A STUDY OF THE TRANSFER OF HEAT BETWEEN A SURFACE AND A LAYER OF MOVING PARTICLES

A. I. Tamarin, V. D. Dunskii, and L. V. Gorbachev

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Results are given for the measurement of the intensity of heat transfer between a layer of disperse material for a slag particle-air system and a vertical surface in motion relative to each other.

Particular attention has been devoted in recent years to the study of the process of heat transfer between a surface and a layer of moving (mixing) particles, given limited times of contact [1–4].

This is associated primarily with the fact that the chemical industry, as well as other branches, employ apparatus in which the heating or cooling of a moving (mixing) layer of disperse material is accomplished through heat-exchange surfaces which are either embedded in or are in contact with the bed. On the other hand, a dense moving (mixing) layer may be regarded as a hypothetical fluidized bed whose porosity is at a minimum and remains constant for the various velocities of particle motion.

The quantitative relationships governing the transfer of heat in a dense moving (mixing) layer may therefore be used to explain the transfer of heat in a fluidized bed.

The exchange of heat between a vertical wall and an agitated layer of glass spheres has been investigated in [1]. The rate of particle replacement at the heat-exchange surface was not measured directly, but estimated from indirect considerations.

The research described in [2] and [3] is of great interest since it provided for the possibility of measuring directly the speed of the disperse material layer relative to the heat-exchange surface. The transfer of heat from a gravitational layer of sand descending within a tube 50 mm in diameter to the wall of that tube was investigated in [2]. The intensity of heat exchange between a layer of finely dispersed powders of various materials and a moving vertical surface was measured in [3]. Many of the experiments in [2, 3] were conducted in a region of relatively low particle velocities and, consequently, in a region of relatively high times of contact with the surface, i.e., Fo > 1. At high speeds of particle motion, when the time of particle contact with the heat-exchange surface is not great (Fo ≪ 1), the temperature gradient is localized within the limits of a single particle row.

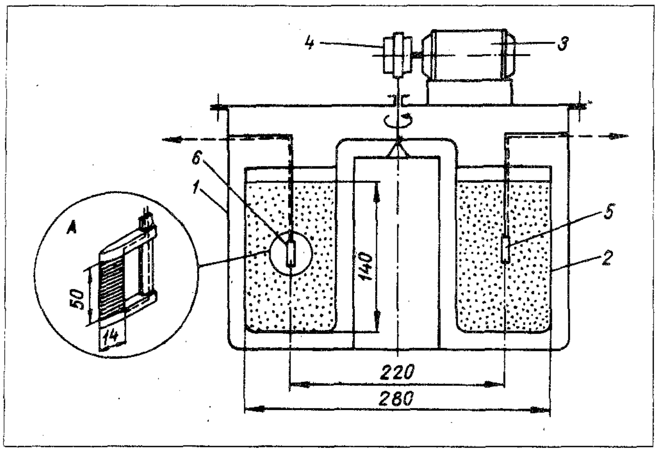

Fig. 1. Schematic drawing of experimental facility: 1) casing; 2) annular box; 3) electric motor; 4) reducing gear; 5) resistance thermometer; 6) sensing element for measurement of heat-transfer coefficient.

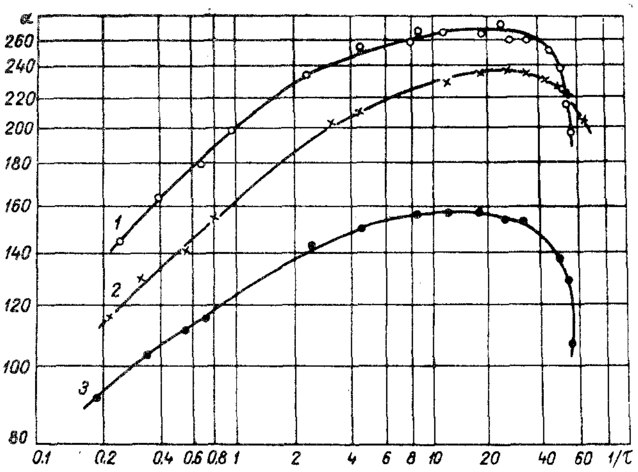

Fig. 2. Experimental relationship between α (W/m^2 • • deg) and $1/\tau$ (sec^{-1}); 1, 2, 3) particle dimensions 0.78, 1.2, and 2.2 mm, respectively.

The intensity of heat exchange between a surface and a single particle in contact with that surface was calculated on a computer in [4].

For the glass bead-air system the calculation showed that with a reduction in contact time the intensity of heat transfer increases and tends toward the limit which is attained with Fo ≤ 0.1. We were therefore interested in determining experimentally the coefficient of heat exchange between a moving particle layer and a surface, for a relatively limited contact time, i.e., 1 > Fo > 0.01.

Figure 1 shows a diagram of the experimental installation. Casing 1 houses an annular box 2 into which the layer of slag spheres is poured (c_p = 752 J/kg • • deg, λ_p = 0.59 W/m • deg, ρ_p = 2720 kg/m^3) from one of three fractions (mean particle diameter 0.78, 1.2, and 2.2 mm).

The box was set into uniform rotation by means of electric motor 3 through reduction gear 4. Revolutions could be altered from 3 to 80 rpm and from 0.3 to 2 rpm by replacing the reduction gears and by varying the voltage at the terminals of the electric motor.

Two nonmoving sensors 5 and 6 of identical design were embedded in the material layer. The sensors were plexiglas plates on which lacquer-insulated 0.12 mm copper wire had been wound, turn by turn. The plate was lenticular in cross section, 2.5 mm thick at the center.

Sensor 5 was used to measure the temperature of the slag-sphere layer and was connected to the measuring bridge circuit as a resistance thermometer.

Sensor 6 was used to measure the intensity of heat exchange between the surface and the particle layer moving relative to it. The sensor was heated by the electric current passing through it. Its surface temperature was kept constant at 60° C, accurate to within 0.2° C. This was achieved by balancing the electrical bridge circuit of which sensor 6 represented one arm.

A device was mounted between sensor 6 and the resistance thermometer 5 measuring the temperature of the layer, this device designed to stir the particles and to prevent sensor 5 from coming into contact with the wake of heated particles behind sensor 6.

On attainment of a steady thermal regime, we measured the following quantities in the system: the temperature of the slag particle layer, the electric current passing through sensor 6, and the number or revolutions executed by box 2. On the bases of these data we calculated the time of contact between the slag spheres and the sensor surface

$$\tau = \frac{b}{\pi Dn}$$

and the coefficient of heat exchange between the sensor surface and the layer of moving particles

$$\alpha = \frac{I^2R}{(60 - t_0)F}.$$

The electrical resistance R of the sensor and its surface temperature were kept constant during the course of the experiments.

The heat losses through the unheated ends of the sensor were determined experimentally by comparing the power dissipated in the layer under identical conditions for three sensors of identical design, but with various test-section lengths of l = 75, 50, and 25 mm. The experiments demonstrated that the losses of heat through the unheated ends of the sensor at l = 50 mm are less than 2%.

The maximum measurement error in the magnitude of the heat-transfer coefficient under the conditions of the experiments did not exceed 5%.

The results of the experiments are shown in Fig. 2 in the form of α as a function of the reciprocal of the contact time.

We see from the graph that when $1/\tau \approx 20$ the maximum is attained. However, any further increase in the velocity of the layer resulted in a reduced coefficient of heat transfer. The circumstance that the maximum heat-transfer coefficient for the three investigated particle fractions lies approximately within an identical range of velocities indicates the discontinuous streamlining of the heat-exchange surface by the layer [bed].

Visual observations of the flow past the particle layer by means of a partially embedded sensor confirmed that the discontinuous flow sets in at a contact time of $\tau \approx 0.05$ sec.

The results of three series of experiments are shown in Fig. 3 in nondimensional Nu and Fo coordinates. The dashed line in this figure is a plot of the data obtained through a computer calculation for a single sphere [4] in contact with the heat-exchange surface of the air-glass sphere system.

We see from the graph that for low velocities of layer motion relative to the sensor, the experimental points for the three particle fractions fall on a single curve. In the region of high velocities of motion, where the flow of the layer past the sensor is discontinuous, the experimental curves for the subject fractions diverge. It may be assumed, however, that in flow without separation the experimental points would lie about a common envelope, approaching the experimental curve derived for larger particles.

It should be noted that the maximum magnitude of the Nu member derived experimentally (large particles) and the theoretical value for a single sphere [4] virtually coincide. Here the relative contact time (Fo) in

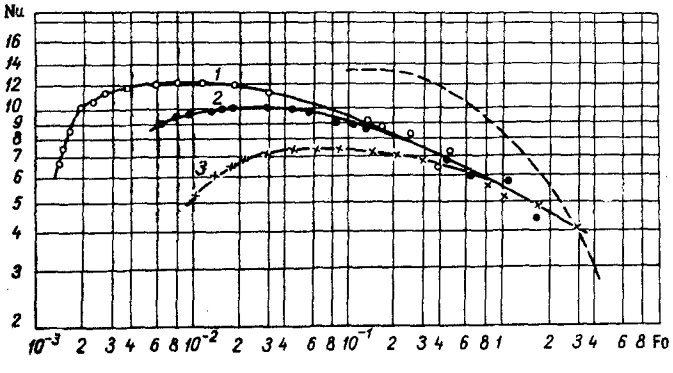

Fig. 3. Intensity of heat transfer between surface and bed as a function of contact time; 1, 2, 3) particle dimensions 0.78, 1.2, and 2.2 mm, respectively; the dashed line denotes the theoretical curve [4].

which the maximum value of the Nu number is attained was on the order of Fo ≈ 0.02 in the experiment, instead of Fo ≈ 0.1 as calculated in [4]. Since the temperature gradient for limited contact time is localized near the point of contact, the conditions for particle adhesion to the surface are of decisive importance.

It is possible that this serves to explain that the experimentally derived $\mathrm{Nu}_{\max}$ values were attained for a shorter contact time than had been calculated [4]. Thus the experiments demonstrate that the intensity of heat transfer in a moving (mixing) and fluidized bed is limited. A further increase in the relative velocity of particle motion in this case and a reduction in their time of contact with the surface will no longer lead to an increase in the coefficient of heat transfer.

For the system in question (air-slag spheres) this condition is expressed by the simple relationship

$$\mathrm{Nu}_{\max} = 12-13.4,$$

which may be used to determine the maximum coefficient of heat transfer between the walls of the apparatus and the mixing or moving layer of disperse material, as well as to evaluate the intensity of heat transfer in the fluidized bed.

NOTATION

Here b and F are the width and surface area of the sensor; n is the number of revolutions; I and R are the electric current and resistance of the sensor; c_p, λ_p, and ρ_p are the heat capacity, thermal conductivity, and density of the solids; Nu is the Nusselt number; Fo is the Fourier number.

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Institute of Heat and Mass
Transfer AS BSSR, Minsk