EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER BETWEEN A FLUIDIZED BED AND A CYLINDRICAL SURFACE

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A description is given of the method and the experimental results of a study of heat transfer between fixed cylinders of various diameters and a cylinder of diameter 10 mm moving in a fluidized bed.

Heat transfer between a fluidized bed and a fixed plane surface or cylinders of large diameter has been studied in sufficient detail [1–3]. The indications are that the heat transfer rate depends on the cylinder radius [4, 5], although there is not enough experimental material confirming this.

In connection with work we performed for hardware factories on heat treatment of wire in a fluidized bed, experimental verification was required of the influence of cylinder (wire) radius on heat transfer.

A parallel investigation was conducted of heat transfer transverse to a cylinder moving in a fluidized bed, the work being connected with a study of conditions of heat treatment of parts in a stream. In a series of papers [6–8] devoted to investigation of heat transfer under conditions of relative motion of a bed of fine-grained material and a heating surface, an examination was made either of heat transfer to the cylinder, but in a continuous moving stream [6], or of heat transfer in a fluidized bed, but of a plane surface [7, 8]. The results indicate that it is quite difficult to evaluate heat transfer in a fluidized bed with motion of poorly streamlined bodies (cylinders) along the perimeter of which there must be variation of bed particle concentration and variation of heat transfer coefficient [6].

Experimental equipment: This was a plexiglas tube of diameter 200 mm and height 800 mm (Fig. 1). The base of the tube was a steel gas distributor (clear cross section 0.55%) with apertures of diameter 0.5 mm, over which was fastened a metal mesh with apertures of 40 μ. Mounted in bearings along the tube axis was a hollow shaft 16/12 mm diam. with a calorimeter fastened to it—a vertical copper cylinder with a nichrome heater inside (the investigations were carried out under steady conditions), and a thermocouple welded to the wall. We used KhA grade KTMS-2 mircothermocouples [9], wrapped in steel sheathing 1 mm in diameter, made by the Cable Industry Scientific Research Institute. The calorimeter was insulated at the ends by textolite plugs penetrating 6 mm into it. The leads were taken out through the hollow shaft to a contact unit—copper rings with throw-off flexible copper connectors sliding on them. The connections of the thermoelectric wires were led off with an intermediate copper collector and taken away side by side so that their temperatures would be the same. A check showed that there was no intermediate thermo-emf, nor was there any parasitic frictional emf during operation of the contact unit, this being verified while the shaft was rotating by means of a potentiometer connected to a stabilized voltage source through the collector. Measurement of the thermo-emf was made with a PP-1 potentiometer to which was fed directly the difference in emf of the thermocouples located in the calorimeter wall and in the fluidized bed. End losses were not taken into account in reducing the experimental data. The temperature drop between the wall and the fluidized bed was checked for two points on the calorimeter wall—at a distance of 3 mm from the end and in the center. The deviation of the measured differences did not exceed 3%. We therefore used only one thermocouple in the working tests, its junction being 65 mm fron the end of the calorimeter. Under these conditions heat removal along the sheath and the thermo-electrodes did not come into play [10].

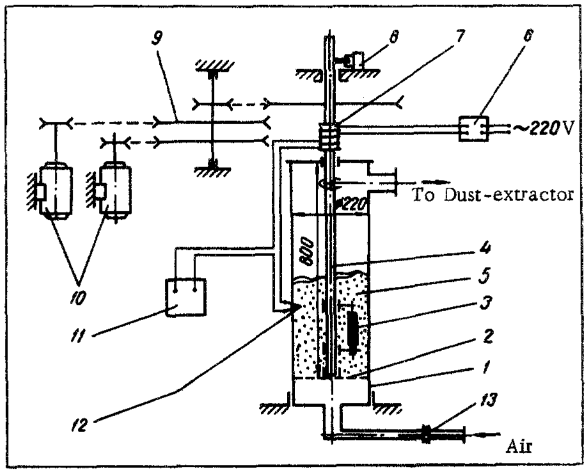

Fig. 1. Experimental equipment: 1) plexiglas tube; 2) air distributor; 3) calorimeter; 4) hollow shaft; 5) fluidized bed; 6) calorimeter supply transformer; 7) contact unit; 8) revolution counter; 9) system of pulleys; 10) electric motors; 11) PP-1 potentiometer; 12) fluidized bed thermocouple; 13) measuring diaphragm.

It was established by preliminary investigations that in transversely moving cylindrical copper calorimeters of diameter up to 10 mm with wall thickness of 1.5 mm, the thermocouple junction could be located at any point of the perimeter. Thermocouples mounted on the front, side and rear of cylinders of diameters 6/3 and 10/7 mm gave completely identical temperatures even at high relative velocities (3.5 m/sec) of the bed and the cylinder, i.e., the mean heat transfer coefficient around the cylinder may be computed from the reading of any of the thermocouples. A similar check for a copper calorimeter 19.8/14 mm diam. had already given a noticeable difference in the thermocouple readings, i.e., there was a clearly detectable temperature gradient around the cylinder under this condition of motion, and therefore there was also a variation of heat transfer coefficient.

The shaft was driven by two dc electric motors through a system of pulleys. The rate of rotation of the motors was controlled by varying the voltage supplied to them.

A single (fixed) calorimeter could be let down into the bed through a hole in the top.

The bed material was white electrical corundum (Soviet standard GOST 3647-59) with particle size 60, 120, and 320 μ, charged to a height of 360 mm above the distributor.

The working tests were made with fixed vertical copper cylinders of diameter 3, 6, 10, and 19.8 mm, fixed vertical porcelain cylinders of diameter 19.7 mm, and a vertical copper cylinder of diameter 10 mm, moving at an angle of 90° to its axis. The height of each cylinder was 130 mm; their axes were located at a distance of 70 mm from the center of the equipment, the lower end being 100 mm from the distributor.

Tests were also conducted with a massive vertical copper calorimeter of rectangular section, thickness 10 mm, and size of plane edges 45 × 100 mm. With its aid the heat transfer on a fixed plane surface in the fluidized bed was evaluated.

Experimental results. Tests were made to evaluate the dependence of heat transfer coefficient α on fluidization velocity ω for fixed vertical cylinders of various diameters. As may be seen from Fig. 2, the heat transfer increases noticeably with decrease of diameter, for cylinders of diameter less than 10 mm. This is confirmed by Antonishin, who conducted an interesting theoretical investigation [4] to explain the dependence of α on the radius of curvature of the heat transfer surface. It is also clear from the work of Varygin [5], who experimented with wire of diameter 0.2 mm.

The heat transfer coefficients for cylinders of diameter greater than 10 mm practically coincide with those for a plane surface (of a "massive" body [5]).

Figure 2 also shows values of the maximum heat transfer coefficient α_{max} for a "massive" body (case of a plane surface), calculated from the formulas of Zabrodskii [1], Varygin and Martyushin [3], Kharchenko and Makhorin [2], and of Todes et al. [11]. It is seen that the most accurate for the conditions of our experiment are calculations based on the formulas of [1] and [3], although they also give a considerable deviation from the test data.

Figure 2 does not show a clear maximum of the heat transfer coefficient [1, 2]: after reaching a least value at a fluidization velocity ω_0, the so-called optimum, α is constant right up to the appearance of a considerable entrainment.

The conclusion may be drawn that the gas velocity ω_0 does not depend on calorimeter diameter, but is determined only by the properties of the fluidized bed.

Figure 2 shows the optimum fluidization velocities ω_0, calculated from the formulas of [11, 3, 2]. They prove to be considerably above the experimental value of ω_0, due, apparently, to the absence of a sharply pronounced maximum in the curve $\alpha = f(\omega)$.

There is evidently an increase in heat transfer coefficient with decrease of particle size.

It is also observed that the heat transfer coefficient of the porcelain cylinder of diameter 19.7 mm turns out to be 10–12% less than that for the better conducting copper cylinder of the same diameter. This is connected, apparently with the quasi-stationary mechanism of heat transfer in the fluidized bed [12].

During the experiment we also found the dependence of α on the velocity of the cylinder ω_0 (0–3 m/sec) at various fluidization velocities ω, starting from critical (ω_{cr}) corresponding to the limit of stability of the bed (Fig. 3). We observe a clear dependence of α both on the fluidization velocity and on the velocity of the cylinder.

The maximum values of α are reached at minimum fluidization velocities. This is in good agreement with the two-phase theory of the fluidized bed, confirming that there is weak heat transfer from the gas phase by bubbles, in whose medium the calorimeter remains longer as the gas velocity ω increases.

At large ω, α drops at the beginning (the cylinder is moving slowly, ω_c = 0–0.7 m/sec). This allows us to postulate that in the motion of the cylinder, a zone of reduced particle concentration is formed on its rear side, while ahead of it there is a dense layer of particles which have not been separated from the cylinder. The zones lower the local α at these points and thereby decrease the mean heat transfer coefficient calculated over the whole surface; on the sides of the cylinder, at small ω_c, replacement of heated particles by cold ones occurs only a little more intensely than replacement due to fluidization. Therefore, when the heat transfer coefficient for the stationary cylinder is large (large ω values and strong mixing of the bed), it falls, in motion of the cylinder at small velocities, until the degree of increase of α on the sides of the cylinder does not predominate over the degree of reduction of α at the front and rear. This postulate is based on the investigations [6] of heat transfer on a cylinder washed by a transverse dense moving stream of quartz sand. The qualitative picture of heat transfer with $\omega = \omega_{cr}$ (there is no mixing by fluidization) is evidently similar to that described in [6].

At velocities ω_c greater than 0.8 m/sec (even at large ω), and in all cases of small ω, α steadily increases with increase of velocity of the cylinder up to a certain value which is always greater than the initial value (with ω_c = 0).

When a definite cylinder velocity is reached (2–3 m/sec) it ceases to have an influence on heat transfer, in the range in which the tests were made. Some constant small value of the heat transfer coefficient is

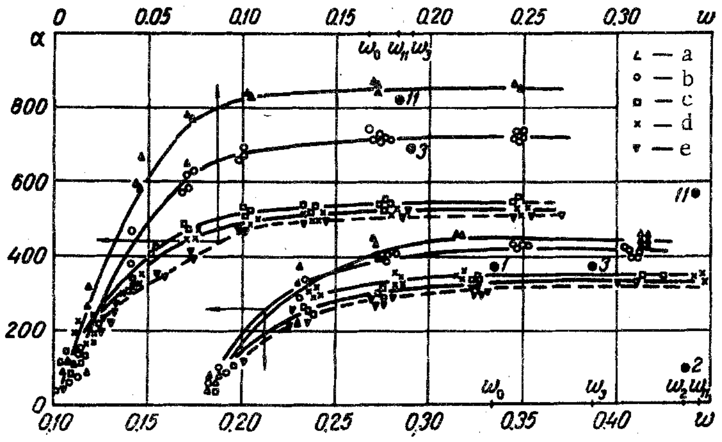

Fig. 2. Dependence of heat transfer coefficient α (W/m^2 · degree) on the fluidization velocity ω (m/sec) for a plane surface (e) and for fixed cylinders of diameter 3 (a), 6 (b), 10 (c), and 19.8 (d) mm for 60μ corundum (upper curves) and 320μ (lower). The points 1, 3, 2, and 11 denote values of α calculated respectively from formulas taken from [1, 3, 2, 11], and the corresponding optimum fluidization velocities, calculated from the same sources; ω_0—experimental value of the optimum velocity.

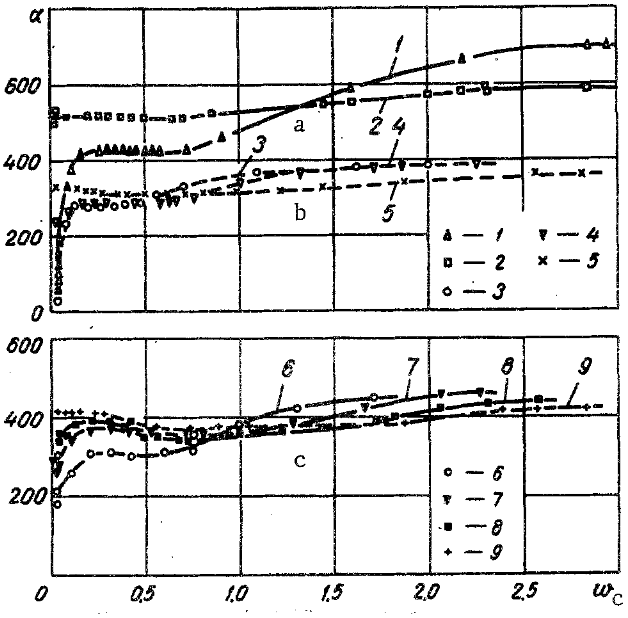

Fig. 3. Dependence of heat transfer coefficient α (W/m^2 · degree) on the velocity ω_c (m/sec) of a cylinder of diameter 10 mm in a bed of 60μ (a), 320 (b), and 120μ (c) corundum at a fluidization velocity ω (m/sec): 1—0.00285; 2—0.1705; 3—0.1826; 4—0.229; 5—0.37; 6—0.419; 7—0.0578; 8—0.1005; 9—0.319.

reached. This is connected with the attainment of a limiting time of contact of the particles with the surface, i.e., with the onset of a time when the particles cannot become noticeably heated during contact, and the intensity of heat transfer is limited only by the thermal resistance between the surface [7, 8, 13] and the particles adjacent to it.

Generalizing the results of the experiments conducted, the conclusion may be drawn that however intense the heat transfer on a motionless surface in a fluidized bed, it may still increase when the motion of the particles relative to the heat transfer surface is intensified and their dwell time in the gas phase is reduced.

This conclusion contradicts the statement of Ernst that "in fluidized beds at sufficient gas velocity, there is an optimum value of the heat transfer coefficient which cannot be exceeded by any intensification of the motion of the solid particles" [7].

REFERENCES

1. S. S. Zabrodskii, Hydrodynamics and Heat Transfer in the Fluidized Bed [in Russian], GEI, Moscow-Leningrad, 1963.
2. N. V. Kharchenko and K. E. Makhorin, IFZh, 7, no. 5, 1964.
3. N. N. Varygin and I. G. Martyushin, Khimicheskoe mashinostroenie, no. 5, 1959.
4. N. V. Antonishin, Dissertation [in Russian], Minsk, 1963.
5. N. N. Varygin, Tr. Moskovskogo in-ta khimicheskogo mashinostroeniya, 26, 33–38, 1964.
6. S. V. Donskov, Teploenergetika, no. 10, 1958.
7. R. Ernst, Chemie—Ingenieur—Technik, no. 3, 166–173, 1959.
8. R. Ernst, Chemie—Ingenieur—Technik, no 1, 17–21, 1960.
9. V. E. Minashin, V. I. Subbotin, P. A. Ushakov, and A. A. Sholokhov, collection: Problems of Heat Transfer [in Russian], 1959.
10. A. N. Gordov, V. A. Krivtsov, A. A. Fraktovnikova, and V. A. Chistyakov, Teplofizika vysokikh temperatur, no. 2, 1965.
11. O. M. Todes, A. K. Bondareva, and A. D. Gol'tsiker, Proc. 2nd All-Union Conference on Heat and Mass Transfer, Papers no. 15–18 [in Russian], Minsk, 5–9 May, 1964.
12. A. P. Baskakov, IFZh, 6, no. 11, 1963.
13. N. K. Harakas and K. O. Beatty, Chemical engineering progress symposium series, 59, no. 31, 1963.

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