INVESTIGATING THE EFFECTIVE THERMAL CONDUCTIVITY OF A VIBRATING BED IN A VACUUM

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UDC 536.2

We describe the experimental installation and give the results from experimental determination of the effective thermal conductivity of a vibrating bed in a vacuum, in the horizontal direction, for various vibration parameters and for various particle sizes of the fine-grained material.

When a fine-grained material is subjected to vibration, the particles are set in motion and the gas phase is set into circulation. A so-called vibrating bed is formed [1-3].

In a vibrating bed, in addition to the mechanism of heat transfer in the fixed bed [4] we have the transfer of heat resulting from the displacement or convection of the particles themselves and from the circulation of the gas phase. Moreover, because of particle collision there is a slight increase in the contact area between the particles. This serves also to intensify the process of heat propagation in the vibrating bed [5].

The ability to transfer heat in a vibrating bed can be characterized by means of the effective coefficient of thermal conductivity.

The circulation of the gas medium that is generated on vibration has a pronounced effect on the nature and intensity of particle motion, particularly for materials exhibiting poor air permeability. With the system in a vacuum, the effect of the medium on particle motion diminishes and at low pressures may be eliminated entirely. Since the nonmoving bed of fine-grained material at these pressures exhibits low thermal conductivity, the transfer of heat, consequently, in the vibrating bed in a vacuum is achieved primarily through the convection of the particles themselves. Evacuating the vibrating bed thus made it possible to determine how the vibration parameters affect the effective thermal conductivity of a fine-grained material.

The determination of the effective coefficient of thermal conductivity was based on a steady-state method. It was assumed that the bed is in the shape of a cylindrical wall with a height l and an inside radius r_1, the outside radius denoted r_2. Since the investigations were carried out at low pressure, the losses from the top surface of the bed could be regarded as equal to zero with a high degree of accuracy, and to reduce the leakage of heat through the bottom of the vessel, thermal insulation was provided. The intensive local mixing of the particles in the vertical direction, as well as the comparatively small height of the bed, allow us to neglect the temperature gradient along the axis of the bed. Measurement of the temperatures in the vibrating bed confirmed this hypothesis.

Proceeding from these premises, we solved the familiar problem of steady-state heat conduction under boundary conditions of the second kind, but with consideration of the heat leakage through the bottom of the vessel. The latter, because of the absence of an axial temperature gradient, could be equated to the effect of internal heat sinks, distributed uniformly over the entire bed, and the volume output of these sinks was determined by the expression

$$q_V = \frac{\Delta Q}{\pi (r_2^2 - r_1^2)\, l}. \tag{1}$$

The final formula for the determination of the effective coefficient of thermal conductivity in the horizontal direction had the form

Kirov Urals Polytechnic Institute, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 16, No. 6, pp. 1039-1044, June, 1969. Original article submitted July 23, 1968.

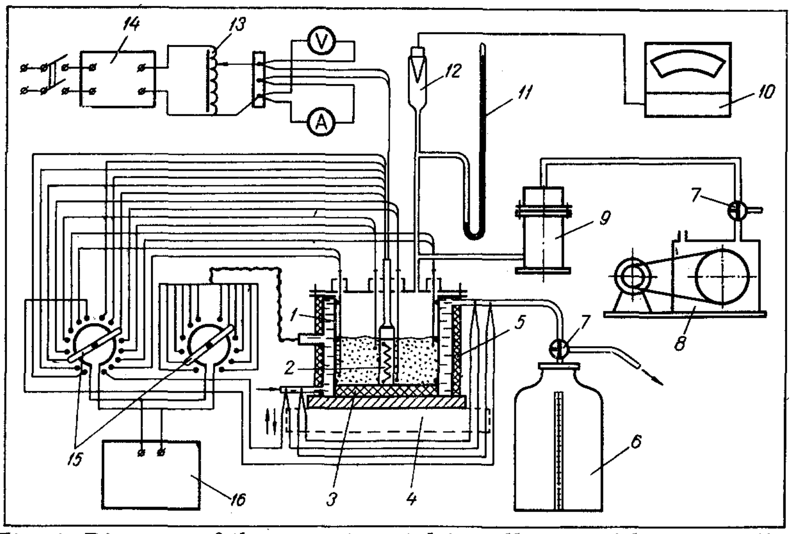

Fig. 1. Diagram of the experimental installation: 1) hermetically sealed vessel; 2) electric heater; 3) Textolite insulation; 4) table of vibration stand; 5) asbestos insulation; 6) metering tank; 7) three-way valve; 8) RVN-20 preevacuation pump; 9) filter; 10) VT-2A thermocouple vacuum gauge; 11) liquid vacuum gauge; 12) LT-2 manometer tube; 13) autotransformer; 14) S-0.09 stabilizer; 15) switch; 16) PP-63 potentiometer.

$$\lambda_{\text{eff}}=\frac{Q_{\text{el}}}{2\pi l(\vartheta_1-\vartheta_2)}\left[\ln\frac{r_2}{r_1}-\frac{\Delta Q}{Q_{\text{el}}}\left(\frac{1}{2}-\frac{\ln\frac{r_2}{r_1}}{\frac{r_2^2}{r_1^2}-1}\right)\right]. \tag{2}$$

The assumption of uniform distribution for the internal heat sink is not entirely valid, since the heat losses under real conditions depend on the temperature of the bed. However, as shown by numerical calculations, failure to account for this factor in the case of overall losses not exceeding 30% leads to an insignificant error smaller than 2%. Equation (2) was therefore taken as the basic working formula for the determination of the effective coefficient of thermal conductivity.

With consideration of the above, we developed an experimental installation whose diagram is shown in Fig. 1. As the fine-grained test material we used electrical corundum of narrow fractions with particle dimensions of 0.32 and 0.16 mm; it was poured into the hermetically sealed vessel 1 (154 mm in diameter) so as to cover completely (with an excess of 3-5 mm) the axially positioned cylindrical heater 2 whose diameter is 15 mm and whose height is 60 mm. The outside wall of the vessel was cooled with running water. The heater was powered from an ac main through voltage stabilizer 14 and autotransformer 13. To determine the heat losses ΔQ we measured the temperature difference for the cooling water ahead of and behind the vessel, and also the water flow rate, using metering tank 6.

The hermetically sealed vessel 1 was attached rigidly to the table of vibration stand 4, executing vibrations in the vertical direction. The ST-80 vibration stands made it possible to smoothly vary the vibration frequency from 30 to 80 Hz, and to vary the amplitude from 0 to 1 mm.

With preevacuation pump 8 the system was evacuated to 80-133 N/m^2, which was monitored by means of the thermocouple vacuum gauge 10, paired with manometer tube 12.

During the experiment, after establishment of the steady-state regime, which was achieved within 1.5-2 h, we repeatedly took the readings of the thermocouples that had been embedded into the surface of the heater and the side wall of the vessel, as well as of the thermocouples located in the vibrating bed at several points near the heater and near the side wall, separated from these through distances of 2-3 mm. We used a PP-63 potentiometer as the measuring device 16.

TABLE 1. Values of Temperatures Measured during the Experiment ($P = 100\ N/m^2$; $d = 0.32$ mm; $I = 1.17$ A; $U = 12.65$ V; $Q_{el} = 14.8$ W; and $G = 0.0058$ kg/sec)

τ, min	t_1, °C	t_2, °C	t_3, °C	t_4, °C	t_5, °C	t_6, °C	t_7, °C	t_8, °C	t_9, °C	t_{10}, °C	t_{11}, °C	t_{12}, °C	t_{13}, °C	Δt, °C
0	21,9	22,4	21,7	22,1	22,8	21,6	132,2	130,5	129,5	34,6	37,2	29,1	29,3	0,52
3										34,0	36,6	28,6	29,7	0,52
6	21,9	22,3	21,7	21,9	22,8	21,6	131,4	129,5	128,5	34,3	34,8	29,0	29,2	0,54
9										34,9	35,8	29,4	29,4	0,56
12	21,8	22,3	21,6	21,8	22,8	21,7	131,5	129,5	128,0	36,0	35,3	29,1	29,9	0,56
15										35,5	36,3	29,3	29,6	0,54
18	21,6	22,1	21,4	21,7	22,7	21,7	132,0	130,0	129,5	36,3	35,7	29,4	30,0	0,54
21										36,6	36,5	29,6	29,9	0,56
24	21,6	22,0	21,4	21,8	22,7	21,6	132,3	130,5	129,0	36,4	35,2	29,4	30,0	0,54
27										36,0	35,8	29,6	29,8	0,54
30	21,5	22,0	21,4	21,8	22,7	21,6	133,5	131,0	129,8	36,2	36,6	29,5	30,0	0,54
	21,7	22,2	21,5	21,8	22,8	21,5	132,1	130,2	129,0	35,5	36,0	29,3	29,7	0,54
	21,9						130,4			ϑ_1=35,75		ϑ_2=29,48		0,54

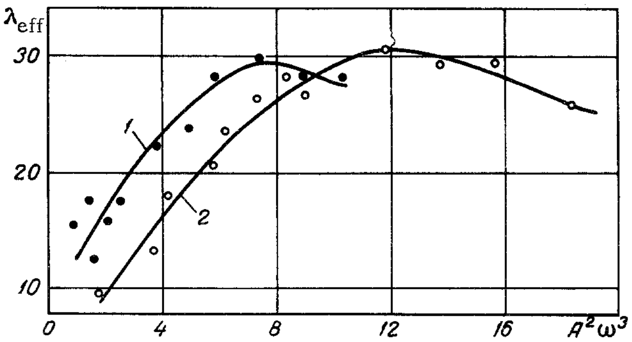

Fig. 2. Effective coefficient of thermal conductivity (W/m · deg) for the vibrating bed in the horizontal direction as a function of the parameter $A^2\omega^3$ (m^2/sec^3): 1) f = 51 Hz; 2) f = 61 Hz; P = 80-133 N/m^2; d = 0.32 mm.

A number of tests were first carried out to evaluate the heat leakage through the bottom of the vessel for various vibration and pressure parameters of the gas medium. In these series of tests, the flow rate and temperature variation of the cooling water was carefully monitored. The effect of the transfer of heat between the outside surface of the water sleeve and the ambient medium was reduced to a minimum by applying insulation 5 and by supplying the cooling water at room temperature. The data for one such test, after establishment of the steady-state regime (when f = 41 Hz, A = 0.58 mm, and P = 100 N/m^2) are given in Table 1.

The heat losses calculated on the basis of these data amount to 1.7 W or 11.5%. In all of the remaining tests, the heat losses ranged within the limits of 8-15%. For such losses and for the instrument design under consideration, as can be established by calculation, Eq. (2) differs from the expression

$$\lambda_{eff} = \frac{Q_{el}}{2\pi l (\vartheta_1 - \vartheta_2)} \ln \frac{r_2}{r_1} \tag{3}$$

by only 1.5-3%, which enables us to use (3) to determine the effective coefficient of thermal conductivity, without concern as to accuracy.

We investigated the effective thermal conductivity of the vibrating bed at frequencies of 41, 51, 61, and 69 Hz. The results obtained with a vibration frequency of 51 and 61 Hz are shown in Fig. 2 as a function of $A^2\omega^3$. If we disregard the energy absorption in the bed, this parameter is proportional to the power which may be received by a unit volume of the disperse material at the vibration frequency and amplitude of the vibration-stand platform; this parameter provides better characterization of the particle-motion intensity [6] than any other.

We see from Fig. 2 that with an increase in $A^2\omega^3$ for a fixed value of frequency the effective coefficient of thermal conductivity passes through a maximum, since there is an increase in the porosity of the bed that is simultaneous with the increase in the intensity of particle motion, and this initially leads to a slowing down of the increase in λ_{eff}, and then to a slight reduction in this magnitude.

TABLE 2. Results from an Experimental Determination of λ_{eff} in the Horizontal Direction

f, Hz	A, mm	P N/m²	d, mm	λ_{eff} W/m. deg
41±2	0,24	105,0	0,32	4,3
	0,29	97,5		9,0
	0,35	102,3		17,8
	0,39	96,7		23,2
	0,43	101,0		18,1
	0,58	100,0		13,5
	0,72	96,7		16,8
41±2	0,29	121,2	0,16	7,9
	0,31	99,5		8,1
	0,35	111,8		11,5
	0,40	95,0		20,3
	0,46	95,0		16,8
	0,56	86,4		16,6

f, Hz	A, mm	P N/m²	d, mm	λ_{eff}, W/m. deg
69±2	0,20	112,0	0,32	14,2
	0,25	120,6		25,2
	0,28	115,0		34,7
	0,29	108,6		30,7
	0,33	112,0		35,9
	0,34	108,6		30,5
	0,38	108,6		23,8
	0,41	105,0		19,2
	0,44	111,0		24,0
	0,45	100,0		23,4
69±2	0,18	1 atm	0,32	57,9
	0,25	1 atm		49,6
	0,33	1 atm		38,4

The tests were carried out at a frequency of 41 Hz with electrical corundum exhibiting an average particle diameter of 0.32 and 0.16 mm. As we can see from Table 2, the reduction in particle size by a factor of 2 for the given frequency has virtually no effect on the magnitude of the effective thermal conductivity.

In this same table we find results from an experimental determination of λ_{eff} for a vibration frequency of 69 Hz in a vacuum, and for purposes of comparison, at atmospheric pressure. In the latter case, the heat losses were greater than 15%, and the tests were then evaluated on the basis of Eq. (2). Comparison of these data shows that the effective thermal conductivity at atmospheric pressure is greater by approximately 40-60% than in a vacuum, since the circulation of the gas medium which arises in this case is propagated over the entire volume of the bed, moreover, it exerts additional perturbing influence on particle motion.

NOTATION

r_1, r_2	are the inside and outside radii of the bed;
l	is the height of the bed;
ΔQ	are the heat losses through the bottom of the vessel;
q_V	is the volume output of the internal heat sinks;
λ_{eff}	is the effective coefficient of thermal conductivity in the horizontal direction;
$Q_{el} = UI$	is the heat flow from the electric heater;
U	is the voltage;
I	is the current;
ϑ_1, ϑ_2	are the average temperatures in the bed, near the heater and the side wall, respectively;
f, A	are, respectively, the frequency and amplitude of vibration;
P	is the pressure of the gas medium;
ω	is the angular frequency;
G	is the flow rate of the cooling water;
d	is the particle dimension;
τ	is the time;
t_1, t_2, t_3, t_4, t_5, t_6	are the temperatures of the side walls of the vessel;
t_7, t_8, t_9	are the temperatures of the heater surface;
t_{10}, t_{11}	are the instantaneous temperatures in the bed near the heater;
t_{12}, t_{13}	are the instantaneous temperatures in the bed near the side wall;
Δt	is the change in the temperature of the cooling water.

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