STUDY OF HEAT EXCHANGE IN A BED FLUIDIZED WITH STEAM

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Experimental data is presented on heat exchange between a water-cooled coil and a bed fluidized with steam.

All of the well-known published data on heat exchange in a fluidized bed [1-3] has been obtained in experiments in which the gases were noncondensing. Nevertheless, steam serves as a protective atmosphere for copper alloy products, so that its use as a fluidizing medium in heating furnaces is very promising. Calculation of the heating time of the products requires knowledge of the coefficient of heat transfer between the surface and the steam-fluidized bed.

Experiments were conducted in a 300-mm-diameter unit in which we fluidized a bed of electrocorundum 400 mm high with a mean particle size d = 0.12 and 0.32 mm. Either steam or air heated to 120-150°C was blown into the unit from below through a gas-distributing grate. The consumption of the given fluidizing agent was kept above the optimum level regarding heat-exchange conditions, i.e., we determined α_{max} in the experiments. The bed temperature could be maintained within the range from 120 to 400°C by its heating through the wall.

The heat-transfer coefficient was determined with a coil made from a copper tube with an external diameter d_{co} = 8 mm and length of 1 m. The heat flux delivered to the coil was calculated from the consumption and heating of the water passed through the tube. Thermocouples for measuring the temperature of the water were installed directly inside the tube. The temperature of the water entering the coil could be regulated. An excess pressure on the order of 0.3 MPa was maintained in the coil to keep the water from boiling. The temperature of the coil wall was calculated using a relation for the coefficient of heat transfer from the wall to the fluid [4]. Also, a thermocouple was embedded in the wall in the middle section to check its temperature.

Two regimes must be distinguished if a bed is fluidized with steam. If the temperature of the outer surface of the coil is higher than the vapor saturation temperature t_s, the vapor will behave as a normal noncondensing gas and the resulting values of maximum heat-transfer coefficient (Fig. 1) will agree moderately well with well-known empirical relations [1-3]. In particular, the standard deviation of the test data from the values found from calculation with the relation in [3]

$$\mathrm{Nu}_{\max} = 0.85\mathrm{Ar}^{0.19} + 0.006\mathrm{Ar}^{0.5}\mathrm{Pr}^{0.33} \tag{1}$$

was 5%. In calculating criteria for a certain temperature, we took the mean between the temperatures of the bed and surface. A similar degree of agreement between the experimental data and results found from Eq. (1) was obtained in the same investigated temperature interval when the bed was fluidized with air.

If the surface temperature of a coil in a bed fluidized with vapor is below the saturation temperature, the heat-transfer coefficient will increase sharply (Fig. 2) due to a change in heat-exchange conditions, especially at low bed temperatures. In our case, vapor condenses on the coil surface and the corundum particles adhere to the coil surface, forming a peculiar "fur coat" of moist particles. The heat-exchange process comes to resemble the drying of a moist corundum product in a fluidized bed. Moisture is evaporated on the outer surface of the coat thanks to the delivery of heat from the overheated particles of the core of the fluidized bed to the moist particles of the coat. The temperature inside the coat is equal to the saturation temperature (this has been confirmed by measurements). The moisture is constantly replenished as a result of condensation of the saturated vapor on the coiled tube.

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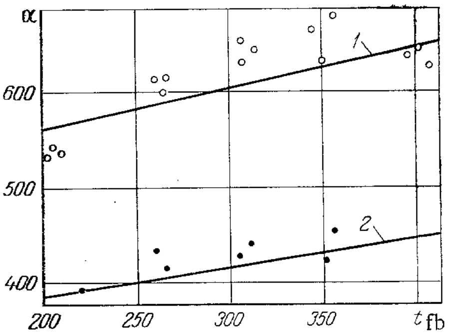

Fig. 1. Effect of temperature t_{fb} (°C) of bed fluidized with steam on heat-transfer coefficient α (W/(m^2•K)) in heat transfer to coil with a surface temperature above the saturation temperature: points) experimental results; curves) estimate from Eq. (1); bed particle size) 1) d = 0.12 mm; 2) 0.32 mm.

The coat acts as a heat pipe which transports heat radically. Here, condensation takes place on the coil, moisture is transported by capillary forces to the outside surface of the coat and evaporates there, and the newly formed vapor is again directed inside the coat to the coil.

The thickness of the coat can be evaluated by equating the heat fluxes on the outer and inner (coil wall) surfaces of the coat:

$$Q=\alpha_{fb}F_t\,(t_{fb}-t_s)=\alpha_d F_{co}(t_s-t_{co}), \tag{2}$$

from which

$$\frac{F_t}{F_{co}}=\frac{d_t}{d_{co}}=\frac{\alpha_d(t_s-t_{co})}{\alpha_{fb}\,(t_{fb}-t_s)}\,. \tag{3}$$

Considering that the ratio α_d/α_{fb} is roughly constant, the thickness of the coat increases with a decrease in coil temperature t_{co} and the temperature of the fluidized bed t_{fb}. The approximate thickness of the coat may be evaluated by calculating α_{fb} from well-known empirical formulas [1-3] and calculating α_d from the formula for the condensation of pure vapor [4]. Actually, the heat-transfer coefficient α_d obtained for a bed fluidized with steam is somewhat lower with the coat than in pure superheated steam.. This is especially true in the case of intensive condensation, when the difference between the wall temperature and saturation temperature is great. This effect is evidently the result of the influence of the particles of the coat on the thickness of the film of condensate which forms on the tube and represents the main thermal resistance during condensation. For the sake of illustration, Fig. 2 shows calculated values [4] for the heat-transfer coefficient α_c in the condensation of pure superheated steam with different temperature drops $(t_s - t_{co})$.

It should be noted that the determining factor in formulas for α_d for both saturated and superheated vapor is usually the difference between the wall temperature and saturation temperature. In our experiments, we calculated α from the difference between the temperature of the core of the fluidized bed, i.e., of the superheated steam, and the wall $(t_{ss} - t_{co})$. Therefore we obtained the following to correct α_c (curves in Fig. 2) with regard for the temperature difference $(t_{ss} - t_{co})$:

$$\alpha_c=\alpha_d\,\frac{t_s-t_{co}}{t_{ss}-t_{co}}\,. \tag{4}$$

Two other, mutually opposing factors affect the thickness of the coating: the coat may be destroyed by turbulent pulsations, and particles of the coat may be held in position by the flow of vapor filtering through the coat to the coil wall. The vapor filtration velocity, calculated from the heat flux, is greater than the velocity associated with the beginning of fluidization of fine particles.

Thus, at t_{fb} = 200°C, t_{co} = 90°C, and α = 1200 W/(m^2•K), the velocity of the saturated vapor in the coat near the surface will be

$$w_f=\frac{qv''}{r}=\frac{\alpha\,(t_{fb}-t_{co})\,v''}{r}=\frac{1200\,(200-90)\cdot 1.67}{2257\cdot 10^3}\approx 0.1\ \text{m/sec}.$$

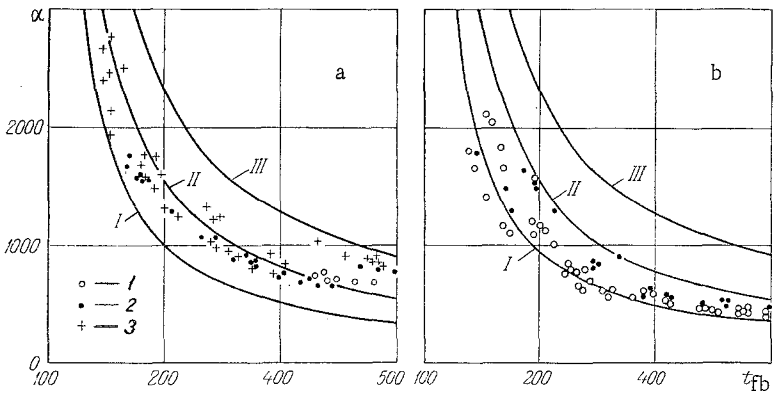

Fig. 2. Effect of temperature t_{fb} (°C) of bed fluidized with steam on heat-transfer coefficient α ($W/(m^2 \cdot {}^\circ K)$) in heat transfer to coil with a surface temperature below the saturation temperature; bed particle sizes: a) d = 0.12 mm; b) 0.32 mm; points — experimental results; 1) $(t_s - t_{co})$ = 5-10°C; 2) 10-20°C; 3) 20-30°C; curves) estimate from equation in [4] for condensation of pure superheated steam: I) $(t_s - t_{co})$ = 5°C; II) 10; III) 20°C.

The velocity of the initiation of fluidization of corundum particles by saturated vapor, calculated by O. M. Todes [5], is about 0.03 m/sec for d = 120 μm and about 0.18 m/sec for d = 0.32 μm.

The velocity of the vapor will be lower near the outer surface of the coat — it is inversely proportional to the ratio of the diameters of the coat and coil. In accordance with Eq. (3), this ratio is equal to

for d = 0.12 μm

$$\frac{d_t}{d_{co}} = \frac{16520\,(100-90)}{560\,(200-100)} \approx 3;$$

for d = 0.32 μm

$$\frac{d_t}{d_{co}} = \frac{16520\,(100-90)}{385\,(200-100)} \approx 4.3.$$

Despite the approximate evaluation (α_d was calculated for the condensation of a pure vapor [4]), the calculated value of d_t corresponds to the value measured experimentally: d_t= 25-30 mm when the transducer is extracted rapidly from the fluidized bed. It is fairly difficult to accurately measure d_t, since the coat on a horizontal coil is not strictly cylindrical and varies along the coil due to the heating of the water circulating in it. Our measurements were obtained in the middle of the coil.

Thus, the vapor filtration velocity is greater than the fluidizing velocity even near the outer boundary of the coat for 120-μm corundum particles. In the steady state, when the particles of the coat are moist, vapor is formed at the outer boundary of the coat as a result of evaporation of this moisture. Here, flow about the coat will be as it is about a normal body. At the initial moment, when the moist coat has not yet formed and the vapor originates from the volume of the bed, the cold body is a sink for the fluidizing agent, and even dry particles may be held near the coil by the vapor flow.

The moisture content of corundum in the coat, measured by weighing particles removed from a rapidly extracted transducer, was about 5%. The coat is intensively moistened when the transducer is lifted slowly through the space above the bed, since heat delivery to the transducer is significantly poorer here than in the bed. In this case, the heat-transfer coefficient at first decreases sharply, subsequently increasing again due to the erosion of the coat by the flowing condensate.

When $\alpha_d(t_s - t_{co}) \leqslant \alpha_{fb}(t_{fb} - t_s)$, there is generally no coat and the empirical values of heat-transfer coefficient obtained are even higher than the theoretical values for pure vapor. In this case, heat exchange beings to be determined by the supply of heat from the hot particles, as in a conventional gas-fluidized bed.

The data presented above was obtained under steady-state conditions. The process of heating bodies with an initial temperature below t_s can be divided into three stages. First the body is heated to t_s at almost the same rate as in pure vapor. The vapor flow moves to the surface and presses dry particles against it. These particles are moistened by condensate, forming a coat. The coat subsequently dries and is destroyed, and the temperature of the body remains nearly constant and equal to the saturation temperature. After complete destruction of the coat, the temperature of the body, as in a conventional bed, is increased further by the noncondensing gas. Thus, a 30-mm-diameter copper cylinder is heated in a bed of 0.12-mm corundum particles from 40 to 100°C in 10 sec. Then the cylinder temperature rises by a total of 1°C over the next 70 sec, after which it begins to exponentially approach the bed temperature, equal to 140°C. The heat-transfer coefficient in the third stage of heating is determined by Eq. (1).

NOTATION

d, diameter, mm; F, area, m^2; Q, heat flow, W; q, heat flux, W/m^2; r, heat of vaporization, J/kg; t, temperature, °C; v'', specific volume of the saturated vapor, m^3/kg; α, heat transfer coefficient, $W/(m^2 \cdot K)$; Ar, Archimedes number; Nu, Nusselt number; Pr, Prandtl number; Indices: co, coil; d, condensate; s, saturation; f, surface; ss, super-heated steam; fb, fluidized bed; c, calculated; t, coat.

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INTENSIFICATION OF HEAT EXCHANGE BETWEEN A FLUIDIZED BED AND CONTAINING WALLS WITH A NONUNIFORM GAS DISTRIBUTION

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The effect of a nonuniform initial gas distribution on heat exchange between a bed and containing walls is studied.

The problem of intensifying heat transfer between a fluidized bed and solids immersed in the bed is very familiar, as are several engineering methods of solving it. However, in certain processing operations it is important to increase heat transfer not to bodies submerged in the bed, but to the walls containing the bed. The rate of heat transfer with external surfaces is usually significantly lower than the rate of heat transfer with the surfaces of bodies located in the core of the bed [1, 2]. This has to do with important qualitative differences in physical patterns of flow of the bed over the respective surfaces [3]. Thus, in practice, increasing the coefficient of heat transfer from the walls of a processing unit to the fluidized bed within often requires the use of special techniques.

It was proposed in [4] that this be done by delivering the gas only to the region of the wall. This led to gushing near the wall and a rapid decrease in heat-transfer coefficient with an increase in filtration velocity, with the usual processing advantages of fluidization being lost. Similar (and more successful) attempts have been to intensify heat exchange with the walls for beds fluidized with droplets of liquid (e.g., see [5]). Heat transfer can also

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