MEASUREMENT OF THE MAXIMUM RATE OF HEAT TRANSFER BETWEEN A BED OF MOVING PARTICLES AND A SURFACE

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The coefficient of heat transfer between a bed of slag pellets (mean diameter 0.78, 1.2, and 2.2 mm) and a vertical surface has been determined for the case of relative motion. The experiments were conducted at small contact times (0.002 < Fo < 1) in several atmospheres (air, CO_2, He).

To a considerable extent the heat transfer between a surface and a bed of dispersed material is determined by the particle-surface contact time. As it decreases, the heat transfer increases, tending in the limit to some constant value [1–4, 6]. At relatively small contact times (Fo < 0.1) the temperature gradient is concentrated mainly near the contact point between the particle and the heat-transfer surface. Experiments in a vacuum have shown [1] that the heat transfer through the contact points (spots) is negligibly small. At small Fo the heat is transferred at the interface mainly through the intermediate layer of gas near the particle contact point.

In [2, 3] we determined the coefficient of heat transfer between a surface and an individual particle numerically. The calculations showed that as the contact time decreases, the heat-transfer coefficient increases and tends to a constant value determined by the thermophysical characteristics of the gas-particle system. These conclusions have been partially confirmed experimentally, but only for air-sand [4] and air-slag pellet [6] systems. Data on the heat transfer between a bed of glass pellets and a surface in relative motion [5] have been obtained for several gases. However, in these experiments the contact time was large (Fo > 1) and, accordingly, the limiting value of the heat-transfer coefficient was not reached.

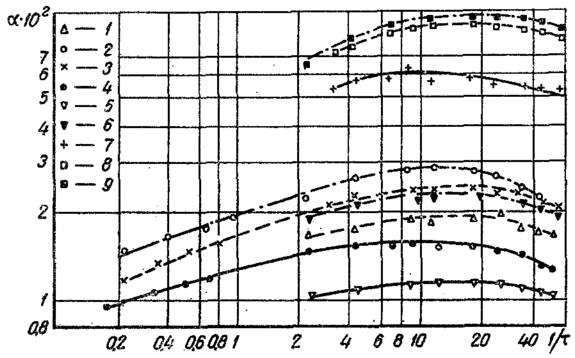

Fig. 1. Heat-transfer coefficient (W/m²·deg) as a function of contact time (sec): 1, 3, 8) CO_2, air, and He, respectively, d = 1.2 mm; 5, 4, 7) CO_2, air, and He, d = 2.2 mm; 6, 2, 9) CO_2, air, and He, d = 0.78 mm.

Let us consider the following simplified model. A bed of spherical particles moves along a stationary flat surface. There is no relative motion of the particles, and the bed may be regarded as a moving porous

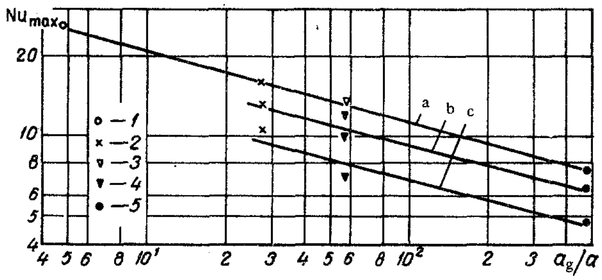

Fig. 2. Heat-transfer coefficient as a function of the thermophysical properties of the system: 1, 3) for glass sphere-freon and glass sphere-air systems [2], respectively; 2, 4, 5) for slag pellets in atmospheres of CO_2, air, and He, respectively (a, d = 2.2 mm; b, 1.2; c, 0.78).

plate. No heat transfer appears at the particle contact points, but it takes place exclusively through the intermediate layers of gas between particles. Close to the stationary flat surface there is a thin film of gas that tends to lag behind the motion of the bed. Since the volume specific heat of the gas is several orders lower than that of the solid particles, the heat flux carried away by the gas flow is small and can be neglected. In this case even in the boundary zone at the heat-transfer surface it is possible to assume that there is no relative motion of the gas in the bed and hence that the heat transfer both within the particle and within the intermediate layer of gas can be described by the Fourier equation [2, 7, 9]

$$\frac{\partial t}{\partial \tau} = a\nabla^2 t.$$

Going over to the stationary coordinate system $x = U\tau$ and introducing the dimensionless coordinates $x = l\chi$, $y = d\eta$, $z = d\xi$, we obtain

for the particles

$$\frac{Ud^2}{al}\frac{\partial t}{\partial \chi} = \left(\frac{d}{l}\right)^2 \frac{\partial^2 t}{\partial \chi^2} + \frac{\partial^2 t}{\partial \eta^2} + \frac{\partial^2 t}{\partial \xi^2}, \tag{1}$$

and

for the gas

$$\frac{a}{a_g}\frac{Ud^2}{la}\frac{\partial t_g}{\partial \chi} = \left(\frac{d}{l}\right)^2 \frac{\partial^2 t_g}{\partial \chi^2} + \frac{\partial^2 t_g}{\partial \eta^2} + \frac{\partial^2 t_g}{\partial \xi^2}. \tag{2}$$

System (1) and (2) describe the heat transfer in the bed. We will solve the problem for the following initial and boundary conditions:

1) the initial temperature of the bed (particles and gas) is constant in space and equal to t_0;

2) the heat-transfer surface has a length l in the direction of the X-axis; its temperature is maintained constant and equal to t_s;

3) the temperature of the bed far from the heating surface is constant and equal to t_0;

4) the heat transfer at the gas-sphere boundary is described by

$$\frac{\lambda}{\lambda_g} \operatorname{grad} t = \operatorname{grad} t_g. \qquad (3)$$

The rate of heat transfer at the boundary between the bed and the surface is

$$\alpha = \frac{q}{t_s - t_0} = \frac{\lambda_g}{d} \frac{\operatorname{grad} t_g}{t_s - t_0}, \qquad (4)$$

where q is the specific heat flow through the boundary.

The solution of the problem can be represented in the form of a function of three dimensionless complexes

$$\mathrm{Nu} = f\left(\mathrm{Fo};\ \frac{a}{a_r};\ \frac{l}{d}\right), \qquad (5)$$

where

$$\mathrm{Fo}^{-1} = \frac{ud^2}{la};\quad \text{and}\quad \mathrm{Nu} = \frac{\alpha d}{\lambda_g}.$$

Relation (5) is valid both for small contact times, when the temperature gradient is concentrated near the contact points of the first row of particles, and for large contact times, when several rows of particles are heated.

The nature of (5) was established by investigating the heat transfer between a surface and a bed of moving particles in various atmospheres.

The experimental apparatus was a sealed chamber inside which revolved an annular basket, filled with a bed of slag pellets. The experiment was repeated for three different mean diameters: 0.78, 1.2, and 2.2 mm. A flat heating surface, rigidly attached to the stationary housing, was immersed in the bed of particles. This surface was 50 mm deep, 14 mm wide, and 2 mm thick. The basket revolved at a uniform speed between 3 and 80 rpm. The velocity of the bed relative to the heating surface was regulated by varying the speed of the basket. To ensure small relative contact times with the heating surface ($\mathrm{Fo} < 0.1$) three coarse fractions (mean diameters 0.78, 1.2, and 2.2 mm) were selected.

The heat-transfer surface was a plastic plate copper-wound with thin copper wire. By connecting it to a bridge circuit, we could keep the temperature constant and measure the dissipated electrical power [8]. The apparatus and technique are described in more detail in [6].

In a typical run the apparatus was first evacuated to a pressure of 1–5 mm Hg. Then the vacuum line was disconnected and a valve opened to admit gas (air, CO_2, or He) into the interior cavity of the apparatus. An excess pressure of several tens of mm H_2O was maintained in the apparatus to ensure the stability of the gas atmosphere in the bed during the experiment.

The results of the experiments are presented in Fig. 1 in the form of a graph of α as a function of the reciprocal of the contact time $1/\tau$. We see that as τ decreases, α increases, reaching a maximum value at $\tau \approx 0.1$ sec. As the speed continues to increase, i.e., as τ diminishes further, α starts to decrease. Obviously, this is related with the movement of particles away from the heat-transfer surface at high speeds. To confirm this assumption, we observed visually the flow of particles over the heating surface when the latter was incompletely immersed in the bed. We found that with increasing basket speed the bed separates from the heating surface and the thickness of the gas boundary film increases.

As seen from Fig. 1, α_{max} depends both on the particle size and on the thermophysical properties of the gas atmosphere.

From the experimental data we tried to determine the behavior of the maximum heat-transfer coefficient, which is reached at small contact times and which no longer depends on Fo. In accordance with (5) the data were correlated in the following form:

$$\mathrm{Nu}_{max} = A\left(\frac{a_g}{a}\right)^m \left(\frac{l}{d}\right)^n.$$

We first investigated the variation of Nu_{max} with the thermophysical characteristics of the system a_g/a. Figure 2 gives $\mathrm{Nu}_{max} = f(a_g/a)$ for the three particle diameters and the three gases used, and also values of Nu_{max} obtained from a computer calculation [2] for glass sphere-air and glass sphere-freon systems. In a logarithmic scale the calculated and experimental points for particles 2.2 mm in diameter lie on a straight line with a slope of 0.26. For parti-

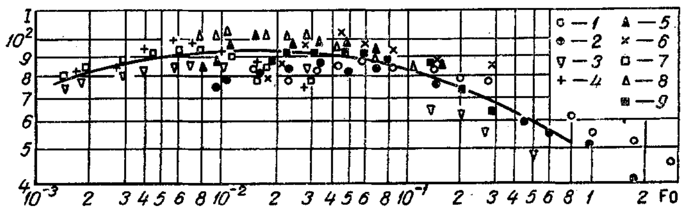

Fig. 3. Heat-transfer rate $I = \mathrm{Nu}[(a_g/a)^{0.26}(l/d)^{0.48}]$ as a function of contact time for a bed of slag pellets: 1, 2, 3) air, d = 0.78, 1.2 and 2.2 mm; 6, 5, 4) CO_2, d = 0.78, 1.2, and 2.2 mm; 9, 8, 7) He, d = 0.78, 1.2, and 2.2 mm.

cles 0.78 and 1.2 mm in diameter the Nu_{max} values are also, in first approximation, correlated by a power function with the same exponent $m = 0.26$.

Similarly we investigated the dependence of the maximum heat-transfer coefficient on the dimensionless length l/d of the heating surface. The results can be presented in the following form:

$$\mathrm{Nu}_{\max} = A\left(\frac{a_g}{a}\right)^{-0.26}\left(\frac{l}{d}\right)^{-0.48}, \quad (6)$$

which is valid when

$$4.7 < \frac{a_g}{a} < 481 \quad \text{and} \quad 6.4 < \frac{l}{d} < 18.$$

The experimental data for the entire range of variation in Fo and for all three gases and all three particle dimensions are presented in Fig. 3 as a function of the Fo number in accordance with relation (5) (in logarithmic scale).

The data are satisfactorily grouped about the same curve with a maximum scatter of 30%, which is perfectly acceptable for the system in question.

The experiments confirm the theoretical conclusion that as the contact time (Fo) decreases, the heat-transfer coefficient increases, tending to a limit. In our case this limit was reached on the interval Fo = 0.08–0.008.

From an analysis of the data we found the value A = 90 for the coefficient in Eq. (6).

Expression (6) can be used to calculate the rate of heat transfer between a moving or agitated bed of particles and a surface, if the contact time is given by Fo < 0.08.

The experimental value of the Fo number, corresponding to Nu_{max}, is close to the calculated value (Fo = 0.1) obtained for the individual sphere-wall system [2].

Expression (6) also permits a qualitative analysis of the law of heat transfer between a fluidized bed and a heat-transfer surface.

NOTATION

x, y, and z are dimensionless coordinates; d and l are the particle diameter and the length of heating surface; t_0 and t_s are the temperatures of the bed and the surface, respectively, °C; q is the specific heat flux; Nu and Fo are the Nusselt and Fourier numbers, respectively; τ is the particle contact time; a and a_g are the thermal diffusivities of the particle and the gas, respectively; and λ and λ_g are the thermal conductivities of the particle and the gas, respectively.

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