INVESTIGATION OF LOCAL HEAT TRANSFER IN A SPOUTED BED BY MEANS OF A TEMPERATURE PROBE

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Results of an investigation of local heat transfer in a spouted bed consisting of fine particles are given. The characteristic curves of the spouted bed have been obtained experimentally. A brief description of the heat transfer mechanism is given.

Known results for the coefficient of heat transfer α between the conical walls of the apparatus and a spouted bed [1–3] provide local and average (over the surface) values. However, no data are available on the distribution of the coefficients of heat transfer from a spouted bed to the surface of a heat exchanger placed inside the bed.

The object of the experiments described was to determine the distribution of heat transfer coefficients over the height and cross section of an apparatus containing a spouted bed consisting of fine particles in various hydrodynamic conditions.

The tests were carried out on a model of rectangular cross section with an area of 45 × 370 mm, a height of 1800 mm and transparent walls. Provision was made for special inserts in the lower part of the chamber which transform it into a flat cone. Air was fed through a 16 mm diameter gauze-covered vertical tube into a rectangular inlet chamber with a cross section of 45 × 55 mm (Fig. 1b). Provision was also made for the introduction of porous distributor plates at the chamber inlet.

The preliminary tests showed that in the investigation of the hydrodynamic conditions of the bed a thin-wire probe gives best results. The probe was made of 0.4 mm diameter and 114-mm long nickel wire bent into a triple-thread vertical coil, which was secured between two copper bar conductors and heated by direct current. The distance between the individual wires of the coil was 10 mm, while its total length was 35 mm.

The heat transfer coefficient for the wire was determined from the equation

$$\alpha = I^2 R_x / F \Delta t.$$

The temperature of the spouted bed was measured with a thermometer having 0.1° C divisions, while the wire temperature was determined from the calibration graph as a function of the U_x/I ratio. The voltage drop across the wire ends U_x and the current were measured by means of 0.2-class instruments.

In most tests the temperature difference Δt between the wire and the spouted bed was 50°–65° C. Special tests carried out in a fluidized bed showed that a change of Δt from 25°–70° C has no marked effect on the heat transfer coefficient. All tests were carried out on alumina Al_2O_3 with the following particle distribution: 0.16-mm particles 0.3–0.6%; 0.16–0.1 and 21.6–9.7%; 0.1–0.063 and 65.3–46%; 0.063–0.05 mm 12.3–29%; 0.05–0 mm 0.9–15%. The initial height of the bed was 210 mm.

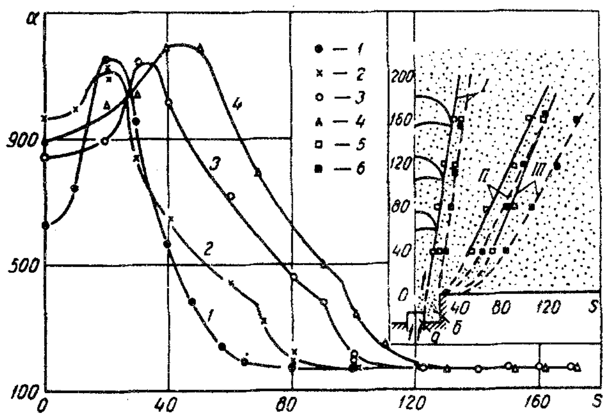

Fig. 1. Distribution of the heat transfer coefficient α, $W/m^2 \cdot °C$ over the cross section and height of the spouted bed at air velocities of 0.53 and 1.3 m/sec (the velocity is everywhere referred to the cross section of the inlet chamber): a) 16-mm diameter tube with gauze; b) 45 × 55-mm inlet chamber; 1) over the cross section at h = 40 mm; 2) 80; 3) 120; 4) 160; 5 and 6) characteristic points for velocities of 0.53 and 1.3 m/sec, respectively; I) lines of maximum α values and jet diameter; II) lines marking interface between descending and rising material; III) lines of stationary material.

The distribution of heat transfer coefficients over the cross section of the chamber was investigated at bed heights of 40, 80, 120, and 160 mm. Since the distribution of α with respect to the vertical axis is symmetric, we investigated the heat transfer only in the right-hand half of the chamber.

With increasing distance from the chamber axis the heat transfer coefficient reaches a maximum and then rapidly decreases to reach a constant value equal for all cross sections; this value is determined by the heat transfer from the wire to the stationary bed. In cross sections above 40 mm from the inlet chamber the decreasing section of the curve has a kink.

Figure 1 shows the location of the characteristic points for velocities of 0.53 m/sec (solid lines) and

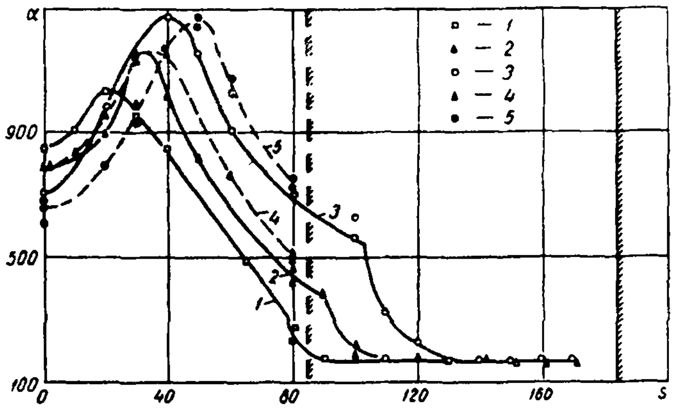

Fig. 2. Distribution of heat transfer coefficients α, $W/m^2 \cdot {}^\circ C$, over the cross section S, mm, at a height of 120 mm; 1) w_0 = 0.25 m/sec; 2) 0.53; 3) 1.3; and 4 and 5) with conical inserts at w_0 = 0.53 and 1.3 m/sec (distance from chamber axis to conical insert is 85 mm at the height considered).

1.3 m/sec (dotted lines). Curves 1 are plotted from the equation $d_s = 11.45 \times (0.115 \log d_c - 0.192)\, G^{0.6}$ [4] for the diameter of the spouted bed in a conical apparatus. In plotting these curves the column diameter d_c in mm was assumed to be equal to twice the distance from the axis to the interface between the descending and stationary material (curve III). The experimental points are close to the straight line I. This implies that the maximum values of the heat transfer coefficient are observed on the boundary of the bed core. From this viewpoint the presence of the above characteristic points has a relatively simple explanation.

The core of the flow is occupied by the rising gas bubbles separated by the fine-grain particles entrained by these bubbles. As a rough approximation it may be assumed that (Fig. 1) the bubble diameter at a given height is equal to the core diameter, in which case the frequency of replacement of the bunches of particles at the surface of the probe determined by the frequency of bubbles passing at a given height is constant over the entire cross section of the core.

The fraction of time during which the probe is in contact with the bunches of particles increases with increasing distance from the axis corresponding to increasing time-averaged particle concentration in the core [5]. This increases the heat transfer coefficient in the direction from the core to the boundary.

The outlined scheme is highly artificial. In fact, there is a large number of small bubbles rising in the core. Rising in the bed each bubble produces in its vicinity a disturbance zone inside which the particles perform a complex circulation. The size of this zone is proportional to the size of the bubble. For this reason growth of the rising bubbles results in a corresponding increase in the size of the region within which the bubbles displace the particles.

The disturbance introduced by the bubble spreads beyond the core of the spouted bed. With the simplifying assumption that in a given cross section the disturbance is the same for all bubbles (i.e., all bubbles in the cross section considered are the same size), disturbance caused by bubbles rising at the core boundary will be noticeable at a greater distance from the axis than a disturbance caused by bubbles rising along the axis. Since the number of bubbles decreases from axis to core boundary, the frequency of displacement of particle bunches beyond the core decreases with increasing distance of the point in question from the axis.

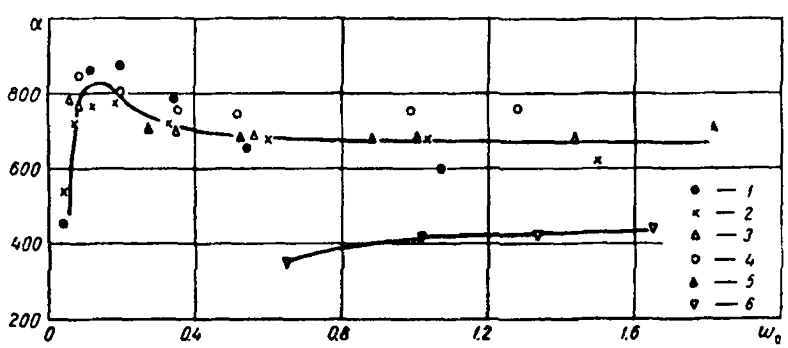

Fig. 3. Dependence of the heat transfer coefficient α, $W/m^2 \cdot {}^\circ C$ along the vessel axis on air velocity w_0, $m \cdot sec^{-1}$: 1) h = 40 mm; 2) 80; 3) 120; 4) 160; 5) 210; 6) 300.

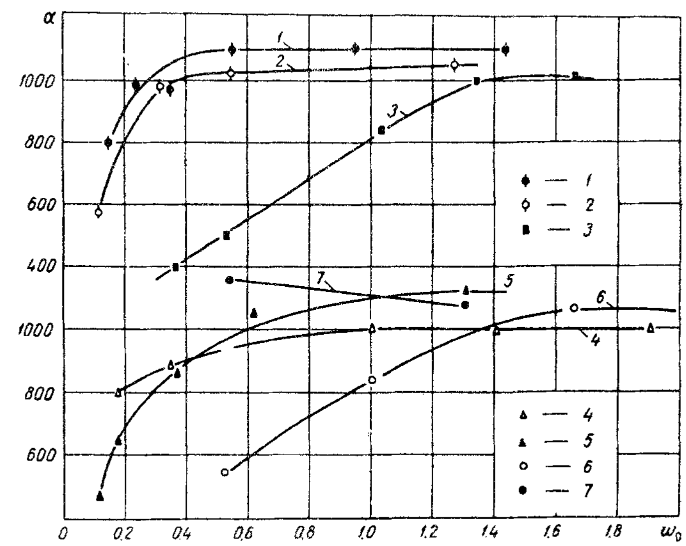

Fig. 4. Effect of free cross section of porous plate on heat transfer coefficient: 1, 2, 3) h = 160 mm, f_0 = 14, 1 and 1% respectively, S = = 35, 35 and 70 mm; 4, 5, 6, 7) h = 120 mm, f_0 = 1, 14, 14 and 100%, S = 35, 35, 55 and 35 mm respectively.

Correspondingly, the coefficient of heat transfer from the probe decreases between lines I and II. The disturbances caused by the bubbles apparently do not extend beyond the region bounded by lines I and II. In the region bounded by lines II and III the material moves in the downwards direction with a velocity decreasing with increasing distance from the axis.

The size and number of bubbles increases with increasing inlet air velocity which results in a widening of the core and a corresponding increase in the dimensions of the zones (Fig. 2). If conical inserts are used, the heat transfer coefficients at the chamber axis and at the core boundary remain practically unchanged. It is interesting to note that at the insert surface the heat transfer coefficient has a sufficiently large value, which increases with increasing air velocity. This is in agreement with the experimental data [1, 2] on heat transfer in conical chambers between the spouted bed and the chamber walls.

The experiments, the results of which are given in Figs. 3 and 4, were intended to establish the effect of porous distributor plates mounted in the inlet cross section of the chamber. All tests were carried out with conical inserts with a cone angle of 60°. The heat transfer coefficient on the chamber axis at a height less than the height of the stationary bed, first sharply increases with increasing velocity and subsequently slightly decreases to remain practically constant despite further increase of velocity. No regularities were observed in the variation of the "axial" heat transfer coefficient with height. The heat transfer coefficient in the fluidized phase (at a height of 300 mm from the inlet chamber when the thickness of the stationary bed is 210 mm) is considerably lower than the heat transfer coefficient in the solid phase.

The effect of the porous plate was investigated at a distance of 35 mm from the axis at heights of 120 (Fig. 4, bottom) and 160 mm (Fig. 4, top).

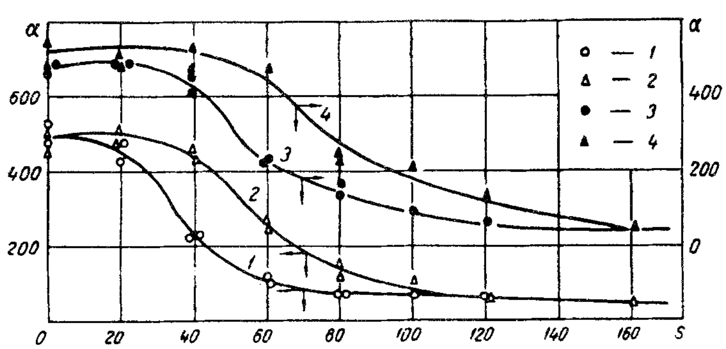

Fig. 5. Distribution of heat transfer coefficient α, W/m²·°C, 8-mm diameter probe over cross section and height of spouted bed apparatus: 1 and 2) h = 80 and 160 mm, w_0 = 0.53 m/sec; 3 and 4) h = 80 and 160 mm, w_0 = 1.3 m/sec.

Figure 4 shows that at high velocities changing the free cross section of the porous plate from 1 to 100% has hardly any effect on the heat transfer coefficient. At low velocities the effect of the plate is insignificant.

The wire probe is a very sensitive instrument for the investigation of the structure of spouted beds. It can also be used in the investigation of the hydrodynamics and heat transfer in other fluidized systems. However, the heat exchangers used in industry are usually made from tubes of much larger diameter. We know from tests with fluidized beds [6–7] that an increase of the diameter of the probe wire from fractions of a millimeter to several millimeters considerably reduces the heat transfer coefficient, which with a further increase of dimensions changes little.

With these facts taken into account, we investigated in the same chamber the heat transfer from a 8-mm copper probe. The copper rod, length 40 mm (in preliminary tests 50 mm) with insulated end faces and a thermocouple embedded in the middle, was heated to 100° C and placed at a definite point in the chamber. The heat transfer coefficient was calculated from the rate of cooling of the calorimeter in regular conditions.

As in an ordinary fluidized bed, an increase in diameter from 0.4 to 8 mm reduced the maximum heat transfer coefficient of the spouted bed to less than half (Fig. 5).

A probe of larger diameter also suggests the existence of the heat transfer region referred to above, but less distinctly. A reduction of the heat transfer coefficient begins approximately at the core boundary (line I, Fig. 1) and ends at the interface between the moving and stationary particles (lines III, Fig. 1). However, the minimum of the heat transfer coefficient on the core axis and the kink on the descending part of the curve cannot be detected by this probe.

The value of the heat transfer coefficient in the core of the spouted bed is, in the investigated velocity range, practically independent of the inlet velocity and is approximately equal to the heat transfer coefficient in an ordinary fluidized bed.

NOTATION

α—heat transfer coefficient, $W/m^2 \cdot {}^\circ C$; S—distance from chamber axis to probe, mm; F—area of wire probe, m^2; I—current in probe circuit, a; Δt—difference between temperature of wire and temperature of spouted bed, °C; R_x—resistance of wire probe, Ω; w_0—air velocity, m/sec; d_s—diameter of jet, mm; d_c—diameter of chamber, mm; G—flowrate of gas, $kg \cdot m^{-2} \cdot hr^{-1}$; h—distance along axis from inlet chamber, mm; f_0—free cross section of porous plate, %.

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