Reduction of the Wall Effect in a Packed Bed by a Hemispherical Lining

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The whole area of packed-bed studies, including heat transfer, fluid flow and reaction, is the subject of considerable research efforts due to the numerous applications. Packed beds are of broad interest, due to their wide use in industrial processes such as gas-liquid absorbers, distillation columns, catalytic reactors, metallurgical processes such as a blast furnace, and heat storage units using phase change materials (Akiyama et al., 1993). When monosize spheres are packed in a cylindrical container, the radial distribution of voidage within the bed is not uniform due to the existence of the wall. In particular, the voidage variations very close to the wall are remarkably larger than in other regions: this is the so-called "wall effect." Some processes have suffered from a pronounced wall effect, since they have small aspect ratio [tube diameter (D)/particle diameter (d)]. Furthermore, the flow maldistribution caused by this larger voidage near the reactor wall can be an important secondary effect of wall. This flow pattern, which is generally referred to as "channeling," will decrease the overall efficiency of reaction and heat transfer.

There have been many articles in the literature regarding the voidage of packed beds (for example, Roblee et al., 1958, Benenati and Brosilow, 1962; Kimura et al., 1955). The principle of their experimental techniques to obtain the radial variation of voidage was identical. They first filled all the interstices in the packed bed with a resin or a wax. Then, the solid cylinder was machined to a successively smaller diameter. By measuring the weight removed and the diameter after each cut, the voidage in each thin annular section was determined. According to their data, a large randomly packed bed of uniform spheres tends to take an average voidage of 0.39. However, the voidage varies locally. The voidage changes in a oscillatory manner near the wall, due to the geometry of the spheres and the curvature of the container wall. Roblee et al. (1958) reported that the oscillatory variations of local voidage near the wall are found from the wall to three-sphere diameter at least. Later, Benenati and Brosilow (1962) confirmed that the annular zone, within which the oscillations of local voidage occur, extends inward a distance of approximately five-sphere diameters. In addition, they showed that the voidage tends to unity on the wall due to point contact and has a minimum at one sphere radius from the wall. Mathematical formulations have also been proposed to describe the voidage variation by exponential forms (Chandrasekhara and Vortmeyer, 1979) and by damped sinusoidal forms (Schulunder, 1977).

The sharp rise in voidage at the wall reduces the resistance to flow in this region; therefore, the velocity tends to be larger in the boundary layer. This has been observed experimentally (Carman, 1937; Metha and Hawly, 1969; Schwartz and Smith, 1953) and also has been reproduced in numerical simulations (Akiyama and Yagi, 1990). In general, channeling becomes more significant when the aspect ratio becomes smaller. The channeling effect is often ignored in many practical applications in spite of its importance, just because the aspect ratio is over 20. In a previous study, the influence of the aspect ratio (D/d) on channeling was examined by numerical simulation based on an extended version of Ergun's equation, and was validated by reliable data of radial gas velocities above the bed (Akiyama and Yagi, 1990). The result in Figure 1 showed that the channeling is still pronounced even with an aspect ratio of 20.3, because the axial velocity at the central axis was 73% of plug-flow value. Recently, it was also confirmed by Fand and Thinakaran (1990) that the influence of channeling exists in packed beds in which the tube diameter is less than 40 particle diameters. It is, therefore, often difficult to eliminate the channeling effect in a laboratory-scale packed bed by increasing the aspect ratio in the experimental apparatus, because of the limitation of particle diameter.

On the other hand, several researchers have tried to eliminate the wall effect without an extreme increase in the aspect ratios in their experiments. Kubota and coworkers (1965) prepared a packed bed of uniform voidage by a unique experimental technique. It consisted of packed monosize spheres of resin (8 mm ϕ) into a cylindrical container (66 mm ϕ), and then filling all the interstices with a paraffin introduced into the container. After curing, the diameter of the solid cylinder was reduced to 50 mm by a lathe. The introduced paraffin was removed by hot water after the reduced cylinder was placed in a pipe (50 mm ϕ). Hills and Paul (1971) deformed the container wall to decrease the local voidage close to the wall in their experiments on the decomposition of calcium carbonate. A sheet nickel liner was placed against the inside of the tube. Hemispherical bulges were randomly

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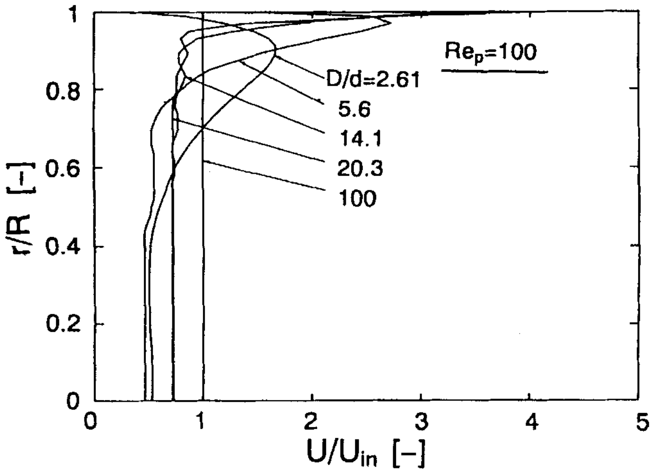

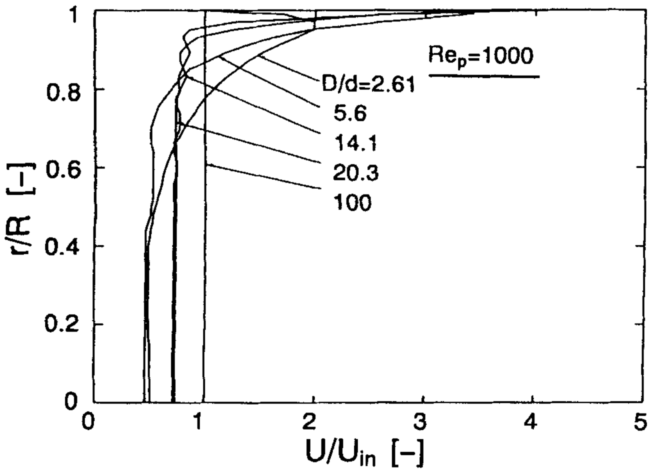

Figure 1. Radial distribution of developed air flow in a packed bed for $Re_p = 100$ and 1,000.

pressed into this liner to project into the bed, thus effectively reducing the voidage at the wall of the bed and therefore minimizing the wall effect.

These two reports greatly contributed to the development of possible experimental methods for reducing the wall effect in a packed bed. However, a generally applicable, experimentally validated, simple method for eliminating the wall effect is needed. In this study, a new method of eliminating the wall effect is proposed. The main feature of this method is to use an easy-lining sheet of regularly arranged, convex hemispheres. The effects of this method on voidage distribution and channeling are experimentally studied by X-ray computed tomography and by measurements of the radial distribution of liquid flow, respectively. One may use the principle of this method in all packed-bed applications for eliminating the wall effect and for improving the efficiency of heat transfer, reaction and so on by promoting uniform fluid flow.

Materials and Methods

Wall deformation

A commercially available sheet with convex hemispheres was used for wall deformation. The hemispheres were distributed in a regularly staggered arrangement. Diameter of the hemispheres was 10 mm. The side of the equilateral triangle connecting centers of neighboring hemispheres was 12 mm. The diameter of the hemispheres was identical to that of the packed particles. The sheet was polystyrene, 0.05 mm in thickness and air was within the hemispheres. The container could be tightly lined with the sheet, since the sheet was flexible. The resulting voidage on the inner wall of the container, calculated from this sheet structure, was 0.370. This value was almost identical to 0.39, which is the average voidage in a large randomly packed bed. The packed particles were alumina balls, 10.13 ± 0.34 mm in diameter, 3,600 $kg \cdot m^{-3}$ in density and with a shape factor of 0.938. The hemisphere was slightly deformed after particle packing; however, the influence of this was almost negligible in the experiments. The volume decrease of hemispheres caused by interpenetration of spheres near the wall was 1.7%, being measured from volume balance by filling the lined beds with water.

X-ray computed tomography

The packing structure of the bed lined by this sheet was observed by X-ray computed tomography (CT). Figure 2 shows a packed bed with the lining of hemispheres for X-ray CT analysis. Particles were randomly packed into a polyvinyl chloride (PVC) tube, which was 100, 70 and 50 mm in diameter and 130 mm in height with agitation of the tube. Consequently, D/d took approximately 10, 7 and 5 in the experiments. Horizontal scans across the bed halfway up were taken by rotating the X-ray source together with an image intensifier through 360 degrees. Middle height of the packed bed was selected as the position of scans in order to avoid the influence of the edge effect of the packed bed. The photographs obtained through the image intensifier showed the cross-sectional area from 60 mm to 70 mm along the axis at intervals of 1 mm. From the black and white photographs, the radial distribution of voidage was numerically estimated by using an image analyzer.

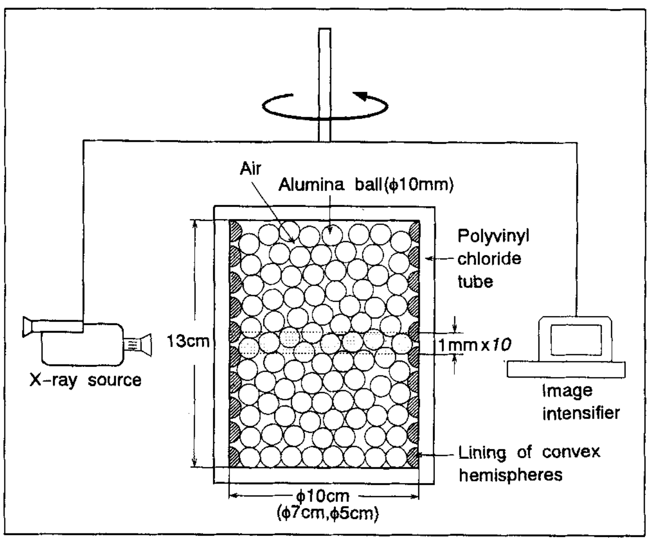

Figure 2. Packed bed with the lining of hemispheres for X-ray CT analysis.

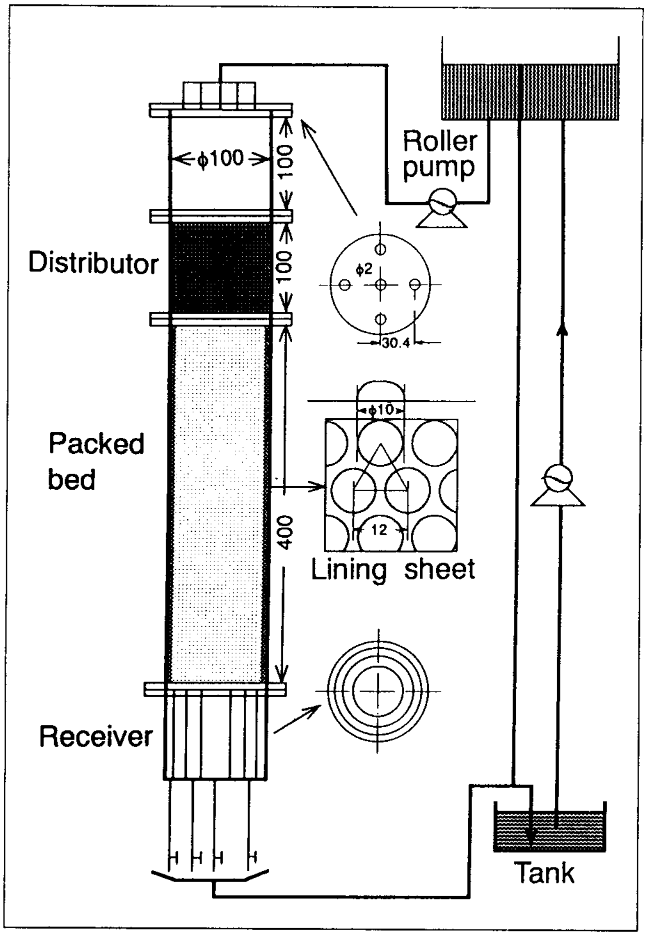

Figure 3. Experimental apparatus for measurement of radial distribution of liquid flow.

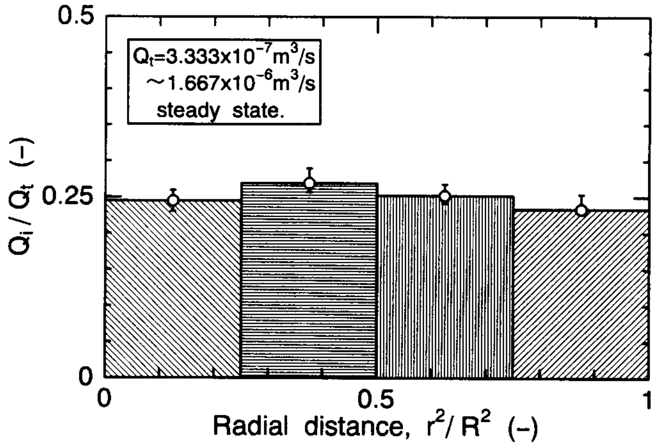

Figure 4. Radial distribution of liquid from the distributor measured by the receiver.

Measurement of liquid flow

Figure 3 shows an experimental apparatus for measurement of the radial distribution of liquid flow. Liquid was uniformly supplied to this bed from five points, and the radial distribution of liquid flow from the bed was observed to examine the effect of the hemispherical lining on channeling. The experimental apparatus used in this study consisted of four parts: a roller pump, a distributor, the packed bed, and a receiver. The packed bed, distributor, and receiver were contained in a transparent acrylic pipe.

The liquid (35 mass % $CaCl_2$ + 0.005 mass % rhodamine B solution) flowed to the packed bed through a distributor bed of alumina balls 1 mm in diameter, and was recirculated at a controlled rate by a roller pump. The aspect ratio of the distributor was 100. The radial distribution of liquid coming from the distributor was almost uniform and showed no significant wall effect (Figure 4).

The packed bed of alumina balls (10 mm ϕ) was 100 mm in diameter and 400 mm in height, and lined with/without the above-mentioned sheet. The height of the bed was sufficient not to influence outflow phenomena. The liquid passed through the packed bed was stored in the receiver, attached to the bottom of the packed bed. The receiver had four compartments of equal cross-sectional area concentrically arranged, to measure the radial distribution of liquid flow. It was made from three thin copper pipes of different diameters (5.00, 7.07 and 8.66 mm ϕ).

Surface properties of the wall are important, because they may have influenced the liquid flow within the bed. The packed particles and the sheet used as the inner wall needed to have the same surface properties for the liquid. For this purpose, material which is easy to coat and has long life was used to coat all packed particles and the sheet. The chemical composition of the coating material was 89% denatured ethyl alcohol 3C, 10% alkyl polysiloxanes as active ingredient, and 1% sulfuric acid (Rain-X "the invisible windshield wiper," U.S. patent 3579540). Measured properties of this liquid for this system had 109.1° contact angle, viscosity of 0.0060 Pa·s, density of 1,334 $kg \cdot m^{-3}$, and surface tension of 0.090 $N \cdot m^{-1}$. These properties were retained after 12 h under experimental conditions.

Results and Discussion

Voidage distribution

A mean voidage in the scanned region was obtained from the difference of water weight used to fill up to the 60-mm and the 70-mm axial positions. In the case of $D/d = 10$, values obtained were 0.382 for the lined bed and 0.406 for the unlined bed. Figure 5 shows photographs of cross sections through the packed bed with/without the lining, taken by X-ray CT. Figure 5a is for the unlined bed, and Figure 5b is for the lined bed. The photographs were 200×200 mm^2 in effective area, 1 mm in slice thickness, using a screen matrix of 320×320, voltage of 120 kV, current of 200 mA, and 4 s of scanning time. White circles correspond to alumina balls and black regions to void space. In Figure 5a, many points of contact between spheres and the wall were observed. In Figure 5b, unfortunately, the polystyrene hemispheres were not shown because of their transparency to X-ray. The number of contact points observed was also very small in comparison to Figure 5a, which implies the existence of the hemispheres near the wall. The hemispheres did not appear in the photographs; however, a local voidage within a sphere radius of the wall can be obtained from the fact that the volume of convex hemispheres is not changed.

By using an image analyzer, a local voidage was estimated

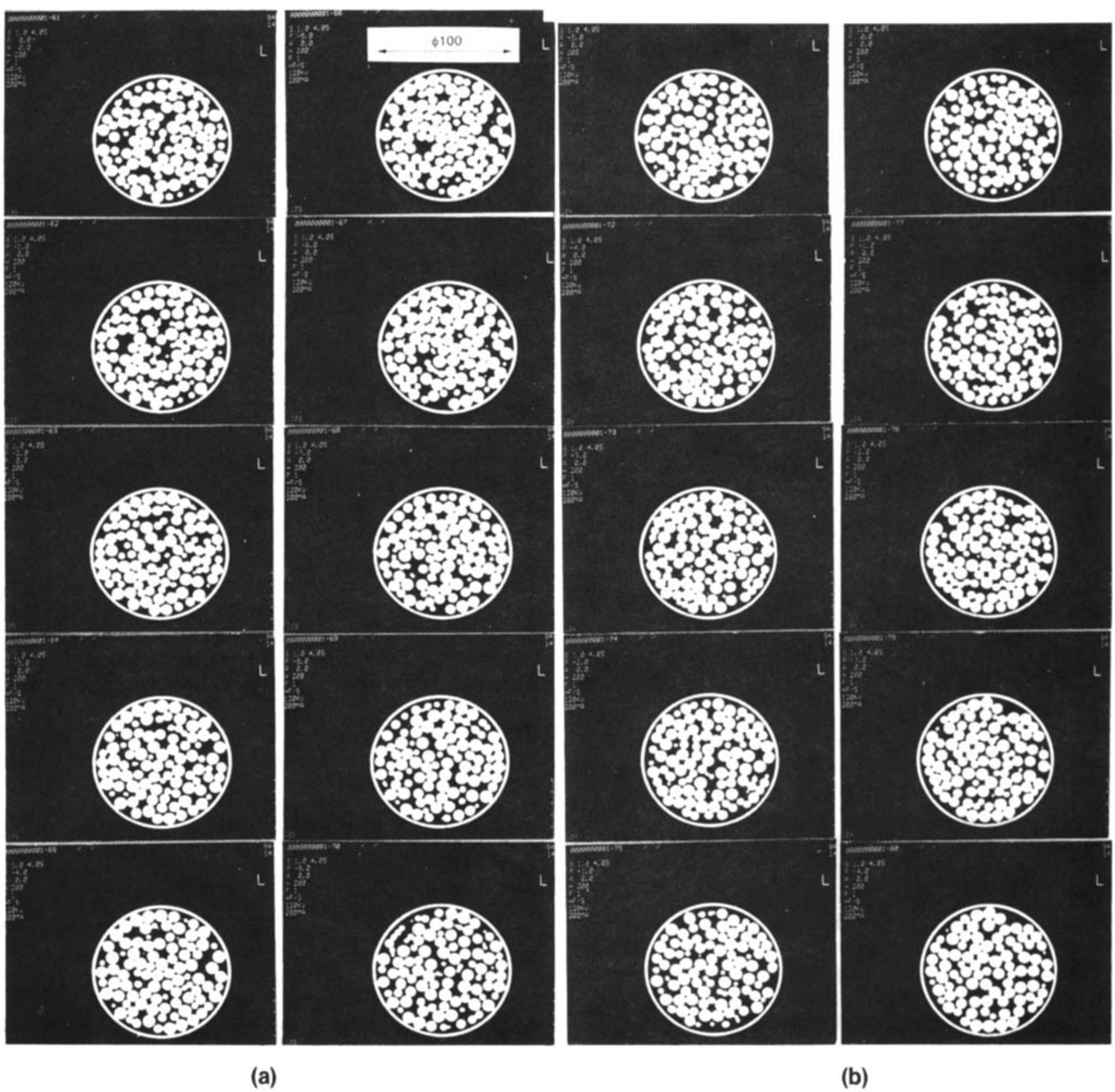

Figure 5. Photographs of sliced packed bed with/without the lining.

(5a) Unlined bed; (5b) lined bed.

from Figure 5. Each photograph of a cross section was divided concentrically with an increment of R/20, and a local voidage in each section was determined. Figure 6 shows the radial distribution of voidage in the packed bed with/without the lining for the cases of $D/d = 10$, 7, and 5. These values were obtained by an arithmetic average of the local voidage in each set of ten photographs. The value 0.37 on the wall for the packed bed with the lining was calculated from the hemisphere arrangement on the lining of sheet. The following differences can be observed between these curves. The lined bed has less voidage near the wall, and smaller mean voidage.

The oscillations in the voidage curve are more damped from the wall to the center, but are still observed in the central part. Mean voidages can be also calculated by integrating each curve in the circumferential direction. The calculated values agreed well with the measured ones. The results demonstrate that for all the cases the lining is effective in preventing sharp voidage rise close to the wall and promoting a smooth voidage distribution.

Flow distribution

Figure 7 shows the transient variation in the radial distribution of liquid flow in the packed bed with/without the lin-

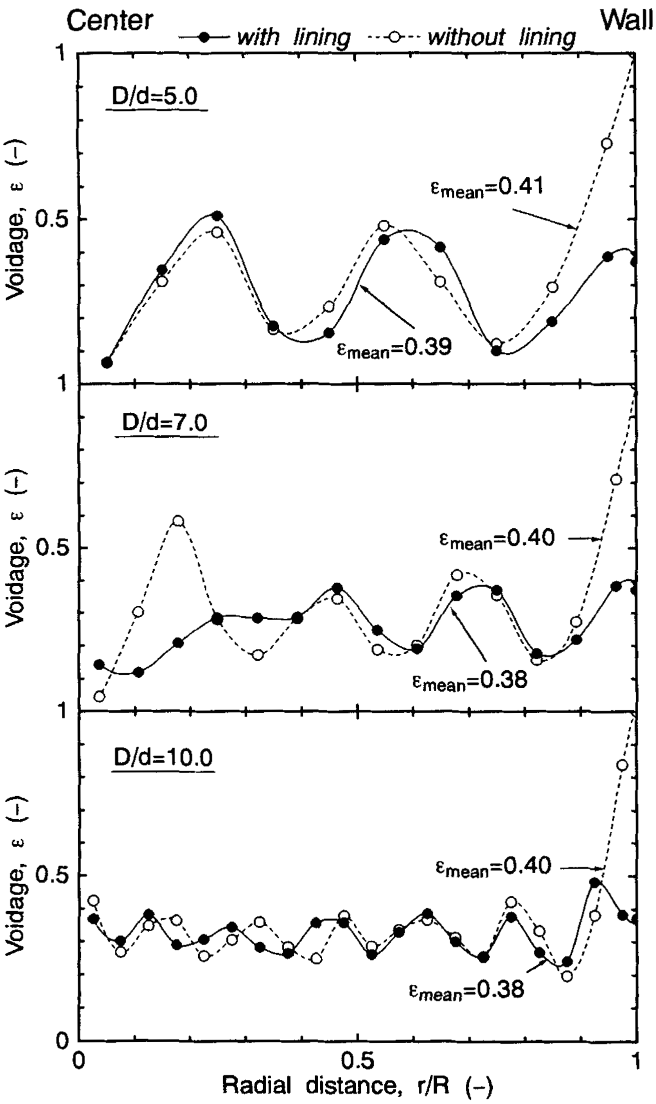

Figure 6. Radial distribution of voidage in a packed bed with/without the lining.

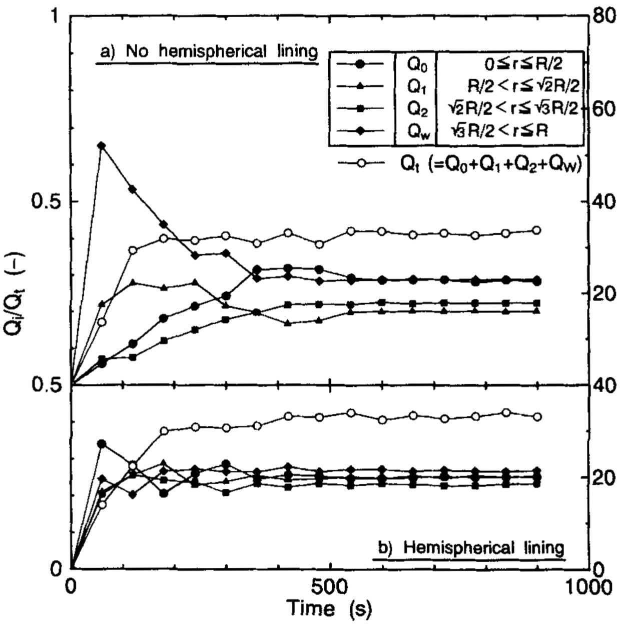

Figure 7. Transient liquid distribution from the packed bed with/without the lining.

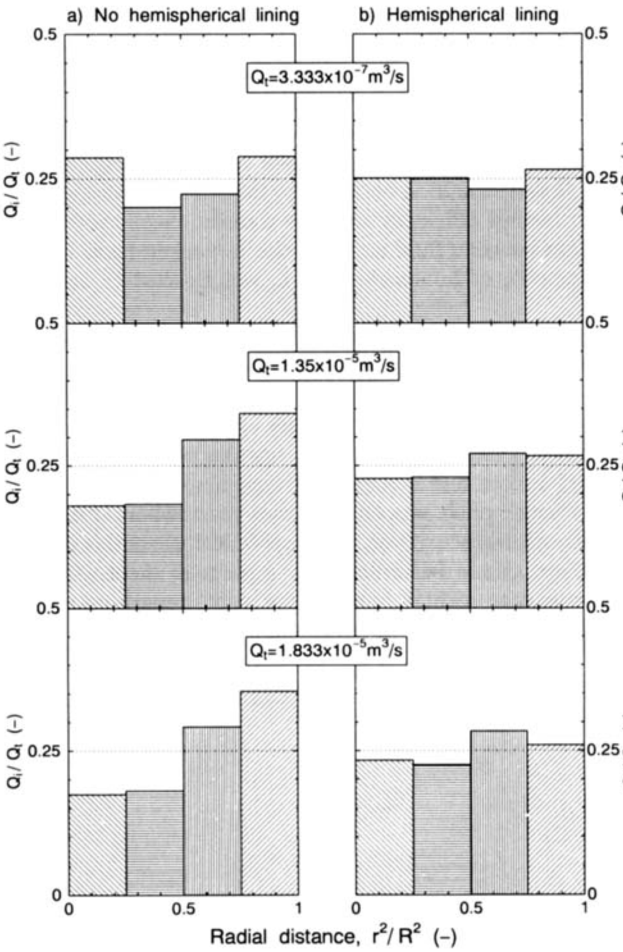

Figure 8. Radial distribution of liquid at different rate of liquid supply.

ing. In Figure 7, Q_t is total flow rate, and Q_0, Q_1, Q_2 and Q_w are local flow rates at each annular region (Figure 3). The radial distribution of liquid flow changed strongly in the initial stage. Specifically, the unlined bed had a large initial liquid flow in the wall area. After this, liquid outflow from the wall area in the unlined bed decreased gradually with time, but channeling clearly existed at steady state. In contrast, the lined bed showed less transient variation, and no appreciable channeling. It took approximately 700 s for the outflows in both cases to reach steady state. Data under the different flow rates was recorded after steady state was obtained.

Figure 8 shows the radial distribution of liquid flow at different flow rates of liquid supply under steady-state conditions. Flow rates were varied between 3.333×10^{-7} and 1.833×10^{-5} m^3/s for the beds with/without the lining. The unlined bed showed more significant channeling phenomena with increasing flow rate, due to increasing resistance to flow. In contrast, the effect of the lining on channeling was apparent. For all cases the lined bed had almost uniform distributions within 0.250 ± 0.025 in fractional flow rate. In these experiments, total holdup ranged from 2 to 5%, and Reynolds number was from 0.2 to 10. Here, Reynolds number is defined as $\rho ud/(1-\epsilon)\mu$, where ρ, u and μ are liquid density, velocity, and viscosity, respectively. For all the cases, the hemispherical lining removed the channeling phenomena caused by large local voidage near the wall and provided nearly uniform distribution of liquid flow. It seems that the channeling in the unlined bed was enhanced with increasing flow rate. The liquid velocity in the central region of the unlined bed except for the case of very small flow rate ($=3.333\times10^{-7}$ m^2/s) reduced to approximately 70% of plug-flow value. This value is almost identical with the predicted one, 73%, in a previous article (see Figure 1, for the case of $D/d = 14.1$), in spite of the different flow rate conditions.

Conclusion

A sheet of convex hemispheres in a staggered arrangement was used to line the inside of a tube to eliminate "wall effect" in a packed bed. To ensure the elimination of the wall effect on voidage distribution, X-ray CT was employed to analyze the packed bed with/without the lining. It showed that the lining was effective in reducing the sharp rise in voidage near the wall, and the lined bed exhibited a more uniform voidage profile as a result. Next, the wall effect on fluid-flow distribution was investigated. Liquid was uniformly supplied to the packed bed with/without the lining, and the radial distribution of liquid outflow was measured. The observed flow in the lined bed was almost uniform in radial distribution. It was, therefore, concluded that the method proposed here is very effective in eliminating the voidage rise near the wall and in reducing channeling in spite of its simplicity. The uniform flow distribution obtained by this method will highly improve overall efficiency of mass transfer, heat transfer and reaction between fluid and particles in packed beds. It offers the benefits of minimizing space, weight, cost or residence time.

The commercially available sheet with convex hemispheres can be used for cold model experiments in a laboratory. For different diameters of a sphere, the arrangement of hemisphere should be correspondingly changed under the same principle. That is, a hemisphere has the same diameter as a packed sphere and a regular arrangement of hemisphere is on a triangle pitch, spaced 1.2 d mm apart, where d is diameter of a sphere. Moreover, for the practical use of this method, the sheet should be replaced by a metallic sheet which has the resistance to high temperature and strength enough for packing and dumping, as Hills and Paul (1971) used.

This study was done as a part of the research project the final purpose of which is to simulate liquid-flow phenomena in a coke-bed metallurgical process. Later, the studies of wetting efficiency, holdup and modeling, refer to two-phase flow operation (gas is also present) which will be carried out using the experimental apparatus developed in this study.

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