.l}$
1.9	0.005	132	135		89	
4.2	0.010	89	120		129	
6.0	0.015	70	106	141	135	49
7.8	0.020	59	98	137	149	92
12.5	0.030	50	92	132	209	66
16.8	0.040	46	88	130	262	42
20.4	0.050	44	86	128	289	79

In the experiments, use was made of helices 17 mm in diameter, the diameter of the helix wire was 3 mm, and the pitch of the helix was 12, 17, and 24 mm.

Using Chromel-Copel thermocouples we measured the powder temperature on the channel axis at the outlet from the heated segment (thermocouple T_1) and the average powder temperature in collector 4 (thermocouple T_2).

The experiments were conducted with predried $Al(OH)_3$ powder with an average particle size of 50 μm and a bulk density of $1.2 \cdot 10^3$ kg·m^{-3}.

If it is assumed that the average velocity of the axial motion of the material V_z is equal to the axial velocity of a helix turn U_{hel}, then $V_z = U_{hel} = ns$; then the theoretical flow rate of the solid phase is

$$G_s = ns\rho_b F\psi . \tag{1}$$

Measurement of the flow rate of the powder on the laboratory setup enabled us to establish that the experimental values of G_s and the values calculated by formula (1) for $\psi = 1$ differ by no more than 10% for the conveyer with a 12 mm pitch in the interval of $(0-20) \cdot 10^{-3}$ kg·sec^{-1}, for the conveyer with a 17 mm pitch in the interval of $(0-15) \cdot 10^{-3}$ kg·sec^{-1}, and for the conveyer with a 24 mm pitch in the interval of $(0-8) \cdot 10^{-3}$ kg·sec^{-1}, i.e., indeed, $V_z = U_{hel}$ and $\psi = 1$ in the indicated intervals.

For the conveyer with a pitch of 12 mm, we conducted a series of experiments on measuring the heat-transfer coefficient in the flow-rate range of $(1.9-20.4) \cdot 10^{-3}$ kg·sec^{-1} for a length of the heated segment of the tube of 900 mm, a wall temperature of 150°C, and an initial powder temperature of 20°C. The powder temperature was measured 30–50 times, after which its values were averaged. The random error is in the interval of ±1.5 K with a confidence level of 0.95.

Results of determining the temperature by thermocouples T_1 and T_2 are given in Table 1. We should note that with a powder flow rate of the order of 2 g·sec^{-1} the temperature measured by thermocouple T_1 is close to the average temperature of the flow, measured by thermocouple T_2. Next, as the flow rate increases from 2.5 to 8 g·sec^{-1} the difference between the readings of thermocouples T_1 and T_2 increases, and it practically

TABLE 2. Temperatures T_1 and T_2 and Heat-Transfer Coefficient α as Functions of the Ratio of the Length of the Heated Segment to the Diameter LD^{-1} for Conveyers with Various Pitches s for a Flow Rate of the Solid Phase $G_s = 7.82 \cdot 10^{-3}$ kg·sec^{-1}

LD^{-1}	$s = 12$			$s = 17$			$s = 24$		
	T_1	T_2	α	T_1	T_2	α	T_1	T_2	α
15	26	59	168	35	66	205	42	69	236
30	36	80	150	64	85	166	76	91	190
45	58	98	148	90	105	183	114	118	227

does not change in the interval of 8–20 g·sec^{-1}, being of the order of 40 K. Thus, there is a two-layer temperature distribution over the channel diameter: the temperature of the flow core is much lower than the temperature of the wall layer (Fig. 1b). In this case, the bulk of the heat resistance is concentrated in a wall layer of thickness $0.5(D - D_{hel})$. Table 1 gives the calculated temperature of the wall layer $T_{w.l}$. We assumed $D_{core} = D_{hel} - \delta = 14$ mm.

Based on the results of measuring the powder temperature we calculated the heat-transfer coefficient α using the logarithmic-mean temperature difference (Table 1). Furthermore, Table 1 gives the wall heat-transfer coefficient $\alpha_{w.l}$, calculated from the values of $T_{w.l}$, as a function of the flow rate. It follows from the table that, in the flow-rate range studied, the heat-transfer coefficient varies from 100 to 300 W·m^{-2}·K^{-1}. Its increase with the flow rate of the powder is due to intensification of the mixing of the latter as the rotational speed of the flexible conveyer increases.

We conducted experiments with a constant flow rate of the solid phase of $7.82 \cdot 10^{-3}$ kg·sec^{-1} for different lengths of the heated segment ($LD^{-1} = 15$, 30, and 45) and with conveyers with different pitches ($s = 12$, 17, and 24 mm).

Table 2 gives readings of thermocouples T_1 and T_2 and the heat-transfer coefficient α as functions of the length of the heated segment for conveyers with different pitches. It follows from the table that the larger the pitch of the helical conveyer, the smaller the temperature difference ΔT between the first and second thermocouples, from which we can infer that the larger the pitch, the more intense the radial mixing of the powder. It can also be seen that the heat-transfer coefficient increases with the pitch of the helix. The quantity α depends weakly on the length of the heated segment.

The error of indirect measurement of α does not exceed 10% in the experiments conducted. The main contribution to it is made by the averaging of the wall temperature over the readings of thermocouples TC_1, TC_2, and TC_3 (the deviations from the average value are ±5 K).

Intense mixing of powder can also be produced when a horizontal rotating cylinder with a degree of filling with the powder of less than 3.14 rad is used as the chemical reactor.

A mathematical model that permits calculation of the coefficient of heat transfer from a powder bed to the surface of a smooth rotating cylinder is given in [5]. One of its main assumptions is the absence of slippage of the powder along the cylinder wall, which, according to [5], leads to a nearly twofold difference between the existing calculated and experimental data. In [11, 12], heat-transfer coefficients are experimentally measured for particles with a size of over 160 μm, and α is shown to depend strongly on the particle size.

A relation for calculating α obtained based on processing the experimental data of [11] is recommended for use for particles with a characteristic dimension of over 200 μm; however, it is inapplicable for calculating the heat transfer of cobalt difluoride powder (one of the most common fluorine carriers in chemical technology), whose particle size varies from 1 to 10 μm. Therefore we performed a laboratory investigation of the heat exchange of CoF_2 powder with the wall of a smooth rotating cylinder. The bulk density of the powder was 800–1000 kg·m^{-3}.

The basic element of the laboratory setup is a steel cylinder (the outside diameter is 0.22 m, the inside diameter is 0.208 m, and the length is 0.17 m) that is rotated using a motor with a variable number of revolutions. The outer surface of the cylinder is washed with a heat-transfer agent (water), incident from nozzles that are mounted perpendicular to the surface. The velocity of incidence of the heat-transfer agent is such that the coefficient

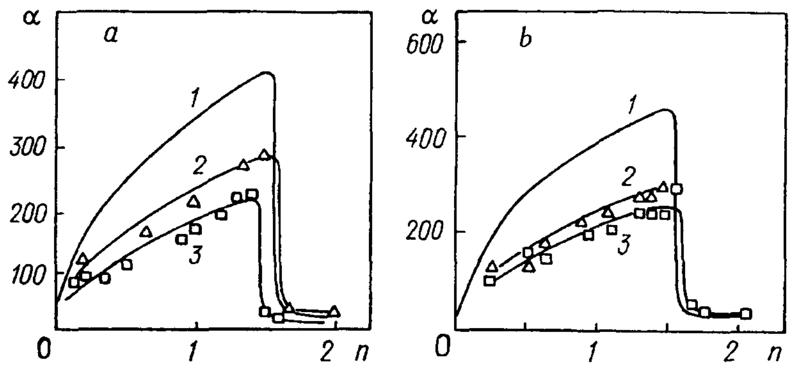

Fig. 2. Heat-transfer coefficient α vs. rotational speed n, obtained by calculation and experimentally (for $\theta = 2.84$ (a) and 2.14 (b)): 1) calculated dependence; 2) experiment, $P = 10^6$; 3) the same, $P = 10^5$.

of heat transfer from the exterior surface of the cylinder to the heat-transfer agent is of the order of 5000 $W \cdot m^{-2} \cdot K^{-1}$. In the cylinder, gas-filled airtight cavities are mounted on the ends using double lateral walls. This enables us to practically eliminate heat flux through the ends of the cylinder (according to estimates, it does not exceed 1–2% of the radial flow).

The powder temperature was measured using three Chromel–Copel thermocouples 200 μm in diameter, arranged parallel to the cylinder axis at different distances from the axis. The position of the thermojunctions can be altered in the radial direction.

In the experiments, the rotational speed of the cylinder was varied and the powder temperature was recorded. Nitrogen was used as the filler gas.

To obtain an experimental value of the heat-transfer coefficient, we determined the volume-average temperature of the powder from the readings of the three thermocouples and calculated α using the logarithmic-mean temperature difference.

The variation in the average temperature of the powder during an experiment was 15–25°C, which does not exceed 30% of the temperature difference, and no variation in α was recorded in an experiment.

Heat-transfer coefficients α obtained in this manner as functions of the rotational speed of the cylinder are given in Fig. 2 for different degrees of filling of the cylinder and pressures of the filler gas in it. It can be seen that α increases with the rotational speed of the cylinder, attains a maximum, and then decreases sharply. Criticality occurs because, at rotational speeds of the cylinder higher than n_{cr}, the powder moves together with the cylinder walls, forming a fixed ring on the inner surface of the cylinder. The maximum α is different for different experimental conditions; it varies from 310 $W \cdot m^{-2} \cdot K^{-1}$ for the cylinder with $\theta = 2.14$ rad and $P = 10^6$ Pa to 220 $W \cdot m^{-2} \cdot K^{-1}$ for $\theta = 2.84$ rad and $P = 10^5$ Pa. A higher heat-transfer coefficient α corresponds to a lower degree of filling. The error of indirect measurement of α does not exceed 6%.

The results in Fig. 2 show that α depends on the pressure; its value at $P = 10^6$ Pa is, on the average, 15–20% higher that at $P = 10^5$ Pa while, according to the calculated data [5], this difference should not exceed 1–2%. Possibly, this is explained by the fact that the drift velocity of 3–4 $mm \cdot sec^{-1}$ for cobalt difluoride particles is much lower than the rate of gas circulation in the segment unoccupied by the powder that is due to the motion of the cylinder surfaces and the powder and can attain 1 $m \cdot sec^{-1}$. In this case, the gas in the cylinder is dust-laden and the gas component must be regarded as a gas suspension. For this system, the fraction of the heat transferred through the segment unoccupied by the powder increases sharply as compared to a dust-free gas [12], and now we cannot disregard this contribution to the transfer of heat, as was done in [5]. On the other hand, the intensity of the heat transfer through the segment unoccupied by the powder increases with the pressure; therefore the values of α increase.

Figure 2 gives, for comparison, dependences $\alpha(n)$ for a cylinder with a diameter of 0.2 m calculated by the mathematical model of [5]. It can be seen that the general form of the heat-transfer coefficients α as functions of the cylinder's rotational speed n obtained experimentally and by calculation coincides, although α_{exp} is, on the

TABLE 3. Factors A and Exponents b in Formula (2) Obtained in Processing Experimental and Theoretical Results ($b_{calc} = 0.5$)

θ	P	A_{exp}	A_{calc}	b_{exp}
2.84	10^5	168.8±12.2	352.8	0.43±0.07
2.84	10^6	223.4±12.6	355.0	0.49±0.07
2.14	10^5	217.8±8.5	406.1	0.51±0.05
2.14	10^6	239.7±8.0	408.6	0.49±0.05

average, 1.5–2 times lower than α_{theor} and the disagreement between the calculated and experimental results increases with the rotational speed. This is explained by the assumptions made in [15] in deriving the calculational formulas, namely, by the absence of slippage of the powder relative to the cylinder wall. Experimental data enable us to assume that the slippage becomes more intense as the rotational speed increases.

The difference between the critical rotational speed n_{cr} measured experimentally and calculated theoretically by the formula

$$n_{cr} = \left(\frac{g}{2\pi^2 D}\right)^{0.5}$$

does not exceed 5% for a cylinder with a diameter of 0.2 m.

In [5], it is recommended that the dependence of α on the rotational speed n be approximated by the power function

$$\alpha = An^b\,, \quad b = 0.5\,. \tag{2}$$

Factors A and exponents b in dependence (2) obtained in processing the experimental results (Fig. 2) using the least-squares method are given in Table 3, from which it follows that the exponent in dependence (2) obtained experimentally practically coincides with the theoretical value while the values of A obtained experimentally and calculated theoretically differ by a factor of 1.5–2.

NOTATION

D, diameter of the channel and the rotating cylinder, mm; D_{hel}, helix diameter, mm; D_{core}, diameter of the flow core, mm; T_{core}, core temperature, °C; $T_{w.l}$, temperature of the wall layer, °C; δ, thickness of the wire of which the helix is manufactured, mm; s, pitch of the screw helix, mm; V_z, velocity of the axial motion of the material, $m \cdot sec^{-1}$; L, length of the heated channel, mm; n, rotational speed, sec^{-1}; G_s, flow rate of the solid phase, $g \cdot sec^{-1}$; ρ_b, bulk density of the powder, $kg \cdot m^{-1}$; F, cross-sectional area, m^2; ψ, coefficient of filling of the conveyer; n_{cr}, critical rotational speed of the cylinder, sec^{-1}; α, heat-transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$; g, free fall acceleration, $m \cdot sec^{-2}$; θ, degree of filling of the cylinder, rad; P, pressure, Pa; U_{hel}, axial velocity of a helix turn, $m \cdot sec^{-1}$; T_1, temperature at the outlet from the heated channel; T_2, temperature of the powder in the collector.

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