THERMAL RELAXATION TIME OF PARTICLES IN A FLUIDIZED BED

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Results are given of an experimental investigation of the thermal relaxation time of particles in a fluidized bed. Values of the coefficient of heat transfer from particles to gas are determined.

The thermal relaxation time for particles in a fluidized bed has been determined experimentally by direct measurement of the temperature of the particles from the moment of immersion in the bed. The temperature difference between the bed and the particle under investigation was measured with the aid of a differential copper/constantan thermocouple (wire diameter 0.2 mm), whose junction was embedded in granules of the test material. To reduce the conduction of heat to the granule along the thermocouple leads, the latter were sheathed with fiberglass over a length of 200 mm from the junction. One of the junctions was located in the fluidized bed, which was heated until steady conditions were established; the other junction was quickly introduced into the bed along with the granule. The thermocouple readings were fed into an oscillograph and recorded on photographic paper. The variation of temperature difference as a function of the residence time of the granule in the bed was simultaneously observed on the oscillograph screen, and the relaxation time was registered with a two-needle timer. For convenience of calculation, before beginning the experiment the "spots" of the two mirror galvanometers (working and null galvanometers) were made to coincide (when the thermocouple emf was zero).

Table 1
Thermal Relaxation Time of Particles at $\Delta t_0 = 30°$ C

Material	Particle size, mm	Gas velocity, m/sec	Fluidization number	Relaxation time, sec		
				according to		Experimental value
				[3]	[1]	
Silica-gel	3.3	3.01	2.32	16.4	—	10.5
MSN copolymer	4.5	3.52	3.14	172	29.9	10.28
MSN copolymer	2.45	2.58	3.61	53	18.9	14.52
MSN copolymer	1.73	1.96	3.79	26	8.7	10.1

The experiments were conducted with a single silica-gel fraction (particle size 3.3 mm) and three polystyrene copolymer fractions (1.73 mm, 2.45 mm, 4.5 mm) at various values of the initial temperature difference. Each measurement was repeated 35–40 times. The thermocouple leads undoubtedly influenced the motion of the granule with the junction, and hence its rate of heat transfer to the medium. However, no significant inhibition of the motion of the granule was observed in the experiments. The results of the experimental determination of the particle thermal relaxation time are given in Tables 1 and 2.

Table 2
Thermal Relaxation time for Various Initial Temperature Differences

Initial temp. difference, °C	Relaxation time, sec	
	for MSN polystrene copolymer (1, 73 mm)	for MSN polystrene copolymer (2, 45 mm)
30	10.46	16.76
25	12.2	20.0
20	11.08	17.88
15	10.24	12.24
10	9.2	11.62

The variation of mean particle temperature may be obtained by considering the particle as a sphere located at time zero in a medium with constant temperature t_c. The solution of this problem has been given in [1].

$$\bar{\Theta} = \frac{t_c - t}{t_c - t_0} = \sum_{n=1}^{\infty} B_n \exp(-\mu_n^2 \mathrm{Fo}). \tag{1}$$

Confining our attention to the first coefficients μ_1 and B_1 and assigning values of $\bar{\Theta}$, we may determine, from the Fo number, the time τ corresponding to a given $\bar{\Theta}$. We substitute in the Bi number the value of the heat transfer coefficient calculated from the equation obtained in [2]. The experimental and calculated relations between temperature difference and time are comparatively close (see figure).

The results of calculations of the relaxation time from Eq. (1), with the temperature difference reduced to 10% of its initial value, and the results of calculations from the approximate equation of Dow and Jakob [3] with the same reduction in temperature difference are presented in Table 1. It can be seen from the table that the experimental data agree better with the results of calculations based on Eq. (1).

From the data on the heating of a particle in the fluidized bed we can calculate the coefficient of heat transfer from particle to gas. We write the heat balance equation for the particle:

$$c_M \gamma_M \frac{\pi d^3}{6} dt = \alpha \pi d^2 (t_c - t) d\tau. \tag{2}$$

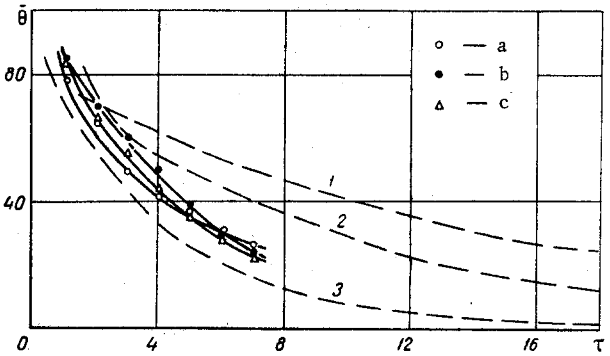
Separating the variables and integrating both sides of the equation over the corresponding limits, we obtain

$$\int_{t_0}^{t_n} \frac{c_M \gamma_M d}{6\alpha} \frac{dt}{t_c - t} = \int_0^{\tau_n} d\tau. \tag{3}$$

From (3), after integration, we obtain an expression for the heat transfer coefficient:

$$\alpha = \frac{c_M \gamma_M d}{6\tau_n} \ln \frac{t_c - t_0}{t_c - t_n}. \tag{4}$$

Values of heat transfer coefficient during the heating process were calculated from (4) at various times in the range from 1 to 7 sec (Table 3). In all the experiments lower values of α were observed in the initial heating period, after which the value of the heat transfer coefficient remained practically constant.



Variation of relative temperature difference with time for MSN particles: 1,2,3) calculation based on Eq. (1) with d = 4.5, 2.45, and 1.73 mm, respectively; a,b,c) experiment at the same particle diameters.

The lower values of the heat transfer coefficient in the initial heating period are evidently due to the influence of heat transmission along the leads of the thermocouple embedded in the granule. As shown in [4], in the initial period, in the presence of conducting thermocouple leads, the rate of change of temperature of the body (and hence the heat transfer coefficient) increases time. The duration of this initial period, which depends on the rate of heat transfer between the thermocouple leads and the bed, has been calculated from an equation obtained in [4]. For our experiments this time was 1.89–2.14 sec. As may be seen from Table 3, a constant value of the heat transfer coefficient was established 3–4 sec after the beginning of heating. It is also possible that in the initial period the slowing down of heating of the particle is caused by the thermal resistance of the cold gas film adjacent to the particle, which endures for some time after immersion in the bed.

Comparative calculations of the heat transfer coefficients were made on the basis of the equation obtained in [5] and an expression for the "true" heat transfer coefficient obtained by the authors of [2]. The results of the calculations are given in Table 3. The experimental values of the heat transfer coefficient are of the same order as those calculated from the equations.

The error in measurement of the heat transfer coefficient arising from transmission of heat along the thermocouple leads was determined approximately by the method described in [4]. The mean value of the error was 22.2%; the maximum value (for the smallest particle diameter) was 40.1%.

Experiments were also performed to determine the time to heat moist particles of silica-gel 3.3 mm in diameter to the temperature of the bed. In this case the granule with the embedded junction of the differential thermocouple was premoistened. In these experiments variation of the temperature difference was determined not only by the oscillograph, but also by a potentiometric recorder, five points of which were connected to the differential thermocouple, while one point showed the temperature of the bed.

The duration of the first period of drying of the particle was 44.15 sec; the duration of the second period was 32.48 sec. It is characteristic that the second period is considerably greater than the relaxation time of a dry particle of silica-gel (Table 1).

The heat transfer coefficient for a moist particle was determined as follows. Since the second period is rather long, it may be assumed that the mean temperature difference in this period is equal to the arithmetic mean of the initial and final temperature differences, i.e., $\Delta t_m = \Delta t_0/2$.

The moisture content of the particle in the second period is small, and so we may assume approximately that the heat transfer coefficient in this period is equal to the heat transfer coefficient for a dry particle. The heat supplied to the particle in the second period is expended in heating the particle and vaporizing the moisture. Taking into account the above assumptions,

Table 3

Values of Coefficient of Heat Transfer from Particles to Gas

Material	Particle size, mm	Heat transfer coefficient, W/m² · deg.										Experimental Nu values
		after heating for, sec							mean value	according to		
		I	II	III	IV	V	VI	VII		[5]	[2]	
Silica-gel, dry	3.3	98.2	103	105	106	111	110	108	108.1	298	480	12.6
Silica-gel, moist	3.3	Average value in first period							169	—	—	19.6
MSN copolymer	4.5	424	500	489	504	511	514	500	503	345	510	80.1
MSN copolymer	2.45	210	247	235	239	253	263	280	252	126	448	22.3
MSN copolymer	1.73	82.5	173	222	263	267	257	262	262	67.4	386	16.3

the amount of heat supplied to the particle in the second period may be written as

$$Q_2 = \alpha\pi d^2 \frac{\Delta t_0}{2} \tau_2. \tag{5}$$

The heat going into heating the particle is

$$Q_{2\mathrm{h}} = c_{\mathrm{M}} \gamma_{\mathrm{M}} \frac{\pi d^3}{6} (t_c - t_0). \tag{6}$$

Then the heat expended in vaporizing the moisture in the second period is

$$Q_{2\mathrm{v}} = Q_2 - Q_{2\mathrm{h}}. \tag{7}$$

The mean moisture content of the particle was determined from weighing data for the individual granule of silica-gel (dry and moist). Thus, when the weight of the dry particle was determined, the total amount of evaporated moisture was known. Then the amount of heat going into vaporization of moisture in the first period may be written as

$$\begin{aligned} Q_1 = Q_{1\mathrm{h}} = Q_{\mathrm{v}} - Q_{2\mathrm{v}} &= \\ = G_{\mathrm{w}} (2490 + 1.97\, t_c - 4.19 t_0) \cdot 10^3 - Q_{2\mathrm{v}}. \end{aligned} \tag{8}$$

Hence the heat transfer coefficient for a moist particle is given by

$$\alpha = Q_1 / \pi d^2 (t_c - t_0) \tau_1. \tag{9}$$

The value of α obtained is shown in Table 3. The heat transfer coefficient for a moist particle is greater than that for a dry particle by a factor of 1.56.

Thus the experimental results show that the relaxation time for large particles and the heating time for moist particles in the fluidized bed are considerable. Therefore in calculating heat transfer in the bed we must take account of heat transfer between the particle and the gas.

NOTATION

t_c) temperature of bed; t_0 and t) initial and variable temperature of particle; t_n) temperature of particle during time interval τ_n; Δt_0 and Δt_m) initial and mean temperature differences; Θ) relative temperature difference; d) particle diameter; c_M) heat capacity of particle material; γ_M) density of particle; Q) heat transmitted to particle; G_W) amount of moisture contained in one particle; μ_n) roots of the characteristic equation $\mathrm{tg}\, \mu = -(\mathrm{Bi} - 1)^{-1} \mu$; $B_n = 6\mathrm{Bi}^2/\mu_n^2 (\mu_n^2 + \mathrm{Bi}^2 - \mathrm{Bi})$. Subscripts: 1 and 2) first and second drying periods; v) vaporation; h) heating.

REFERENCES

1. A. V. Luikov, Theory of Heat Conduction [in Russian], Gostekhteorizdat, 1952.
2. L. K. Vasanova and N. I. Syromyatnikov, Khimicheskaya promyshlennost, no. 11, 1963.
3. W. Dow and M. Jacob, Chemical Engineering Progress, 47, 637, 1951.
4. M. A. Kaganov and I. S. Lisker, IFZh, no. 9, 1963.
5. N. A. Shakhova and A. I. Rychkov, MIKhM, 12, 1957.

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