LOCAL HEAT TRANSFER BETWEEN A VERTICAL CYLINDER AND A FLUIDIZED BED

B. V. Berg, A. P. Baskakov, and B. Serééteriin

UDC 532.546:536.244

The heat-transfer coefficients for a vertical cylinder in a fluidized bed have been determined experimentally. The value of such a coefficient is found to vary considerably along the cylinder height.

The peculiar characteristics of a fluidized bed are such that the heat-transfer coefficients along the horizontal surface of an immersed body are very low [1, 2, 3]. For this reason, there is a tendency to place large surfaces in a vertical position. Furthermore, industrial fluidization apparatus is designed for a vertical arrangement of heat-transfer surfaces [4, 5].

The presence of circulating particle streams [6, 7, 8] particularly noticeable near large surfaces immersed in the bed causes particles to slide along such a surface very slowly. In view of this, it is reasonable to assume that the heat-transfer coefficient α_Z will vary along the height of a surface. Such a heightwise variation was noted in [9] in the case of a cylinder 6.35 mm in diameter. At different heights of the cylinder (total height 610 mm) immersed vertically in a fluidization vessel 104 mm in diameter, the authors of [9] obtained heat-transfer coefficients deviating from linearity by as much as 200 W/m^2·deg. For cylinders with large diameters, and especially for flat surfaces in the vicinity of which the pulsations of "packets" play a minor role, such differences in heat-transfer rates should be still more significant.

In this study we have determined the local coefficients of heat transfer from a vertical tube to a bed. The test procedure provided for the measurement of the temperature t_2 of the outside tube surface under steady-state conditions, while the temperature t_1 of the inside surface remained constant and there were no heat losses at the ends of the tube.

Solving the Laplace equation

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial Z^2} = 0 \tag{1}$$

with the given boundary conditions, the temperature field in the wall can be determined and then α_Z can be calculated from the formula

$$\alpha_z = -\frac{\lambda\left(\frac{dT}{dr}\right)_s}{t_2 - t_{cw}}. \tag{2}$$

Here $(dT/dr)_s$ is the temperature gradient along a normal to the outside cylinder surface. Considering that the heat-transfer coefficient at the outside cylinder surface depends only on the height coordinate Z (the problem is systematic with respect to the angle), a solution of Eq. (1) with boundary condition (2) and $\partial T/\partial Z = 0$ at $Z = 0$ and $Z = h$ will easily yield

$$\alpha_z = \frac{\lambda}{t_2 - t_{cw}}\left[\frac{t_1 - \frac{a_0}{2}}{r_2 \ln\frac{r_2}{r_1}} + \sum_{k=1}^{\infty} a_k \frac{k\pi}{h}\cos\left(\frac{k\pi}{h} Z\right)\right]$$

S. M. Kirov Ural Polytechnical Institute, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 21, No. 6, pp. 985-991, December, 1971. Original article submitted January 20, 1971.

$$\times \frac{K_1\left(\frac{k\pi}{h}r_2\right)+\frac{K_0\left(\frac{k\pi}{h}r_1\right)}{J_0\left(\frac{k\pi}{h}r_1\right)}J_1\left(\frac{k\pi}{h}r_2\right)}{K_0\left(\frac{k\pi}{h}r_2\right)-\frac{K_0\left(\frac{k\pi}{h}r_1\right)}{J_0\left(\frac{k\pi}{h}r_1\right)}J_0\left(\frac{k\pi}{h}r_2\right)}\Bigg]. \quad (3)$$

The heat losses at the end surfaces can be reduced almost to zero by placing the cylindrical probe –calorimeter with its lower end on the gas distributor mesh and its upper end above the fluidized bed level. The constancy of the temperature at the inside surface of the tubular probe can be ensured by means of a steam–water bath [10]. In order to obtain a clearly defined temperature field t_2 at points with different α_z coefficients, a probing tube of a material with a low thermal conductivity λ should be used.

The results which will be shown here were obtained with cylindrical Plexiglas fluidization vessels D = 100 and 200 mm in diameter with fluidized corundum particles d = 120 and 320 μ in size and closely packed 375 mm high.

A tubular glass calorimeter (Fig. 1) was placed along the vessel axis; its inside temperature was maintained constant by intensive boiling of water. The lower part of the calorimeter–probe was passed through the gas distributor mesh so as to permit visual observation of the boiling process in that region. Gas distributor meshes used in this experiment had a 1.77% active section. The catalyst in all tests was air at room temperature with a relative humidity ranging from 60 to 83%.

The level of the boiling water in the calorimeter was always maintained at a height of 500 mm through a connection to a reservoir. The boiling temperatures of water in the lower and in the upper zone of the calorimeter differed by not more than 0.8°C over the height of the fluidized bed [11]. The temperature inside the calorimeter was checked with Chromel–Alumel thermocouples installed in the vapor and in the water space respectively. The Nichrome heater coil for the calorimeter was completely immersed in water, its turns being uniformly spaced along the calorimeter wall. The vapor space in the probe was connected to the atmosphere.

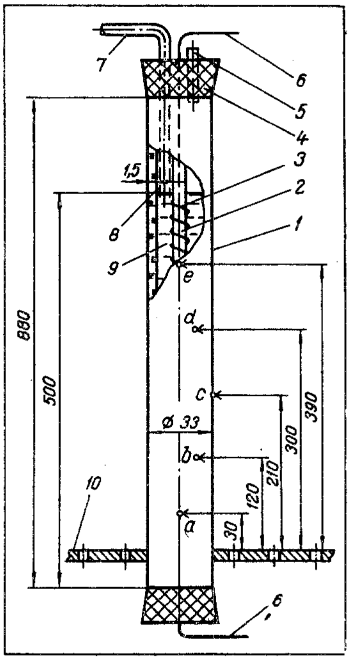

Fig. 1. Probe–calorimeter: 1) tube of thermometric glass; 2) porcelain center rod; 3) Nichrome coil; 4) rubber stopper; 5) vapor drain-tube; 6) leads to the heater element; 7) connecting tube to the reservoir; 8) vapor space in the probe; 9) water space in the probe; 10) gas distributor mesh; a, b, c, d, e are points at which the temperature was measured.

The temperature of the outside surface of the glass wall was measured with Chromel–Alumel thermocouples and 0.1 mm thick electrodes. The hot junctions (five points) and the thermoelectrode leads were secured to the probe surface with BF-2 adhesive. The hot junctions were spaced around a helix 90 mm (in most tests) apart at an angle over one third the circumference. During tests the calorimeter was moved along the axis for temperature measurements at intermediate points. After completion of the work, in order to account for any possible errors the calorimeter was cut off at the points where thermocouples had been secured and its wall thickness was measured along its height as well as around its circumference. The thickness was found to have been fluctuating within 1.5 ± 0.075 mm.

The temperature of the fluidized bed, as recorded for each test at several points along the radius, the angle, and the height, varied only slightly (±1°C) and was maintained in various tests at a level of 30-60°C.

The measurements were in all cases performed with the aid of PP-1 and PP-63 potentiometers.

Eighteen $t_2 = f(Z)$ graphs have been plotted from test data at various fluidization rates w. They all display the

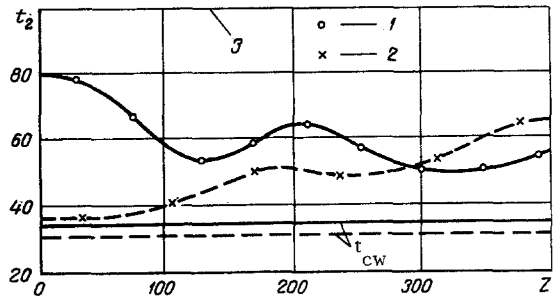

Fig. 2

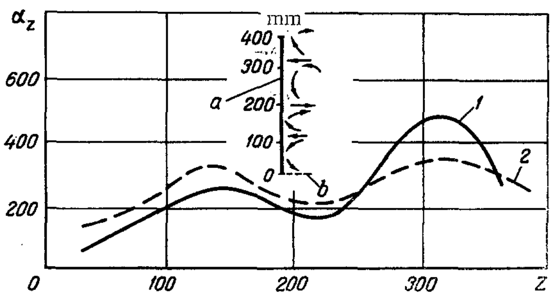

Fig. 3

Fig. 2. Trend in the temperature variation at the outside surface of the calorimeter wall: 1) in the D = 200 mm vessel with d = 320 μ, t_{cw} = 35°C, w = 0.214 m/sec; 2) in the D = 100 mm vessel with d = 120 μ, t_{cw} = 31°C, w = 0.1 m/sec; 3) temperature level t_1. Z, mm; t_2, °C.

Fig. 3. Variation of the heat-transfer coefficient along the cylinder height in the D = 200 mm vessel: 1) d = 320 μ and w = 0.196 m/sec; 2) d = 120 μ and w = 0.115 m/sec; a) cylinder boundary; b) air distributor. α_z, W/m^2·deg; Z, mm.

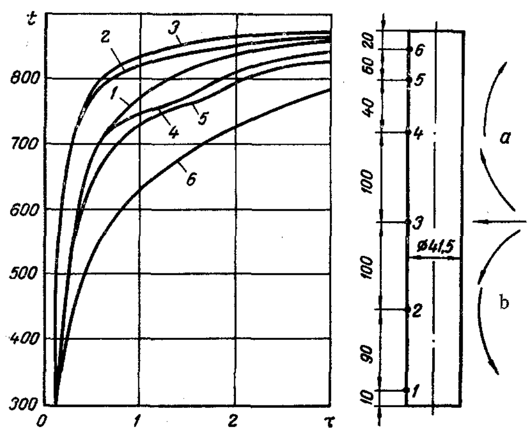

Fig. 4. Heating of a vertical cylinder in a fluidized bed: 1, 2. . . , 6 denote locations of thermocouples secured to the surface zone of the cylinder. t, °C; τ, sec.

same trend (Fig. 2): for a vessel of a certain diameter the temperatures remained at the same average level regardless of the particle size and of the fluidization rate, although the extrema depended on these factors.

The Fourier expansion coefficients for function $t_2(Z)$ were calculated from the empirical $t_2 = f(Z)$ graphs by the practical method of harmonic analysis with appropriate schedules [12].

Some calculated values of α_z are shown in Fig. 3. The maximum relative error possible here, taking into account the inaccuracies of all measurements and of the test curve approximation by a trigonometric Fourier polynomial, is estimated at ±15%. As can be seen in Fig. 3, the heightwise fluctuations of α_z about its mean value were much larger than that error. The difference between maximum and minimum α_z was, as a rule, at least 50%. In many cases this difference was twice or three times as large.

The hypothetical pattern of particles circulation in the bed, as shown in Fig. 3, is based on this α_z distribution.

The calculated mean (integral)-over-the-height values of α_z agree fairly well with the mean-over-the-surface test values of heat-transfer coefficients for cylinders 130 mm high, which we have obtained earlier in [13] with the D = 200 mm vessel.

It is to be noted that the magnitude of the heat-transfer coefficient for a small thermal probe does not depend on the depth of immersion in a fluidized bed. Therefore, we used a cylindrical vessel 75 mm in diameter for determining the coefficient of heat transfer between a copper ball 20 mm in diameter and a fluidized bed of 120 μ corundum particles (the height of the poured mass was 250 mm) with air at room temperature as the catalyst. The coefficient α was determined by the method of cooling the ball at various heights in the fluidized bed under regular thermal conditions. At a fluidization rate of 0.1 m/sec at distances of 50, 100, 150, and 200 mm from the gas distributor mesh, the values obtained for α were respectively 308, 384, 389, and 393 W/m^2·deg, i.e., there was no perceptible variation of α over the height of the intially poured bed. Therefore it is not the distance from the mesh itself, but the length of the heat-transfer surface that affects the value of α.

Apparently, the cylinder immersed in a fluidization vessel produces, itself, circulating currents around its surface. In view of this, local as well as mean heat-transfer coefficients may generally not be the same in different vessels and for surfaces of different dimensions.

In parallel with those experiments we performed analogous experiments with a porcelain calorimeter 19 mm in diameter and 3 mm in wall thickness, in the D = 100 mm fluidization vessel with 120 and 320 μ corundum particles. The trend of the temperature curves under these conditions remained the same as before (Fig.2).

Due to the presence of an α_Z field at the surface of a vertical cylinder, segments of heat-treated metal parts may be heating or cooling at different rates at different heights. We have determined experimentally the heating rates for surface segments of a vertical steel (35Kh2NM) rod 41.5 mm in diameter at different heights. The rod, with Chromel–Alumel thermocouples cemented to it, was immersed in a furnace with a fluidized bed of 320 μ corundum particles. The temperature was 900°C, the furnace dimensions were 300 × 600 mm in the plan view, and the gas distributor was capped. The rod was disposed along the furnace axis with its lower end 50 mm away from the axes of the holes in the caps. The heating thermograms were recorded with an ÉPP-09MI instrument.

The resulting heating curves are shown in Fig.4. As can be seen here, the heating rate is different for the individual rod segments. Hypothetical streams of particles are also shown; the contours of these streams were drawn on the basis of the curves obtained earlier. The difference in the cooling rates for the same segments of the rod immersed in a fluidized bed (230 × 570 mm vessel, 120 μ corundum particles) at a temperature of 900°C was no smaller after the rod had been heated than during its heating.

It appears then, on the basis of all our test results, that an increase in the fluidization number, with all other conditions unchanged, causes the extreme values of α_Z slightly to approach the mean values, although the difference still remains large in most cases. At the same fluidization number, the α_Z extrema are more pronounced in fluidized beds with coarse particles than in fluidized beds with fine particles.

In summary, considering the results of [9] and our data, it has been established that a vertical body, say, a cylinder, produces an extended thermal boundary layer which affects the heat transfer with the fluidized bed. This effect must be taken into consideration in the study of heat-treatment processes involving metal parts in a fluidized bed as well as in the design of heat-treatment plants and various fluidized beds for heat exchangers.

NOTATION

- α is the heat-transfer coefficent, W/m^2·deg;
- λ is the thermal conductivity of the probe wall, W/m·deg;
- t_{bc} is the temperature of the fluidized-bed core, °C;
- t_1, t_2 are the temperatures of the inside and outside probe surface, respectively, °C;
- r_1, r_2 are the inside and outside radii, respectively, of the probe–calorimeter, m;
- h is the height of the probe segment participating in the heat transfer, m;
- d is the dimension of the fluidized-bed particles, μ;
- a_0, a_k are Fourier expansion coefficients for the function $t_2 = f(Z)$;
- J, K are Bessel functions;
- w is the fluidization rate, m/sec;
- D is the diameter of the fluidization vessel, mm;
- Z is the height above the gas distributor mesh at which temperature t_2 is measured.

LITERATURE CITED

1. A. P. Baskakov, Fast Nonoxidizing Heating and Heat Treatment in a Fluidized Bed [in Russian], Metallurgiya, Moscow (1968).
2. R. Noack, Chemie–Ingenieur–Technik, No.6, 371 (1970).
3. N. V. Antonishin and S. S. Zabrodskii, Inzh.-Fiz. Zh., 6, No.11 (1963).
4. V. A. Antifeev, A. P. Baskakov, V. F. Onokhin, and V. I. Svetlakov, Technology of Hot Stamping [in Russian], No.2, Izd. Uralsk. Politekh, Inst., Sverdlovsk (1965), p.75.
5. A. P. Baskakov, B. V. Berg, A. S. Zavarov, I. V. Kirnos, and P. V. Sadilov, Progressive Methods of Metal and Alloy Heat Treatment, Papers of the All-Union Seminar [in Russian], May 19-21 (1970), Kommuna, Voronezh (1970), p.90.
6. I. N. Taganov, L. G. Malkhasyan, and P. G. Romankov, Teor. Osnovy Khim. Tekhnolog., 1, No.3 (1967).
7. I. N. Taganov and P. G. Romankov, Teor. Osnovy Khim. Tekhnolog., 2, No.5 (1968).
8. N. I. Gel'perin, V. G. Ainshtein, and V. B. Kvasha, Principles of the Fluidized-Bed Technique [in Russian], Khimiya, Moscow (1967).

9. H. S. Mickley, D. F. Fairbanks, and R. D. Hawthorn, Paper No. 8, Heat-Transfer Conference, New York, August 14-17 (1960).
10. G. N. Kruzhilin and V. A. Shvab, Zh. Tekh. Fiz., 5, No. 4, 703 (1935).
11. D. L. Timrot, S. L. Rivkin, A. M. Sirota, and N. B. Vargaftik, Tables of Thermodynamic Properties of Water and Steam [in Russian], GÉI, Moscow–Leningrad (1958).
12. A. M. Lopshits, Schedules for Harmonic Analysis and Synthesis [in Russian], Gostekhizdat, Moscow (1948).
13. B. V. Berg and A. P. Baskakov, Khim. Promyshl., No. 6, 439 (1967).