THE TRANSFER OF HEAT FROM A BED OF FINELY DISPERSED MATERIAL FLUIDIZED BY A STREAM OF GAS OR THROUGH APPLICATION OF VIBRATIONS

S. S. Zabrodskii, I. L. Zamnius, S. A. Malyukovich, and A. I. Tamarin

Inzhenerno-Fizicheskii Zhurnal, Vol. 14, No. 3, pp. 448–453, 1968

UDC 536.248

We have measured the intensity of the transfer of heat between a bed of finely dispersed material (particle dimensions <100 μm) and a surface set into the bed. The bed has been fluidized by the filtration of a gas through the bed, or by means of vibration.

To enhance heat- and mass-transfer processes, industry has recently begun to employ the fluidized bed [1]. An inert granular material is selected as the intermediate heat carrier in such a system. The intensity of the process depends in great measure on the particle dimensions of this material. It has repeatedly been confirmed [2–9] by experiment that with a reduction (up to a certain limit) of the particle dimensions of the fluidized bed, the value of α_w is increased. The purpose of the experiment described in this article was to determine this limit in corundum, i.e., to find the particle diameter at which the value of α_w attains a maximum value, and how it varies with a further reduction in the particle dimensions when electrocorundum is fluidized with a gas or through application of vibrations.

The tests on a bed fluidized by gas were carried out on a quartz column 64 mm in diameter and 1000 mm in height. A stainless-steel strip with a cross section of 1.2 × 6 mm, with a winding pitch of 12 mm, was wound in a spiral exhibiting a diameter of 40 mm and a height of 120 mm along the axis of the column, at a height of 50 mm above the gas-distribution grid. The ends of the spiral were welded to steel rods 20 × 5 mm in cross section, and these served simultaneously as current conductors and mounts for the spiral. The spiral strip was immersed into the fluidized bed and heated by the electrical current passing through it. To determine the temperature of the spiral, thermocouples were embedded at three points along the length of the spiral. The temperature of the spiral was automatically kept constant throughout the experiments.

The temperature of the fluidized bed was recorded by means of thermocouples positioned above the gas-distribution grid at distances of 45, 90, and 165 mm. The power dissipated by the heater was determined from the magnitude of the current and from the voltage dif-

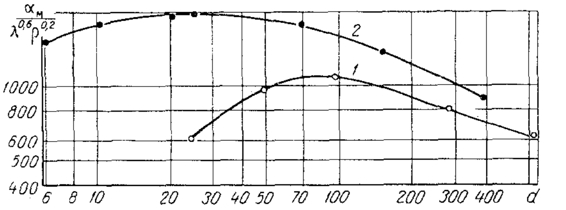

Fig. 1. Complex $\alpha_m/\lambda^{0.6}\rho^{0.2}$ versus particle diameter (μm): 1) for air-fluidized bed; 2) for vibrofluidized bed.

ference at the ends of the spiral. We calculated the coefficient of heat transfer between the surface of the heater and the bed from the magnitude of the power dissipated within the bed and from the average temperature difference.

As demonstrated by the calculations carried out in accordance with [12], the end losses of the heater did not exceed 2%. The studies were carried out for a heater-surface temperature ranging up to 1000° C. The initial height of the bed was 175 mm.

The tests were carried out on corundum with an average particle diameter of 24, 48, 95 μm (ρ = = 3750 kg/m^3) and sand with grain diameters of 280 and 630 μm (ρ = 2600 kg/m^3). The narrow fractions of particles exhibiting a dimension of ≤48 μm were produced by elutriation on an industrial installation. The dimensions were monitored microscopically. The fine dust was first removed from the larger corundum and sand particles. The average particle dimensions were

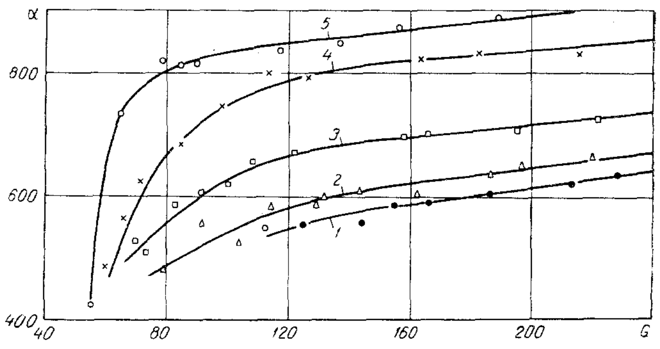

Fig. 2. Heat-transfer coefficient α (W/m^2 · deg) versus filtration rate G (kg/m^2 · hr) for corundum particles d_m = 48 μm at temperatures: 1) 155; 2) 310; 3) 430; 4) 520; 5) 675° C.

determined from the dispersion curve or by means of a microscope, and the mean-square deviation did not exceed 16%.

Curve 1 in Fig. 1 shows the experimental results, which are also given in Table 1. Each experimental point has been obtained by averaging several of the experiments carried out at various bed temperatures.

Table 1

The Value of the Heat-transfer Coefficient for Corundum Particles with d_{av} = 95 μm as a Function of the Filtration Rate at Various Temperatures

t	G	α_w	t	G	α_w	t	G	α_w
160	166	476	530	74	600	600	163	940
	193	573		87	675		219	965
	222	587		100	722		281	1000
	258	673		120	787		383	990
	290	685		143	810	760	65	836
	366	770		164	815		78	900
	412	766		208	865		92	915
	445	735		239	880		112	925
445	93	593		258	915		132	960
	108	620		278	903		157	970
	119	680		296	925		183	990
	147	715		320	915		198	1020
	180	786	600	67.5	734		260	1050
	194	795		85	815	850	79	955
	214	825		108	872		113	1000
	289	894		132	881		155	1030
	331	905		138	922		214	1090
	448	880						

The scatter of the points did not exceed 10%, thus not exceeding the limits of measurement accuracy. To describe the experimental data derived for various temperatures in the two materials (corundum and sand), we employed the following empirical relationship from [9]:

$$\alpha_m = 35.8\ \lambda^{0.6} \rho^{0.2} d^{-0.36}\ \text{W/m}^2 \cdot \text{deg}. \qquad (1)$$

The experimental data were processed in the form of the complex $\alpha_m/\lambda^{0.6}\rho^{0.2}$ as a function of the particle diameter. The heater-surface temperature was chosen as the governing temperature. The system adopted for the processing of the experimental data made it possible to ascertain the quantitative relationship governing the change in the maximum heat-transfer coefficient as a function of particle dimensions in the fluidized bed. In the region of large particles, the quantity α_m increases with an increase in the particle dimensions, in accordance with relationship (1). In the region of the fine particles (<100 μm), curve 1 (Fig. 1) attains a maximum, subsequent to which we find a reversal in the shape of the function: the heat-transfer coefficient diminishes as the particle dimensions become smaller. This is obviously associated with the overheating of the fine particles relative to the larger particles, said overheating taking place as a result of an impairment in the intensity of mixing within the bed (owing to the agglomeration of the finely dispersed particles), as well as because of the reduction in the heat capacities of individual particles.

We know that the forces of adhesion between the particles—brought about by the presence of a moisture film—diminishes the temperature rises. We also know [11] that with a temperature in excess of 250–300° C there are virtually no electrostatic forces of adhesion, and the friability of the material must improve as a result. The experiment confirmed that a bed made up of particles 24 μm in size cannot be fluidized by air at room temperature, while at temperatures above 250° C the bed is satisfactorily fluidized.

The bed is not homogeneous in this case, and the motion of individual particle clusters is clearly visible; this is due primarily to the van der Waals forces. Moreover, the clustering of the particles is confirmed by the fact that the velocity for the onset of fluidization is higher in the system than that given theoretically according to [13]. Naturally, a further increase in the temperature of the bed will not improve the mixing of the material and the values of α_m derived for various higher bed temperatures corresponded to the identical particle diameter.

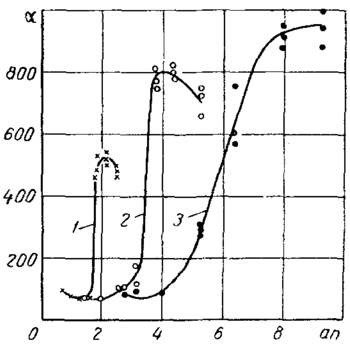

Fig. 3. Heat-transfer coefficient α (W/m^2 · · deg) versus vibration rate an (cm/sec) for corundum particles d_m = 68 μm: 1) a = = 1 mm; 2) 2; 3) 4.

Table 2

Values of the Heat-transfer Coefficient for Corundum Particles 150 μm in Size, for Various Vibration Parameters

n	$a = 1$ mm			$a = 2$ mm			$a = 4$ mm		
	an	$a\omega^2$	α_w	an	$a\omega^2$	α_w	an	$a\omega^2$	α_w
400	0.67	1.77	100	1.34	3.54	90	2.67	7.08	100
600	1	3.97	80	2	7.94	80	4	15.88	110
800	1.33	7.02	75	2.67	14.05	80	5.33	28.10	370
1000	1.67	11.02	90	3.34	22.04	190	6.68	44.08	700
1200	2	15.76	560	4	31.52	630	8	32.04	740
1400	2.34	21.70	610	4.68	43.40	660	9.36	86.80	750
1600	2.67	28.2	620	5.34	56.40	680	10.68	112.80	—

We should note the nature of the relationship between α_w and the filtration rate for the very fine particles (Fig. 2). The heat-transfer coefficient in this case increases monotonically as the filtration rate of the air increases, and this continues all the way to the regimes at which the material is carried out of the bed, without reaching the maximum value. The heat-transfer coefficients obtained at the boundary of material removal from the bed as the maximum attainable values due to entrainment have been conditionally plotted in Fig. 1 on a par with the usual values of α_m. As we can see from curve 1 in Fig. 1, smaller values of α_w are attainable for particles 48 μm in size than for particles 95 μm in size.

On application of vibrations to the bed, the monotonic nature of the relationship between α_w and the velocity an set in at a corundum-particle dimension smaller than 10 μm.

We know that the possibility of transmitting energy to a particle by means of an air stream is impaired with a reduction in particle dimension, since noticeable entrainment of the material from the bed begins for relatively low speeds, whereas the forces of surface interaction between the particles increase approximately in inverse proportion to the particle diameters. It is therefore natural that the finely dispersed materials cannot be brought to the fluidized state, nor can they be brought to a state of violent mixing within the bed exclusively by means of gas filtration. Additional energy must be introduced into the bed for the fluidization of such materials, e.g., the energy of mechanical vibrations.

As is well-known, we can fluidize a bed of finely dispersed powder by subjecting the column to vertical vibrations. The intensity of heat transfer from the bed to the surface in the case of high column-vibration rates is independent, in this case, of the air filtration rate [10], and the subsequent tests were therefore carried out on a column without gas filtration.

A plastic column (110 mm in diameter and 500 mm in height) with a solid bottom was mounted on a vibrator platform which executed vertical oscillations with an amplitude of up to 4 mm, with a frequency range from 0 to 25 Hz. A cylindrical sensor, 8.6 mm in diameter and 30 mm in height, was mounted vertically along the axis of the column, and this sensor vibrated together with the column. The sensor was positioned at a height of 20 mm above the bottom. Its surface was made up of a tightly wound copper wire, 100 μm in diameter.

The sensor was connected into an electrical bridge circuit which made it possible to maintain a constant surface temperature of 60° C, and in addition, it was possible to measure the power dissipated from the sensor [10]. The bed temperature was measured with a copper resistance thermometer. This series of experiments was conducted with narrow electrocorundum fractions (average particle dimensions of 6, 10, 20, 24, 68, and 150 μm, and on sand grains 389 μm in size). The initial material layer in the column was 70 mm in height.

The experimental data derived for corundum particles of 68 and 150 μm are shown in Fig. 3 and in Table 2. We see from the curves that the heat-transfer coefficient does not vary linearly as the rate of vibrations (an) increases. With an increase in the vibration rate there is a drop in the growth rate for α_w, and we even find a maximum for the curve which is extended farther as the vibration amplitude increases. A similar shape for the function $\alpha_w = f(an)$ and the presence of a maximum in the curve were observed in virtually all of the investigated fractions. The experiments with fine particles (5–7 μm) represented an exception, with the growth rate for α_w slowing down somewhat, although remaining positive within the region of high an. In these cases, we arbitrarily assumed the largest of the measured quantities to be the value of α_w.

The results from experiments carried out with particles of various diameters are given in Fig. 1 in the form of the complex $\alpha_m/\lambda^{0.6}\rho^{0.2}$ as a function of particle dimensions (curve 2) for purposes of comparison with data derived for a fluidized bed. The coefficient α_m was determined for a vibration frequency of 23.4 Hz and an amplitude of 4 mm.

As shown in Fig. 1, in both of these cases the intensity of heat transfer initially rises with a reduction in particle dimensions, and then it falls. In the region of relatively large particles (>100 μm) both of the curves become inclined parallel straight lines. In a logarithmic coordinate system the slope of these straight lines is 0.36, i.e., the dependence on the dimensions of the particles is analogous to relationship (1).

It is interesting to note that curve 2 (the vibration-fluidized bed) is higher than curve 1 (the gas-fluidized bed) over the entire investigated range of particle dimensions. Even in the region of relatively large particles, where the forces of surface interaction are slight, the heat-transfer intensity in the vibration-fluidized bed is virtually 35% higher than in the gas-fluidized bed. It is obvious that in the vibration-fluidized bed the mixing of the material is more intensive than in the air-fluidized bed, even for a higher particle concentration.

This investigation has demonstrated that in the fluidization of a bed of finely dispersed material by means of vibration it is easy to attain high heat-transfer coefficients (on the order of 1000 $W/m^2 \cdot deg$) for a bed into which surfaces have been immersed, even in the case of low heat conduction by the gaseous medium of the bed (the air at room temperature). The use of vibration-fluidized beds of finely dispersed materials thus becomes promising on an industrial scale.

NOTATION

α_w and α_m are the coefficients of heat transfer between the surface and the bed, and their maximum values, $W/m^2 \cdot deg$; λ_g is the gas thermal conductivity, $W/m \cdot deg$; ρ is the density of the material particles, kg/m^3; d is the particle dimension, in μm; a is the vibration amplitude; n is the frequency of vibration, in rpm.; ω is the angular velocity of vibration; t is the wall temperature, in °C; G is the mass velocity, in $kg/m^2 \cdot hr$.

REFERENCES

1. Collection: Application of the Fluidized Bed in the National Economy of the USSR, Proceedings of the All-Union Seminar held in September-October 1963 at the Tsvetmetinformatsiya VDNKh, 1965 [in Russian].

2. H. S. Mickley and C. A. Trilling, Ind. Eng. Chem., **41**, 1135, 1949.

3. H. S. Mickley and D. F. Fairbanns, A. I. Ch. E. Journ., **1**, 374, 1955.

4. A. Baerg, J. Klassen, and P. E. Gischler, Can. Jr. Research, **28**, 287, 1950.

5. R. D. Toomey and H. F. Johnstone, Chem. Eng. Progr., Symposium, ser. 5, **49**, 51, 1953.

6. A. Jakob and G. L. Osberg, Can. J. Chem. Eng., **35**, no. 1, 1957.

7. E. Wicke and F. Fetting, Chem. Ingn. Tech., **26**, no. 6, 1954.

8. C. Heerden, A. P. Nobel, and D. W. Krevelen, Gen. Disc Heat Transf. IME London, ASME, 1951.

9. S. S. Zabrodskii, Hydrodynamics and Heat Transfer in a Fluidized Bed [in Russian], GEI, 1963.

10. A. I. Tamarin, S. S. Zabrodskii, and I. L. Zamnius, collection: Study of Heat- and Mass-Transfer in Industrial Processes and Equipment [in Russian], Nauka i tekhnika, Minsk, 1966.

11. V. L. Ganzha, S. S. Zabrodskii, and S. A. Malyukovich, DAN BSSR, **12**, no. 2, 1968.

12. A. V. Luikov, Theory of Heat Conduction [in Russian], GITTL, 1952.

13. V. D. Goroshko, R. B. Rozenbaum, and O. M. Todes, Izvestiya VUZ., Neft i gaz, no. 1, 1958.

27 July 1967

Institute of Heat and Mass Transfer AS BSSR, Minsk