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THE EFFECT OF ORIENTATION ON THE HEAT TRANSFER FROM A FLAT SURFACE IN AN AIR FLUIDIZED BED

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NOMENCLATURE

$\bar{d}$,	average particle diameter;
d_{pi},	median particle diameter in size interval i;
h,	surface heat transfer coefficient;
q,	heat flux;
T_b,	fluidized bed temperature;
T_w,	probe surface temperature;
U_{mf},	fluid velocity at minimum fluidization;
x,	mass fraction of sand in size interval i;
θ,	probe angle.

INTRODUCTION

SEVERAL measurements have been reported for the heat transfer to or from a tube immersed horizontally in a fluidized bed [1–4]. Of specific interest to the present study is the observed variation of the local heat transfer coefficient along the circumference of the tube surface [1]. Consistent with this result would be a variation of the heat transfer with respect to the orientation of a flat plate immersed in a fluidized bed. Fillippovskii and Baskakov [5] have measured this variation for a large, heated plate which would correspond in size to the exterior wall of their fluidized bed. They found that the heat transfer coefficient reached a maximum value when the heated surface of the plate had a slight positive angle of attack. This angle is defined to be 100° in the present nomenclature.

To gain a better understanding of the heat transfer in a fluidized bed from angled surface, a series of tests was carried out for a small immersed surface. These experiments used a specially built heat transfer probe for determining the local heat transfer coefficients.

EXPERIMENTAL APPARATUS

The system consisted of a Plexiglas chamber of square cross-section, 20.3 cm × 20.3 cm, and 52.7 cm high. The insertion of probe mounting panels reduced the cross-section to 19.1 cm × 20.3 cm. At the bottom of the chamber, a porous stainless steel plate of 20 μm pore diameter was used as the distributor. Air was supplied to the system from a plenum shaped like an inverted pyramid. The volume inside the plenum was filled with steel wool to distribute the incident air stream over the cross-section.

The heat transfer probe was constructed by fixing a flat Minco electrical resistance heater (115.4 Ω) to a rigid insulating plate. The front surface of the heater was covered with a 1.5 mm thick aluminum plate to which a thermocouple was attached. The aluminum plate protected the heater from bombardment by the fluidized bed particles and also provided a uniform surface temperature. The aluminum plate was 3.85 × 3.85 cm, the effective heat transfer area. The insulating plates, on the back side, were comprised of three layers of phenolic laminate, each 1.5 mm thick. A schematic diagram of the probe is shown in Fig. 1.

The probe was positioned in the fluidized bed by fixing a length of screw rod to the rear layer of the phenolic laminate. The ends of the screw rod fitted into holes that were drilled in the Plexiglas mounting plates mentioned above, which fitted snugly against the chamber walls. The angle of the probe could be changed by rotating the screw rod.

The particles comprising the fluidized bed were Ottawa fine white sand. This material is primarily quartz, and has a solid density of 2720 kg m^{-3}. The particle sizes ranged between 0.09 and 0.28 mm. The average particle diameter $\bar{d}_p$ was calculated by sifting a sample through graduated screens and using the following formula recommended by Botterill [6]: $\bar{d}_p = [\sum_i (x/d_p)_i]^{-1}$. This gave a value of 0.182 mm.

The test conditions were a series of variations of the following parameters: probe location, probe angle, fluid flow-rate, and heat flux. The last parameter was used to distinguish one data point from another. The probe was located at the center of the bed at three different probe elevations, namely: at 5 cm from the base for the 'bottom zone'; at 10 cm for the 'middle zone'; and at 15 cm for the 'splash zone'. At the 10 cm elevation, additional tests were made adjacent to the wall. For these tests, the heat transfer surface was always in a plane normal to the wall. At each location measurements were made at six different angles in 30° increments* ranging from the horizontal position with the aluminum plate facing away from the air stream (0°), to the vertical position with the aluminum plate parallel to the air stream (90°), to the horizontal position with the aluminum plate now facing toward the air stream (180°). Figure 1 shows the probe and the specification of the angle.

At each position, three different flow rates were used: two constant rates and a rate roughly equal to the minimum fluidization value. The minimum fluidization velocity was determined experimentally and varied between 0.046 and 0.054 m s^{-1}. The two higher velocities were 0.073 m s^{-1} and 0.098 m s^{-1}. At the highest velocity the fluidized bed expanded to a height of 20.0 cm from a packed bed height of 17.5 cm.

The thermocouple on the probe provided the temperature in the fluidized bed, T_b. This measurement was made in the absence of heating. Note that the probe has an asymmetric construction relative to the heating element. A constant heat flux, q, was applied to the heating element and the thermocouple output for the aluminum plate at the angles θ, and $\pi - \theta$ was recorded. An energy balance on the probe for these two conditions yields

*Accordingly, data points are not shown in the figures.

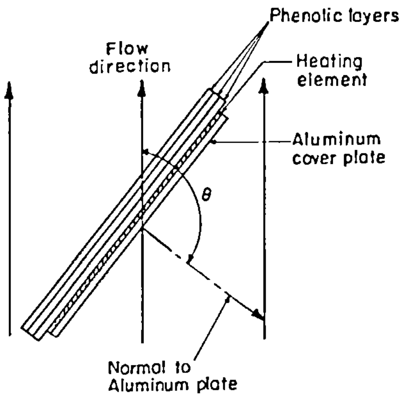

Fig. 1. Heat transfer probe.

$$q = \frac{T_{w_1} - T_b}{\dfrac{1}{h_\theta} + R_i} + \frac{T_{w_1} - T_b}{\dfrac{1}{h_{\pi-\theta}} + R_{Al}};$$

$$q = \frac{T_{w_2} - T_b}{\dfrac{1}{h_{\pi-\theta}} + R_i} + \frac{T_{w_2} - T_b}{\dfrac{1}{h_\theta} + R_{Al}} \qquad (1)$$

where R_i and R_{Al} are the thermal resistance of the insulation and the aluminum plate, respectively, and h_θ and $h_{\pi-\theta}$ are the heat transfer coefficients at the discussed angles. The solution to the equations yields the heat transfer coefficients at the angles θ and $\pi - \theta$. This method has the advantage that it does not require the insulation of one side of the probe while measuring the heat transfer coefficient on the other side. Therefore, a thin probe can be used in these measurements to minimize the disturbing effect of the probe thickness on the flow. It is noted that the experiments reported in ref. [5] utilize a complex system of insulation of the probe which cannot be employed with small immersed surfaces.

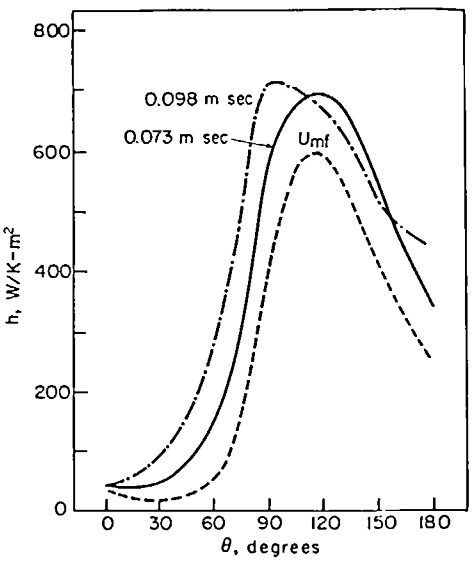

Fig. 3. Heat transfer vs probe angle, probe elevation 10 cm.

RESULTS AND DISCUSSION

The results of the tests are presented in Figs. 2–5. The values presented are a time average over a period of 10 min. At least three runs were performed at each condition. The experimental error was calculated to be 8% of the measured value. In general, the curves exhibit low values of the heat transfer coefficient at small angles; i.e. near 0°. This is followed by a rapid increase to a peak between angles of 90° and 120°, and then a decrease as the angle goes to 180°. It is clear that probe angle has a considerable effect on the heat transfer. The increase in the heat transfer as a function of angle is very steep and is probably a consequence of the rapid transition between packed bed and fluidized bed behavior in the vicinity of the heat transfer surfaces.

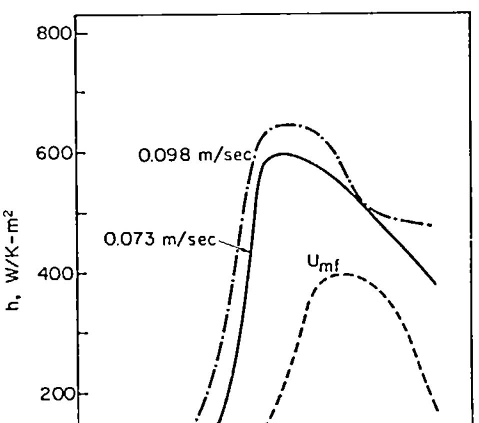

Fig. 2. Heat transfer vs probe angle, probe elevation 15 cm.

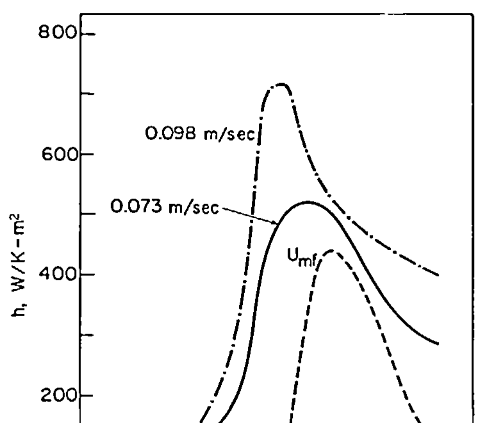

Fig. 4. Heat transfer vs probe angle, probe elevation 5 cm.

The low values of the heat transfer for small angles are characteristic of a packed bed. It seems plausible that the probe, which is horizontal at 0°, blocks the vertical air stream and causes the particles in contact with the heat transfer surface at the top of the plate to be unfluidized. The 30° angle is the angle at which sand particles experience 'solid flow' due to gravity. Figure 3 indicates that in a fully fluidized regime, at the 10 cm elevation, the heat transfer starts to increase rapidly between the angles of 30° and 45°. As the probe moves to a vertical orientation (90°), there is less blockage of the air stream, the particles are more readily fluidized and the heat transfer increases.

From Figs. 2–4 it is seen that the angle at which the heat transfer starts to increase rapidly, decreases with an increase in flow rate. This is probably related to the more vigorous mixing and movement of particles at the higher air flow rates. Figure 5 is for the region near the wall and shows that at the same flow rates the angles at which the rapid increase in heat transfer starts are larger near the wall than in the center. This indicates that the mixing and the movement of particles near the wall is less vigorous than in the center. This is, indeed, a well-known and an amply documented phenomenon [5]. Note also that the heat transfer coefficient in the center of the fluidized bed is larger than near the wall.

A more subtle and interesting result is the angle at which the peak heat transfer occurs. For the velocity U_{mf} the peak is reached at about 120° at all locations. For the higher flow rates, there is an increase in the heat transfer and a general shift in the peak towards 90°. It is also interesting to observe that the maximum value of the heat transfer coefficient at U_{mf} increases (about 45%) with increases in elevation of the probe from 5 to 10 cm. However, further increase in elevation to 15 cm results in a substantial decrease in the heat transfer coefficient.

A possible explanation for the change in the angle at which the peak heat transfer occurs is now given. For angles greater than 90° the heat transfer is affected by two different phenomena. With an increase in angle the probe surface presents a larger effective heat transfer area to the mainstream of particles. The larger effective heat transfer area will promote the overall heat transfer to the surface. However, an increase in angle may also cause the particles to be held against the surface, perhaps sliding along the surface and creating a 'boundary layer'. This would certainly reduce the heat transfer. A higher flow rate or angle will increase the 'boundary layer' effect.

For the experimental conditions analyzed in this work, the maximal heat transfer at flow rates near U_{mf} occurs at 120°. This is probably due to the two effects discussed above. As the flow rate increases and with it the vigorous mixing of particles, the relative significance of having a larger effective heat transfer surface will decrease while the 'boundary layer' effect will increase. When the surface is at 90° the particles would not be significantly constrained and therefore would be more rapidly replaced by new particles which would promote the heat transfer. According to the explanation given above, the peak angle should shift to 90° for higher flow rates. Note that as the flow rates increase, the increase in heat transfer at 90° is much greater than at 120°. This is consistent with the proposed effect of the 'boundary layer' as is the observed decrease in the heat transfer for angles greater than the angle at which the peak occurs at all flow rates.

Applying this discussion to the measurements near the bedwall (cf. Fig. 5), it is seen that there is a noticeable shift in the peak towards 90° (although the peak does not actually reach 90°, even at the highest flow rate). This is in accordance with the discussion above and the observations that the movement of the particles near the wall is less vigorous than in the center.

It is emphasized that the results presented have been obtained for the one particle size and bed configuration presented in the text.

CONCLUSIONS

An experimental study has been performed to determine the heat transfer on a small surface immersed in a fluidized bed. Measurements were made at various angles of the surface relative to the general direction of the air flow. The experimental results show a strong variation for the heat transfer coefficient with respect to the angle. Minimal heat transfer coefficients were obtained when the heat transfer surfaces faces away from the direction of the flow. The maximal heat transfer coefficient was measured for angles between 90° and 120°.

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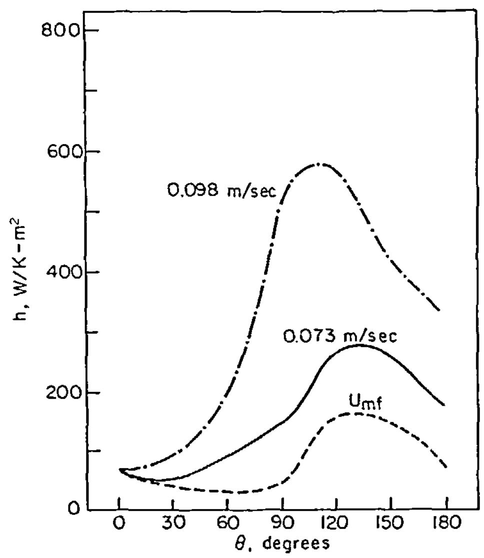

FIG. 5. Heat transfer vs probe angle, probe near wall, elevation 10 cm.

REFERENCES

1. R. Chandran, J. C. Chen and F. W. Staub, Local heat transfer coefficients around horizontal tubes in fluidized beds, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **102**, 152–157 (1980).
2. S. C. Saxena, N. S. Grewal, J. D. Gabor, S. S. Zabrodsky and D. M. Galershtein, Heat transfer between a gas fluidized bed and immersed tubes, in *Advances in Heat Transfer* (edited by T. F. Irvine, Jr., and J. P. Hartnett), Vol. 14, pp. 149–247. Academic Press, New York (1979).
3. J. Cretu, L. Yang and S. C. Saxena, Heat transfer to a single smooth vertical tube immersed in air fluidized bed, *Lett. Heat Mass Transfer* **8**, 465–474 (1981).
4. W. E. Genetti, R. A. Schmall and E. S. Grimmett, The effect of tube orientation on heat transfer with bare and finned tubes in a fluidized bed, *A.I.Ch.E. Symp. Ser.* **67**(116), 90–96 (1971).
5. N. F. Fillippovskii and A. P. Baskakov, Investigation of the temperature field in a fluidized bed close to a heated plate and of heat transfer between them, *Int. Chem. Engng* **13**, 5–9 (1973).
6. J. S. M. Botterill, *Fluid-Bed Heat Transfer*, Chap. 2, Section 6. Academic Press, New York (1975).