Apparent Viscosity of Gas-Solid Fluidized Systems

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As WITH other operations, knowledge of all aspects of fluidization is necessary for most efficient use to be made of the technique. Although there are many applications at present, a full understanding is lacking of all factors that determine fluidization quality. This investigation was undertaken as a step to more complete information by providing rheological data on fluidized systems.

Bed homogeneity and stability are basic indications of the quality of fluidization. They have been studied by a variety of methods including measuring a fluidized bed's transmission of a beam of light (*6*), γ-ray absorption (*2*), x-ray absorption (*7*), pressure fluctations as indicated by sensitive detectors (*13, 14*), capacitive changes (*1, 9, 11*), and apparent viscosity (*3-5, 10, 12, 15, 16*). While very satisfactory for certain conditions, all the methods have their limitations. The capacitive method is applicable only with specific kinds of solids, and the x-ray and γ-ray absorption methods require rather elaborate equipment and special safety precautions. All beds, however, exhibit rheological properties, and rheological behavior, moreover, is directly related to interparticle forces and interparticle friction, both of which are basic to a clarification of fluidization phenomena.

Previous attempts to determine a fluidized bed's viscosity are open to one or more criticisms. In several cases a paddle-type spindle was used in conjunction with a Stormer viscometer. The rotating paddle undoubtedly disturbed the flow pattern within the bed. In a few instances, the paddle was large in comparison to the bed, so that the resulting data could at best be only a description of gross phenomena. The first problem, then, was one of devising suitable measuring equipment.

APPARATUS

In view of the unsatisfactory character of a paddle-type spindle, a new spindle (Figure 1), was devised for use with a Model LVF, Synchrolectric viscometer (Brookfield Engineering Laboratories, Inc., Stoughton, Mass.) This spindle consisted essentially of two thin-walled brass cylinders located concentrically within one another and mounted axially to the viscometer through a small shaft. Since in use the spindle was suspended vertically into the fluidized bed, it exposed a very small area in the direction of gas flow. Even rotating, it retained its very small exposure, yet the relatively large surface area parallel to the gas stream path provided adequate sensitivity. The spindle and instrument were calibrated with glycerol.

The fluidized bed itself was formed inside a plastic tube 1.75 inches in inside diameter and 18.5 inches in length. A piece of strong cloth (stretched between the lower end of the tube and the base chamber on which the tube was mounted), because of its relatively large resistance to gas flow, distributed the flow essentially uniformly across the tube and supported the static bed. The tube was open at the top. The fluidizing medium was air from a compressed air line; its relative humidity was very nearly constant at about 15%. The pressure drop across the bed was measured with a U-tube manometer using water as the manometric fluid. Air flow rates were established using U-tube manometers and orifices calibrated with a standard gas meter. Electrostatic effects, as evidenced by the particles hanging on the wall, were encountered only in the case of polystyrene beads. They were eliminated by adding approximately 0.2 weight % of fine carbon powder, apparently as a result of increasing the bed's conductivity. The general arrangement of the apparatus is shown in Figure 2.

PROCEDURE

To initiate fluidization, air was admitted into the system at an increaing rate until fluidization was observed, the vessel being of clear plastic. Air flow rate, pressure drop, and bed height were noted, and using known values for particle density, shape factor, fluid density, and fluid viscosity the condition was checked by the correlation of Leva, and others (*8*). Unless there was a leak or some other difficulty, agreement with the correlation was excellent; in fact, the procedure described was used as a leak detector in early phases of investigation. Following this initial start-up, the air flow rate was increased until the bed became fully turbulent. This was done to ensure that no portion of the bed remained immobile. Finally the air flow rate was decreased to the desired operating conditions and 10 to 20 minutes were allowed for the bed to stabilize before rheological measurements were made.

Viscosity data were taken with the spindle at a number of different points along the vertical axis of the bed, but, due to the violence of particle motion near the upper surface, no measurements were made less than 2 inches below the surface. The position of the spindle was established by measuring the vertical distance from the base of the bed to the lowest edge of the spindle. After each change of spindle position, a short waiting period was allowed to permit equilibrium conditions to be re-established in case equilibrium had been altered in any way. With beds of fine particles, especially, external vibrations were eliminated because these have a considerable effect on the bed. Several measurements were recorded for each condition, but mean values were used in the final correlations.

MATERIALS

Four groups of glass beads having medium diameters on a number basis of 123, 99, 88, and 44 microns, a silica alumina cracking catalyst with a medium diameter of 45 microns, and polystyrene beads with a 349-micron median diameter made up the solid component of the systems studied. All were essentially spherical in shape. The glass beads, the catalyst, and the polystyrene beads had specific gravities of 2.47, 2.12, and 1.05, respectively.

GENERAL BEHAVIOR

When a stream of gas passes upward through a supported and laterally-confined mass of solid particles, reproducible changes in physical behavior are observed that go through successive stages as the gas velocity is increased. When the velocity is just sufficient to support particles, the condition

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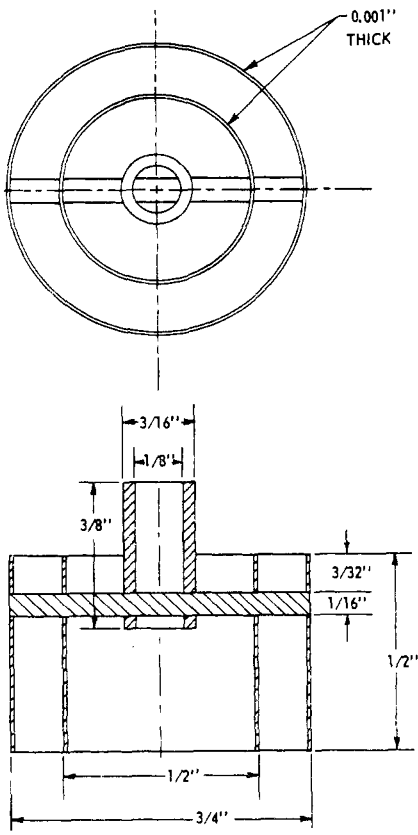

Figure 1. Design of viscometer spindle

is one of "incipient fluidization". Beyond this point a slight increase in gas velocity causes an expansion on the bed and creates a dense fluid state in which the bed particles rest more upon a cushion of gas than directly upon each other. As the flow rate increases still further, the expansion of the bed reaches a maximum after which any further increase in flow rate has little effect upon bed height and pressure drop. This latter type of bed is called an aggregated fluidized bed. It is composed of two phases, a continuous phase, consisting of uniformly distributed particles in a supporting gas steam, and a discontinuous phase, consisting of gas particles at lower concentration. The latter appear to be essentially solid-free gas bubbles, but since there is no boundary between the bubble and the continuous phase, particles could be scattered throughout this phase (*17*). Single, continuous-phase fluidization remains stable until the maximun bed height is reached, and then any additional gas flow passes through the bed in the form of a discontinuous phase. When the bed is not greatly expanded, there is considerable turbulence in the bed and considerable energy is lost in inelastic collisions between particles. The degree of turbulence in a fluidized system depends primarily on the amount and dimensions of the discontinuous phase elements—ordinarily called bubbles—passing through the bed. An increase in gas velocity increases the proportion of discontinuous phase elements. This apparently increases the chance of collisions and coalescence of the discontinuous phases and results in a decrease in the void fraction within the continuous phase and produces as well high density at the interface. As a result the amount of shear exerted on any measuring instrument is increased.

RESULTS

The data obtained in these experiments relate to local phenomena within the fluidized bed, and it is necessary to analyze the data by sections rather than as a whole since at least three sections exhibit different, yet characteristic, responses to the variables controlling fluidization. Section I covers the lower third of the fluidized bed, section II is the center part of the bed, and section III is the upper third of the bed.

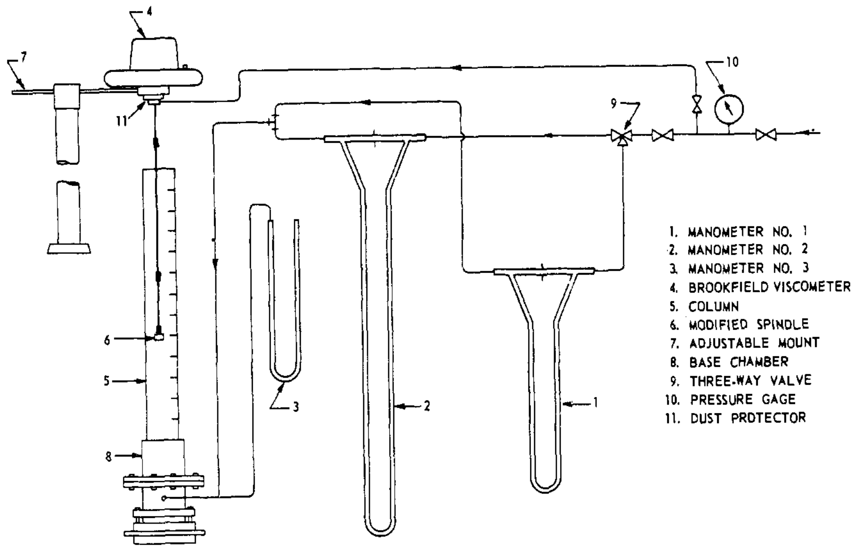

Figure 2. Schematic arrangement of apparatus

Rheological phenomena in section I were similar to those reported by previous workers. For example, apparent viscosity is generally considered to decrease with increasing flow rate and to increase with increasing particle size as shown in Figure 3. In addition, apparent viscosity increases with increasing bed weight, other things such as particle size remaining reasonably constant.

In section II, apparent viscosity changes only slightly with wide variation in flow rate. This is best seen in Figure 4, a plot of typical data. A transition region was found in section II also. Its location shifted somewhat with different conditions; its extent varied also, being narrower for coarser particles. Transition phenomena were also

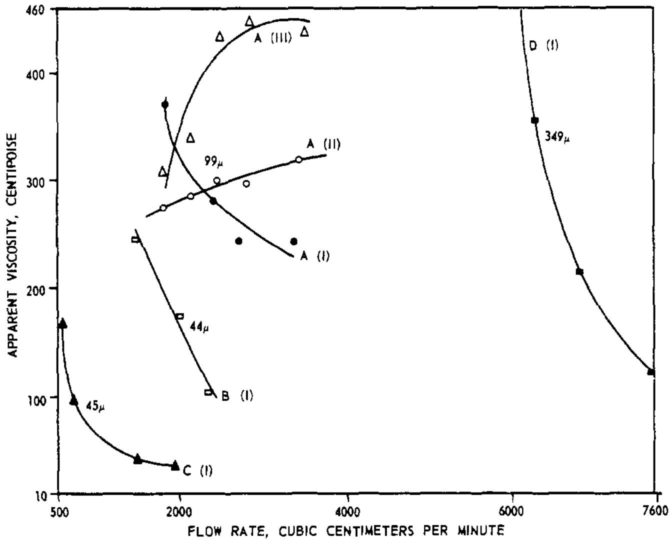

Figure 3. Change of apparent viscosity with air flow rate through fluidized beds

Curves A (I), A (II), and A (III) refer to conditions in sections I, II, and III; they were obtained with a 400-gram bed of glass beads 99 microns in median diameter

Curves B, C, and D all represent conditions in section I

Curve B is for a 400-gram bed of glass beads 44 microns in median diameter

Curve C is for a 200-gram bed of silica alumina catalyst 45 microns in median diameter

Curve D is for a 300-gram bed of polystyrene beads, 349 microns in median diameter observed in Bakker and Heertjes' (*1*) capacitive porosity measurements.

Figures 3 and 4 indicate that apparent viscosity increases with increasing flow rate in section III. The relationship between viscosity and particle size or bed weight in the section seemed, however, to be generally random and unpredictable.

Since spindle rotation rate is proportional to rate of shear of the fluidized bed, and the torque indicated by the Brookfield viscometer is proportional also to the shearing stress of the bed, the experimental data permitted construction of shear diagrams, some of which are shown in Figure 5. Each gas-solid fluidized system behaved as a pseudoplastic at low flow rates, but generally approached Newtonian behavior as flow rates increased.

The reproducibility of all apparent viscosity data was between 80 and 95%, the higher figure applying to finer particles.

CONCLUSIONS

The apparent viscosity of gas-solid fluidized systems may be conveniently measured with a spindle of the type decribed, and greater use of apparent viscosity should permit local phenomena to be understood better. A gas-solid fluidized bed exhibits three distinct sections, each respondingly differently to changing conditions. In the lower portion of a fluidized bed, apparent viscosity decreases with increasing flow rate; in the middle region, a shift in either direction is possible, but changes are not likely to be great in any event; and in the upper part of the bed apparent viscosity increases with increasing flow rate. At low flow rates, all regions demonstrate pseudoplasticity, while, at higher rates of flow, the behavior approaches Newtonian character.

The results suggest several interpretations. A decreasing apparent viscosity with increasing gas flow rate in the lower levels of a fluidized bed might be explained as being due to particle agglomerates. Since the number and size of the agglomerates would be expected to decrease as gas flow increased, this should reduce interparticle friction and, hence, apparent viscosity. Increasing viscosity and flow rate in the upper portion of a bed might be due to a correspondence between average particle velocity and viscosity by analogy with the fact that the increasing viscosity of a gas at elevated temperatures is due to increased molecular motion. Most likely, however, the dominant factor causing the observed viscosity behavior is simply the number of particles present in the section. A greater number of particles is present in section I at low gas velocities than at higher velocities; this decrease in number leads to a decrease in apparent viscosity. At high gas velocities a large number of particles is transported from section I to section III giving an apparent increase in viscosity in section III. In section II, the number of particles and the viscosity can shift in either direction.

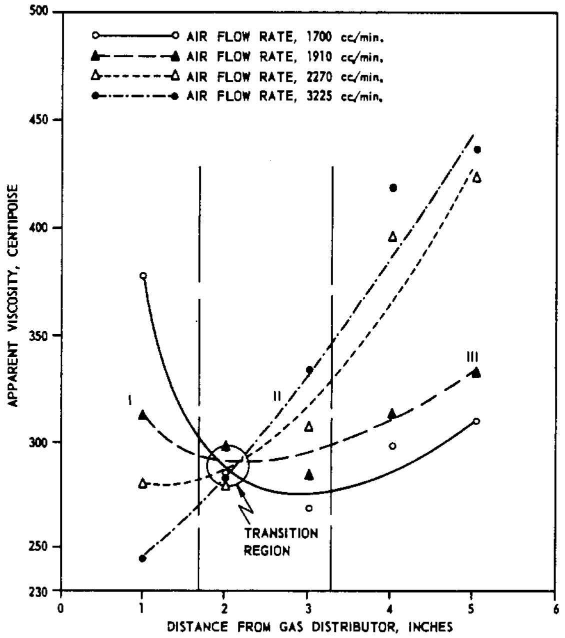

Figure 4. Change of apparent viscosity with position in a fluidized bed produced with 400 grams of glass beads 99 microns in median diameter

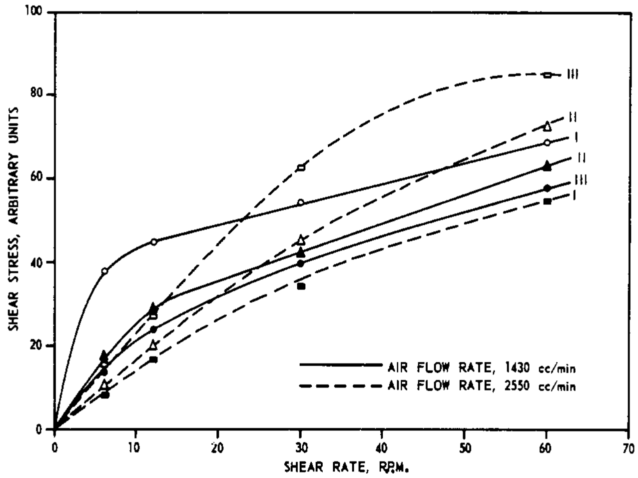

Figure 5. Shear diagram

Curves are designed in accordance with the section of the column in which tests were made

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