Particulate Fluidization and Sedimentation of Spheres

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Particulate fluidization and sedimentation data were taken over the Reynolds number range of 0.005 to 1,800 by means of glass spheres in both water and ethylene glycol. Porosities for each series of measurements varied from about 0.50 to 0.91 and larger. The closely sized samples of spheres used were obtained by grinding between glass plates. The data for Reynolds numbers up to about 0.5 are in excellent agreement with the laminar theory of Ruth and the porosity function from Ruth's theory gave a satisfactory correlation of all the data, both laminar and turbulent.

The problem of the motion of a cloud of solid particles through a fluid has been treated theoretically by a number of investigators. Thus for the case where the concentration of solids is very small, solutions to the problem have been obtained by Einstein (*4*), Kermack *et al.* (*9*), Burgers (*2*), and others, For engineering applications, however, the more difficult problem of concentrated beds of particles moving in fluids is of greater importance than the limiting case of dilute beds. Sedimentation and fluidization, perhaps the two most common examples of this kind of motion, may be either particulate or aggregative, depending upon whether the particles appear to be evenly dispersed and moving independently or unevenly dispersed and moving in groups.

Steinour (*17*) experimentally studied the sedimentation of fine-pearl tapioca particles in the laminar range and found that for porosities up to 0.80 the results could be correlated by a modified form of the equation of Kozeny (*10*); namely

$$u = \frac{\epsilon^3}{(1-\epsilon)} \frac{D^2(\delta - \rho)g}{36k\mu} \tag{1}$$

Brinkman (*1*) modified Darcy's equation for flow through a compacted bed to apply to flow through an expanded bed and obtained the equation

$$u = \frac{V}{1 + \dfrac{D}{2\sqrt{p}} + \dfrac{D^2}{12p}} \tag{2}$$

where

$$p = \frac{D^2}{72}\left[3 + \frac{4}{(1-\epsilon)} - 3\left(\frac{8}{1-\epsilon} - 3\right)^{\frac{1}{2}}\right] \tag{3}$$

Verschoor (*19*) obtained experimental data in the laminar range which agree with Brinkman's theory, but the validity of the comparison is doubtful since the particles used were highly nonspherical.

Lewis *et al.* (*11*) studied the fluidization of glass spheres and found that their results could be best correlated by

$$u = V\epsilon^{4.65} \tag{4}$$

The data of reference *11*, however, were all for $Re > 0.1$ and hence not strictly laminar. Richardson and Zaki (*14*) examined theoretically the laminar sedimentation of particles arranged in adjacent horizontal layers so as to offer minimum flow resistance and found that Equation (4) was an approximation of their theoretical results. Jottrand (*8*) studied fluidization of nonspherical particles (crushed sand) in water in the laminar regime, mostly at porosities above 0.70. He concluded that Equation (4) is valid only for aggregative fluidization and that when the fluidization is particulate the correct equation is

$$u = V\epsilon^{5.6} \tag{5}$$

The effect of particle shape upon Jottrand's data cannot be completely evaluated at this time.

Ruth (*16*) derived an equation describing laminar fluidization and sedimentation. This equation, in the limit of infinite bed expansion, extrapolates to Stokes's law and for porosities approaching those of compacted beds becomes almost identical to the Kozeny equation. Ruth's analysis will be presented in more detail in a later section.

Hawksley (*7*), utilizing a viscosity expression formulated by Vand (*18*), presented the equation for the settling of a suspension as

$$u = \epsilon^2 \exp\left[\frac{-2.5(1-\epsilon)}{1 - \dfrac{39}{64}(1-\epsilon)}\right] V \tag{6}$$

Hanratty and Bandukwala (*5*) reported a large number of fluidization and sedimentation tests and found that Equation (6) correlated the laminar data well.

In view of the lack of complete experimental verification of any existing theory, it was decided that additional carefully taken experimental data were needed. The present paper describes the resulting experimental work and compares representative data with some of the previously mentioned theories and experiments. The complete experimental work is described in reference *12*.

One question which has received but little attention in the past is the relation between fluidization and sedimentation. Hawksley considered that sedimentation was adequately described by his theory but that fluidization was a much more complex process. The fluidization and sedimentation data of reference *5*, however, are identical when plotted for instance as ϵ against *Re*. Happel and Brenner (*6*) have recently shown theoretically that circulation of particles throughout a bed results in a decrease in the pressure drop through the bed. Since circulation occurs to a greater extent in fluidization than in sedimentation, this result can be interpreted as meaning that the flow resistance of a particle bed is less in fluidization than in sedimentation. It is hoped that the data presented herein will shed some light upon this problem too.

EXPERIMENTAL

Preparation of Sphere Samples

Inasmuch as serious doubt can arise in determining the correct average diameter of a sample of spheres if the size variation is large, considerable effort was made to obtain very closely sized sphere samples.

First the spheres were separated by screening with Tyler screens varying successively in aperture ratio by $1:\sqrt[4]{2}$. The spheres of each sample were then rolled down a slightly inclined glass plate, and those which rolled to one side or refused to roll were discarded.

A portion of the sample was then ground between two flat glass plates, with the aid of carborundum compound, until a uniform diameter was reached. The grinding apparatus employed four such sets of glass plates, with the top plates being mechanically moved in eccentric fashion over the lower stationary plates. Various numbers of 5-lb. lead weights could be placed on the top plates to control grinding speed. Carborundum finishing compound grade A280-V8-WS was used in all cases except for the two smallest size spheres ground, 35 and 48 mesh, for which Carborundum finishing compound grade AA440-V7-WS was used. Estimates of grinding progress were made by periodically removing a number of spheres from between the plates and measuring them. Periodic reversal and replacement of the glass plates were necessary because of wear. Experimental difficulties in grinding increased with decreasing sphere size, and grinding was not attempted for spheres smaller than 48 mesh.

Next the individual samples were fluidized, and the spheres at the top of the bed

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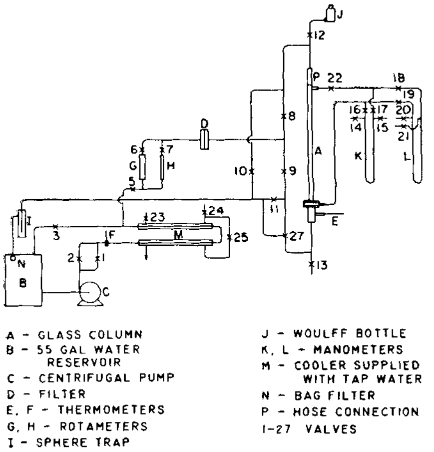

Fig. 1. Apparatus used for studies with water.

were slowly siphoned off with a glass tube and discarded, until a fairly sharp top interface was obtained at greater than 95% porosity. This removed particles that had been damaged in grinding or that contained large air bubbles.

Sphere Measurement

Size determinations for both ground and unground samples were then made. To obtain a correct average about 200 randomly selected spheres from each sample were measured. For diameters of 28 mesh and larger, ordinary micrometer calipers were employed; for the smaller spheres a filar micrometer was used.

The size variation for each sample of ground spheres was less than 5% as compared with almost 20% before grinding. The scale of surface roughness for the ground spheres was negligible compared with the sphere diameter.

Density Measurements

Liquid-density measurements were taken in a 25-ml. specific gravity bottle at 25°C. The density of the glycol at 25°C. was 1.110 g./cc. Density measurements of the spheres were obtained by first weighing the specific gravity bottle empty, next filling it about two thirds full of spheres and weighing, and finally filling it with water at 25°C. and again weighing. From these three weighings, the density of water at 25°C., and the volume of the specific gravity bottle at 25°C., the density of the glass spheres was computed.

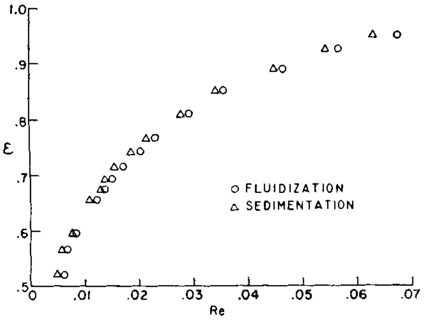

Fig. 2. Comparison of fluidization and sedimentation data for ground 48-mesh spheres in glycol.

Viscosity Measurements

Viscosity-temperature values for liquids used in this work were obtained with a precision viscosimeter, a constant-temperature bath, and a pump to circulate the bath water through the viscosimeter.

Free-fall Velocity Determination

Free-fall velocities in water were measured in a 4-in.-diameter, 5 ft. long thermally insulated Pyrex column. It was necessary to introduce the spheres at the center of the top cross section to prevent wall effect.

Free-fall velocity data for spheres in ethylene glycol were taken in a 1,000-ml. graduate cylinder of 6.1-cm. I. D.

Runs with Distilled Water

The small glass column employed for runs with distilled water was 2.603 cm. in diameter and 110 cm. long. Pressure taps were located at the top and in the flange assembly at the bottom. Both mercury and water manometers were available for pressure-drop measurements, but these data are not included in this paper. A 1/10°C.-thermometer was located immediately below the column for accurate temperature measurement.

Figure 1 shows a diagram of the over-all apparatus. As set up, it can be used for making permeability studies by passing liquid down through the column but these studies also are not included in this paper. Distilled water from a 55-gal. stainless steel drum *B* was pumped by *C* through a cooler *M*, the purpose of which was to remove pumping heat. A gate and a needle valve, 1 and 2, provided accurate flow control. Next the water passed through a pair of rotameters, *G* and *H*, and on through an Orlon cloth filter *D*. From the filter the water flowed through valves 9 and 27 into the bottom of the column and then passed up through the column, through valve 10, and back into the reservoir *B*. For fluidization and sedimentation work valves 8 and 11 were kept closed, while valves 9 and 10 were open. To prevent troublesome rust sediment from clogging the screen bed support, all piping and valves between the Orlon filter and the column were of stainless steel, aluminum, and brass.

To save time and to obtain fluidization and sedimentation data at the same porosities, it was ultimately decided to take sedimentation data immediately after the bed height, manometer reading, flow rate, and temperature were read for the fluidization run. This was done by turning the two-way stopcock 27 to stop the liquid flow to the column and simultaneously starting a stop watch. The time required for the top interface of the bed to pass various measured marks on the column was noted.

For use with larger particles a column 120 cm. long and 5.508 cm. in diameter was used. Operation with this column was similar to that of the smaller one, except that no pressure-drop measurements were made and flow rates were determined from the weight of effluent collected in a measured time.

Runs with Ethylene Glycol

The fluidization apparatus, not shown, for use with ethylene glycol was similar in

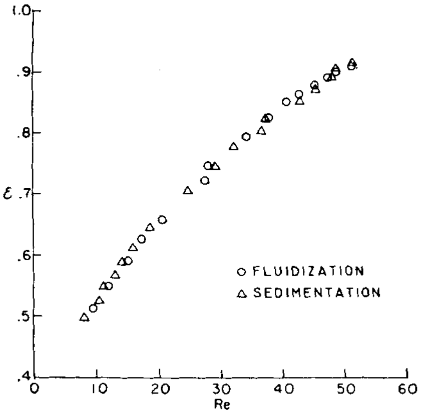

Fig. 3. Comparison of fluidization and sedimentation data for 28-mesh spheres in water.

principle to the water apparatus. For small particles and hence small flow rates the test section used was 115 cm. long and 2.477 cm. in diameter. A 5-cm.-diameter glass tube, for thermal insulation, surrounded the test section. The bed support was of cloth. A 1/10°C. thermometer was installed directly before the column. A Sigmamotor pump was used to pump the glycol from a 5-gal. reservoir to a constant-head tank provided with overflow line and located about 7 ft. above the top of the column. Rough flow rates were taken with a rotameter, but exact flow measurements were made in volumetrically calibrated collection tubes. The experimental procedure was essentially the same as with the water apparatus.

For the larger particles a 120-cm.-long, 5.508-cm.-diameter column was used. Operation was the same as just described, except that the constant-head tank provided insufficient flow and the solution was pumped directly to the column by means of a small centrifugal pump.

Since ethylene glycol is hygroscopic, the specific gravity of the liquid used was periodically checked to ensure that it had not changed from its original value.

RUTH'S THEORY

Since the theory of Ruth has not yet been published, it is developed in some

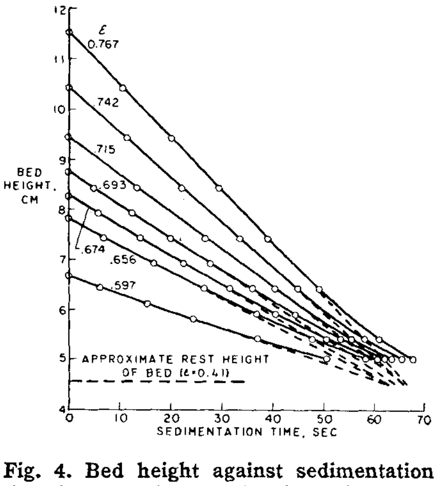

Fig. 4. Bed height against sedimentation time for ground 48-mesh spheres in glycol.

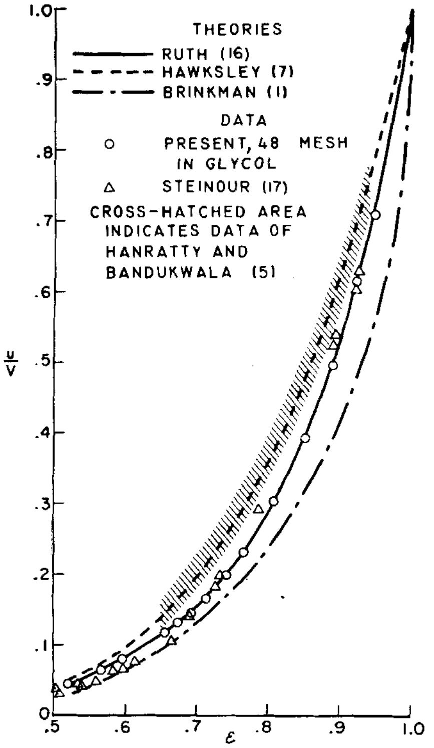

Fig. 5. General comparison of existing data and theories for the laminar regime.

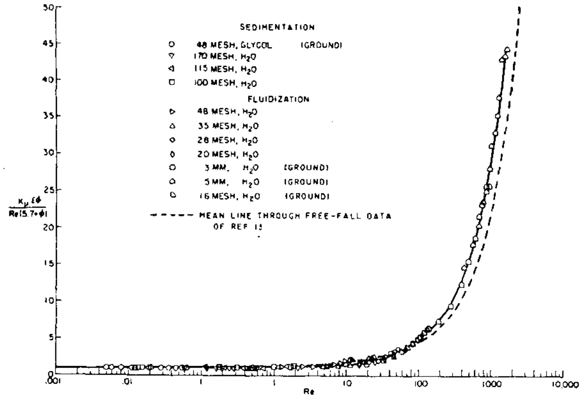

Fig. 6. Single-line correlation of present data over the entire Reynolds number range.

detail in this section. For purposes of brevity the original derivation (*16*) has been slightly modified.

The well-known drag force for the very slow motion of a sphere was given by Stokes as

$$F = 3\pi\mu u D \tag{7}$$

A more general expression for the resistance force, for the case where more than one particle is present, can be written as

$$F = f(\epsilon)\cdot 3\pi\mu u D \tag{8}$$

The limiting conditions on f are

$$\left.\begin{aligned} \epsilon \to 1.0: &\quad f(\epsilon) \to 1.0 \\ \epsilon \to \sim 0.48: &\quad f(\epsilon) \to \frac{2k(1-\epsilon)}{\epsilon^3} \end{aligned}\right\} \tag{9}$$

The first of these conditions is obtained by a consideration of Stokes's law, Equation (7). The second is obtained by comparison of Equation (8) with the equation derived by Kozeny for the case of compacted beds of spheres. The quantity k is a constant which must be determined experimentally. A suitable expression for $f(\epsilon)$ is

$$f(\epsilon) = \frac{1}{\epsilon} + \frac{2k(1-\epsilon)}{\epsilon^3} \tag{10}$$

This expression identically satisfies the first of limiting conditions (9) and for not too small k approximates the second very closely. Since at any rate Kozeny's equation is not an exact solution, there is no reason to demand exact agreement with it in the compacted-bed porosity range.

If the only body force acting upon the spheres is the force of gravity, then the force to be resisted by the drag force is

$$F = \frac{\pi D^3}{6}(\delta - \rho)g \tag{11}$$

Equating the drag and buoyancy forces as given by Equations (8) and (11) respectively and making use of Equation (10) for $f(\epsilon)$, one obtains the following equation:

$$u = \frac{1}{\left[\frac{1}{\epsilon} + \frac{2k(1-\epsilon)}{\epsilon^3}\right]} \cdot \frac{D^2(\delta - \rho)g}{18\mu} \tag{12}$$

If a new quantity φ is defined as

$$\varphi = \frac{\epsilon^2}{(1-\epsilon)} \tag{13}$$

then Equation (12) may be rewritten as

$$u = \left[\frac{\epsilon\varphi}{2k+\varphi}\right]\cdot\frac{D^2(\delta-\rho)g}{18\mu} \tag{14}$$

It may be noted that Equation (14) may also be written as

$$\frac{u}{V} = \frac{\epsilon\varphi}{2k+\varphi} \tag{15}$$

Equation (14) can be rearranged to

$$\frac{K_u}{Re}\left[\frac{\epsilon\varphi}{2k+\varphi}\right] = 1 \tag{16}$$

where

$$K_u \equiv \frac{gD^3(\delta-\rho)\rho}{18\mu^2} \tag{17}$$

and

$$Re \equiv \frac{Du\rho}{\mu} \tag{18}$$

RESULTS AND DISCUSSION

General Considerations

The nominal sphere sizes, diameters, densities, and the comparison of experimental free-fall velocities with the experimental data of Pettyjohn and Christiansen (*13*) for the spheres used in these studies are given in Table 1. The agreement for the free-fall velocities is seen to be good.

Except in the case of the 3- and 5-mm. spheres for which the top interface of the bed oscillated somewhat at the higher porosities, the beds fluidized quite evenly and uniformly. The top interface of the fluidized bed was easily distinguishable for the porosity range covered in this investigation.

To compare the processes of fluidization and sedimentation, the data have been plotted as ϵ against Re for two different sphere-liquid combinations in Figures 2 and 3. If the two processes

TABLE 1. PROPERTIES OF SPHERES

Nominal sphere size	D, cm.	δ, g./cc.	Deviation of experimental free-fall velocity from that predicted by ref. *13*, %
20 mesh	0.09029	2.629	−2.66
28 mesh	0.06586	2.630	−1.21
35 mesh	0.04590	2.667	−1.21
48 mesh	0.03445	2.671	−5.08
100 mesh	0.01645	2.582	−1.37
115 mesh	0.01399	2.587	−6.38
170 mesh	0.01015	2.575	0.89
16 mesh, ground	0.09769	2.656	−2.80 (in glycol)
48 mesh, ground	0.02872	2.671	2.14 (in glycol)
3mm., ground	0.3360	2.572	
5mm., ground	0.5056	2.514	

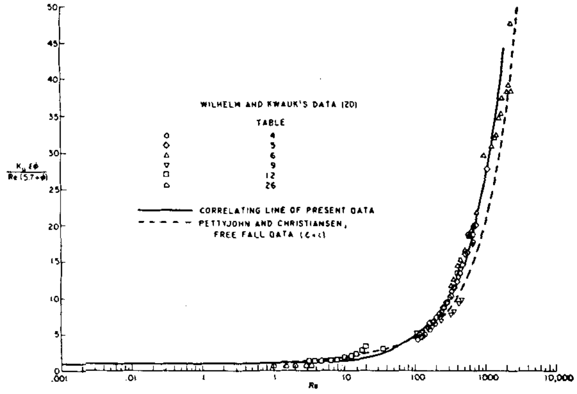

Fig. 7. Comparison of correlating line for present data with the data of Wilhelm and Kwauk (19).

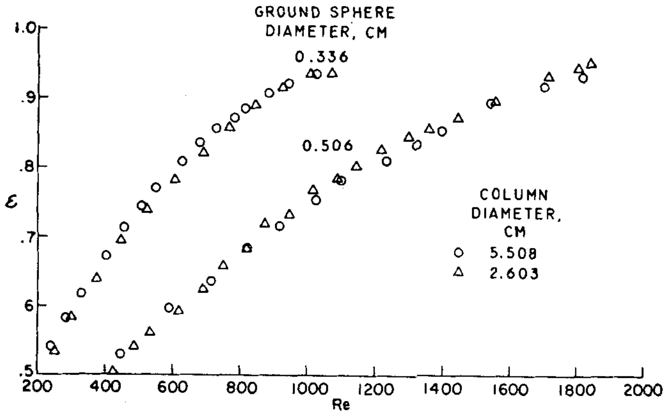

Fig. 8. Study of wall effect.

were identical, it would be expected that the data for each figure would fall upon a single curve. However a close scrutiny reveals that generally for the same porosity the Reynolds number is slightly less for the case of sedimentation; that is the flow resistance of the sedimenting bed is greater than that of the fluidized bed. This trend was also noticed for considerable other data not presented here. This finding appears to be in qualitative agreement with the previously mentioned theoretical results of reference *6*. The difference between the fluidization and sedimentation data appears to decrease somewhat for higher Reynolds numbers; thus the difference in Figure 3 is less than that in Figure 2. The effect does not appear large enough to make possible quantitative conclusions at this time.

Generally plots of bed height against sedimentation time were straight lines, demonstrating uniform beds and lack of interparticle forces. However a slight curvature was noted for large times during the sedimentation of the ground 48-mesh spheres in glycol, as shown in Figure 4. This curvature could conceivably be caused by the particles taking on an electrical charge and was neglected in the computation of sedimentation velocities, as shown by the dotted lines.

Laminar Correlation

The only data of the present investigation which are completely in the laminar regime of flow are those for the ground 48-mesh spheres in glycol. These data are plotted as u/V against ϵ in Figure 5, where they are compared with the theory of Ruth, Equation (15), for $k = 2.85$. The agreement is seen to be very good. The Stokes's velocity used in obtaining u/V was calculated separately for each run, with the proper temperature used.

The fact that the value of the Kozeny constant k is just over half that of about 5.0 recommended for compacted beds [for example Carman (*3*)] leads to the belief that the particles have rearranged themselves in such a way as to approximately halve the resistance of the bed in the flow direction. This conclusion appears to have been reached also in references *7* and *14*.

In Figure 5 the present data are compared also to a number of theories and the data of references *5* and *17*. The data of reference *17* are seen to be in reasonably close agreement with the present data. Data from the literature for nonspherical particles are not included, since the effect of particle shape is not yet understood.

The correlation given by Equation (4), as reported by references *11* and *14*, is not plotted in Figure 5 but agrees very closely with the theoretical line of reference *7*.

Correlation of All Data

Since the porosity function described by Ruth was successful in correlating the laminar data, it was decided to employ the same porosity function in trying to correlate the turbulent data too. This was done by plotting $\epsilon\varphi/(5.7 + \varphi) \cdot K_u/Re$ against Re as shown in Figure 6, where k has been taken throughout as 2.85.* The small differences between fluidization and sedimentation as evidenced by Figures 2 and 3 have been neglected for the purposes of this plot, and both types of data are plotted. At the higher Reynolds numbers fluidization data only are shown because sedimentation data in this range were relatively inaccurate. Conversely at very low Reynolds numbers the fluidization data were the least accurate. It is seen that the data give a satisfactory single-line correlation. The porosity range of the data presented is 0.48 to 0.96. The scatter of the data in Figure 6 in the neighborhood of $Re = 10$ to 40 could conceivably be caused by a transition from laminar to turbulent tube flow.

For the laminar and near-laminar regime it can be seen from Equation (16) that the value of the ordinate of Figure 6 should be equal to 1. This is nicely verified by the fact that the ordinate is approximately 1 up to a Reynolds number of about 0.5.

The free-fall ($\epsilon = 1$) data of Pettyjohn and Christiansen are approximated by the dotted line in Figure 6. If the Reynolds number effect for a fluidized bed were similar to that of a free-falling sphere, it would be expected that the present data would fall along the dotted line. That they do not fall exactly along it is not surprising, since the flow patterns for the two cases are obviously not identical. The correlating line drawn through the data should be of practical interest in most fluidization and sedimentation work, however, since it is valid over the porosity range of 0.48 to 0.96.

It is quite important to notice that the data for the ground and unground spheres all fall along the same correlating line in Figure 6. Since the size variation within the ground sphere samples is less than 5%, while that in the unground is less than 20%, it would appear that the samples of spheres used in the present investigation are uniform for all practical purposes; that is, there is no uncertainty as to the effective diameter characterizing each sample.

For comparison purposes the correlating line of the present data, as determined in Figure 6, is compared in Figure 7 with data obtained by Wilhelm and Kwauk (*20*). The data chosen from reference *20* are those for fluidization of spherical particles by water. Although the scatter here is considerably more than in Figure 6, a mean line through the data would not deviate greatly from the correlating line obtained from Figure 6.

Richardson and Zaki (*15*) reported laminar and turbulent data indicating a logarithmic relationship between u and ϵ (for constant temperature) with the slope a function of the terminal-velocity Reynolds number and equal to 4.65 for the laminar regime. The latter case, as given by Equation (4), does not represent the present data as well as the theory of

*Tabular material has been deposited as document No. 5974 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or 35-mm. microfilm.

Ruth, as previously mentioned. However all the data do show an approximate logarithmic relationship between u and ϵ.

To determine whether there was an appreciable wall effect in any of the data it was decided to fluidize the largest spheres employed in the investigation, the 0.336 and 0.506-cm.–diameter spheres, in a column of diameter 2.603 cm. Comparison of these data with the data for the same spheres fluidized in the 5.508-cm.–diameter column should then give a measure of the maximum wall effect. Such a comparison is made in Figure 8, where porosity is plotted against Reynolds number, and it is concluded that wall effect is negligible.

SUMMARY

A careful experimental study, over a wide Reynolds number range from 0.005 to 1,800, was made of fluidization and sedimentation of glass spheres, with both water and ethylene glycol used. Porosities varied from about 0.50 to 0.91 and larger. Closely sized and spherical particles were obtained by grinding the particles between glass plates. For Reynolds numbers up to about 0.5 the data are in very good agreement with the laminar theory of Ruth, while the porosity function from Ruth's theory gave a satisfactory correlation for all the data, both laminar and turbulent. There were small but consistent differences between the fluidization and sedimentation data which indicated that for an expanded bed of given porosity more flow resistance is experienced in sedimentation than in fluidization.

ACKNOWLEDGMENT

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NOTATION

D = particle diameter
D_c = column diameter
f = undetermined function of porosity
g = acceleration of gravity
K_u = function of particle and fluid properties, Reynolds number evalualted for Stokes's velocity [Equation (18)]
k = constant
p = permeability coefficient
u = fluidization velocity based on empty column cross section, or absolute velocity of top interface of bed in sedimentation
V = Stokes's velocity
ϵ = volume fraction of voids
μ = fluid viscosity
ρ = fluid density
δ = particle density

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Effect of Liquid on Interparticle Forces in Gas-fluidized Beds

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In an investigation of the behavior of an air-fluidized bed of glass spheres under varying interparticle forces, the results obtained are explained by hypothesizing the coexistence of particulate and aggregative fluidization. As interparticle forces are increased, a greater portion of the particles are in aggregative fluidization, resulting in a decrease in bed height. In this study water added to the fluidizing air increased the interparticle forces. Up to 0.5 mass % water was used, with a fluidized bed of glass spheres 0.013 to 0.035 in. in diameter. The resulting decrease in bed height has been correlated by means of a theoretical equation for the increase in interparticle forces due to the added water.

The widely differing natures of liquid- and gas-fluidized beds were observed in early laboratory fluidization experiments and received the names *particulate* and *aggregative* fluidization respectively (*11*). It has been suggested that the cause of aggregative fluidization is the attraction of individual particles for each other, usually termed *inter-particle forces*. The need for further information concerning interparticle forces has been indicated by several authors. Gamson has stated that a shape factor is needed to correlate particle heat and mass transfer data taken in aggregative fluidization with similar data from particulately fluidized beds and fixed beds (*3*). Workers who have studied heat transfer from surfaces in contact with the fluidized bed have also suggested that the attraction of particles for each other may be a factor in the correlation of heat transfer data (*1, 10*).

Interparticle forces may be divided into two groups, those due directly to the motion of fluid through the solids, and those forces not directly caused by the flowing fluid. The first class of forces are due to two causes: Bernoulli forces and the tendency of a flowing fluid to seek the path of least resistance. The latter phenomenon is very well described by

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