Particles Flow Pattern and Local Heat Transfer Around Tube in Moving Bed

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Flow visualization of flowing particles around a tube of various types of tube arrangements in a moving bed was studied using X-ray video films to obtain a relation between particles behavior and local heat-transfer coefficients. A stagnant part of solid particles was observed on the tube in the case of a staggered arrangement. This part did not appear in the case of the single tube and the single row of tubes. The measured local heat-transfer coefficients around a tube was decreased in this stagnant part. Furthermore, influences of different tube arrangements both on flow patterns of particles and on local heat-transfer coefficients between tubes and bed were examined.

Introduction

Moving bed technology has been developed in the field of heat and mass transfer and reaction between solid particles and gas. In practical use, the blast furnace is typical. Recently, the moving bed has been applied to the pyrolyzer, the adsorber, the dust collector, and the heat exchanger. However, the application field is still not wide in comparison with fluidized-bed technology. The merits and demerits of moving bed technology must be made clear. One of the big issues is how to achieve a smooth movement of solid particles while preventing bridge formation. The information on the flowing behavior of particles around a tube is important for the design and operation of a moving bed with horizontal tube banks.

The experimental methods for flowing behavior of particles can be divided into three broad categories: visual and photographic work; X-ray and γ-ray investigations; and "flow-freezing" techniques (Tüzün et al., 1982). Among those methods, X-ray video films have promise for obtaining useful information in flow experiments. Athey et al. (1966) and Cutress and Pulfer (1967) adopted the X-ray cine-film technique for observing the interstitial voidage within the flowing material. Bransby et al. (1973), Bransby and Blair-Fish (1975), and Lee et al. (1974) determined individual particle trajectories within a bed of sand. There are, however, few reports about the flowing behavior of particles around a tube in a moving bed using X-ray systems.

In addition, the heat transfer between tubes and a bed is quite an important problem for a moving bed heat exchanger (Takeuchi et al., 1990). Many researchers have done work on flowing bed heat transfer. Denloye and Botterill (1977) concluded that the heat-transfer coefficient increases with decreasing particle residence time, using a plate-type heater. Colakyan and Levenspiel (1984) proposed a heat-transfer model of the heat-transfer coefficients between immersed tubes and a moving bed of solid particles. This model is based upon the well-known "packet" theory and contains resistance due to an intervening gas layer between the heat-transfer surface and the first row of particles. The model is sometimes useful for making correlation of different kinds of experimental data. Their results were, however, based upon experiments using a single heat-transfer tube. It is not yet clear whether or not their results are applicable to individual heat-transfer tubes in tube banks.

Almost all researchers used a plate-type and/or a single tube in a moving bed for their experiments. In this study, X-ray video films of the particles flowing around a tube of different arrangements were taken in a moving bed to investigate the relationship between the local heat-transfer coefficient and the flowing pattern of particles. In addition, different distributions of local heat-transfer coefficients were obtained for different tube arrangements according to different flow patterns.

Experimental Studies

The experimental setup and an X-ray video system is shown in Figure 1. The dimensions of a test hopper which was made of PMMA plates were 1.00 m high, 0.204 m wide, and 0.160 m deep. An inclined sidewalls of the test hopper made an angle of 57° with the horizontal. The discharge opening at

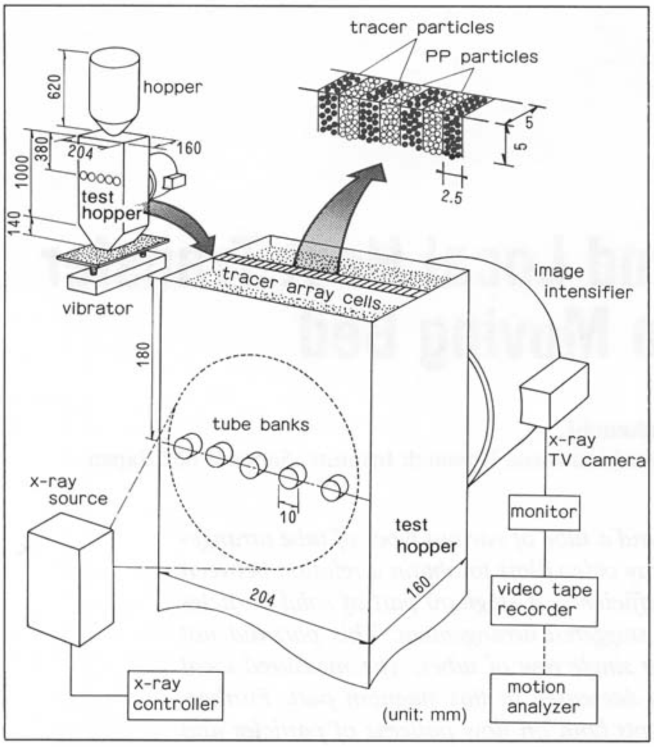

Figure 1. Experimental apparatus.

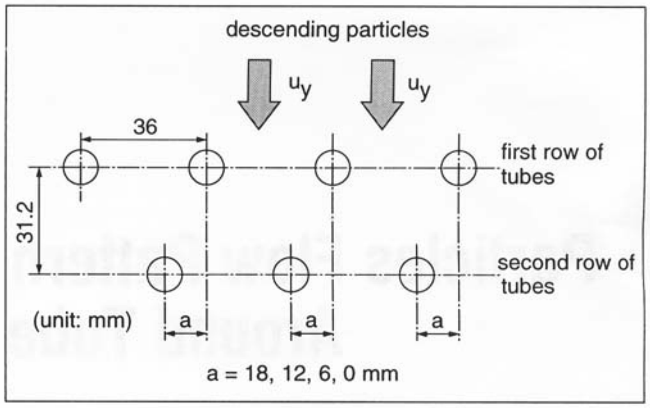

Figure 2. Additional arrangement of tube banks with changing *a* value.

the bottom was 0.052 m wide. A vibrator with a horizontal plate was set below the test hopper. The distance between the discharge of the test hopper and the horizontal plate was changeable to adjust velocity of descending particles. An additional hopper was installed on the top of the test section. Copper tube banks were inserted into the test hopper horizontally, and their location was about 0.38 m below the top of the test hopper. At the elevation of tube banks, the flowing state of particles was in the plug-flow region. This was confirmed by the radiography of the test hopper without tube banks. The outer diameter of tubes was 10 mm. The arrangements of the tubes were a single tube, a single row of tubes, two rows of tubes, and three rows of tubes. In the last two cases, a staggered arrangement was used and experiments were done with changing particles descending velocity and pitch between the tubes. Furthermore, the different tube arrangements were introduced with changing *a* value (Figure 2) to get different flowing pattern of the particles around tube banks. When *a* was equal to 18 and 0, the arrangement corresponded to a staggered and a square arrangement, respectively.

Polypropylene was the solid particle used and was sieved between 0.71-mm and 0.35-mm sieves. The density was 910 kg/m^3 and the poured angle of repose measured was 38°. A contrast medium, barium sulfate, was applied to the polypropylene particles to make a tracer. The density of the tracer particles was about 1.1 times as large as that of the polypropylene.

X-rays were taken by medical equipment at 40–100 kV, using 20-mA constant current. X-ray video films were obtained using an X-ray television camera. X-radiograph, which was recorded on a video tape, was 60 frames/s. The flowing behaviors of tracer particles were investigated by a motion analyzer.

On the elevation of 0.180 m above tube banks, tracer particles were set in the horizontal midline using tracer array cells. To observe the gross flowing behavior of the particles around tube banks, tracer particles were set like a solid line. In this experimental system, the size of individual particles was too small to resolve their trajectories. The tracer was placed like a striped line and, as an attempt, the trajectory of each edge of the striped line element was followed to analyze the displacement and the velocity of the edge. The shape of the striped line element of tracer particles was almost a rectangle. Its transverse length was about 2.5 mm and the longitudinal one was about 5.0 mm, as shown in Figure 1; therefore, that was large enough to pursue its trajectory using a motion analyzer and to obtain velocity of the elements.

Local heat transfer was measured using a heat-transfer probe (Figure 3). It was made by a PMMA cylinder partly covered with a stainless foil. The thickness of the foil was 0.020 mm. Two bus rings were connected to each end of the foil, and electrical power leads were attached to them. A uniform heat flux from the tube surface to the bed was achieved by Ohmic heating. A single thermocouple of 0.090-mm CA wire was attached to the inside of the foil. This probe was used instead of one of the copper tubes. The local surface temperature of foil was measured by rotating the heat-transfer probe around its axis. The reference temperature was measured by a thermocouple which was located at 70 mm

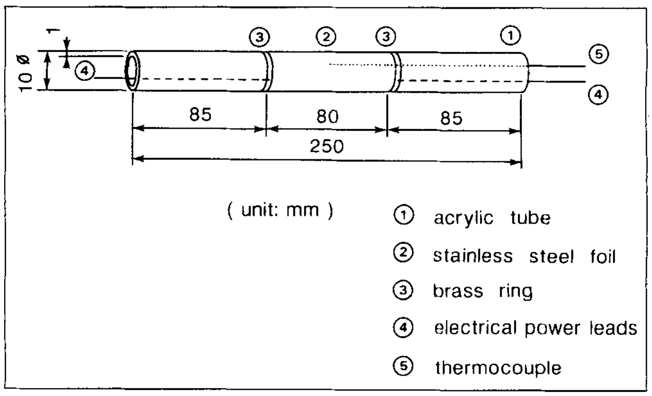

Figure 3. Heat-transfer probe.

upstream from the heat-transfer probe. A local heat-transfer coefficient was evaluated from the equation

$$h = \frac{q}{A(T_w - T_b)} \qquad (1)$$

Krall and Eckert (1973) measured local heat-transfer coefficients around a cylinder in air flow, using a similar structure probe. The heat-transfer coefficient was preliminary measured in the condition of air forced convection. The results were well correlated with McAdams (1942) equation with an accuracy of $\pm 10\%$. During the heat-transfer experiment, the whole experimental apparatus was set in a temperature-constant room, and the particles which were descending from the test hopper were returned to the upper one.

Results and Discussion

Using a solid line-type of tracer particles, the flowing pattern around a tube with the passage of time was obtained. In Figure 4, typical X-ray radiographs by video frames are shown. The field of vision is circular, and the blackest bodies in each picture are copper tubes inserted into the bed. The cross sections of the tubes which were not located in the center part of the frame showed not a circle but a transformed oval, because this X-ray system equipped a point-type of X-ray source. Only the part around the center of a flame was available for analysis. Some relatively white circles are holes which are on both sides of the bed wall for inserting copper tubes. Figures 4a and 4b were taken when the tubes were arranged in a single row and two rows, respectively. Below the tubes in each flame there are V-shaped void regions. The great difference between Figures 4a and 4b was the existence of a stagnant part on the tube. Figure 4b, frames 2 and 3 on the tube of the second row, where caps of tracer particles caused by relatively stagnant particles can be seen.

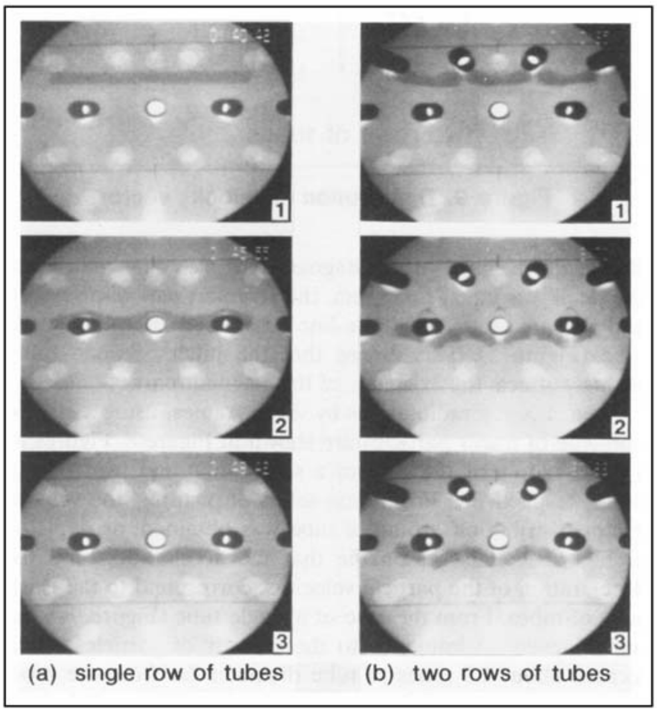

Figure 4. Typical X-ray video frames using solid line of tracer particles.

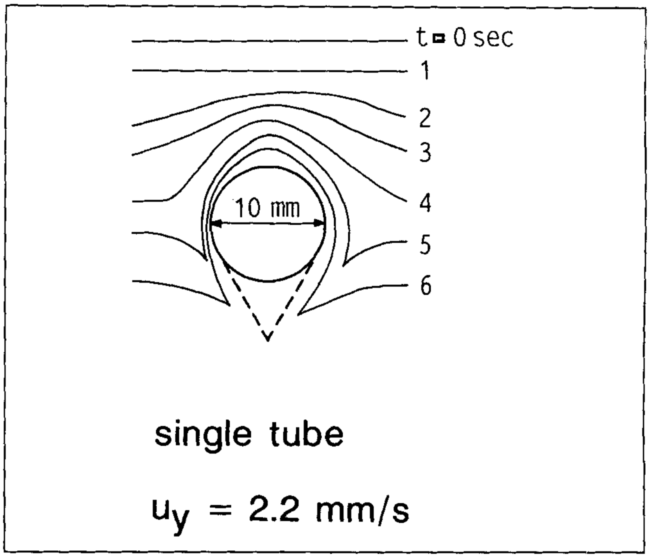

Figure 5. Time-line in single tube.

Based upon X-ray video films, the time-line of the descending particles was depicted for the case of a single tube in Figure 5. The circle represents the outline of a tube, and the area enclosed by the broken line below the tube shows the void region. As is shown by the time-line at $t = 0$ and 1 s, the velocity distribution is a plug-flow type with a contact velocity of 2.2 mm/s. The influence of the blocking by tube on the velocity distribution was shown within 1 and 2 s; and after 6 s the particles covered the upper part of the tube. Then, the tracer particles went down and they were replaced by the background particles. A similar flowing pattern around a tube was also obtained in the arrangement of the single row of tubes.

A different flowing pattern was observed on the second row of tubes in the arrangement of two rows. Figures 6a and 6b were obtained at the particle descending velocities, 2.8 mm/s and 25 mm/s, respectively. In both cases, stagnant parts which showed an inverse V-shape were formed on tubes. In

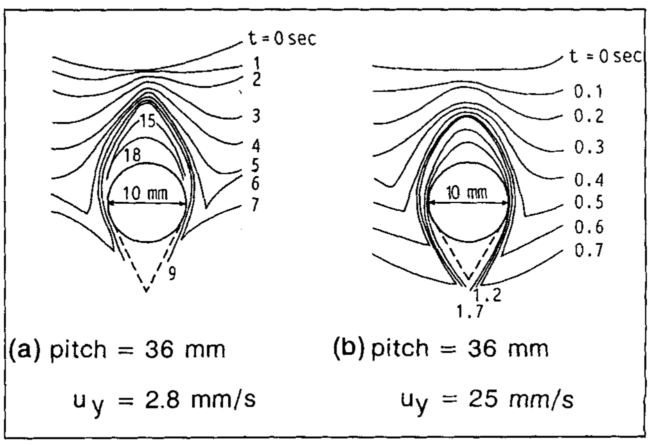

Figure 6. Time-line in two rows of tubes.

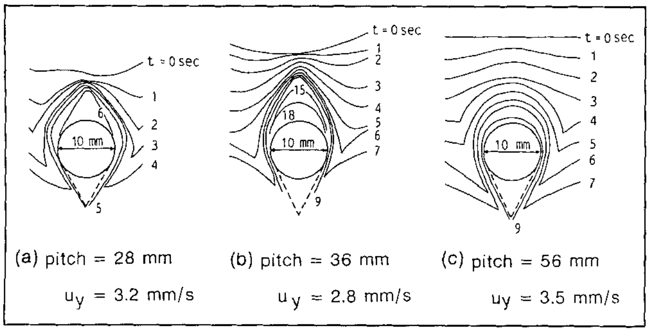

Figure 7. Effect of pitch on existence of stagnant part.

the arrangement of three rows of tubes, similar stagnant parts were also observed on the tubes, with the exception of the first row. This demonstrated that in the arrangement of *n* rows of tubes in staggered tube banks, stagnant parts of the particles should exist on each tube, not including the first row of tubes. From Figure 6, it is clear that the descending velocity of the particles does not have an influence on the existence of the relatively stagnant part, but has an effect on the residence time of particles. Around a tube of staggered banks, there are three regions, namely, a relatively stagnant one on the tube, a void one below the tube, and a normal moving bed region along both sides of the tube.

The influence of the pitch between tubes on the existence of the stagnant part was also examined using three different pitches. The results were shown in Figure 7. The particle velocities showed small differences among these three, but according to the result from Figure 6, the velocity has little influence on the existence of the stagnant part. If the pitch changed, the shape of the stagnant part also changed. When the pitch was equal to 56 mm, the stagnant part disappeared and the pattern of the time-line resembled that of a single tube (Figure 5). This means that the pitch between tubes strongly affects the existence of the stagnant part.

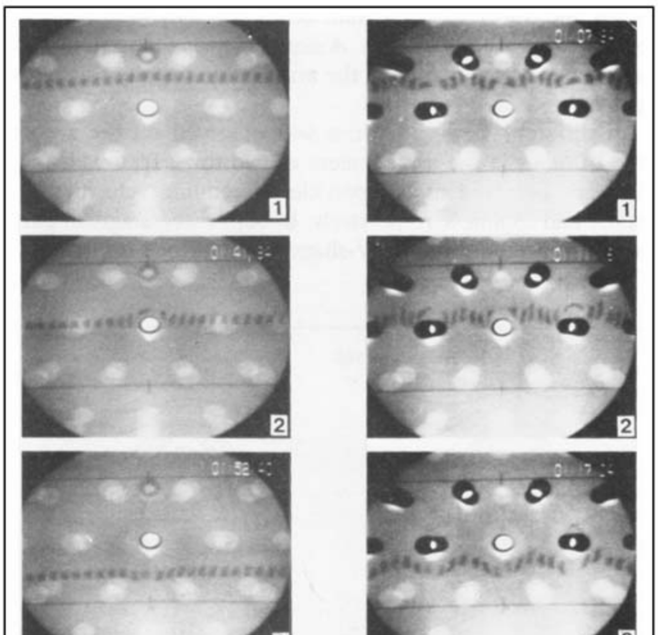

Figure 8. Typical X-ray video frames using a striped line of tracer particles.

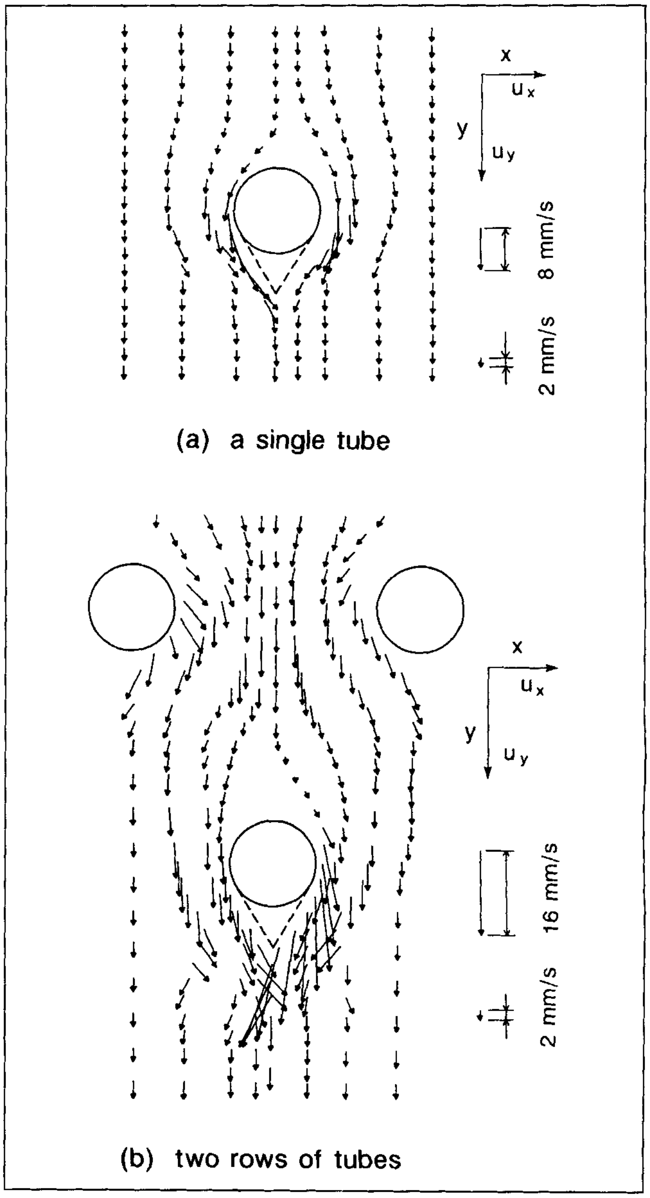

Figure 9. Distribution of velocity vector.

Typical X-ray radiographs by video frames, using a striped line-type of tracer particles are shown in Figure 8. Figures 8a and 8b represent the case of a single tube and two rows of tubes, respectively. From time series of pictures, the velocity vector distribution around a tube was obtained, as depicted in Figure 9. It is reasonable that the acceleration and the deceleration of the particle velocities correspond to the existence of tubes. From the case of a single tube (Figure 9a), the tube showed no influence to the velocity of particles which located about 1.5 times of tube diameter far from the tube. In the arrangement of two rows of tubes (Figure 9b) there are two distinguishable points in comparison to a single tube. First, on the tube the movement of the particles is damped.

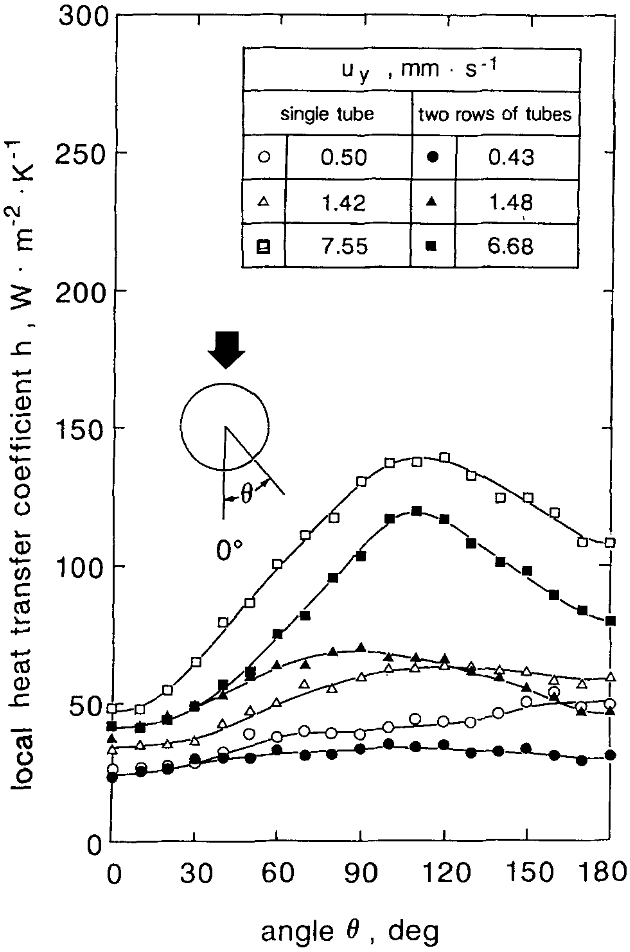

Figure 10. Comparison of local heat-transfer coefficient.

Secondly, the velocity fluctuation is large on the boundary of the void region below the tube. However, this analysis method has a defect. Before approaching the tubes, each element of the tracer had a rectangle shape, and near the tubes this shape was distorted, as is shown in Figure 8a, frame 2, and 8b, frame 2. It is not easy to analyze precisely this way, but promises to bring qualitative information.

The local heat-transfer coefficients around a tube are plotted in Figure 10. The open and closed symbols represent the values which were obtained in a single tube and the second tube of two rows, respectively, for three different particle descending velocities. At the lowest velocity, the open symbols showed higher values than the closed ones especially around the top part of the tube. This fact corresponds to the existence of stagnant part particles on the top of the tube. Such a tendency is also recognized at the middle velocity. It is clear that the heat-transfer coefficient between a tube and a moving bed increases with a decrease of the particles residence time on the surface of the heat-transfer tube. This is consistent with earlier results by Denloye and Botterill (1977). At the highest velocity, the shapes of the distribution curve for both tube arrangements were similar. This implies that the stagnant part does not move permanently, but moves with a smaller velocity than the surrounding particles. With a relatively high velocity, a stagnant part still exists, as is shown in Figure 7b, but the residence time of a particle is short enough to increase the local heat-transfer coefficients.

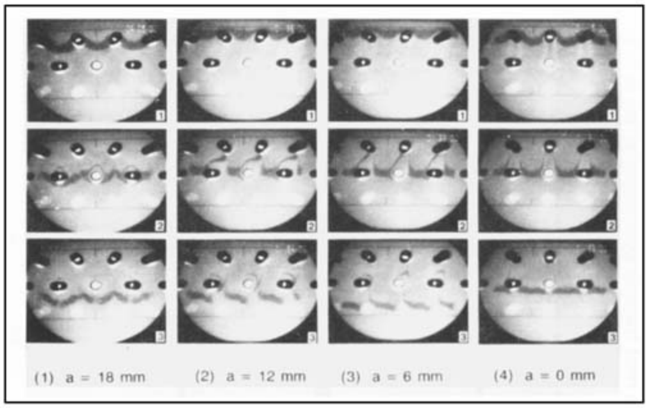

Figure 11. X-ray video frames for different tube arrangements.

Figures 11a, 11b, 11c, and 11d show the time-series pictures in the two rows of tubes with different values of a. These were obtained when the particle descending velocity was about 3.3 mm/s. From these radiographs, the time-line for different arrangements were depicted in Figure 12. The stagnant part which was located on the tube at $a = 18$ moved clockwise at $a = 12$, and its height increased at $a = 6$. When a is equal to zero, a stagnant part was established between the

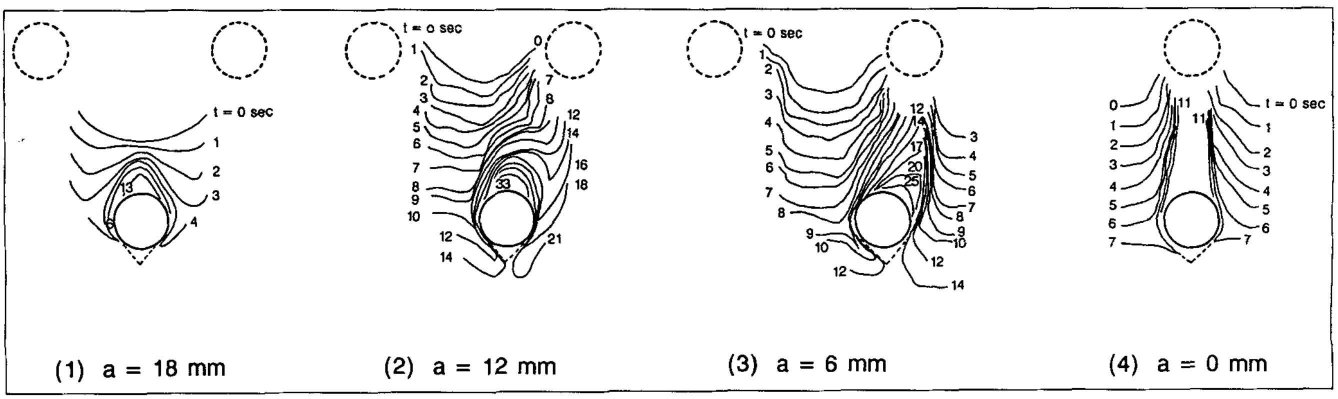

Figure 12. Change in flow patterns affected by *a* values.

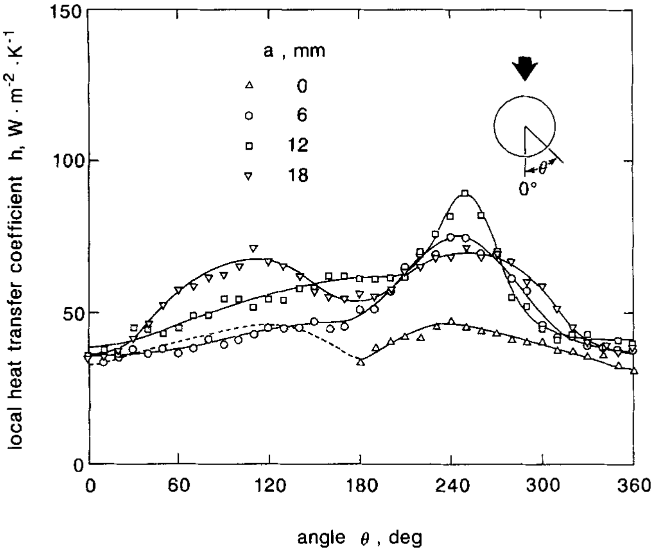

Figure 13. Distribution of local heat-transfer coefficients for different tube arrangements.

first and the second tube. It looks like one plate, so particles on the righthand side and those on the left were never exchanged through this stagnant part.

For each arrangement, the local heat-transfer coefficients were measured, as shown in Figure 13. It is clear that the local heat-transfer coefficient was strongly affected by the tube arrangements. This is mainly caused by the different flow pattern of particles, as is described in Figure 12. The minimum values of the heat-transfer coefficients were obtained at around $\theta = 0°$ for each a value, but the maximum values were obtained at different angles. These maximum points corresponded with the parts where the particles velocity showed the highest value around the tube. After integration of the local heat-transfer coefficients, the overall heat-transfer coefficients were calculated. They ranged from 40 to 56 W/(m^2·K). The largest and the smallest were obtained at $a = 18$ and 12 and $a = 0$, respectively. The heat-transfer coefficient could be controlled by changing tube arrangements simply.

Conclusion

Flow visualization of flowing particles around an immersed tube in a moving bed was analyzed by X-ray video films. Local heat-transfer coefficients around a tube were also measured that showed the influence of the particle flow pattern on them. The results suggest the following:

- Stagnant part in which the movement of particles is relatively slower than surrounding particles exists above a tube below the second row of tubes in staggered tube banks.
- Stagnant part is not affected by the descending velocity of particles, but by the pitch of tubes.
- For a relatively small descending velocity of particles, the value of local heat-transfer coefficient decreases in a stagnant part.
- Small change in tube arrangements affects both the flow pattern of particles and the distribution of the local heat-transfer coefficient.

Notation

A = surface area of the stainless steel foil, m^2
h = local heat-transfer coefficient, W/(m^2·K)
q = electric power supplied to the probe, W
t = time, s
T_b = reference temperature, K
T_w = surface temperature of the stainless steel foil, K
u_x = solid particle velocity in x-direction, m/s
u_y = solid particle velocity in y-direction, m/s
x = horizontal coordinate, m
y = vertical coordinate, m
θ = angular coordinate, °

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