Convective Solids Settling Induced by a Buoyant Phase

Quantitative measurements of the effect of a third phase of buoyant solid particles on the settling rates of suspensions of heavy particles are reported. It is found that for a wide range of concentration of both buoyant and heavy particles, the settling rates of both solid phases are greatly increased. If the phases are dilute, the settling velocities of both are retarded. The total settling time of heavy particles can be halved, but only under conditions that the light phase is unaccelerated. This suggests that small gas bubbles would form a more satisfactory buoyant phase. The high concentrations of thickened suspensions which result from the acceleration process are also reported.

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SCOPE

Gravity thickening and settling of suspensions of solids in a liquid phase are extremely slow processes. The early observation of Boycott (1920), that blood settles faster in an inclined tube than in a vertical one, has led to the suggestion that the insertion of inclined partitions into settling tanks will accelerate the rate of sedimentation. The process has been definitively analyzed by Acrivos and Herbolzheimer (1979) who found that the improvement was mainly a result of increased area available for creating clear fluid.

It was first noted by Whitmore (1955) that acceleration of settling can also result from the presence of large numbers of neutrally buoyant particles in a suspension of heavy ones. Recently this was extended by Weiland and McPherson (1979) who found that large-scale density driven convection is induced in a suspension by the presence of a third positively-buoyant particulate phase. Although both reports describe a form of streaming, buoyant particles were found to establish it far more quickly and reproducibly. Unfortunately the method used for measuring settling rates was disturbing to the process, because it is quite capable of setting up convection on its own.

The present work is a more quantitative study using a completely nondisturbing technique. One species of particles was coated with fluorescent dye and measurements were made under ultraviolet illumination. This also allowed the observer to see quite clearly the flow patterns which resulted from the action of an added buoyant phase and to trace the sequence of events which brought about the convective motion.

CONCLUSIONS AND SIGNIFICANCE

The presence of buoyant particles is found to cause immediately the formation of clusters of predominantly one particle species or the other. The clusters ascend and descend, ejecting any of the foreign species remaining within them. These fast moving clusters create pathways for others to follow and the resulting chains of clusters quickly evolve into streams of the less populous species imbedded in a continuum of suspension containing the more populous species exclusively. The settling process is greatly accelerated unless both particle species are dilute, in which case settling is retarded.

The total settling time can be reduced to one-half in the system studied but optimum conditions for accelerating the overall process for one species are found to result in slow settling for the other. Originally dilute suspensions of heavy particles can be quickly concentrated manyfold using a third more-concentrated phase. Problems found with speeding up the overall rise of buoyant particles simultaneously with accelerating the settling of heavy ones suggests that small gas bubbles may be more satisfactory settling promoters since they would not have to be separated at all.

Numerous major industrial processes use sedimentation and thickening for separating solids from liquids on a large scale. The mining and minerals processing industries provide a host of examples including the thickening of hydrate suspensions in the Bayer extraction of alumina from ores and the settling of coal washings and mine tailings. The main driving force is gravity and the primary concern is with relatively concentrated suspensions.

Sedimentation and thickening are too common to need their importance emphasized; they are slow processes and require very large-size equipment. Any means of accelerating them would be of enormous benefit. Here, we shall describe progress on a novel means of acceleration first reported by Whitmore (1955) using particles of neutral density and Weiland and McPherson (1979) using buoyant particles. The key to the method lies in the use of *buoyant* particles, which also separate, but, when added to a sedimenting suspension in sufficient quantity, induce structured, vertically-directed convection currents in the suspension. These currents have been found to convey particles at greatly increased rates and lead to a clean separation of particles from the fluid, and heavy and light particles from each other.

There is a vast literature on experimental, semi-empirical and theoretical attempts to calculate the bulk sedimentation velocity

TABLE 1. PROPERTIES OF MATERIALS USED

	Buoyant Phase	Heavy Phase	Fluid
Material	PVC	Lead Glass	Thallium Formate (aq.)
Sauter Mean Size	107 μm	100 μm	—
Standard Deviation	± 11 μm	± 11 μm	—
Density (g/cm^3)	1.40	2.96	2.24
Viscosity (cP) at 20°C	—	—	2.09_1

as a function of particle concentration, shape, and size distribution. An exhaustive review can be found by Happel and Brenner (1965) and the more recent literature has been nicely summarized by Fitch (1979). Our present interest is not with the theory or practive of thickening *per se*, but rather, is with a new means of accelerating it.

Flocculation can be viewed as a chemical method of improving settling rates; it does not directly concern us here, although it should be mentioned that flocculation can be used in conjunction with the process we are about to describe.

Mechanical methods have been proposed to increase gravity settling rates. For example, the use of inclined walls to promote settling originates in the work of Boycott (1920). He observed that blood, settling in narrow tubes, does so a good deal faster if the tube is inclined rather than vertical. The process has been definitively analyzed by Acrivos and Herbolzheimer (1979) for arbitrary suspension concentration and vessel geometry, and a discussion of the previous literature may be found there as well. In the present context, perhaps the most important conclusion of their analysis is that, although a convective motion is set up, the enhancement of settling in inclined vessels is largely due to the increase in surface area available for creating clear fluid. When buoyant particles are added, however, it is the convection currents which are directly responsible for the improvement.

The original work of Weiland and McPherson (1979) on the effect of a buoyant particulate phase on settling was done using a diver to follow supposed density interfaces. The diver was a thin-walled annulus whose density could be adjusted to match that of a particular region of the settling suspension. There are two major causes for doubting results obtained by such means. In the first place, the presence of a large foreign object can itself cause a convective flow; this has been well documented by Kast (1960), Robins (1962), Inouye et al. (1954), and Coutts and Crowther (1925). Thus, the diver is likely to be quite disturbing to the process being examined. In the second place, as will be made clear in a subsequent section, the interface, which Weiland and McPherson postulated as a boundary separating a suspension of rising particles only, and a suspension containing both rising and sinking particles, does not exist.

Once separation of the two solid phases into an upward-settling suspension of buoyant particles and a downward-settling suspension of heavy particles (with clear liquid in between) has taken place, one can easily follow the settling process just by observing the interfaces, which are characteristic of thick settling suspensions. From the observed velocities, one can easily infer the velocity during the accelerated rate period. Thus, the data of Weiland and McPherson are probably qualitatively correct but must be viewed with suspicion as quantitative measurements.

We shall begin with some qualitative visual observations of the sequence of events which takes place during the settling of a thick suspension of heavy particles in the presence of large numbers of buoyant ones in a vertical tube. This is followed by quantitative measurements of the increases in settling rates obtained by using a buoyant particulate phase, and the concentrations of thickened slurry which result.

EXPERIMENTAL

The experiments were equivalent to batch settling tests and were conducted in a precision-bore glass tube 55 cm long and exactly 2.54 cm internal diameter. The tube was mounted on a wall and held in place with spring clips so that it could be quickly set up after mixing the suspension. The tube in its mounting arrangement was vertically aligned to one part in ten thousand using a theodolite.

The heavy and buoyant particle phases were lead glass and polyvinylchloride, respectively. Narrow size ranges were obtained by screening through new sieves (British standard size). Both phases were sized on an Electrozone Celloscope (Particle Data Inc.) connected to a PDP 8/m computer and were found to be log-normally distributed. The Sauter mean sizes, width of the distributions and other physical properties are given in Table 1.

The supporting fluid used was an aqueous solution of thallium formate whose density was adjusted (through concentration) to be midway between the densities of the buoyant and heavy particles. (Thallium formate is extremely poisonous and suitable precautions were observed.) After trying a large number of surfactants and dispersants, it was found that the soluble part (an inorganic polyphosphate) of a commercial cleansing agent was quite effective in preventing agglomeration and flocculation of glass and PVC with each other and among themselves. This was checked by observation of a small amount of suspension under a microscope; with a suitable dispersant, particles remained motionless, otherwise they could be seen to quickly move together into small groups.

The requirement of a *nondisturbing* method of distinguishing one set of particles from another was met by dyeing the PVC with a fluorescent dye extracted from commercially available marking pens and making observations and measurements under ultraviolet illumination in a temperature-controlled darkroom. In this way, the buoyant particles signalled their presence by emitting light, while the heavy particles virtually disappeared from view. A number of photographs were obtained in this way and the process was also recorded on motion picture film.

Mixing was accomplished by tumbling the tube containing a large air bubble, end-over-end and was judged complete when quick observation under ultraviolet light showed no variations or gradations in the uniformity of the emitted yellow light. After a few more tumbles, the tube was quickly placed in its bracket on the wall and observations began.

QUALITATIVE OBSERVATIONS

The type of motion and sequence of events observed depended very much on: (i) whether the suspensions were relatively dilute or concentrated; and (ii) whether one solid phase was in great excess over the other or both were present in roughly equal proportions.

When the suspension was relatively concentrated and contained slightly more of the heavier particles than buoyant, light-emitting ones (but both in amounts exceeding several volume percent) the initially uniform mixture immediately became grainy and large clusters containing predominantly heavy or light particles formed. These clusters moved up or down, depending on composition, colliding and interacting with each other. In so doing, heavy (dark) clusters, for example, ejected whatever buoyant (yellow) particles they contained. It seemed that a large proportion of the overall settling took place by the rapid ascent and descent of clusters containing virtually one particulate phase only.

This stage gradually evolved into one in which smaller packets of particles of buoyant material only could be seen to be following each other in procession and these slowly merged together into streams. These streams contained buoyant particles exclusively and moved in a continuum of suspension containing only heavy particles. Streaming continued until the heavy and light phases had almost completely separated vertically. At that stage, a few short trailing chains of loosely connected clusters of buoyant particles remained, and these quickly completed the ascent out of the surrounding suspension of heavy particles.

We were then left with an ascending suspension of buoyant particles overlying a descending suspension of heavy ones, separated by clear fluid in between. The presence of even the most minute quantity of light-emitting (buoyant) particles in the final

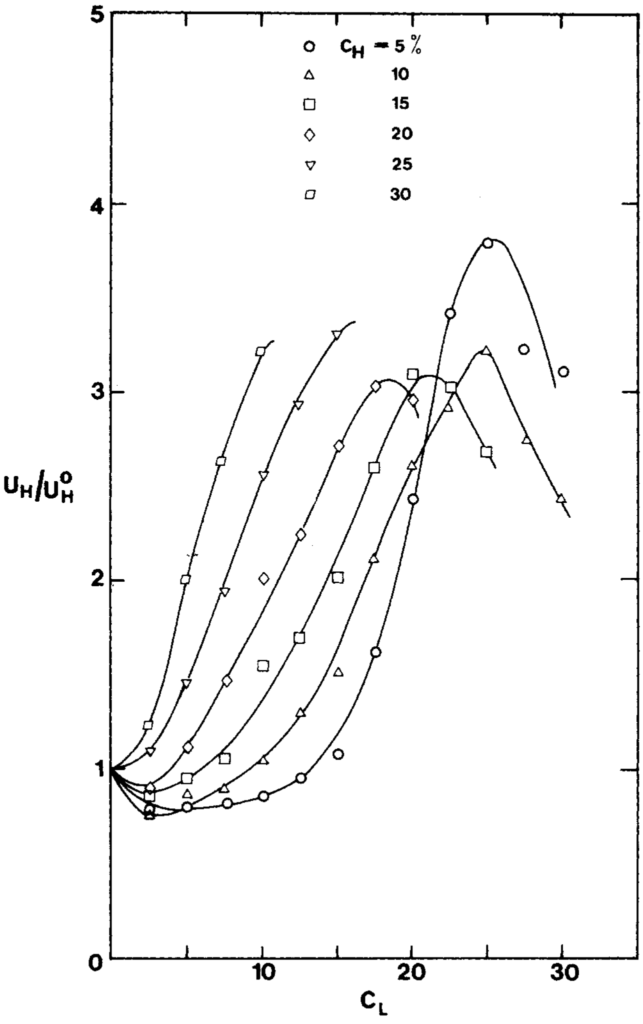

Figure 1. Enhancement of settling velocity of heavy particles resulting from buoyant phase.

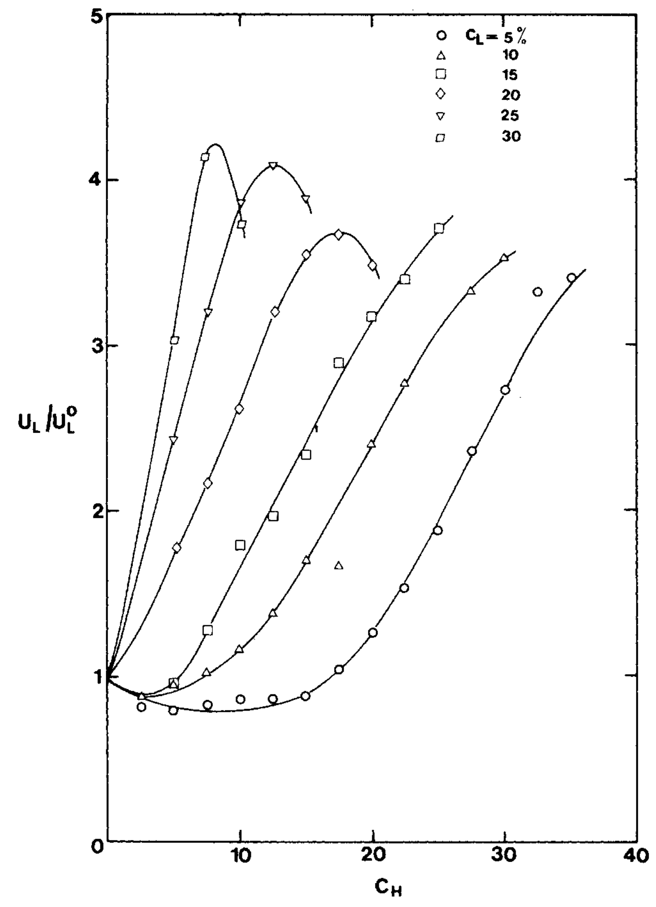

Figure 2. Enhancement of rising velocity of buoyant phase due to heavy particles.

settling suspension would have been obvious—none were ever observed unless one phase was initially in great excess over the other and the total concentration of the suspension was such that the limits of mobility (i.e., packed-bed concentrations) were approached. The foregoing description also applies to the case of buoyant particles being in excess over heavy ones, but then it is the heavy phase which forms into streams imbedded in a rising continuum of buoyant phase.

When one particulate phase was in great excess over the other the streams which formed were of the less populous phase but were grainy in appearance. They are more accurately described as chains of clusters similar in appearance to the chains seen just before vertical disengagement of suspensions initially containing large amounts of both types of solids.

When heavy and light particles were present in amounts of only a few percent each, the style of motion was radically different. Although small scale nonuniformities could sometimes be seen, the predominate pattern was one of rise and descent of single ungrouped particles with collision between the two types. As will become apparent when we discuss quantitative measurements of settling velocity, this concentration range corresponds to retardation of settling.

RESULTS AND DISCUSSION

Quantitative measurements were made of the increase in settling velocity obtained with the aid of buoyant particles, the reduction in total settling time and the degree of thickening found immediately after the buoyant and heavy phases had disengaged from each other vertically.

The settling velocities, Figures 1 and 2, have all been normalized on measured velocities, when a single phase (heavy or light particles) was present alone. As noted previously, when both phases are present together, well defined interfaces do not exist until after vertical disengagement. Therefore, the velocities reported in the figures are effective velocities, inferred from the measured position above the bottom or below the top of the tube at which disengagement took place, divided by the time taken.

Figure 1 shows the relative increase in settling velocity of heavy particles plotted against the vol.% of added buoyant phase with concentration of heavy particles as parameter. Corresponding results for the rise velocity of the buoyant phase are shown in Figure 2. Referring to Figure 1, it is immediately evident that depending on the concentration of heavy particles, there is a region in which small amounts of buoyant phase *retard* settling but that this is followed by a region of greatly accelerated settling. If the initial concentration of heavy particles is already quite high, the addition of buoyant ones seems always to speed up settling. Similar remarks apply to the data of Figure 2 with appropriate interchange of the words buoyant and heavy.

The reason for the retardation at low concentrations lies in the qualitative observations given earlier. In the dilute range, lateral segregation into clusters does not take place so that particles rise and fall as individuals and interfere with each other by collision and hydrodynamic interaction. As concentrations increase, loosely bound clusters begin to form and although still in the retarded region, the curves turn upward. Further increases

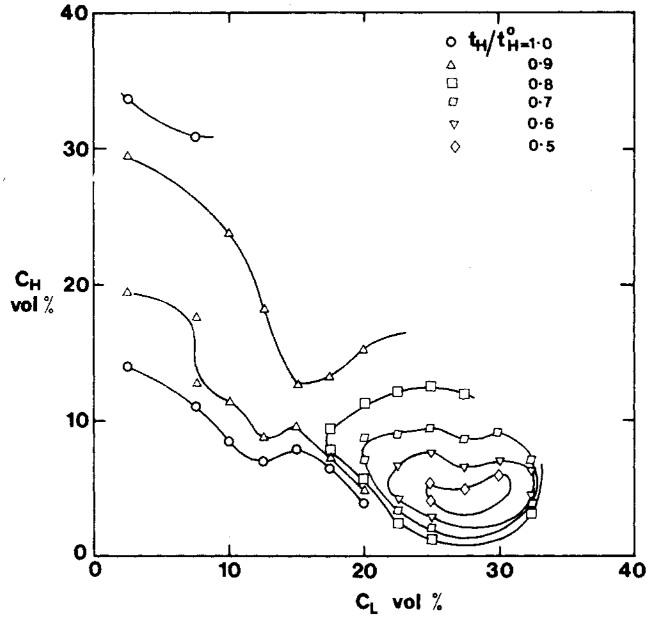

Figure 3. Reduction in total settling time of heavy particles.

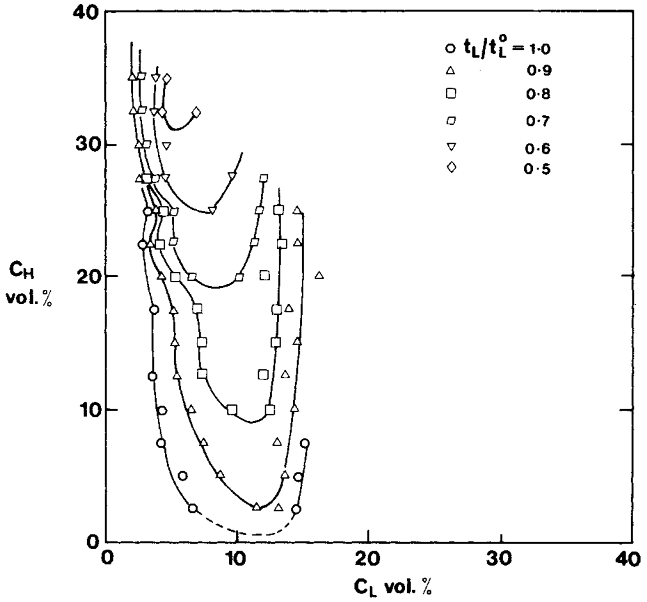

Figure 4. Reduction in total rise time of buoyant particles.

in concentration result in the dominance of streaming (large-scale convection) until at the very concentrated end the addition of more particles results in a suspension barely able to move. Thus, the curves again turn downward and end when the suspension is so thick it is essentially a packed bed.

Settling rates can be greatly increased when sufficient concentration of both heavy and light particles are present together. Simple mass balance or continuity considerations lead one to expect that the suspensions which result at the top and bottom of the tube, following vertical separation, will be very much more concentrated than they were initially. Concomitant with this, they then will settle very much more slowly. Thus, we have an accelerated rate period followed by one in which the now thickened suspensions settle quite slowly. If one is interested in decreasing the *overall* settling time, both periods must be considered together.

The improvement, or otherwise, in overall settling time can be assessed through the ratio of the times taken with and without added particles of the other species. The contours shown in Figures 3 and 4 represent constant values of this ratio. Thus, a contour marked 0.8 indicates that the *total* settling time with both species present is 80% of what it would be when one of the species was present alone. The points shown in these figures were obtained by interpolation of plots of raw data in the form

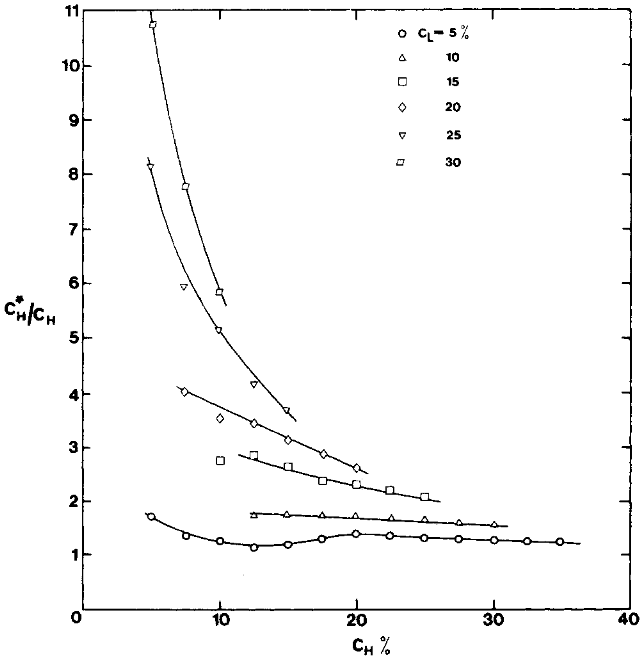

Figure 5. Normalized resulting concentration of thickened slurry of heavy particles.

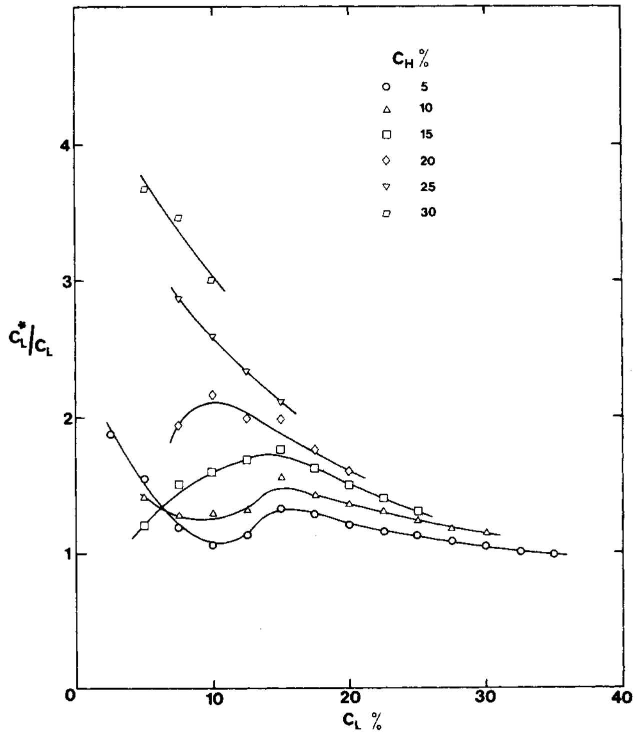

Figure 6. Normalized resulting concentration of thickened slurry of buoyant particles.

settling time ratio against initial concentration of one species with the concentration of the other species as parameter. Several points need to be made.

First, there are concentration ranges in which the *overall* process is slowed down, despite the fact that when heavy and light particles are present together, both settle faster. The slow rate at which the separated suspensions settle, more than compensates for the period of accelerated settling and the net gain is negative.

Secondly, the overall reduction in total settling time is, at best, not as spectacular as the accelerated settling velocity data of Figures 1 and 2 would indicate. Again, this is caused by the extreme thickness of the resulting separated (but still settling) suspensions. Their high concentration makes them settle very slowly and a substantial part of the initial gain in velocity is lost.

The third point is perhaps of even greater importance. If one is going to use buoyant particles to improve the settling of heavy ones, the added buoyant phase should settle at least as fast as the heavy particles. Figure 3 shows that the greatest reduction in *total* settling time of the heavy phase occurs when it is relatively dilute (less than 10 vol.%) and the added buoyant phase is concentrated (25 to 30 vol.%). But from Figure 4, these concentrations are among the worst ones from the point of view of fast separation of the buoyant phase. The buoyant phase settles fastest *overall,* when the heavy one is slowly settling or even retarded.

We have been dealing here with an added *solid* phase and the evidence is fairly convincing that such a procedure would be unsatisfactory as a process improver, because undoubtedly the buoyant solid particles would have to be recycled in any practical application. If, however, we think of using small gas bubbles as the buoyant phase, operation at the right hand side of Figure 3 would be satisfactory since the presence of small *gas* bubbles in the separated liquid may be inconsequential. Thus, nearly a factor of two reduction in total settling time would be possible. Of course, the gas bubbles must not preferentially wet the solid (we are not interested in floatation), but this would be easy to prevent in oily organic liquids and would be preventable in aqueous systems with appropriate choice of surfactant. The potential use of small gas bubbles as settling promoters is under investigation.

Buoyant solid particles can be very useful, however, in the acceleration of *thickening.* The degree of thickening, given as the ratio of thickened to initial heavy solids concentration, which is achieved using various amounts of buoyant phase is shown in Figure 5 as a function of the initial concentration of heavy particles in the suspension. Corresponding results for the resultant concentration of thickened slurry of buoyant particles are shown in Figure 6. The concentration of thickened slurry refers to the suspension of heavy or light particles found in the bottom or top sections of the tube immediately following vertical separation of the mixture into two separate suspensions.

The degree of concentration of thickened suspensions of buoyant particles is always less than for heavy particles under seemingly identical conditions. However, the packed bed voidage for buoyant phase was measured to be 0.55 compared with 0.37 for glass. This difference results from PVC being nonspherical, and automatically sets different limits on the maximum concentration of the two suspensions. Again, one of the disadvantages of operating with *solid* buoyant particles becomes evident; every time a separation is made, the buoyant phase must be recycled and with it goes part of the liquid originally present in the suspension to be thickened. Thus, the system continually becomes more diluted until, in a continuous process, one ends up recycling buoyant suspension without being able to feed any heavy suspension at all.

Part of this problem could be overcome by arranging (through size and buoyancy) for the light particles to rise much more quickly so that one recycles concentrated buoyant suspension (and draws off particle-free fluid as well). The need, never to allow the buoyant recycle to become diluted, would probably result in the use of some kind of filter. The proper choice of buoyant phase would then be one which is freely filtering so that gravity drainage would be adequate. The alternative is to use gas bubbles as the buoyant phase and completely obviate the need for recycle.

Nevertheless, the above data show that settling rates of suspensions can be greatly increased through the simultaneous use of a rising, buoyant particulate phase. The concentrations of the resulting thickened suspensions are high and are quickly achieved. These results also show that there are regions of concentration which lead to retardation which must be avoided. The effects we report, however, are very strong ones. Clearly, much remains to be done—the phenomenon is of fundamental fluid mechanical interest and the potential applications are enormous. One possibly fruitful line of research is into the ability to achieve similar effects with the use of small gas bubbles as settling promoters.

ACKNOWLEDGMENTS

This work was done while the authors were at the University of Queensland, Australia, and was supported by the Australian Research Grants Committee under grant F 7915186. Y.P.F. gratefully acknowledges the financial support of a University of Queensland Postgraduate Scholarship.

NOTATION

c = concentration, vol.%
t = time
u = velocity

Subscripts

H = heavy particles
L = light particles

Superscripts

0 = without added particles of opposite kind
* = refers to suspension after vertical separation

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Manuscript received June 23, 1980; revision received August 29, and accepted October 15, 1980.