Radial Porosity Variations in Packed Beds

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The radial variation of void fraction in randomly packed beds of spheres, cylinders, Raschig rings, and Berl saddles was investigated. After packing, the beds were filled with paraffin, which was then allowed to solidify. Slabs were cut from the bed, and annular rings were removed by two different experimental techniques. An analysis of experimental error revealed that reproducibility, for the sample size used, between different parts of the same bed and different beds was quite good.

For highly irregular shapes such as Berl saddles results indicate that the void fraction decreases regularly from one at the wall to the average porosity at about 1 particle radius from the wall. This is in agreement with work of other investigators using irregularly shaped packings; most commercial packings would probably fit in this category.

For regularly shaped particles results are quite different. For spheres and cylinders cycling was observed for more than 2 particle diam. into the bed, the amplitude decreasing as distance from the wall was increased. The maxima and minima were observed at integral multiples of the particle radius. For Raschig rings a hump was observed at about 1/2 particle radius from the wall. The void fraction then decreased to its average value at 1 particle radius and then remained constant.

A common technique in the chemical industry for obtaining extended solid-fluid interfacial areas or good fluid mixing is to pass the fluid through a bed of solid particles. Such systems as catalytic reactors, packed absorption and distillation towers, packed filters, and pebble type of heat exchangers depend on this technique. The design of these units is based upon mechanisms of heat and mass transfer, fluid flow, and pressure drop of the fluid through the bed of solid. These mechanisms in turn are all sensitive to the porosity of the bed. Since the particles in a packed bed are normally arranged in a random order, coupled with the fact that the particles are often of highly irregular shapes, the mathematical treatment of porosity is difficult. In addition, it has long been recognized that the confining wall of the packed bed exerts a decided influence on the porosity of the bed, especially in the region close to the wall, and wall effects have received some attention. The packing in this region is not so tight as in the core of the bed; thus the porosity near the wall is relatively high.

The present work was designed therefore to study the influence of the confining wall on the porosity in a packed bed and was limited to uniformly shaped particles in a cylindrical bed. In the following section a few of the basic mathematical concepts nesessary for this work are reviewed. In succeeding sections experimental results are presented and discussed.

THEORY

Definitions of Void Fractions

In a volume partially filled with solid particles each point can be identified as either being in a solid particle or not. A point void fraction can thus be defined as

$\delta_p =$ 0 if the point is located inside a solid particle

$\delta_p =$ 1 if the point is not located inside a solid particle

If the point void fractions are summed along some line in the volume, then a line void fraction can be defined as

$$\delta_L = \frac{1}{L}\int_L \delta_p \, dL \qquad (1)$$

where L is the total length of the line. An area and volume void fraction can be similarly defined

$$\delta_A = \frac{1}{A}\int_A \delta_p \, dA \qquad (2)$$

$$\delta_V = \frac{1}{V}\int_V \delta_p \, dV \qquad (3)$$

In some very regular systems one or more of the void fractions may be true constants or regular functions of system dimensions. In the more usual case however the void fraction varies in some statistical fashion, and average values must be used to represent the void fractions. It is of course important to separate random variation from regular variations which are functions of the system parameters. The work described in this paper is concerned with cylindrical packed beds, and since the chief source of nonrandom variations in the void fraction is the outer wall, it would be expected that one could properly represent the void fraction of an area which is concentric with the outer wall by an average value. There is no reason to suspect any orienting forces other than those of the outer wall, and since all points on a concentric shell are equally affected, only random local variations should be present. Throughout all of the work reported here this assumption has been made. The assumption was checked and verified as will be described later. The void fraction values given then in this paper are primarily the area void fractions δ_A.

Void Fractions in Regular Beds

In conjunction with experimental measurements of void fraction, calculations were also made for some regular arrangements of spheres in cylindrical beds; spheres were used because they showed the most radial variation of void fraction and are the easiest to handle mathematically. In Figure 1 the area void fraction is plotted vs. distance from the wall for two types of regular packing arrangements and for some experimental data. Each arrangement consists of layers of spheres, the particles in each layer being arranged in a hexagonal pattern. The difference between the two packing arrangements is in the relative location of two adjacent layers of spheres; in the hexagonal-cubic arrangement adjacent layers are identical. The centers of the spheres in each layer are directly over the centers of the corresponding spheres in the layer below. The center of a sphere was arbitrarily placed in the center of the bed. A similar curve would result if an interstice were placed at the center of the bed. In the hexagonal-hexagonal packing the centers of the spheres in one layer are directly over the interstices in the row below; this results in a denser packing than the hexagonal-cubic. The values in Figure 1 were calculated by obtaining the expression for the area of intersection of a sphere and a cylinder and evaluating the resultant elliptic integral by a series expansion. The radial values of area void fraction then were integrated over the appropriate ranges to give points which are comparable to the experimental values. A smooth curve was then drawn through the points.

Also of interest theoretically are the curves for void fractions of spherical particles against a plane wall. These are shown in Figure 2 for two orientations: a cubic arrangement (A) in which the spheres next to the wall are arranged in a square pattern and the adjacent layer is identical (distance between layers is 1 particle diam.), and a hexagonal-cubic arrangement (B) in which the layer touching the wall is hexagonal and the adjacent layer is identical with a 1-particle-diam. distance between layers. Results are shown for 1 particle diam. from the wall. As in Figure 1 the points represent integrated averages, and the curves were drawn through the points.

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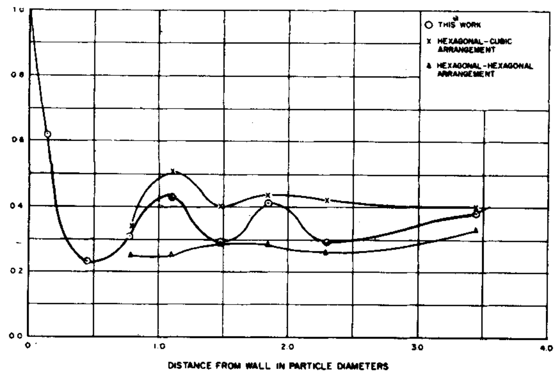

Fig. 1. Calculated area void fraction for regular packing arrangements in the center of a bed and experimental void fractions from Figure 3 plotted vs. distance from the wall.

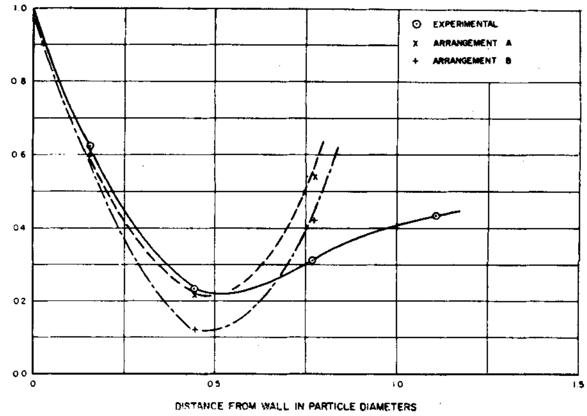

Fig. 2. Calculated area void fraction for regular packing arrangements against a flat wall and experimental void fractions from Figure 3 plotted vs. distance from the wall.

WORK OF PREVIOUS INVESTIGATORS

In the past, work has been done on over-all voidage (*2*, *3*, *4*, *8*) incidental to the study of a specific mechanism. Relatively little work has been done to investigate porosity differences within packed beds.

Shaffer (*7*) measured void space by rotating a packed column 90 deg. to a horizontal position and introducing a known amount of liquid into this section, raising the liquid level in increments. He assumed that void space would be the same everywhere at the same radial position, and by introducing imaginary annular sections of the same width as the height of the liquid level increments he was able to estimate void fraction as an average value for an annular area. He applied the results from the first annular section in calculating the next by assuming that the part of the second liquid-level increment that also includes the first annular section has the same void fraction as that of the first annular section. His results indicated that this assumption was in error; therefore the quantitative value of his results are questionable.

Makoto, et al. (*5*) measured radial void fraction variations by putting crushed calcium carbonate in a glass tube and filling it with paraffin. After solidification the glass was removed and the rod-shaped section shaved on a lathe, much the same as one of the techniques used in the present work. Their packing material, as a result of the method by which it was prepared, consisted of a variety of shapes and sizes. Their results are not applicable to beds of regularly shaped particles.

EXPERIMENTAL TECHNIQUES

The area void fraction is the desired experimental measurement, and some consideration was given to direct measurement (for example, by photographic techniques). However experimental difficulties were great, and the method selected was to measure the volume void fraction of a series of thin concentric rings. These values are then approximations to the area void fraction. Beds were prepared by pouring the packing into a cardboard cylinder. Several methods of pouring were compared for reproducibility by measuring the over-all void fraction of a test bed. It was found that without tamping results were reproducible within about ±1% and that methods of pouring differed by approximately ±2%. Tamping the side of the cylinder thoroughly until no further change occurred produced about a 5% decrease in over-all void fraction. Two somewhat different methods of filling beds were used. For the experiments which will be described in section 1 the beds were filled by inserting a 3.35-in.–diameter tube inside the 6.70-in.–diameter bed, filling the inner tube with spheres, and slowly raising the inner cylinder. This method has been discussed by Leva (*4*). The bed was not tamped. In the experimental technique of section 2 the bed was filled by simple, rapid pouring and tamped two or three times. In both cases the top row of particles was manually leveled by arranging a few particles, and a screen was placed on the bed to prevent the packing from floating in the hot wax. The bed was preheated to 180°F., and molten wax was added in five or six small batches at about 15-min. intervals to allow air to escape. A soaking period of about 1 hr. at 180°F. was followed by a slow cooling period of more than 8 hr. The cardboard cylinder was then removed and the samples were prepared for analysis.

Two methods were used for preparing and analyzing these samples:

1. The bed was divided into a series of slabs of approximately 1 particle diam. thickness. This thickness was selected rather arbitrarily, but subsequent analysis showed it to be satisfactory. These slabs were cut in half along a diameter, and then each semicircular slab was cut into a number of annular rings by using a set of specially constructed holders. All the slabs were carefully identified during the analysis, since one of the important problems under study was the reproducibility of measurements made in different parts of the bed. The bed used in this part of the work was 6.70 in. in diam., and cork spheres of 0.76 in. diameter were used as packing. Slabs were ¾ in. thick and annular rings approximately ¼ in. in width.

Analysis for void fraction was made by accurately measuring the volume of the slab before and after removal of the annular ring, melting the material removed, separating the cork from the wax, and calculating the void volume from the weight of wax and its density. A material balance was made for each measurement by adding the weight of wax and cork and comparing it with the loss in weight of the slab. All balances checked within 0.61%. The void fraction was calculated from the void volume and the total volume.

2. This method worked satisfactorily for cork spheres; however it was found to be unsatisfactory for more brittle material such as those used in the Berl saddles. Consequently another technique for obtaining annular rings was devised. A slab of the bed was mounted in a lathe chuck turning at 3,200 rev./min. Annular rings were shaved off with a sharp tool bit. Some chipping was observed at the edges of the slab, and therefore it was necessary to enclose the slab between two wooden supporting disks which were turned down with the bed disk. A collecting hood was devised to surround the lathe chuck, and the resulting annular ring was obtained as a fine powder consisting of paraffin chips, packing chips, and wood supporting-disk chips. The material from each annular ring was weighed on a triple beam balance, and the sum of these weights was checked against the difference in weight of the disks before and after being turned down. All balances checked within 1%. After weighing, the paraffin was separated from the wood retainer and packing by dissolving the paraffin in boiling benzene. The mixture was filtered, and the filtrate passed through a steam heated condenser. The benzene vapor leaving the collecting flask was condensed and recovered, and the hot wax was air-stripped to remove any remaining benzene. Residual solid material was washed four or five times with benzene to remove residual paraffin.

In addition to the weights of each annular ring, measurements were made of the dimensions of the disks before and after being turned down. The wood-retainer–disk volume was calculated from the dimensions taken for each ring; this was multiplied by the wood density to get the equivalent weight of wood moved. When this weight was subtracted from the weight of solids separated from the paraffin, the weight of packing was obtained. The packing volume was then calculated by using the known packing density, and the volume of wax was obtained from the weight of wax and the density of the wax.

A volume balance was made by checking the sum of the volumes of the component parts against the volume removed as calculated from the dimensions of the section. This deviation for individual cuts was as high as 10%, the average deviation was about 3%, and the deviation for the over-all volume was less than ½%. These inaccuracies in volume balances may be accounted for by the limited precision in the diameter measurements. Because of small increments in the large diameter of the disks an error in measuring the diameter could cause a deviation of up to 10%. The excellent over-all volume check and the fact that the material balances checked so closely are reasons for believing that the volumes of paraffin and packing are quite accurate. The void fraction was calculated by dividing the volume of paraffin by the volume of packing plus paraffin.

A total of five beds were studied in this manner. Four of the beds had a 6.7-in. diameter, and the packings used were ½-in. nominal-size Berl saddles made of carbon; wood cylinders ½ in. in diameter and height; carbon Raschig rings with 0.496-in. O.D., I.D. 0.358 in., and height 0.498 in.; and ½-in. spheres made of composition cork. A fifth bed was prepared by packing a 3.35-in.–diameter bed with ½-in. nominal-size Berl saddles made of carbon.

TABLE 1. EXPERIMENTAL VOID FRACTIONS FOR BED OF SPHERES

Bed diameter = 6.70 in.
Sphere diameter = 0.76 in.

Disk and section	Radius of annular ring (in.) Distance from center of bed to center of ring							
	3.24	3.01	2.76	2.51	2.23	1.93	1.61	0.72
1*A*	0.60	0.27	0.29	0.42	0.30	0.33	0.25	0.36
4*A*	0.62	0.25	0.30	0.38	0.31	0.37	0.30	0.36
4*B*	0.61	0.24	0.34	0.45	0.27	0.45	*	*
6*A*	0.64	0.25	0.31	0.40	0.22	0.39	0.29	0.42
6*B*	0.63	0.22	0.28	0.40	0.31	0.35	0.23	0.34
8*A*	0.57	0.18	0.36	0.45	0.28	0.48	0.34	0.37
8*B*	0.63	0.17	0.37	0.48	0.30	0.47	0.26	0.40
9*A*	0.68	0.30	0.27	0.43	0.27	0.40	0.34	0.38
9*B*	0.57	0.20	0.32	0.48	0.30	0.41	0.25	0.42
Average	0.62	0.23	0.31	0.43	0.29	0.41	0.29	0.38

*Unable to analyze owing to bed imperfection. Paraffin did not fill voids satisfactorily.

EXPERIMENTAL RESULTS

Experimental results are presented in Figures 3 to 6 and Figure 7. The points indicated on the graphs are, as described previously, actually void volumes for a small annular ring about the point. Smooth curves have been drawn through the points, and these curves are approximations to the area void fraction. In Figures 4, 5, and 6 each point represents an experimental value; in Figure 3 however each point represents an average of several experimental values. In Table 1 the values from which the Figure 3 averages were obtained are shown. Detailed experimental results can be obtained in References *1* and *6*.

EXPERIMENTAL ERROR

The results in Table 1 are particularly significant, since they reveal the reproducibility of measurements made at the same radial position but at different parts of the bed. Because a sample volume is subject to random variations in void fraction, it was important in this work to establish the effect of position in the bed on the experimental void fractions. One bed was divided into nine disks, and each disk was cut on a diameter into two parts. One part was labeled *A* and the other *B*; the *A* parts were all from the same original half of the bed. The results in Table 1 are shown for each half disk and for each of the number of annular rings from this half disk. An analysis of variance was made on the data in Table 1. This analysis showed that there was a highly significant difference in porosity between samples taken at different radial distances, while no significant difference in porosity existed between samples from sections *A* and *B*, that is, opposite sides of the bed or samples at different horizontal levels within the bed. These results indicate then that at least for the size samples taken in this work the only significant source of variation in void fraction is the radial distance from the center of the bed. When the results in Table 1 are put together, a standard deviation was determined for the average void fraction. This deviation was 0.0126 expressed in void fraction units. Two confidence limits, 50% and 95%, were determined on the average void fraction by using the *t* test. These were ±0.009 void fraction units at the 50% level and ±0.025 void fraction units at the 95% level. These limits were quite low, in fact surprisingly so, and simply mean that void fractions can be predicted quite accurately with small samples.

It should be emphasized that each of the average void fractions in Table 1 differs significantly from each of the others. For example the last two columns in Table 1 are for distances from the wall of 2.32 and 3.46 particle diam. and would be expected to show the least difference. Yet the probability that these could be samples from the same population can be determined by a *t* test and is less than one in a thousand.

Since the beds were randomly packed, one would normally expect to have essentially no more variation between layers in the same bed than between layers in corresponding beds. This assumption was not checked directly, although other results with spheres as shown in Figure 4 were consistent. In Figures 4, 5, and 6 results are reported for one or two disks as indicated in the figures. Corresponding values were not obtained in each disk, and thus direct comparison is difficult. However the results as plotted in these figures indicate a very good check between corresponding disks. This is further confirmation of the theory that the samples chosen were of such size that they gave good estimates of the void fractions.

DISCUSSION OF RESULTS

Spheres

The experimental results for the radial variation of void fraction of spheres are

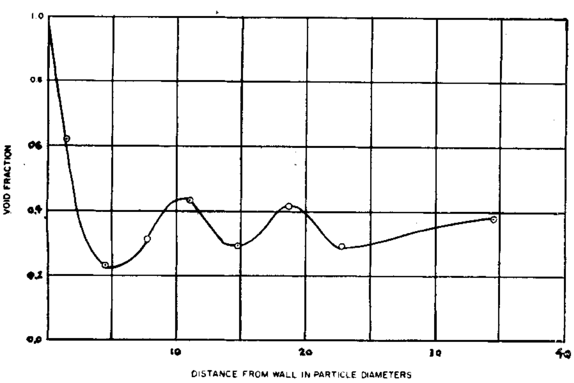

Fig. 3. Area void fraction vs. distance from the wall for 0.76-in.–diam. spheres in a 6.7-in.–diam. cylindrical bed.

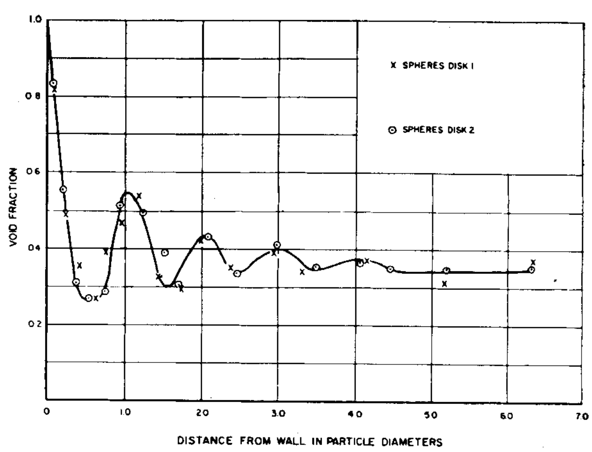

Fig. 4. Area void fraction vs. distance from the wall for 0.49-in.–diam. spheres in a 6.7-in.–diam. cylindrical bed.

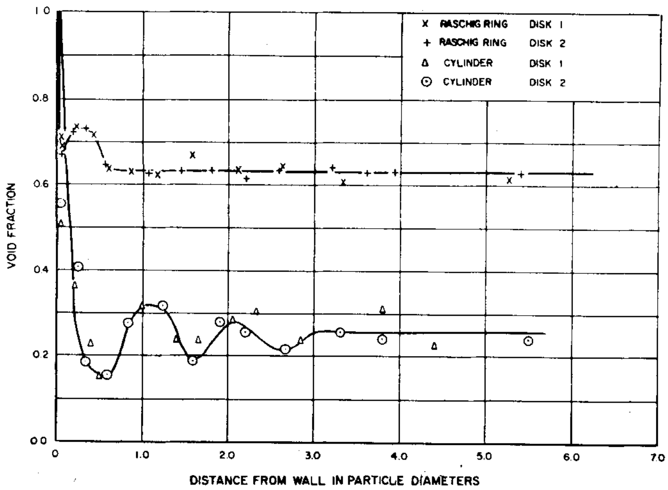

Fig. 5. Area void fraction vs. distance from the wall for 1/2-in. cylinders and 1/2-in. Raschig rings in a 6.7-in.-diam. cylindrical bed.

shown in Figures 3 and 4. In each case the void fraction has the limiting value of 1 at the wall, reaches a minimum at 1 particle radius in from the wall and a maximum at 1 particle diam. from the wall, and continues cycling for some distance into the bed. In Figure 7 the data from Figures 3 and 4 are plotted together for comparison. These results were rather unexpected, in that it had not been anticipated that the wall effect would continue to have an effect beyond 1 particle diam. from the wall. The explanation however is quite simple and consists of recognizing that because of the wall a layer of spheres is oriented on the wall. In fact each sphere in the bed which touches the wall is thus uniquely oriented. The net effect will then be that more spheres than usual are located adjacent to the wall, resulting in a concentration of sphere centers at 1 radius from the wall and a consequent minimum in porosity at that point. Similarly at 1 diam. from the wall there will tend to be a greater porosity than normally because this is the point of maximum porosity for a sphere which is oriented at the wall. This can be shown somewhat more graphically by examining Figure 2 which shows the variation in void fraction for a layer of spheres at a flat wall. The values for two arrangements of spheres on the wall are shown: a cubic arrangement on the wall (A) and a hexagonal arrangement on the wall (B). Experimental results are also shown in Figure 1 for the data in Table 1. Once again the calculated values for the regular arrangements were integrated to make them comparable with experimental data, and smooth curves were drawn through the points.

In Figure 1 the experimental results from Figure 3 are plotted together with the calculated results obtained by assuming a hexagonal-cubic or hexagonal-hexagonal arrangement in the bed as described under Theory. The actual results are intermediate between the two types of regular packing. The effect of the wall, which is not included in the calculations for the regular beds, accounts for the increased cycling.

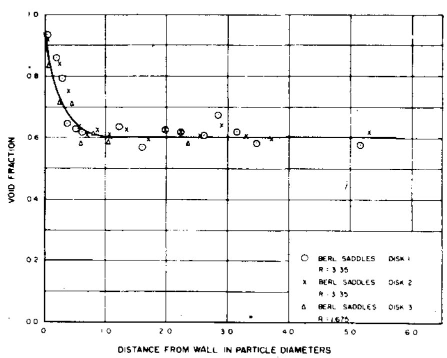

Fig. 6. Area void fraction vs. distance from the wall for 2/1-in. Berl saddles in 6.7- and 3.35-in.-diam. cylindrical beds.

The combination of a layer of particles adjacent to the wall and a regular arrangement in the bed can thus give a qualitative explanation of the cycling observed. However because of the random nature of the actual packing arrangement it is not likely that the curves can be calculated, and experimental results such as Figure 7 should be used rather than any calculation for regular arrangements.

In Figure 7 separate curves are drawn for each bed-diameter–to–particle-diameter ratio (the term *diameter ratio* will be used in the following). Examination of these curves shows that the maximum and minimum points occur essentially at fixed multiples of particle radius. This clearly indicates that *the orienting* influence of the wall provides layers of spherical particles the centers of which are separated by 1 diam. from the next layer. There is some indication that for the bed with the smaller diameter ratio the spacing is somewhat less than 1 diam. after 1½ radii from the wall. It is difficult to determine whether this effect is significant. It if is, then it might be explained by the fact that since the diameter ratio is small, there might be a tendency for hexagonal clusters in the center of the bed to be uniquely oriented. This is supported by the observation that the cycling does not damp out as regularly for the smaller diameter ratio bed. In general the results from the two different sets of data agree quite well, with the exception of the maximum point at the first particle diameter from the wall. This discrepancy might be explained by either of two causes:

1. Since the two sets of data were obtained by different experimenters, using different techniques and different diameter ratios, the difference might be attributed to variations in experimental technique and methods of packing the bed. However the reproducibility of results indicated under Experimental Errors and the data of Figure 4 plus the excellent agreement of the data in Figure 7, with the exception of that at 1 particle diam. from the wall, leads the authors to feel that this is not the explanation.

2. It is difficult to estimate what effect the diameter ratio has on the void fraction at 1 particle diam. from the wall; however a qualitative explanation of the observed difference can be made. It has been shown that near the wall the

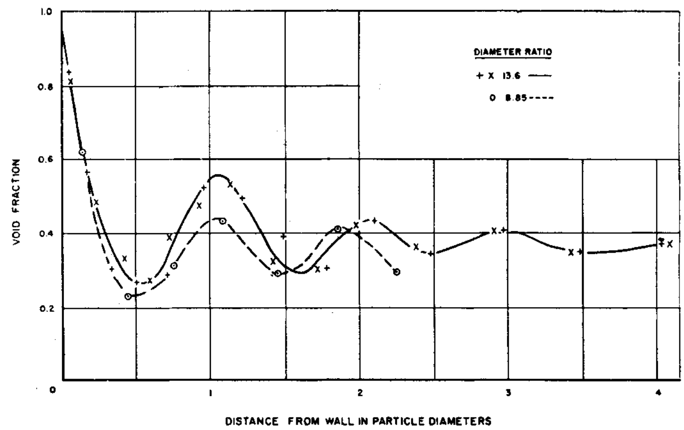

Fig. 7. Area void fraction vs. distance from the wall for 0.76- and 0.49-in.—diam. spheres in a 6.7-in.-diam. cylindrical bed.

particles are oriented in cylindrical layers 1 particle diam. thick. The porosity at 1 diam. is thus a measure of the degree of separation of the first two layers. At certain diameter ratios there could be exactly room for an integral number of spheres in the outer layer and an integral number in the next row. It would then be expected that there would be a minimum of mixing and a high pososity. At other diameter ratios there will be a certain amount of mixing taking place with a subsequent lowering of the porosity. This failure of the outer two layers each to contain an integral number of particles would seem to be more critical for smaller diameter ratios, where the number of spheres involved in any one layer is smaller. It might be expected that this effect would persist beyond the first diameter, but the damping plus experimental variations makes it difficult to detect.

Table 2. A Comparison of Void Fractions For Spheres and Cylinders

Distance to wall, particle diam.	δ_A (spheres)	δ_A (cylinders)	Ratio
0.5	0.27	0.16	0.59
1.0	0.54	0.32	0.59
1.5	0.31	0.21	0.68
2.0	0.42	0.27	0.64
2.5	0.34	0.22	0.65
3.0	0.40	0.25	0.63

It will be noted in Figure 7 that the experimental points are much closer together for the large-diameter ratio and consequently represent smaller annular rings. As has been discussed previously, the area void fraction is a point property, and if an average value is obtained over a volume, some smoothing must result. However for the data shown in Figure 7 no significant changes occur if the data for the 13.6-diam. ratio bed is smoothed to make it comparable with that for the 8.8-diam. ratio bed. The void fraction in the center of the bed is 0.38 for Figure 3 and 0.35 for Figure 4; the discrepancy may be owing to differences in the manner of packing or to the difference in diameter ratio.

Cylinders

The variation of void fraction with radial position for a bed of cylinders is shown in Figure 5 and is very similar to that obtained with ½-in.–diameter spherical particles in the same size bed. The cylinders tested were ½ in. in height and diameter. When these results are compared to the results for spheres in Figure 4, an interesting result is observed; the ratio of any point void fraction in the bed of cylinders to the same point in the bed of spheres is approximately 0.67. This is shown in Table 2. This ratio happens to be the ratio in volume of a sphere and a cylinder. Because of the similarity between the shapes of these cylinders and spheres, it would be expected that their radial porosities would be quite similar, although there does not seem to be any reason why the void fraction ratio should be inversely proportionate to particle diameter.

Raschig Rings

Contrary to expectations the void fractions in Figure 5 obtained with Raschig rings showed no relation to the void fractions of the cylinders. The over-all porosities would naturally be much higher for the Raschig rings than for the cylinders. The first ⅛ diam. in from the retaining wall did yield a void-fraction value close to that obtained for cylinders; however at ⅛ diam. the inner void ring of the Raschig ring began, and at ¼ diam. the void fraction increased from 0.69 to 0.73. A maximum value was obtained at approximately ¼ diam. from the wall and then decreased to 0.63 at ½ diam. The void fraction then remained substantially constant for the remainder of the bed. Some calculations made with a solid row of Raschig rings arranged symmetrically on the outer wall of the container indicated that the hump could be explained by such an arrangement.

Berl Saddles

Two beds of Berl saddles were examined, the results being given in Figure 6. The ratio of bed to particle diameter for the second bed was just one-half the ratio for the first bed. The void fraction for each bed decreased from unity at the retaining wall to a relatively constant value 1 particle radius from the wall. The average value for the larger bed was approximately 0.62 and for the smaller bed 0.59; no significance is attached to this difference. The constant void fraction across the bed could be expected because of the irregularity in the shape of the saddles, which did not allow any appreciable orientation which might result in a definite pattern. It should be noted that only one disk was analyzed in the case of the smaller bed; however it agreed well with the data obtained from the larger bed.

These results agree quite well with those of Makoto, et al. (5). For beds of irregularly shaped particles they found a regular decrease in void fraction from the wall to a point about 0.6 diam. from the wall. The void fraction was constant throughout the rest of the bed. Their packing material undoubtedly included a variety of sizes and shapes of packing.

CONCLUSIONS

The radial variation of porosity in packed beds varies significantly with the type of packing used. For commercial packings, which are normally widely varying in size and highly irregular in shape, the porosity can well be assumed to vary from 1 at the wall to the average pososity value at about 1 particle radius from the wall. This was verified by using Berl saddles and is in agreement with work of other investigators.

However for regularly shaped particles such as spheres, cylinders, and Raschig rings the situation is much different. This is particularly important because many of the theoretical studies of heat transfer, mass transfer, and fluid flow in packed beds have been made by using spheres and other regularly shaped particles. The results for these particles can be summarized as follows:

1. For spheres a minimum porosity was observed at 1 particle radius from the wall, with alternate maximums and minimums occurring at successive particle radii. The amplitude of the cycling decreased as distance from the wall increased, but significant differences were found beyond 3 particle diam. from the wall. As a preliminary conclusion it can be stated that the data seemed independent of bed to particle diameter with the exception of the maximum value at 1 particle diam. from the wall. The data in Figures 3, 4, and 7 summarize these results.
2. For cylinders the results were quite similar to those for spheres. Results are given in Figure 5. It should be observed, however, that the only cylinders tested in this work had a diameter equal to their height; for other shapes different results might be obtained.
3. For Raschig rings a minimum void fraction at ¼ particle radius from the wall was observed with a maximum at ½ radius. After 1 particle radius from the wall the void fraction remained constant through the bed. Results are given in Figure 5.

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