Solids Mixing in Fluidized Beds

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The movement of solids associated with the rise of a single gas bubble in an incipiently fluidized bed has been determined. The bulk volume, measured at the porosity of incipient fluidization, of tracer solid which is transported across the original interface between undyed glass spheres in the upper region and dyed glass spheres (tracer solid) in the lower region, is approximately 30% of the bubble volume. The measurements relate to bubble volumes from 14 to 200 ml. in a glass column, 4 in. diam. Solids used were glass spheres of diameter 380 μ. The profile created when a bubble rises through a layer of fluidized tracer solids into the fluidized solids above the tracer layer has been approximately determined. The distance by which the solids were displaced upward, due to the passage of the bubble, was found to be greater than would have been the case if the behavior were that of a sphere in an inviscid liquid.

THE WAKE OF SINGLE BUBBLES

The mixing of particles in gas-fluidized beds is rapid, so that in reactors a relatively uniform temperature exists throughout the fluidized bed.

Rowe and Partridge (*11*) argue that an isolated bubble rises through a fluidized bed as if it were a solid sphere rising through a nearly inviscid liquid, and layers of particles through which the bubble moves are drawn up into a "spout" behind it. Also, each bubble carries with it a wake of circulating particles, and shedding of portions of this wake occurs as the bubble rises.

Davidson and Harrison (*3*) have shown that isolated gas bubbles in fluidized beds have a rise velocity similar to that of large air bubbles in a liquid as discussed by Davies and Taylor, (*4*) who observed that a spherical cap bubble in liquid is followed by a wake approximately contained within the sphere depicted in Figure 1*a*. Hence a volume of liquid, greater than that of the bubble, rises with it. This bubble-induced liquid motion accounts for the rapid mixing in gas-sparged liquids. A similar motion of fluidized solids in the wakes of gas bubbles in a fluidized bed explains the rapid solids mixing.

Rowe and Partridge (*12*) determined by x-ray photographs the shape of bubbles in fluidized beds as in Figure 1*b*, and determined the *wake angle* and the *wake fraction*. The wake fraction is the volume fraction of the hypothetical sphere, depicted in Figure 1*b*, which encloses the spherical cap bubble and its wake. Rowe and Partridge found in the case of glass spheres that the wake fraction varied from 0.26 to 0.38 as the particle diameter changed from 220 to 50 μ. On the other hand, in the case of silver sand, they found that the wake fraction remained constant at 0.19 over a similar variation in particle size. If the wake fraction represents the fluidized solids moving with the gas bubble, then

$$\frac{\left(\begin{array}{c}\text{volume of fluidized solids}\\ \text{moving with bubble}\end{array}\right)}{(\text{volume of bubble})} = R = \frac{\text{wake fraction}}{1 - (\text{wake fraction})}$$

and for glass spheres the volume ratio R varies from 0.37 for diameters of 220 μ to 0.61 for diameters of 50 μ.

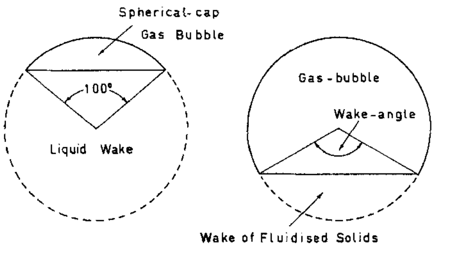

Fig. 1. Simplified representation of a gas bubble in liquid (*a*) and in a fluidized bed (*b*). The wake is represented as the volume required to complete the sphere[4,12].

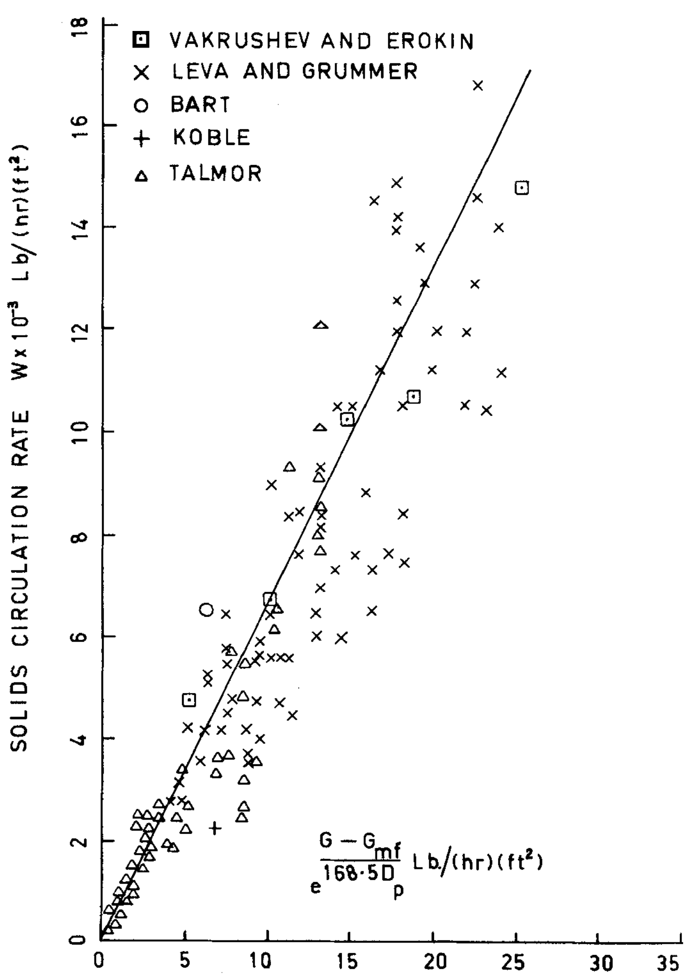

Fig. 2. Solids circulation rate in a fluidized bed.

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SOLIDS MIXING INTERPRETED AS DUE TO THE MOTION OF THE WAKE

Marsheck and Gomezplata (*8*) studied particle flow patterns in a fluidized bed, 9.5 in. diam. They concluded that particles appeared to flow up in those areas where the bubbles rise and to flow down in the surrounding regions; also the bubble flow pattern appeared to establish the particle flow pattern.

Talmor and Benenati (*14*) determined solids movement in bubbling air-fluidized beds by a tracer technique employing cation exchange resin in the hydrogen and sodium forms. Beginning with a layered bed of tracer and nontracer, they fluidized the bed with air for varying lengths of time and determined the amount of tracer solid which crossed the original interface. Their data could be represented by the equation

$$W = 654\,(G - G_{mf})\,\exp\,(-168.5\,D_p) \qquad (1)$$

Equation (1) was shown by Talmor and Benenati to correlate also the data of Koble (*5*) and of Leva and Grummer (*6*). Figure 2 shows in addition the data of Bart (*1*) and of Vakrushev and Erokin (*15*). Equation (1) thus provides an apparently satisfactory correlation for solids transport over the following range of parameters:

Bed diameter: 1.25 to 4.00 in. (the dimensions of Vakrushev and Erokin's column are not given)
Particle diameter: 0.00264 to 0.0257 in. (or 67.1 to 654 μ)
$G - G_{mf}$: 0 to 329 lb./(sq. ft.) (hr.)
G/G_{mf}: 1 to 26
Particle density: 47 to 165 lb./(cu. ft.)
Size distribution: mixed and uniform
Solids: microspheres, round sand, sharp sand, silica gel, ion exchange resins, cracking catalyst, coke

If it is assumed that the solids motion in the fluidized bed is due to the movement of solids in the wake of the bubble, then

$$\text{mass velocity of solids} = W = (U - U_{mf})R(1 - \epsilon_{mf})\,\rho_S \qquad (2)$$

From Equations (1) and (2) it follows that

$$R = \frac{654\,\rho_G}{(1-\epsilon_{mf})\rho_S}\exp\,(-168.5\,D_p) \qquad (3)$$

For glass spheres of bulk sp. gr. = 1.67 at incipient fluidization, fluidized by air of density 0.076 lb./(cu. ft.)

$$R = 0.476\exp\,(-168.5\,D_p) \qquad (4)$$

Hence the Talmor and Benenati correlation, Equation (1), could be interpreted to mean that $R = 0.017$ for glass spheres of diameter 508 μ when fluidized by air under atmospheric pressure and that R increases to 0.205 for spheres of 127 μ diameter.

DRIFT PROFILE FOR MOTION OF A SPHERE IN INVISCID FLUID

When a sphere moves in an ideal fluid, the individual fluid particles which are pushed aside by the sphere in its motion do not return to their former positions but are displaced permanently in the direction of its motion (*2, 7, 10*). The volume of fluid thus displaced equals in volume 50% of the volume of the sphere.

EXPERIMENTS ON SINGLE BUBBLES

Noble (*9*) described experiments in which a horizontal thin layer of tracer particles, in an incipiently fluidized bed, was displaced by passage of a single bubble. Rowe and Partridge (*11*) reported briefly (1) that by making beds in several layers of differently colored material it had been shown that the bubble wake is continuously accumulating fresh material; (2) in a bed a foot or so deep, the wake dilution with fresh material is such that virtually no material from the bottom 2-in. layer is carried to the top of the bed by the passage of a single bubble; and (3) in rough terms, a bubble displaces about two-thirds of its volume upward through an average height of one bubble diameter, and the displacement volume is made up of about 75% in the drift profile and 25% in the wake. Rowe et al. (*13*) concluded, without presenting the detailed evidence, that for particle diameters greater than 100 μ each bubble draws up a drift profile behind it calculated as for the drift profile created by a sphere in an inviscid fluid. In addition, Rowe et al. conclude that the bubble gathers up a wake of about one-quarter the total sphere volume and carries this up the bed, shedding fragments from the wake which is however replenished with new material. The initial wake material is gathered from a depth less than the bubble diameter and includes material from the very bottom of the bed when bubbles originate there. For particles less than 60 μ in diameter, the same mechanism is considered by Rowe et al. to apply but is aided by another mechanism akin to turbulence.

PRESENT WORK

The present work is similar to that of Noble and of Rowe et al., in that a single bubble formed in an incipiently fluidized bed in solids containing tracer material rises through tracer-free solids.

Experimental Techniques

Woollard (*16*) and Rowe et al. (*13*) have reviewed the techniques. In this work a glass pipe of diameter 4 in. and height 18 in. was used as the fluidization column. The gas distributor was a brass plate 1/16 in. thick, with 0.04-in. diam. holes drilled on 0.5-in. square pitch. A foam rubber screen was glued to the plate. The bubble injector tube, 5/16 in. bore, was flush-mounted in the distributor plate. A flow straightener was employed. Bubbles were injected from a pressure chamber 3⅜ in. bore. The pressure drop across the distributor was nearly 70% of the pressure drop through the bed.

The particles used were glass spheres with average particle size of 380 μ and 95% of the particles within the range 300 to 500 μ.

The glass spheres to be used as tracer material were cleaned and subsequently treated with a solution of dye and salt, allowed to drain, and oven-dried. The oven-dried dyed spheres were vigorously fluidized to remove all loose salt and dye and were then ready for use. The solution with which the spheres were treated was prepared from 28 g. of common salt and 5.6 g. of Paramine Black dye dissolved in 1 liter of water and then filtered. The incipient velocity of the treated spheres was about 5% greater than that of the untreated spheres.

The bed was prepared in two layers—a layer of untreated spheres above a layer of dyed spheres. The lower layer of tracer material (the dyed spheres) was introduced into the empty column, while air entered the column at a rate sufficient to fluidize the bed so formed. To introduce the upper layer of tracer-free material (undyed spheres), the air rate to the bed was reduced below the incipient fluidizing rate to eliminate bubbles and the tracer-free material was carefully introduced.

The air rate was then increased to a value just above the incipient fluidizing rate and a single bubble was discharged from the pressure chamber. When the bubble had passed through the bed the air rate was reduced. Moist air was then blown at low velocity through the defluidized bed to "fix" the dyed spheres.

The bed was then investigated as follows: The upper surface was photographed. Then a layer 0.5 cm. deep was removed and analyzed for its content of tracer spheres by shaking the spheres with water and measuring the conductivity of the resultant solution. The same procedure was repeated on successive layers of the same depth.

A series of runs was performed in which the expansion of the bed on bubble injection was compared with that calculated from the pressure in the pressure vessel. The volume determined from the pressure was from 5 to 10% greater than that measured by bed expansion. The values used are those from the pressure vessel.

Throughout the investigations the humidity of the air used for fluidization was approximately 50%.

Experimental Results

In Figure 3 a set of photographs is presented showing the appearance at different layers after passage of the bubble. The photograph of the top of the bed shows the mixing action that occurs there as tracer reaching the top of the bed is spread across the surface.

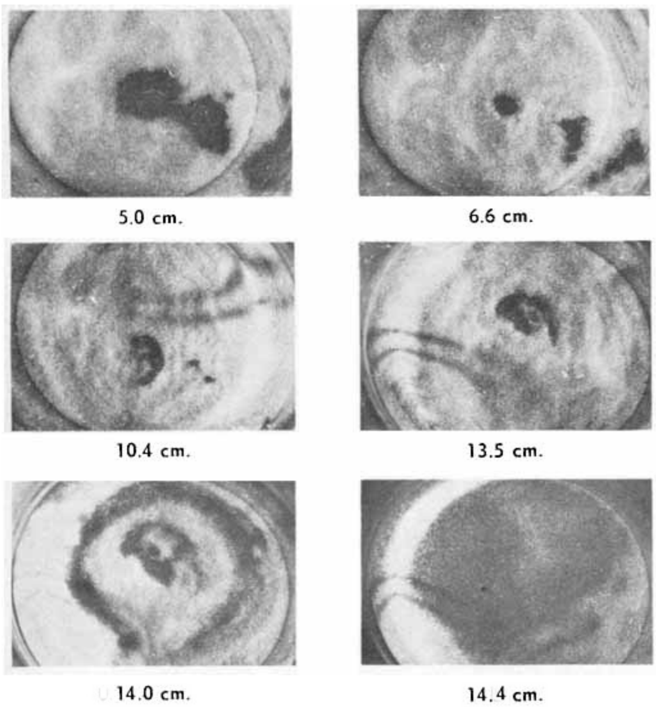

Fig. 3. Photographs showing displacement of tracer into the upper section of the fluidized bed. The bubble appears to split. Note the scattering of tracer across the top of the bed as the bubble bursts. 14.4 cm. represents the top of the bed.

Table 1. Bulk Volumes of Solid, at Incipient Fluidization Porosity, Transported by a Single Bubble, Expressed as Percent of Bubble Volume. Glass Spheres 380 μ Diameter Fluidized by Air at Atmospheric Pressure

Bubble volume, ml.	Height of tracer, cm.	Bed height, cm.	Volume displaced as percent of bubble volume: Above initial level	Volume displaced as percent of bubble volume: Above the non-displaced tracer level
193	7.2 to 10.3	17.8 to 25.9	29	37
98	4	4.5 to 14.4	27	37
52	4	4.3 to 25.9	29	44
17.5	4	4.3 to 14.4	37	54

Figure 4 shows the profile of displaced tracer from the same run. Since tracer is displaced above the initial tracer level, undyed spheres are displaced downward into the zone originally occupied by tracer. Near the walls tracer material is undisturbed. A horizontal line is drawn tangential to the tracer profile and labeled *nondisplaced tracer level.*

The experimental measurements yielded the mass of solids displaced, and this could be converted to the bulk volume, at minimum fluidization porosity, of the solids displaced. The data expressed in this form are presented in Table 1.

Note that the data are expressed with respect to two different levels, one of which is the initial interface level and the other of which is the nondisplaced tracer level.

The volume displaced above the initial interface level appears to be approximately 30%, rather than the 50% obtained theoretically for a sphere in an inviscid fluid (*2, 7, 10*). Strictly speaking the theoretical analysis for a sphere in an inviscid fluid is valid only for an infinite fluid and not a confined one as in the present case; hence data are also reported in Table 1 with respect to displacement above the nondisplaced tracer level.

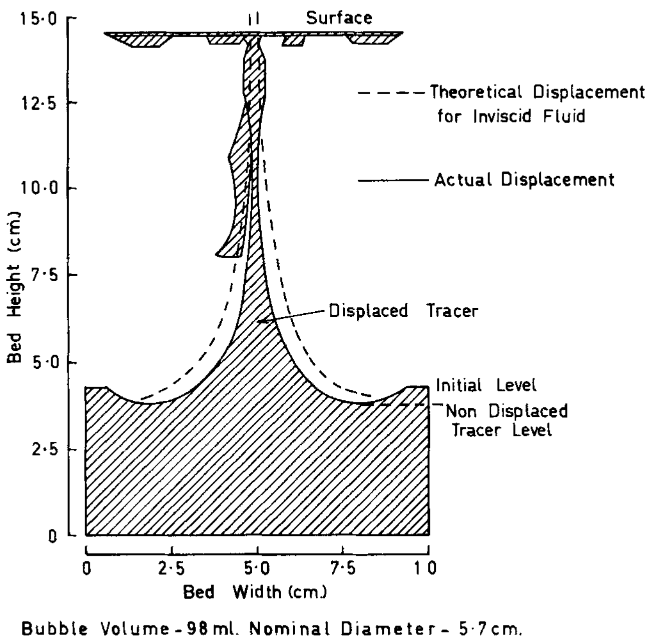

Fig. 4. Profile of displaced tracer, same case as Figure 3. The dashed line shows the profile for a sphere of the same volume as the bubble in an inviscid fluid[7].

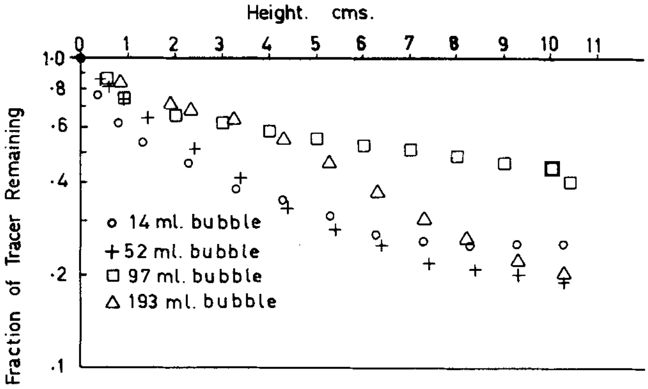

Fig. 5. Fraction tracer remaining vs. height. The fraction tracer remaining at a given height is the fraction of the tracer transported by the bubble beyond that height. Height is here measured from the nondisplaced tracer level.

In Figure 5 is displaced the fraction of tracer remaining with the bubble at different heights above the nondisplaced tracer level. In Figure 6 the height is expressed in dimensionless terms related to D_B the diameter the gas bubble would have if it were spherical. Also plotted in Figure 6 is a theoretical line for the tracer displacement produced by a sphere in an inviscid fluid calculated from Lighthill's study (7).

It is clear that the tracer displaced by the bubble is displaced further than is the fluid displaced by a sphere in an inviscid fluid.

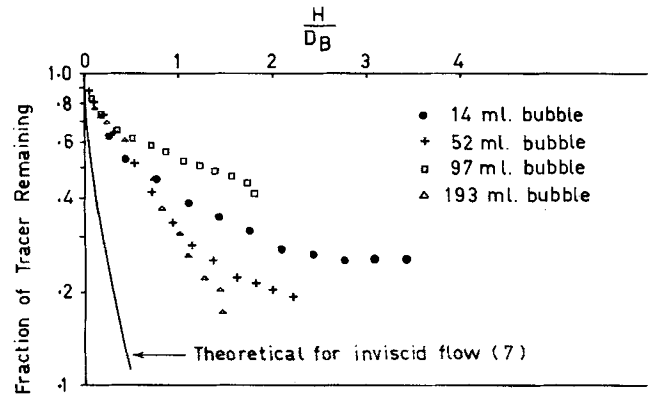

Fig. 6. Fraction tracer remaining vs. number of bubble diameters H/D_B. The full line is for a sphere, of the same diameter as the bubble in an inviscid fluid(7).

DISCUSSION

The displacement above the original interface, at about 30% of the bubble volume, is somewhat less than the theoretical value of 50% for a sphere in an unbounded inviscid fluid. This observation may be compared with the statement of Rowe et al. (*13*), that each bubble draws up a drift profile equal to 50% of its volume and that the bubble also carries with it a wake of about one-quarter the total sphere volume. It should be noted that the volume referred to by Rowe et al. is not the bubble volume but the volume of sphere comprising both bubble and wake. Hence these authors conclude that the drift profile has a volume equal to two-thirds the bubble volume and the wake has a volume equal to one-third the bubble volume, the total volume of material displaced being equal to the bubble volume.

In the present investigation the total volume of material displaced was only 30 to 40% of the bubble volume. This figure agrees quite well with the figure of Rowe et al. for the volume of wake but is less than half their value for the total volume displaced. Rowe et al. have not presented the detailed evidence for their conclusions.

In the case of a freely bubbling bed, the Talmor and Benenati correlation, Equation (1), predicts that the solid transported across the interface is only 40% of the total volume of bubbles passing the original interface, in the case of glass spheres of diameter 380 μ. The discrepancy between this value and the figure of 30 to 40% for a single bubble needs further investigation. In this paper additional data have been added to the Talmor and Benenati correlation for solids movement, thus providing additional confirmation of its validity.

The data reported are for 380 μ glass spheres in a 4-in. diam. column, with bubble volumes from 14 to 190 cc. In practice, at the high gas rates usually employed, the volume of bubbles, depending of course on the equipment, would extend to much larger values. Bubbles much smaller than 14 cc. would rapidly coalesce to form larger bubbles. The chief need therefore appears to be an extension of the measurements to much larger volumes, and a study of the transition region to slug flow.

The influence of particle size also needs study since there are clear indications in the work of Rowe et al. on single bubbles; and in the correlation of Talmor and Benenati for solids circulation rate in a freely bubbling bed, of variations due to particle size.

CONCLUSION

A technique has been developed for studying the solids movement associated with the rise of a single bubble in a fluidized bed. The results show some but not complete agreement with the findings of Rowe and ci-workers.

NOTATION

D_B = equivalent diameter of bubble
D_p = particle diameter in.
G = superficial mass velocity of fluidizing gas, lb./(sq. ft.) (hr.)
G_{mf} = superficial mass velocity of fluidizing gas at minimum or incipient fluidizing conditions, lb./(sq. ft.) (hr.)
H = bed height
R = ratio of volume of dense phase, at incipient porosity, transported by the bubble to the volume of the bubble
U = superficial velocity of fluidizing gas, ft./hr.
U_{mf} = superficial velocity of fluidizing gas at minimum or incipient fluidizing conditions, ft./hr.
W = solids superficial mass velocity across a horizontal plane, lb./(sq. ft.) (hr.)
ϵ_{mf} = porosity of dense phase at minimum fluidization velocity
ρ_G = gas density, lb./cu. ft.
ρ_S = absolute density of solid particles, lb./cu. ft.

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