HEAT TRANSFER BETWEEN A DENSE BED OF GRANULAR MATERIAL AND A VIBRATING CYLINDER FOR TRANSVERSE FLOW

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The authors present the results of an investigation of the heat transfer between a dense bed of sand and a cylinder vibrating at various frequencies and amplitudes in the horizontal and vertical planes. An equation is derived for determining the relative rate of heat transfer as compared with a stationary cylinder.

The problem of intensifying the heat transfer between a dense bed of granular material and a heating surface at right angles to the flow is one of considerable practical importance. One method of intensifying heat transfer is vibration, but the only published data relate to tests on a tubular heater [1, 2] with vibration of the vessel through which the material moves. These tests were made over a very limited range of variation of the operating conditions and are therefore inconclusive. We have investigated the same problem over a rather broad range of variation of the parameters, studying the effect of the direction of vibration (horizontal and vertical), the amplitude and frequency of the vibrations, and the velocity of the granular material.

For comparison we also investigated the heat transfer from a stationary cylinder. The test material was dry quartz sand (mean particle size $d_p = 0.3$ mm) flowing down a vertical shaft under stationary thermal conditions. The mean coefficient of heat transfer between bed and cylinder (outside diameter $d = 33.5$ mm) was determined in the usual way: from the amount of heat transferred and the difference between the mean temperature of the cylinder surface and the temperature of the oncoming flow of material.

Apart from the heat transfer we studied (by visual observation of the motion of colored layers) the nature of the flow over the cylinder at different material flow rates and vibration parameters. The experimental setup is shown schematically in Fig. 1.

In order to produce the vibrations we used a mechanical vibrator from which the cylinder was cantilevered across an insulating coupling. In view of the shortness of the cylinder the amplitudes of the vibrations at different points were practically the same.

The vibrator made possible horizontally or vertically directed cylinder vibration with various parameters.

In the experiments we measured the power of the electric heater, the temperature of the cylinder surface (12) copper-constantan thermocouples—see Fig. 1), the vibration frequency and amplitude at three points along the length of the cylinder, the temperature of the sand in front of the cylinder, the flow rate of granular material, and its bulk weight (section method).

The height of the column was selected so as to ensure stabilized motion and exclude the effect of the outlet on the velocity distribution over the section containing the cylinder. The relative width of the column [B/d] was 5.98, which, according to [3, 4], ensures self-similarity of motion with respect to that simplex.

Thus, the motion and hence the heat transfer were determined only by the dimensions of the cylinder, the velocity of the bed, and the vibration parameters.

The ranges of variation of the principal characteristics are presented in Table 1.

Figure 2a shows the mean heat transfer coefficient as a function of the material velocity for series I–V of Table 1 and without vibration (series X).

All these relations and the data presented in Table 2 indicate an increase in α with bed velocity. The bed velocity has its most important effect on α in the absence of vibration; as the vibration amplitude increases, the effect of bed velocity becomes less marked (Table 2).

The exponents in the relations $\alpha = Cv_b^n$ are equal to 0.26 without vibration and to 0.243 and 0.105 for vibration at amplitudes of 0.81 and 3.15 mm, respectively (Fig. 2a).

Table 1

Range of Variation of Principal Characteristics

Direction of cylinder vibration	Series no.	Bed velocity v_b, mm/sec.	Vibration amplitude 2A, mm	Vibration frequency f, Hz	Vibration velocity $v_v = 4Af$, mm/sec	$\frac{v_v}{v_b}$
Vertical	I	0.36— 7.1	0.81	21	34	4.80— 94.5
	II	1.25— 6.92	1.21	20	48.4	6.97— 38.4
	III	1.3 — 7.2	2.83	20	113.2	15.3 — 87.2
	IV	0.35—11.3	1.183	20	47.3	4.18—135.0
	V	0.35—10.73	3.15	20	126.0	12.0 —360.0
Horizontal	VI	1.28—11.7	0.71	20	28.4	2.43— 22.2
	VII	3.8 —10.82	3.11	13	80.4	7.95— 21.2
	VIII	1.3 —10.8	0.71	13	18.5	1.74— 14.2
	IX	1.33—10.73	3.11	20	124.4	11.6 — 93.6
Without vibration	X	0.3 —11.3	—	—	—	0

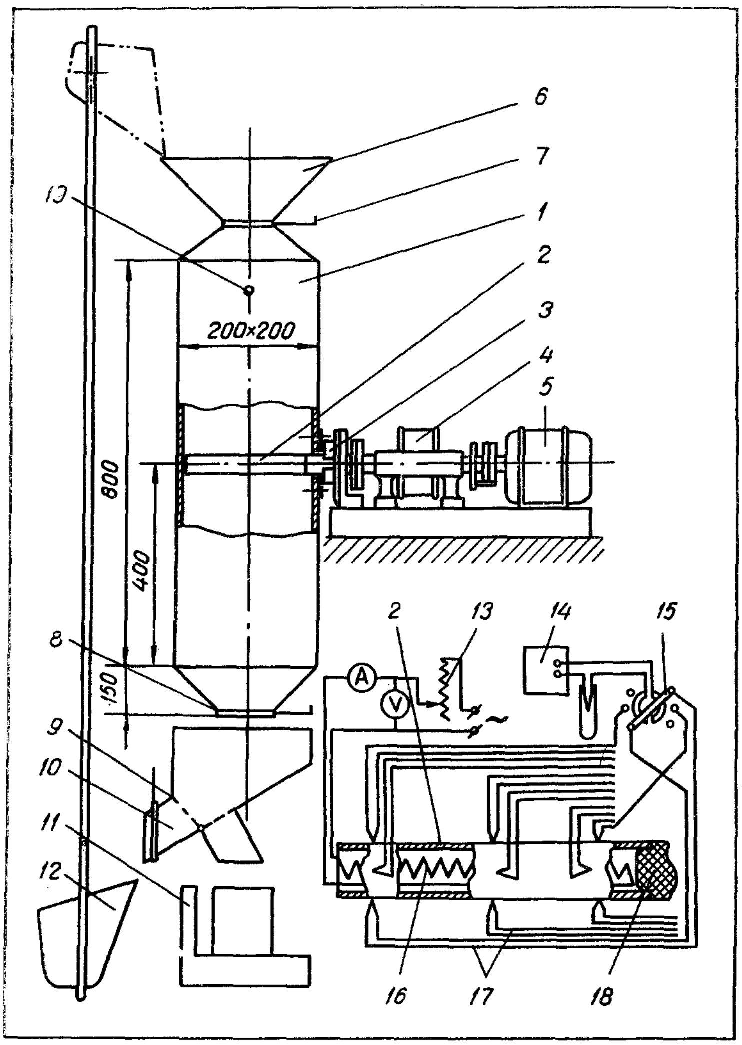

Fig. 1. 1) Column; 2) test cylinder; 3) vibrator; 4) speed regulator; 5) electric motor; 6) feed hopper; 7) upper gate; 8) lower gate; 9) flap; 10) discharge hopper; 11) scales; 12) skip hoist; 13) autotransformer; 14) potentiometer; 15) switch; 16) electric heater; 17) thermocouples; 18) thermal insulation; 19) mercury thermometer.

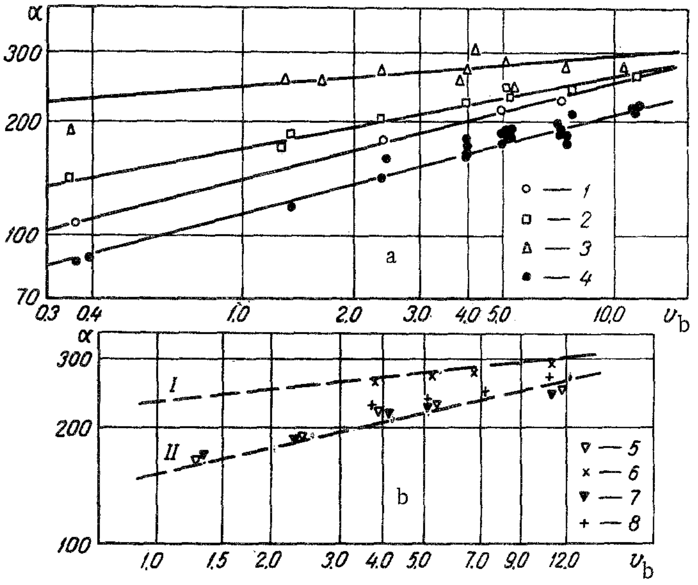

Fig. 2. Heat transfer coefficient (α, W/m^2 · g) as a function of bed velocity v_b, mm/sec: a) for vertical vibration; 1) vibration amplitude 2A = 0.81 mm, frequency f = 20 Hz; 2) 1.20 mm and 20 Hz, respectively; 3) 3.15 mm, 20 Hz; 4) 2A = 0, f = 0; b) for horizontal vibration; 5) vibration amplitude 2A = 0.71 mm, frequency f = 20 Hz; 6) 3.11 mm and 20 Hz, respectively; 7) 0.71 mm, 13 Hz; 8) 3.11 mm, 13 Hz; I) from data for vertical vibration with parameters 2A = 0.81 mm, f = 20 Hz; II) the same, 2A = 3.15 mm, f = 20 Hz).

Table 2

Intensification of Heat Transfer K at Various Relative Vibration Velocities

v_b, mm/sec	2A, mm	$\alpha, \frac{W}{m^2 \cdot deg}$	$K = \frac{\alpha_v}{\alpha_0}$	$\frac{v_v}{v_b}$
0.55	0	98	1	—
	0.81	125	1.275	61.7
	3.15	239	2.44	235.2
11.2	0	233	1	—
	0.81	258	1.11	2.83
	3.15	300	1.29	10.79

In the tests with and without vibration the bed velocity exerted its greatest influence on heat transfer in the region of v_b less than 2–3 mm/sec.

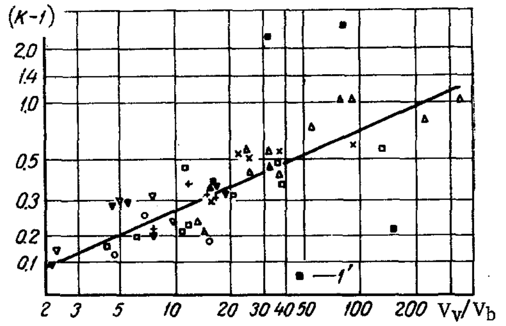

Fig. 3. Heat transfer rate as a function of relative vibration velocity: 1') According to the data of [1, 2]; for the rest of the notation see Fig. 2.

A comparison of the data obtained for stationary and vibrating cylinders at the same bed velocities points to the intensification of heat transfer as a result of vibration, this intensification, other things being equal, being the more appreciable, the greater the vibration amplitude. At the same amplitude the increase in heat transfer coefficient due to vibration is especially large in the region of low bed velocities (Fig. 2a, Table 2).

An analogous effect of bed velocity and vibration amplitude is also indicated by the results (Fig. 2b) of horizontal vibration experiments (series VI–IX, Table 1). These experiments, in which the frequency was varied as well as the amplitude, also reveal an increase in the rate of heat transfer as the frequency rises from 13–20 Hz, other things being equal. The graphs of heat transfer coefficient versus velocity obtained for horizontal and vertical vibration with the same parameters almost coincide. This is clear from Fig. 2b, where, apart from the data on horizontal vibration (experimental points), we have also plotted data on vertical vibration (lines I and II).

Thus, the rate of heat transfer does not depend on the relative direction of vibration and gravitational motion of the bed, and the corresponding mechanisms of the effect on heat transfer may be assumed to be analogous, being chiefly associated with the change in the nature of the flow over the cylinder under the influence of bed velocity and vibration.

As visual observations revealed, the flow pattern is not identical over the circumference of the cylinder: a prism of stationary material (stagnant zone) is formed at the front of the cylinder, the lateral surfaces are washed by the moving bed, and at the rear of the cylinder there is a separation zone (air pocket). This picture (the presence of stagnant and separation zones) is typical of flow over both stationary (in agreement with the data of [3, 4]) and vibrating cylinders. The increase in heat transfer coefficient with increase in velocity is attributable to a decrease in the size of the stagnant zone and the thickness of the boundary layer on the lateral surfaces.

Vibration causes additional changes in the flow pattern: reduction of the stagnant and separation zones and more intense mixing of material at the lateral surfaces leading to an increase in its effective thermal conductivity.

Thus, under the influence of vibration the fraction of the surface occupied by zones of high thermal resistance is reduced and the motion over the rest of the surface is intensified. These effects increase with increase in vibration frequency and amplitude and are especially noticeable at low bed velocities, when flow in the absence of vibration is least favorable.

These factors lead to a fall in the over-all thermal resistance of the moving bed and to an increase in the average heat transfer coefficient over the circumference.

Moreover, vibration is responsible for another effect that leads to an intensification of heat transfer—a certain compaction of the material and hence a further increase in its effective thermal conductivity. The visually observed compaction of the material is confirmed by determining the mean packing density of the moving bed over the volume of the column, which increases somewhat with the vibration amplitude. At the maximum amplitude ($2A = 3.15$ mm) the packing density increases from 64 to 68% (i.e., by 4% as compared with the experiments without vibration), which leads to an increase in the effective thermal conductivity of the bed from 0.262 to 0.311 $\mathrm{W/m^2 \cdot deg}$, i.e., by 19%. For a more thorough analysis of the effect of changes in packing density it would be necessary to determine it as the mean not over the entire volume of the column but only in the region of the cylinder, where it is most affected by vibration.

It follows from the above data that the heat transfer is determined by the rate of gravitational motion of the bed and the rate of vibration, which, by analogy with the gravitational motion, can be characterized by the vibration velocity $v_v = 4Af$. The influence of one factor is most apparent in the region where the intensity of the other is low.

Thus, the intensification of heat transfer by vibration is determined not by the absolute parameters, but by the relative vibration velocity v_v/v_b. This is confirmed by the results of a combined analysis of all the experimental heat transfer data obtained for stationary α_0 and vibrating α_v (Fig. 3).

Using the method of least squares, we obtained, with a probable error of ±12%, the following relation describing the heat transfer between a moving bed and a vibrating cylinder:

$$K = \frac{\alpha_v}{\alpha_0} = 1 + 0.107 \left(\frac{v_v}{v_b}\right)^{0.43}.$$

This relation holds within the following limits:

$$\frac{v_v}{v_b} = 1.74 - 357; \quad \frac{B}{d} > 2.0;$$

$$2A = 0.71 - 3.15\ \mathrm{mm}; \quad f = 13 - 20\ \mathrm{Hz};$$

$$v_b = 0.36 - 11.3\ \mathrm{mm/sec}; \quad v_v = 18.5 - 126\ \mathrm{mm/sec};$$

$$d_p = 0.3\ \mathrm{mm}; \quad d = 33.5\ \mathrm{mm}.$$

The equation obtained reflects the effect on heat transfer of the bed velocity and the vibration parameters over a quite broad range of variation and indicates that in the region investigated frequency and amplitude have an almost equal effect on heat transfer.

The conclusion that the intensification of heat transfer is determined by the relative vibration velocity is consistent with the data of [5] obtained for a vibrating cylinder in a transverse air flow. In [5] an appreciable increase in heat transfer was noted only at considerable ratios of vibration velocity to free-stream velocity.

An effect of vibration on the heat transfer of a dense bed flowing over a bundle of tubes was also observed in [1, 2] in tests on a tubular heater for granular materials (dry iron ore from the Lisakovskii deposit and moist aluminum fluoride powder). The tests were conducted with the heater housing vibrating at a frequency of 47 Hz and amplitudes of 0.1 and 0.24 mm (8 tests in all) and without vibration (3 tests) at bed velocities of 0.2–1.3 mm/sec.

In most of the experiments described in [1, 2] vibration led to an intensification of heat transfer. The experimental data of [1, 2] have been plotted in Fig. 3. As may be seen from the figure, on the average these data are consistent with our own, but are characterized by significant scattering (up to 150%). It should be noted that the conclusion drawn in [1, 2] concerning the important influence of vibration with respect to heat transfer intensification should not be regarded as general.

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