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PARTICLE PRESSURES IN FLUIDIZED BEDS

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PROJECT UPDATE

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*Annual
Report*

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SUMMARY

This project studies the "particle pressure", which may be thought of as the force exerted by the particulate phase of a multiphase mixture, independently of those exerted by other phases. The project is divided into three parts. Two of these are experimental studies to measure the particle pressures generated in gas and liquid fluidized beds, using special probes developed especially for this purpose. The last part involves measuring the growth and propagation of instabilities, and using a generic stability model, back out the values of all the normally modeled terms (revealing information about both particle forces and particle fluid interactions).

Particle Pressures about Bubbles in Two-Dimensional Gas-Fluidized Beds: Previous work has shown that bubbles are responsible for the generation of particle pressures in gas-fluidized beds. This phase of the research was aimed at trying to understand how single bubbles generate particle pressures. Initially, it was thought that the particle pressures resulted from the particle motion induced by the passage of bubbles. The results were quite surprising as they indicated that this is not the case. Instead, the bubbles absorb much of the interstitial gas from the surrounding particle bed leaving that material defluidized; the defluidized material is no longer supported by the gas-flow and must be supported over contacts with neighboring particles - i.e. they are supported by the particle pressure. In contrast, any pressures induced by particle motion are relatively insignificant. The behavior can be understood from studies of the gas flow patterns around bubble. There is evidence that there is partial refluidization far below the bubble. Also, "fast bubbles" exhibit a much smaller effect than slow bubbles; a fast bubble moves faster than the fluidizing gas so that the bubble carries its own gas that recirculates through a low concentration "cloud" about the bubble, reducing the gas absorption from the surrounding material. However, in all cases, the defluidized zone extends several bubble diameters away, out to the edge of our current bed, indicating that a wider bed is necessary to completely map the particle pressure field. Such a bed is currently under construction.

Note that this result requires a rethinking of how fluidized beds behave. In particular, there will be limited contact between the particles and the fluidizing gas in the defluidized regions around bubbles; yet, it is that contact that one would want to maximize in chemical reacting systems. Also, it has interesting implications about the way that multiphase systems are modeled; the particle pressures resulting from defluidization are not in anyway reflected in the particle motions, as one would expect from an particle phase motion equation, but, arise solely from the interaction terms.

Particle Pressures in Liquid-Fluidized Beds: Without bubbles one can expect the particle pressures generated in liquid fluidized beds to be small. This required the development of a special transducer, made especially for this purpose. In liquid beds, the particle pressure can only be a byproduct of the natural instabilities of the bed and/or turbulence induced particle motions. The measured particle pressures appear to be uniform throughout the bed. The particle pressure traces the following pattern as the superficial liquid velocity is increased: With zero superficial velocity, the particle pressure is large as the weight of the bed is supported across interparticle contacts. As the velocity is increased the particle pressure drops as progressively more of the bed is supported by fluid forces. Appropriately, it reaches a minimum at minimum fluidization. After the bed is fluidized, the particle pressure rises sharply due to the agitation of the bed. But eventually the particle pressure reaches a maximum and begins to decline when the bed has expanded and the particle reduced concentration causes a corresponding reduction in the particle pressure.

Alternative Quasi-theoretic Approach: Particle forces, in particular a particle phase "elasticity," (i.e. the derivative of the particle pressure with respect to the void fraction) has often been called upon as possible mechanisms to account for the stability of fluidized beds. Yet the actual magnitudes of such forces are unknown. But rather than directly measure the elasticity, this portion of the project reverses the process. First, a light attenuation technique is employed to measure the growth and propagation of instabilities within then bed. (Questions are often raised about how accurately such measurements can be calibrated, however, a relatively simple calibration technique was developed here that eliminated any uncertainty.) The measurements are employed in a generic stability analysis allowing us to back

out values for all terms that normally must be modeled, including those involving particle forces. The model is "generic" in the sense that none of the modeled terms, i.e. the particle forces and the fluid-particle drag terms, are assumed. Instead they are determined as the result of this theoretical/experimental process. Preliminary results, for 1mm glassbeads, indicate that typically assumed particle-phase elasticities fall above the values obtained from this analysis. The measurements of the viscosities are of the same order as measurements in gas-fluidized beds. Also, comparing the measured values of the drag laws indicate that the Richardson-Zaki equation provides a good fit to the fluid-particle drag while the Ergun equation and the Foscolo-Gibilaro model do not.

Particle Pressures in Fluidized Beds

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1.0 INTRODUCTION

The particle pressure may be thought of as the force per unit area exerted by the particulate phase of a multiphase mixture and, as such, reflects the total momentum transport that can be attributed to the motion of particles and their interactions. It has a direct analog in the kinetic theory of gases in which the pressure acting on a surface is visualized as a result of the impacts of molecules. The same picture can be applied to particle-fluid situations with the particles taking the place of molecules. The only difference between the two cases is that solid particles may, in addition to short-duration collisional impacts, transmit a force via long duration contacts. (E.g. the weight of a particle, or an assembly of particles, resting on a surface).

Multiphase flows have long been modeled as interpenetrating continua. In general this technique involves writing separate conservation equations for each phase. Typically, the equations for the fluid and solid phases look individually like usual single-phase equation with the addition of a coupling term, $\mathbf{F}$, that describes the interphasial forces.

$$\rho_f \epsilon \left(\frac{\partial \mathbf{V}_f}{\partial t} + \mathbf{V}_f \cdot \nabla \mathbf{V}_f \right) = \nabla \cdot \boldsymbol{\tau}_f + \rho_f \epsilon \mathbf{g} + \mathbf{F} \quad (1.1)$$

$$\rho_p (1 - \epsilon) \left(\frac{\partial \mathbf{V}_p}{\partial t} + \mathbf{V}_p \cdot \nabla \mathbf{V}_p \right) = \nabla \cdot \boldsymbol{\tau}_p + \rho_p (1 - \epsilon) \mathbf{g} - \mathbf{F} \quad (1.2)$$

Here ϵ is the void fraction (the volume fraction for the fluid phase), $\mathbf{V}_f$ and $\mathbf{V}_p$ are the fluid and particle velocities, ρ_f and ρ_p are the fluid and particle densities, and $\boldsymbol{\tau}_f$ and $\boldsymbol{\tau}_p$ are the fluid and particle phase stress tensors. This work concerns itself with $\boldsymbol{\tau}_p$, which strictly should be interpreted as the stress tensor induced by the particle phase that also acts on the particle phase. One of the difficulties in accurately applying (1.1) and (1.2) is that there is very little understanding of how to model the particle phase stresses. This study employs an experimental method that has been developed for measuring the component of the particle stresses that is exerted normal to the walls of a fluidized bed.

The difficulty in measuring the particle pressure is that the total pressure exerted on a surface - the pressure that would be measured with a standard flush mounted pressure transducer - is the sum of the particle pressure and the pressure exerted by the fluid that resides in the interstices between the particles. Furthermore, in many cases in which the motion is driven by fluid pressure - for example, fluidized beds or slurry flows - the particle pressure may be a small fraction of the total. Conceptually, such a measurement is not complicated, nor is the measurement terribly difficult. Essentially all one has to do is measure the total force acting on a surface and then let that fraction due to the fluid

pressure balance itself out. Campbell & Wang (1990) described a very simple transducer for this purpose. That probe consisted of a solid diaphragm that is flush mounted into the bed wall. Small holes on either side of the diaphragm admit fluid, but no particles into a chamber behind the diaphragm. The face of the diaphragm experiences the total pressure exerted by both the particles and the fluid, while the rear experiences only fluid forces. Thus, the net deflection of the diaphragm reflects the contribution of the particle forces only. That probe has been used to make the particle pressure measurements on the vertical side walls of gas-fluidized beds that were presented in Campbell & Wang (1991) (although it could be used in many other flow situations).

Campbell & Wang (1991) showed that the particle pressures in gas-fluidized beds were generated largely by the passage of bubbles. In particular, they showed that the average particle pressure exerted on the side walls scaled with the average size of the bubble. This immediately brings to mind two questions: (1) what is it about bubbles that leads to particle pressure generation and (2) would there be measurable particle pressures in liquid-fluidized beds which, while unstable, do not bubble? This project is largely aimed at answering these two questions. To attack the first problem, we have built a two-dimensional gas-fluidized bed into which bubbles may be injected and the distribution of particle-pressure measured. For the latter, other experiments are being performed in liquid fluidized beds.

However, it soon became apparent that the particle pressures generated in liquid beds are extremely small. This has pointed that phase of the research in two directions. The first is the design and construction of a third, and more sensitive, form of the particle pressure transducer. The second approach arose from reflection on what ultimately was the utility of the current research. To a large extent, this research was motivated by interpenetrating continua multiphase-flow models such as that described by equations (1.1) and (1.2). The classic fluidization problem to which these models have been applied is to understand the stability of a uniform state of fluidization. The only way in which a fluidized bed has been shown to be stable is through a particle-phase elasticity - i.e. it is stabilized through the particle pressure. Furthermore, once instabilities develop, the particle pressures will have significant effect on the growth and propagation of voidage disturbances. Naturally, of course, the instabilities will also be influenced by the manner in which the fluid-particle drag and other terms are modeled. This, led to the development of a "generic" stability model, in which all modeled terms are left unspecified. From analyzing this model, we have developed an experimental plan that, by measuring the characteristics of voidage disturbances and comparing with the theory, we can back out appropriate values for the modeled terms. The results will, not only, yield insight into the particle pressure, but also of the fluid drag. The latter results is used to evaluate common models for these terms.

2.0 PARTICLE PRESSURES IN GAS-FLUIDIZED BEDS

2.1 A New Particle Pressure Transducer

The first achievement under this grant was to develop a new version of the particle pressure transducer. The transducer used by Campbell & Wang (1991) is shown in Figure 2.1.1a and used the deflection of a solid diaphragm to determine the pressure measurement. The displacement of the diaphragm is measured by a MTI Accumeasure capacitance probe with a 0-0.13mm range. Two screen covered holes were drilled at diametrically opposite points around the periphery to admit gas to the rear of diaphragm and balance the gas pressure. The holes were placed at the same vertical position in the channel and thus at the same gas pressure, eliminating any gas flow through the void behind the diaphragm. There are two difficulties with this design. The first is that it acts as a fluidic R-C circuit and thus behaves like a low pass filter to the gas that must flow to the rear of the diaphragm; the resistance is applied by the small size of the holes and the covering screen while the capacitance is a result of the large gas-filled cavity behind the diaphragm. The dynamic effects of these were examined experimentally in Campbell & Wang (1990). While the low-pass filter effects would not alter the time-averaged measurements given in Campbell & Wang (1991), they might alter instantaneous measurements. The second problem arises from uncertainties about the effect of lubrication forces acting between the particles and the diaphragm; i.e. could the lubrication forces slow the particle and bias the measurements for small particles?

Both these concerns can be avoided by the new probe design, shown in Figure 1b.

Here the solid diaphragm is replaced by a stretched screen which is spotwelded onto a ring. At the same time, the volume behind the screen is made as small as possible. (Here the gap is 0.13mm which was determined by the range of the capacitance probe.) This is done for two reasons. First it minimizes the capacitance and secondly, it resists the tendency of the external gas to leave the bed and travel through the gap behind the screen. Using a screen for a diaphragm also has two advantages. First, the large area minimizes the resistance for the gas to flow across the diaphragm. Secondly, if large lubrication forces do come into play, they will leak through the openings and not slow the approach of the particle. Repeating the tests in Campbell & Wang (1990), Campbell & Rahman (1992) showed that the current probe has none of the dynamic characteristics of the old probe. The construction of this new probe was conceived long ago, but a suitable screen material was not available. Usual woven screens cannot hold tension when spotwelded. (We did try to attach a screen using but the probe responded in strange ways that attributed to the glue being more flexible than the screen.) The screen

we used in the current probe is not woven but etched from a continuous metal sheet. It is manufactured by Buckbee-Mears Precision Etched Products Group (model #2-2-8). The holes are approximately $70\mu\text{m}$ in diameter and are arranged in a hexagonal pattern on a .05mm (.002in) thick sheet. This probe was developed during the first year of the project and resulted in Campbell & Rahman (1992).

2.2 Particle Pressure Measurements around Single Bubbles in a Two-Dimensional Gas-Fluidized Bed

The results of Campbell and Wang (1991) indicate that particle pressures, measured along the side wall of a gas-fluidized bed, are primarily generated by the passage of bubbles. The primary evidence lies in the observation that the average values of the particle pressure scales with the equivalent diameter of bubbles. However, it is clear that the pressure obviously cannot be uniform across the bed. In particular, the particle pressure must go to zero in the particle-free region inside the bubble. Furthermore, the side wall of the bed may be a peculiar region as the particles pushed aside by the passage of a bubble cannot cross the wall, and therefore, the walls must affect the bubble motion in their immediate neighborhood.

The easiest way to determine the distribution of the particle pressure around a bubble is to perform the experiment in a "two-dimensional" fluidized bed. This is a term used to describe beds that are extremely thin in one dimension. In such a situation, bubbles span the small breadth of the bed so that it is possible to make a measurement of the particle pressure across a bubble without actually inserting a probe in the bed. The position of bubbles may be localized by artificially injecting bubbles into a bed held near minimum fluidization.

Figure 2.2.1 is a schematic of the two-dimensional bed. The test section is 152cm high, 46cm wide, but only 2.5cm deep. It is fed by an air supply system that passes air through a ten inch packed bed and several of the Buckbee-Mears (2-2-8) 70mm etched screens to assure a uniform airflow. The air flow is usually set so that the bed is at minimum fluidization conditions. Then bubbles are injected through a porous plate covered port, located 9 inches above the distributor. The bubble injector consists of a series of plenums which are pressurized through a precision pressure regulator. Firing a solenoid valve admits pressurized air into the bed, causing a bubble to form. Different plenum pressures will discharge different quantities of gas allowing some control over the bubble size. Finally 25 ports are cut into the face of the channel to admit the particle pressure transducers. Sixteen of the ports are configured in 4 lines of 4, spaced at 6 inch intervals above the injection port; in each line, the ports are spaced 2 inches apart, spanning the area from the center of the bed to one wall. The other 9 ports (not shown) are located at intermediate locations across the bed, to allow a finer spatial resolution. Four particle pressure probes are available to be inserted in any of

Figure 2.2.1: Schematic of the two-dimensional fluidized bed.

the ports.

Bubbles are tracked and followed by an image processing system. The image originates in an Image Technology Methods, Datavision 262, video camera. The image is sampled by a Data Translation 3851 frame grabber with 8MB of memory that is mounted inside an IBM clone computer with a 50MHz 80486 processor. The 3851 board possesses an external trigger which allows the acquisition of the images to be synchronized with the acquisition of the particle pressure data. (The data acquisition is performed in a separate 33MHz 486 IBM clone; digital outputs from that computer are used to trip a relay which injects the bubble and to fire the external trigger of the 3851 as well as to sample the particle pressure information. This tightly synchronizes the entire experimental process.) The 8MB of memory permit 25 frames to be acquired at a rapid rate and stored on the board.

Both the acquisition and interpretation of the images are controlled by Data Translation's Global-Lab Image^G Software package. This package provides many powerful image processing options. The most useful for this phase of the project is the ability to detect and analyze "particles" (which in this context refers to bubbles). In particular, it locates the center-of-area of the bubble which we use as a reference for the bubble location, calculates the area of the bubble, the average radius from the center-of- area, and so on.

Figure 2.2.2 shows a time history of the particle pressures measured by the four probes which are located eighteen inches above the injection point and 0, 5, 10 and 15cm along the horizontal direction from the bed centerline (the corresponding plots are shown in order starting at the top of the figure). The figure is also labeled with the locations where the top and bottom of the bubble cross the probe, as well as the locations where the bubble erupts from the surface of the bed and the point when the bed, at least visually, settles back to its original state. At the time it crosses the probes, the bubble has a equivalent radius of about 10cm and thus, the bulk of the bubble crosses the positions of the first two probes.

Naturally, the particle pressure is zero when the bubble passes the probes as there are no particles present. Surprisingly though, the particle pressure is also zero above the bubble. Significant particle pressures may first be seen along the sides of the bubble. (The bottom two figures, which represent the two probes outside of the bubble, show an

Figure 2.2.2: The time history of the particle pressures in a bed of 1mm glassbeads. The four plots come from 4 probes mounted 46cm above the injection point. From top to bottom, the probes are mounted 0, 5, 10, 15cm from the bed centerline.

Figure 2.2.3: Photographs of the gas flow around a bubble rising in a two-dimensional fluidized bed, made visible by NO_2 injection. (a) a fast bubble (the bubble rises faster than the gas flow). (b) a slow bubble (the bubble rises slower than the surrounding gas flow). From Rowe et al. (1971)

elevated particle pressure starting at about $t=0.4\text{s}$, at which time the top two, over which the bubble passes, show zero particle pressure.) The largest particle pressure are observed in the particle wake and furthermore, are seen in the far wake. (This was shown when the same data is plotted against the bubble position; such a plot was given in our second year progress report.) In fact, the largest measurements occur just before the bubble erupts from the bed, a full 40cm (about two bubble diameters) above the probes. It is possible that the large pressures are a byproduct of eruption. But it seems more likely that the passage of a bubble causes severe disruption in the structure of a bed which seems to persist long after the bubble passes.

The most likely explanation is that the bubble defluidizes all of the material in its wake. Once defluidized, the material is no longer supported by the gas flow and must simply rest on the material below it. The steadily increasing particle pressure is related to the increasing hydrostatic weight of the defluidized material above it. However, the maximum pressure is somewhat smaller than the hydrostatic value, indicating that partial refluidization is taking place during this process. On reflection this is not surprising. It takes a large gas velocity to fluidize the 1mm particles. Bubbles in such a bed are known as "slow bubbles" as the bubbles' rise velocity (which is solely a function of the bubble size) is smaller than the gas velocity required to fluidize the material; consequently, the gas, on the average, travels through the bubble. The gas flow about such a bubble is shown in Figure 2.2.3b. There it can

be seen that the passage of a bubble, attracts all of the gas within the bed, extending at least two bubble diameters from the edge of the bubble. This can be anticipated, as the bubble represents a void through which the gas may travel with nearly zero pressure drop; in contrast, the pressure drop the bubble would experience while passing through the bed would approximately equal the hydrostatic weight of the bed. Consequently, the bubble represents a very attractive alternative path and absorbs nearly all the gas in the bed. This leaves surrounding areas with insufficient gas to remain fluidized. This accounts for why the bed becomes defluidized on the sides of the bubble (evident in the third and fourth probe traces in Figure 2.2.2). Note, however, that within a bubble diameter, the flow below the bubble has returned to its undisturbed pattern. As the bed is at minimum fluidization, the gas velocity generates just enough pressure drop to support the bed locally, but not enough to support the additional defluidized material being piled on from above. This explanation accounts for (1) why the particle pressure increases until eruption, (2) the pressure are never as large as would expected if all the material above the probe were defluidized and (3) why the pressure return quickly to normal after eruption. Also, although not readily apparent from Figure 2.2.3b due to the mixing of tracer gases, the majority of the gas must be leaving the top of the bubble, keeping that region well fluidized; the defluidized regions appear on the sides and in the wake of the bubble.

Note that it was the original intent to make three-dimensional plots of the particle pressure surrounding these bubbles. An example of such a plot was given in the document prepared for the DOE review that was to be held this fall and was subsequently canceled. However, due to the dominance of the particle pressures generated in the far wake, these graphs are very difficult to interpret. In fact it is even very difficult to see exactly where the bubble is. We will return to this in the future, most likely to make more detailed studies in the immediate vicinity of the bubble. However, it is clear that the bed used to make the measurements shown here is too narrow and cannot be used to make such maps without concerns about wall interference; Figure 2.2.2 indicates that the defluidized region spans the width of the bed (i.e. the fourth trace is taken next to the bed wall shows a signal as large as the first trace which was taken near the bed center). Consequently we have built a larger bed (more on this later). In the meantime, we have used the current bed to gain further insight into this defluidization phenomenon. This is much easier to see by examining the time traces from the probe in the center of the bed than on full 3-D plots and, for the most part, only centerline time traces will be presented in the following. (Furthermore, the centerline data should show the minimum amount of wall interference.)

Further experiments have been performed to try and flesh out the meaning of these results. However, it is difficult, even by carefully controlling the gas injection, to inject perfectly reproducible bubbles. As a result, it is convenient to assess and scale out the effect of bubble size. The results of

Campbell & Wang (1992) for a freely bubbling bed showed that the particle pressure scaled with the equivalent bubble diameter, i.e. $P_p/\rho_p g D_e$ is approximately a constant (here P_p is the particle pressure, ρ_p is the density of the solid material, g is the gravitational acceleration and D_e is the equivalent bubble diameter). To check if this scaling can be applied to single bubbles in 2-D beds, three different bubble sizes were injected. The time-traces measured by the centerline probe are shown in Figure 2.2.4. Here the particle pressure is scaled by the bubble diameter according to the above rule and the time axis is scaled by the eruption time so that the peaks in the traces will approximately line up. Now, the scaling of the particle pressure is somewhat complicated by the fact that the bubble will grow as it rises through the bed so that the bubble diameter is not constant. We ran test plots using as the characteristic size, (1) the instantaneous bubble diameter (i.e. scaling each measurement with the diameter of the bubble at the time of the measurement) and also two constant bubble diameters measured (2) when the bubble crosses the probe and (3) just before eruption from the bed. The choice of characteristic bubble size seems to have an insignificant effect on the results. Thus, for simplicity, we chose the effective bubble diameter just before eruption for the scale for the effective bubble diameter in this, and all plots that follow; the choice was made as it is simpler to implement than using the instantaneous value and seemed to produce slightly better agreement than using the bubble diameter at the probe position. Figure 2.2.4 indicates that, indeed, the magnitude of the particle pressure scales with the bubble diameter. Most of the subsequent data will be similarly scaled so as to eliminate the effects of minor variations in bubble diameter.

Obvious next steps are to test for the results of (1) placing the probe deeper inside the bed and (2) using a deeper bed depth above probes at the same position. Both place more potentially defluidized material above the probes. The corresponding scaled

Figure 2.2.4: Time traces of the scaled particle pressure, $P_p/\rho_p g D_e$ for several bubble sizes.

centerline traces are shown in Figure 2.2.5. For comparison, Figure 2.2.5a is from a 109cm deep bed with the probe mounted 46cm above the injection point, conditions which are similar to those used in Figures 2.2.2 and 2.2.4. Figure 2.2.5b shows data from the same bed depth, but with the probe mounted 15cm lower, i.e. 31cm above the injector. Figure 2.2.5c shows the case where the probes are mounted at the same position as 2.2.5a, but the bed depth has been increased 17.5cm. In other words, Figure 2.2.5b and 2.2.5c represent cases with different probe positions, but with almost the same depth of material above the probe. Consequently, it is not surprising to see that the results are very similar. Comparing with Figure 2.2.5a, it is easy to see that the magnitudes of the particle pressures are not increased, but the peak is spread out for the deeper measurements; this is indicative of the refluidization discussed above. Furthermore, note that after eruption, particle pressures measured deeper in the bed (Figure 2.2.5bc) takes longer to disappear than that in Figure 2.2.5a. This indicates that the refluidization begins at the free surface and propagates downward through the bed.

This interpretation also suggests a possible effect of the fluidizing gas velocity. The higher the velocity, the more gas that is available for refluidization, which would suggest smaller particle pressures. However, it is difficult to perform experiments of this type above minimum fluidization, as the bed will then bubble freely on its own.

Figure 2.2.5: Effect of probe position of the particle pressure measurements along the bubble centerline for beds composed of 0.5mm glassbeads. (a) 109cm deep bed, probes 46cm above the injection point, (b) 109cm bed, probes mounted 31cm above the injection point, (c) 126cm deep bed, probes mounted 46cm above the injection point.

Figure 2.2.6: Time histories of particle pressures along the channel center for various fluidization velocities.

Figure 2.2.7: Particle pressures generated in a freely bubbling bed. (a) A time trace showing several bubble passages. (b) A detail of the trace from bubble that nearly passes up the center of the channel.

Figure 2.2.8: Time traces of the scaled particle pressure, $P_p/\rho_p g D_e$ for both fast and slow bubbles generated in beds of 0.5mm and 0.25mm glassbeads.

However, the bubbles generated when just slightly above minimum fluidization will be small so that a large injected bubble will dominate the signal. Figure 2.2.6 shows the signal from injected bubbles in a bed fluidized at 0%, 5% and 10% above minimum fluidization. Clearly, as might be anticipated from the defluidization argument, the magnitude of the particle pressure decreases as the fluidization velocity is increased. But in a freely bubbling bed the gas velocity may be twice the minimum fluidization velocity. Figure 2.2.7 shows the time trace of the particle pressure in a freely bubbling bed fluidized at 60% above minimum fluidization. The traces from all four probes are shown. Here Figure 2.2.7a shows the time trace generated by several bubble passages while Figure 2.2.7b shows an expanded view of the trace from a single bubble that passes directly in front of the probe. This trace has entirely lost the particle pressure peak associated with eruption and, though initially large after the bubble passage, decreases steadily until another bubble passes nearby and dominates the signal. How much the change in behavior is due to the larger fluidization velocity or to the simultaneous presence of other bubbles is unknown at this time but could be tested by injecting multiple bubbles.

This may also signal an unexpected influence of the particle size. Figure 2.2.3a shows the gas pattern around a "fast" bubble. The rise velocity of a bubble in a fluidized bed, like the rise velocity of a bubble in a liquid, depends only on the size of the bubble and is independent of the particle size. Yet, the gas velocity required for minimum fluidization is strongly dependent on the particle size. Thus, for small particles, it is possible that the bubbles rise at a faster velocity than the gas. This is "fast-

bubble" behavior and requires that the bubble carry a quantity of gas with it as it moves; thus, a portion of the gas that travels through the bubble center recirculates through a low particle-concentration "cloud" that surrounds the particle. Such a cloud is clearly seen in Figure 2.2.3a. Intuitively, the fact that the bubble carries some of its constituent gas with it, implies that it will make less demands on the gas from the surrounding material and cause a smaller degree of defluidization. It is unfortunate that, since the bubble rises faster than the gas, a tracer gas will never catch up with the bubble and thus one cannot map out the surrounding gas flow pattern, such as that shown for a slow bubble in Figure 2.2.3b; consequently, it is difficult to predict the degree of gas-flow deviation caused by a fast bubble. However, a clue might be garnered from the particle pressure traces shown in Figure 2.2.8. This shows the time-trace of the scaled particle pressure generated by both fast (0.25mm glassbeads) and slow (0.5mm glassbeads) bubbles. The measurements were taken from the center probe and represent the particle pressures through the bubble centerline. Interestingly, both traces show nearly the same magnitude of the particle pressure at the time that the probe initially encounters the bubble wake (i.e the first significant, non-zero particle pressure). For the fast bubbles, the magnitude remains nearly uniform thereafter, except for a small peak near eruption; but, the particle pressures generated by a slow bubble continually increase until they manifest a similar peak near eruption. This would seem to indicate that a fast bubble carries a nearly uniform-sized region of defluidized material with it, reflected in a nearly uniform generation of particle pressure. A slow bubble appears to carry an increasingly larger region of defluidized material with it as indicated by the steadily increasing values of the particle pressure seen in Figure 2.2.2. However, given enough time, (e.g. Figure 2.2.5) the particle pressure generation appears to approach a uniform value, even for slow bubbles (to document this will require experiments on a deeper bed such as is the proposed future work described in the following sections). While that argument seems to suggest a continuous transition between the two types of behavior, other evidence seems to suggest that the transition occurs rapidly. For example, Campbell & Wang (1992) saw no effect of particle size on their results. Yet, in order to avoid clogging of the fluid pressure ports in their probe, no particle sizes below 0.5mm (i.e. no sizes that would generate fast bubbles) were tested. Indeed, in the current experiments, little noticeable differences can be seen between the results for 1mm and 0.5mm glassbeads (Figure 2.2.2 and most of the rest). But all of those measurements are for slow bubbles. If the diameter is decreased by another factor of two to 0.25mm, a transition is made from slow to fast bubbles and a significant change in behavior is observed, (e.g. Figure 2.2.8,) suggesting a significant effect of the slow/fast bubble transition that is in need of investigation.

2.3 Significance of the Current Results

All of this suggests a rethinking of the manner in which gas-fluidized beds are generally considered. An example of this thinking is the so-called "two-phase" theory of fluidization in which it has been commonly assumed that, in a bubbling bed, the particulate phase rests at minimum fluidization, while all the excess gas rises in the form of bubbles. But studies (e.g. Hailu et al., 1993) that have tried to estimate the amount of gas carried by bubbles indicate that more gas resides in the bubbles than would be predicted by the two-phase theory; this is directly in concert with the current results which indicate that the bubbles absorb much of the gas from the surrounding material causing at least local defluidization. These results seems to explain video tapes of coal combustion in 2-D beds which show coal particles flaring while inside bubbles, but becoming extinguished when they reenter the bed in what now appears to be a defluidized region. Yet, despite such evidence to the contrary, the two-phase theory is still believed in some circles.

The original interpretation of the results of Campbell & Wang (1991) was that the particle pressure was generated by the large scale movement of particle that were *en-masse* disturbed by the passage of a bubble much like the flow pattern of a fluid about a rising gas bubble. As the bubble rises, it pushes particles out of the way and, intuitively, those particles can transmit a force out to the walls that is sensed as particle pressure. Such ideas are inspired by the simple model for the gas pressure field about bubbles that was described in Davidson (1961). That model analyzed cylindrical or spherical bubble shapes and assumed potential flow-like motions for the particulate phase. Surprising, it makes better predictions of the gas pressure field than more complicated models - at least that through the bubble centerline (Littman & Holmolka, 1973). The Davidson model derives its gas-pressure field by integrating an equation like (1.1) using a simplified interaction term; in this sense the derivation, if not the result, is similar to the way in which the pressure would be derived about a rising gas bubble in a homogeneous fluid. At first glance, considering the success of this simple model, we expected that the particle pressure field would result from a similar integration of an equation like (1.2). Somewhat prophetically, the Davidson model predictions for the gas-pressure far outside the bubble become increasingly less accurate (in what we now know is a defluidized region; that violates the assumption of the model that the entire region outside the bubble is in a state of uniform fluidization). Also, a conjugate solution for the particle pressures which is presented in Davidson & Harrison (1963), produces largely negative particle pressures surrounding a bubble that cannot be justified on any physical grounds. (While awaiting the construction of the experimental apparatus for this project, we tried to adapt this model to more realistic dimpled bubble shapes, using the technique described in Collins, 1965, but eventually concluded that this approach was fundamentally flawed.) Indeed, the pressure induced by the particle motion might explain the small particle pressures generated upstream of the bubble, and the sharp peak that is usually observed when the central probe

first encounters the wake behind the bubble. (The top of the bubble splits the particles into two streams which pass around the opposite sides of the bubble only to meet again at the bubble rear; the collision of the two streams potentially produces large particle pressures and is probably responsible for the characteristic raised dimple observed on the bottom boundaries of bubbles.) But these effects are barely noticeable compared to those resulting from defluidization - an effect that was unanticipated at the initiation of this investigation.

These results might help explain the oft-commented observation that bubbles in two-dimensional beds behave differently than those in three-dimensional beds. A bubble in a two-dimensional bed may only absorb gas along its perimeter which only spans the narrow dimension of the bed (here, only 2.5cm in width); in a three-dimensional bed, the bubble can absorb gas over its entire surface. Whether or not this leads to a greater or lesser degree of defluidization has yet to be answered, although the particle pressure traces in a freely bubbling 2-D bed are similar to those reported by Campbell & Rahman (1992) for a 3-D bed. (Depending on the outcome of the current work, these results may form the basis for a continuation proposal to study the growth in the type of half-cylindrical bed that is often used to make 3-D bubble measurements).

2.4 Proposed Future Work

It is clear from Figure 2.3.2 that the defluidized region encompasses the entire width of our current 2-D bed (whose dimensions are based on the assumption that the particles would approximately follow a potential flow solution, à la the successful gas-pressure theory of Davidson, 1961, and thus nearly disappear within a bubble diameter). Also, the data suggests that the current bed's 127cm maximum depth may be too small to observe complete refluidization behind a bubble. Consequently, given the unexpected nature of these results, we have built what may be the largest two-dimensional bed in the world. Its dimensions are $234 \times 117 \times 1.28$ cm and are largely dictated by the dimensions of a standard 4' by 8' Plexiglas sheet (in contrast, most 2-D beds, e.g. that used by Rowe, 1971, for the results shown in Figure 2.3.3, are seldom more than a foot in width); however, if Rowe's results are any guide, these dimensions should span the defluidized region. As of the time of this writing, the bed nearly completed. We had hoped to have some data in time for this proposal, but preliminary tests performed in January indicated that the large Plexiglas faces flexed extensively when bubbles were injected and are currently being reinforced.

With the new bed, we should be able to accurately map out the defluidized region about the

bubbles. This should help eliminate any questions about the effects of the finite size of the beds on the results presented above. We will also make detailed studies of the particle pressures generated in the immediate vicinity of the bubble and to try and assess the effect, if any, of the particle motions on the results. Two bubbles will also be injected, one after the other, and be simultaneously present within the bed. This will approximate the situation in a freely bubbling bed and test whether bubble interactions are responsible for the more rapid refluidization seen there. (For example, the high velocity gas exiting the top of the second bubble might refluidize the material in the wake of the first.)

3.0 PARTICLE PRESSURES IN LIQUID FLUIDIZED BEDS

Liquid fluidized beds are immune from bubbling and thus, any particle pressures that are generated must come from a very different source. Originally we intended to make measurements in a liquid fluidized bed using the same type of probe shown in

Figure 2.1.1 (i.e. that used to make the gas-fluidized bed measurements). Unfortunately, we were unable to find an appropriate displacement transducer that could accurately measure the deflection of the diaphragm and could also operate within a liquid environment. Originally, we had thought to measure the displacement by sensing changes in the resistance in the circuit through the liquid between the moving diaphragm and a stationary electrode. (After all, we use a capacitance measurement to perform the same function in the gas-fluidized bed.) However, we found that this was too unstable, probably due to local variations in the liquid resistance. Then we discovered an eddy current device that could be operated across a liquid medium. Unfortunately that transducer was only available with a 1mm range, forcing us to use only a few percent of the available range for our measurements; this proved to be too insensitive. Still, an alternative had to be found.

3.1.1 A Third Design for the Particle Pressure Transducer

Our inability to discover an appropriate displacement sensor necessitated significant redesign of the particle pressure probe for use in liquid fluidized beds. An early version of this probe was described in last year's report. The new design is shown in Figure 3.1.1. Instead of using the displacement of a diaphragm, we make a direct measurement of the force applied to a rigid plate using a sensitive load cell. The plate is perforated with holes to permit the flow of fluid through to the backside which

balances the fluid pressure. The surface is covered with a loose piece of silk that acts as a screen to prohibit the passage of particles to the pressure plate; as the silk is loose, it does not absorb any of the applied force, leaving it, instead to be measured by the load cell.

It was difficult to find an appropriate load cell as it had to be invulnerable to the liquid environment. We decided on a Wagner Instruments, LPM 530 load cell with a 50 gmf range. This was the smallest range cell that we could find that could be appropriately configured for this purpose. Using a 4.5cm diameter plate, the full range scale is approximately 31mmH₂O, (although we have found that it is able to withstand slightly higher pressures). Assuming 1% resolution, we should be able to resolve about 0.3mmH₂O, however, experience, based on the repeatability of measurements suggests that the measurements are accurate to about 1mmH₂O. After the initial results presented in last years report, we found that, despite the claim of the manufacturer, the output of the load cell was slightly sensitive to the surrounding fluid pressure and, consequently, would experience a slight zero shift whenever the flow velocity, and thus the surrounding pressure, changed. To eliminate this scatter, we devised a thumbscrew

driven system that pushes the screen forward and unloads the plate, even when the bed is in operation. With the screen forward the particles are held away from the pressure plate and the only force experienced by the load cell is the surrounding fluid pressure; this is used to set the zero point for the subsequent particle pressure measurement, eliminating the pressure effect.

3.1.2 Preliminary Measurements using the New Transducer

Some preliminary measurements made with the new probe are shown in Figure 3.1.2. The measurements were made on a 13×13cm square bed of 1mm glassbeads. The probe was mounted at various vertical positions on the side of the bed. Surprisingly the measurements are independent of position along the bed; even when the probe is stationed outside the initial packed bed, (and thus the particle pressures are zero until the bed has expanded sufficiently to reach the probe,) the particle pressures join with the other measurements as soon as the particles cover the probe. When the probe lies within the original packed bed, the particle pressure is initially large at zero velocities

as all of the weight of the bed is supported across interparticle contacts. As the velocity is increased, yet before the bed becomes fluidized, the particle pressure decreases monotonically as progressively more of the material in the bed is supported by fluid forces. After minimum fluidization, the particle pressure rises quickly as the particles develop free agitated motion. However, it drops slowly as the

velocity is further increased, probably reflecting the decreasing concentration of particles as the bed expands. This seems to indicate two competing processes. The first is the agitation of the bed, either as individual particles reacting to a turbulent flow, or by the larger scale motion of voidage instabilities. Increasing the superficial velocity will increase both contributions. However, at the same time, the bed expands, reducing the local concentration of particles which should work to reduce the particle pressure. At the largest velocities, the reduced concentration wins the tug-of-war and draws down the particle pressure.

3.1.3 Proposed Future Work

Unfortunately, the threads in the screw system used to move the screen that covers the pressure plate were stripped at the end of these measurements and the probe was returned to the shop for repairs. Sometime during this process, the load cell, one month out of warranty, was damaged and developed a zero drift; although the zero drift was slight, it is of the same order as the small particle pressures being measured here. Consequently, this phase of the project has been put on hold while awaiting delivery of a new transducer. Eventually though, we intend to repeat these experiments for multiple particle sizes and, from those measurements hope to understand the scaling of these forces.

Also, these measurements are similar in appearance to the behavior of the heat transfer coefficient in liquid-fluidized beds (e.g. Grewal & Zimmerman, 1988). In the latter stages of this investigation, we also hope to simultaneously make heat transfer measurements to see if the two phenomena can be related. (The bed is equipped with two sets of probes ports, located on opposite sides of the channel, which will allow the simultaneous mounting of the particle pressure probe and a heat transfer sensor.)

3.2.0 Alternative Quasi-theoretic Approach:

It is most likely that, given the small magnitudes of the particle pressures in a liquid bed, it will be nearly impossible to directly measure the small pressures that occur near the neutral stability point. This is unfortunate, as those are the particle pressures that affect the stability of the bed. It has been shown many times (e.g. Anderson & Jackson (1968), Garg & Pritchett (1975), Batchelor (1988)) that an "elasticity" of the particle phase can stabilize the bed. (Here, the elasticity is defined as $E_p = -\frac{dp_p}{d\epsilon}$, where ϵ is the void fraction.) Jackson (1985) argues that the large value required of the elasticity could not be generated by particle fluctuations and stability must arise from some other mechanism. Here though, we came up with another idea to indirectly measure the particle elasticity in a manner that is

particularly appropriate for inclusion in stability models.

The idea arose from a class project performed by Chengzhen Jin, one of the students supported by this grant. He performed a survey of the various stability analysis and (although not required for the assignment) derived one of his own that was a hybrid of the many models he studied. This analysis, like its predecessors, models the particle and fluid phases as separate, but coupled continua, (e.g. like equations 1.1 and 1.2,) makes assumptions about the forms of the constitutive behavior, the interfacial drag, particle elasticity, bulk viscosity, etc. and predicts the onset of instability, the initial growth rate and velocities of voidage disturbances. Of course, the results depend on the assumed forms of the constitutive behavior. We realized that this process could be reversed. I.e. one could create a generic stability analysis (i.e. one that make as few assumptions as possible). Then by comparing the theory with measured properties such as the wave growth and velocity, back out appropriate values for the modeled terms. As will be shown in the following, the model may be reduced to different wave equations in the near and far field and making measurements in those locations yield additional information. (The measurements of El-Kaissy & Homsy (1976) confirm different near and far-field behaviors.)

A similar idea was used by Ham et al. (1990). They measured the location of the onset of instability in a small fluidized bed and extracted the particle-phase elasticity from an analysis based on Batchelor's (1988) theory, although they still made assumptions about the nature of the drag law. By measuring additional properties we can extend this idea to determine all other modeled properties of the stability analyses. Measurements of the drag and viscosity will be valuable in themselves as they allow the evaluation of various models that are in common use.

This phase of the project was not included in the original proposal. However, two students, Xiao Hu and Chengzhen Jin, who are performing the two-phases of the liquid bed investigation, were brought to USC on University Merit Fellowships which paid their stipend during the academic year. Consequently, the grant only paid their summer salaries and it was possible to support three students under this project rather than the two allowed for in the budget. This has allowed the project to branch out into this new area.

3.2.1 The Generic Stability Model

The model is based on standard interpenetrating continuum techniques and is a slight modification of that presented in last years report. Its development will be briefly outlined below, omitting many of the details common to other models of this type. The equations appropriate to the one-dimensional propagation of plane voidage waves in the z-direction are (in dimensionless form):

Conservation of Mass:

$$\text{fluid phase: } \frac{\partial \epsilon}{\partial t} + V_f \frac{\partial \epsilon}{\partial z} + \epsilon \frac{\partial V_f}{\partial z} = 0 \quad (3.2.1)$$

$$\text{solid phase: } - \frac{\partial \epsilon}{\partial t} - V_p \frac{\partial \epsilon}{\partial z} + (1 - \epsilon) \frac{\partial V_p}{\partial z} = 0 \quad (3.2.2)$$

Following the standard procedure, combined phase equation (e.g. a combination of particle and fluid phase momentum equations such a 1.1 and 1.2.) is used for conservation of momentum:

$$\begin{aligned} (1 - \epsilon) \epsilon \left(\frac{\partial V_f}{\partial t} + V_f \frac{\partial V_f}{\partial z} \right) - (1 - \epsilon) \epsilon \rho \left(\frac{\partial V_p}{\partial t} + V_p \frac{\partial V_p}{\partial z} \right) = \\ - \frac{1}{R_e} F_f - \epsilon E \frac{\partial \epsilon}{\partial z} - \frac{\epsilon}{R_{e\eta}} \frac{\partial^2 \epsilon}{\partial z \partial t} + [\epsilon (1 - \epsilon) (\rho - 1)] \frac{1}{F_r} \end{aligned} \quad (3.2.3)$$

where, $E = \frac{E_{p0}}{J_0^2 \rho_f}$, $F_f = \frac{F_D}{\mu_f J_0 / (d_p)^2}$, $R_e = \frac{\rho_f J_0 d_p}{\mu_f}$, $R_{e\eta} = \frac{\rho_f J_0 d_p}{\eta_p}$, $F_r = \frac{J_0^2}{g d_p}$, $\rho = \frac{\rho_p}{\rho_f}$, d_p is the particle diameter, J_0 is the superficial fluid velocity ($J_0 = \epsilon V_f$), and E_p represents the effective elasticity of the particulate phase, η_p represents an effective viscous resistance to voidage growth, and F_D represents the drag force. In writing (3.2.3) it is assumed that the resistance of the particle phase to a voidage disturbance has both an elastic and viscous component. I.e:

$$\sigma_p = E_p \epsilon + \eta_p \frac{\partial \epsilon}{\partial t}$$

Anderson & Jackson (1968) come to the same conclusion using a viscous interparticle stress term. By comparison, the η_p is the equivalent of the $(\lambda_s + \frac{4}{3}\mu_s)$ term that appears in that paper and may be thought of as the viscous resistance to growth in particle volume.

3.2.2 The Stability of the State of Uniform Fluidization and What can be Learned from It.

Let ε_0 , V_{f0} , V_{p0} , P_{f0} , P_{p0} , describe the void fraction, velocities and pressures that correspond to a state of uniform fluidization. Under those conditions: $\varepsilon_0 = \text{const}$, $V_{f0} = J_0/\varepsilon_0$, $V_{p0} = 0$, $\partial P_{p0}/\partial z = 0$. Let it then be disturbed by ε' , v_f' , v_p' , p_f' , p_p' . I.e:

$$\begin{aligned}\varepsilon &= \varepsilon_0 + \varepsilon' \\ V_f &= V_{f0} + v_f' \\ V_p &= V_{p0} + v_p' \\ p_f &= P_{f0} + p_f' \\ p_p &= P_{p0} + p_p'\end{aligned}$$

As, in the uniform state the fluid-particle drag, F_f , results in the bulk pressure gradient:

$$F_f = F_f(\varepsilon, V_f - V_p)$$

so:

$$\left(\frac{\partial F_f}{\partial (V_f - V_p)} \right)_0 (v_f' - v_p') + \left(\frac{\partial F_f}{\partial \varepsilon} \right)_0 \varepsilon' = A(v_f' - v_p') - C \varepsilon'$$

Where:

$$A = \left(\frac{\partial F_f}{\partial (U_f - U_p)} \right)_0, \quad C = - \left(\frac{\partial F_f}{\partial \varepsilon} \right)_0$$

After substituting into (3.2.3), using (3.2.1) and (3.2.2) to replace v_f' and v_p' in favor of ε , and eliminating higher order terms one finds:

$$\mathcal{A} \frac{\partial^2 \varepsilon'}{\partial t^2} + \mathcal{B} \frac{\partial^2 \varepsilon'}{\partial z \partial t} + \mathcal{C} \frac{\partial^2 \varepsilon'}{\partial z^2} + \mathcal{T} \frac{\partial \varepsilon'}{\partial t} + \mathcal{G} \frac{\partial \varepsilon'}{\partial z} = \mathcal{E} \frac{\partial^3 \varepsilon'}{\partial z^2 \partial t} \quad (3.2.4)$$

where

$$\begin{aligned}\mathcal{A} &= [(1 - \varepsilon_0) + \rho \varepsilon_0], \\ \mathcal{B} &= 2 V_{f0} (1 - \varepsilon_0), \\ \mathcal{C} &= V_{f0}^2 (1 - \varepsilon_0) - \varepsilon_0 E, \\ \mathcal{T} &= \frac{A}{R_e \varepsilon_0 (1 - \varepsilon_0)}\end{aligned}$$

$$g = \left[\frac{A V_{f0}}{R_e \varepsilon_0} + \frac{C}{R_e} + \frac{(\rho - 1)(1 - 2\varepsilon_0)}{F_r} \right]$$

and:

$$s = \frac{\varepsilon_0}{R_{e\eta}}$$

Then equation (3.2.4) can be rewritten in the form of wave equation (Whitham, 1974, Liu, 1982):

$$\tau \left(\frac{\partial}{\partial t} + c_1 \frac{\partial}{\partial x} \right) \left(\frac{\partial}{\partial t} + c_2 \frac{\partial}{\partial x} \right) \varepsilon' + \left(\frac{\partial}{\partial t} + a_1 \frac{\partial}{\partial x} \right) \varepsilon' = \nu_e \tau \frac{\partial^3 \varepsilon'}{\partial x^2 \partial t} \quad (3.2.5)$$

where:

$$\tau = \frac{\mathcal{A}}{\mathcal{F}}$$

$$\nu_e = \frac{s}{\mathcal{A}}$$

$$c_1, c_2 = \frac{1}{2} \frac{\mathcal{B}}{\mathcal{A}} \left\{ 1 \pm \sqrt{1 - 4 \frac{\mathcal{CA}}{\mathcal{B}^2}} \right\}$$

$$= \frac{V_{f0}(1 - \varepsilon_0)}{[(1 - \varepsilon_0) + \rho \varepsilon_0]} \left\{ 1 \pm \sqrt{1 - \frac{[(1 - \varepsilon_0)V_{f0}^2 + \varepsilon_0 E][(1 - \varepsilon_0) + \rho \varepsilon_0]}{V_{f0}^2(1 - \varepsilon_0)^2}} \right\} \quad (3.2.6)$$

$$= V_m \left\{ 1 \pm \sqrt{1 - \frac{[(1 - \varepsilon_0)V_{f0}^2 + \varepsilon_0 E][(1 - \varepsilon_0) + \rho \varepsilon_0]}{V_{f0}^2(1 - \varepsilon_0)^2}} \right\}$$

where $V_m = \frac{V_{f0}(1 - \varepsilon_0)}{[(1 - \varepsilon_0) + \rho \varepsilon_0]}$ is weighted mean velocity.

and:

$$a_1 = \mathcal{G}/\mathcal{T} = \frac{\left[\frac{A V_{f0}}{Re \epsilon_0} + \frac{C}{Re} + \frac{(\rho - 1)(1 - 2\epsilon_0)}{Fr} \right]}{\frac{A}{Re \epsilon_0 (1 - \epsilon_0)}}$$

The quantities, c_1 and c_2 represent the dynamic wavespeeds and a_1 represents the kinematic wavespeed in the material. Stability requires $a_1 < c_1$ and instability arises when: $a_1 > c_1$.

It is possible to obtain simplified forms of these equations in the region near and far from the distributor using techniques derived from Whitham (1974) and Liu (1982). Near the distributor, waves will move approximately with the dynamic wavespeed, c_1 (as c_1 represents the wavespeed moving away from the distributor) we can approximately have:

$$\frac{\partial}{\partial t} \doteq -c_1 \frac{\partial}{\partial x}$$

except for the term that already involves c_1 , (Whitham (1974)) apply this to Eq(3.2.5), get:

$$\left(\frac{\partial}{\partial t} + c_1 \frac{\partial}{\partial x} \right) \epsilon' + \frac{c_1 - a_1}{c_1 - c_2} \frac{1}{\tau} \epsilon' = \overline{\nu_e} \frac{\partial^2 \epsilon'}{\partial z^2} \quad (3.2.7)$$

where $\overline{\nu_e} = \frac{\nu_e c_1}{(c_1 - c_2)}$ is a dimensionless effective viscosity. Now, assume a plane wave disturbance of the form:

$$\epsilon' = \alpha_0 e^{a_h t + i\omega_h(t - z/U_h)}$$

Substituting into Eq(3.2.6) yields the local growth rate:

$$a_h = \frac{a_1 - [c_1 + \tau \overline{\nu_e} k_h^2 (c_1 - c_2)]}{(c_1 - c_2) \tau} \quad (3.2.8)$$

and local wavespeed:

$$U_h = c_1 = \frac{V_{f0}(1-\varepsilon_0)}{[(1-\varepsilon_0) + \rho\varepsilon_0]} \left\{ 1 + \sqrt{1 - \frac{[(1-\varepsilon_0)V_{f0}^2 + \varepsilon_0 E][(1-\varepsilon_0) + \rho\varepsilon_0]}{V_{f0}^2(1-\varepsilon_0)^2}} \right\} \quad (3.2.9)$$

where k_h is the wave number, $k_h = \omega_h/U_h$.

For the long wave region (low frequency waves, far way from the distributor), waves will move with the kinematic wavespeed, a_1 (Liu (1982)). We then approximately have:

$$\frac{\partial}{\partial t} \doteq - a_1 \frac{\partial}{\partial x}$$

except for the term that already involves a_1 , (Whitham (1974)) and the viscous term, η_p can be neglected. Applying this to Eq(3.2.5), yields:

$$\left(\frac{\partial}{\partial t} + a_1 \frac{\partial}{\partial x}\right) \varepsilon' = \mathfrak{D} \frac{\partial^2 \varepsilon'}{\partial z^2} \quad (3.2.10)$$

where $\mathfrak{D} = \tau(c_1 - a_1)(a_1 - c_2)$, is a dimensionless diffusivity. Inserting:

$$\varepsilon' = \alpha_0 e^{a_1 t + i\omega_l(t-z/U_l)}$$

into Eq(3.2.10), reveals the local growth rate:

$$a_l = - \mathfrak{D} k_l^2 = - \tau(c_1 - a_1)(a_1 - c_2) k_l^2 \quad (3.2.11)$$

(where $k_l = \omega_l/U_l$) and then wavespeed:

$$U_l = a_1 \quad (3.2.12)$$

From Eq(3.2.8), (3.2.9), (3.2.10) and (3.2.11), one finds:

$$E = U_h^2 (\rho - 1) + 2 V_{f0} U_h - V_{f0}^2 + \frac{(U_h - V_{f0})^2}{\varepsilon_0} \quad (3.2.13)$$

and:

$$A[V_{f0}(1-\varepsilon_0) - U_h] + C(1-\varepsilon_0)\varepsilon_0 - 2\bar{\nu}_e k_h^2(U_h - V_m) R_e \varepsilon_0 (1-\varepsilon_0)[(1-\varepsilon_0) + \rho\varepsilon_0] \quad (3.2.14)$$

$$= 2 a_h(U_h - V_m) R_e \varepsilon_0 (1-\varepsilon_0)[(1-\varepsilon_0) + \rho\varepsilon_0] - \frac{R_e}{F_r} \varepsilon_0(1-\varepsilon_0)(\rho-1)(1-2\varepsilon_0)$$

and:

$$A[V_{f0}(1-\varepsilon_0) - U_l] + C(1-\varepsilon_0)\varepsilon_0 = -\frac{R_e}{F_r} \varepsilon_0(1-\varepsilon_0)(\rho-1)(1-2\varepsilon_0) \quad (3.2.15)$$

and:

$$A a_l = - R_e \varepsilon_0(1-\varepsilon_0)[(1-\varepsilon_0) + \rho\varepsilon_0] (U_h - U_l)(U_h + U_l - 2 V_0) k_l^2 \quad (3.2.16)$$

with the four equations, (3.2.13), (3.2.14), (3.2.15) and (3.2.16), we can solve for the four unknowns:

$$A = \left(\frac{\partial F_f}{\partial (V_f - V_p)} \right)_0, \quad C = - \left(\frac{\partial F_f}{\partial \varepsilon} \right)_0, \quad E = \frac{E_p}{J_0^2 \rho_f} \quad \text{and} \quad \bar{\nu}_e = \frac{\nu_e c_1}{(c_1 - c_2)}.$$

The last two, E and $\bar{\nu}_e$ reveal the elasticity and viscosity of the particle phase. The first two, A and C , are derivatives the the fluid force with respect to the velocity difference between the phases, $V_f - V_p$, and the void fraction, ε . Both derivatives are easily computed from existing drag laws. Comparison of the predictions with the measured values yield insight into the appropriateness of the various models.

3.2.3 The Concentration Measurement Technique

These measurements are made on a tubular fluidized bed with a 2.5cm diameter. The distributor is constructed of a porous plate composed of 20 μ m particles ensuring a huge pressure drop, and thus, a uniform fluidizing velocity. The instantaneous concentration is determined using a light attenuation technique that is schematically shown in Figure 3.2.1. A nearly uniform light is provided by two small ALS 4mW diode lasers. Each signal is sensed by a Melles Griot silicon photodiode that is placed at the end of a 6 mm diameter and 20 mm long cylindrical channel, that has been painted black to eliminate noise from scattered waves. The 35.56 mm spacing was chosen on the basis of many trial and error tests, to eliminate any crosstalk between the channels. The attenuation of each beam provides an instantaneous measurement of the particle concentration and cross-correlating the signals provides a measurement of the wavespeed.

3.2.4 Concentration Calibration

The difficulty with all light attenuation systems is the calibration against concentration. In particular, the problem is to create a system with a known particle concentration upon which such a calibration might be based. However, we have developed a technique that nearly eliminates this problem by basing the calibration, not on the local concentration which is somewhat uncertain, but on the total volume of particles in the bed which is easily determined from the weight of particles divided by their density.

Like all attenuation systems, the light intensity decreases exponentially as it crosses the bed. That is, the intensity I , at a distance x within the bed, is related to the initial intensity I_0 , by:

$$I = I_0 \exp[-(\lambda_a + \lambda_s)\nu x] \quad (3.2.17)$$

where λ_a and λ_s are the appropriate, but unknown constants for absorption and scattering of the light by particles and ν is the solid concentration. (Note, as we use clear water, the attenuation by the water is insignificant. Also, as the photodiodes are placed at the end of a blackened tube, scattered light does not reach the diode and is lost from the measurement just as if it were absorbed by the particles.) This then gives a key to the solid concentration, ν . I.e.:

$$\nu = \frac{\ln I_0}{(\lambda_a + \lambda_s)d} - \frac{\ln I}{(\lambda_a + \lambda_s)d} \quad (3.2.18)$$

where d is the inside diameter of the tube. Thus as the signal s , obtained from the photodiode should be proportional to the intensity I , it should correlate to the solid concentration as:

$$\nu = A \ln s + B \quad (3.2.19)$$

A preliminary calibration (which assumed that the average concentration in the bed equaled the concentration at the center of the expanded bed) confirmed the calibration in (3.2.10). The next step in the calibration is to integrate (3.2.19) along the depth, H of the bed. Thus, if V_p is the total volume of particles in the bed:

$$V_p = \frac{\bar{\nu} \pi d^2 H}{4} = A \int_0^H \langle \ln s \rangle dy + BH \quad (3.2.20)$$

where $\bar{\nu}$ is the average solid concentration, d is the bed diameter and $\langle \ln s \rangle$ is the time-average of the log of the signal derived from the photodiode at each position y . Equation (3.2.20) was applied to six expanded beds of 1mm glassbeads, all with mean concentrations within the range of interest of this investigation. (Naturally, separate calibrations must be made for each material.) A and B were determined by least-squares fitting to that data. The calibration proved to be extremely accurate; in fact, the maximum error for all the integrated concentration profiles was less than 0.1%.

3.2.5 Preliminary Results

The first experiments have all been performed with 1mm glassbeads. Representative voidage signals taken at two different vertical positions along the channel for a mean voidage, $\epsilon_0 = 0.526$, are shown in Figure 3.2.5.1. Each plot show the two traces derived from the two transducers at each position. These traces are analyzed using MATLAB software. The corresponding powerspectra of these signals is shown in Figure 3.2.5.2. The dominant frequencies are close to 1Hz and thus, to accurately determine the frequency, data is sampled for long periods of time 120 secs at a relatively low sampling frequency of 20 Hz. The cross-correlations of the signals, that are used to yield the wavespeeds, are shown in Figure 3.2.5.3; these show a periodic structure that reflects the periodic nature of the wave, but there is a distinctly larger peak, corresponding to the time it takes a wave to pass between the two photodiodes. Note, to accurately determine the time delay requires sampling at a high frequency; consequently, the signals used to derive the cross-correlations were separately sampled at 100Hz for a period of 40 seconds. The amplitude of the waves is determined in two steps. First the signal is put through a low pass filter to remove any DC component.

Then it is autocorrelated and the peak represents the amplitude of the signal. The two autocorrelations, corresponding to the signals given above, are shown in Figure 3.2.5.4. All these measurements are similar to those of El-Kaissy & Homsy (1976).

The results of these measurements of the distribution of the amplitude wavespeed and dominant frequency along the channel are shown in Figures 3.2.5.5-3.2.5.7. In particular note the two different regimes for wave growth, near and far from the distributor; this data shows that, near the distributor, the wave amplitude increases linearly on a log plot, while far away the amplitude growth rate becomes very small.

Again, these measurements are similar to those of El-Kaissy & Homsy (1976).

Finally, Figures 3.2.5.8-3.2.5.11 shows the properties of fluidized beds that are interpreted from the above data through the generic stability analysis. Notice that all the data points contain error bars. The errors were determined by sensitivity tests on the generic model. The sensitivity study employs both measured values and error estimates on each measurement. (From the consistency of the measurements so far, it is estimated that the frequency error will be within 15%, velocity within 5%, and the amplitude error within 5%.) The error estimation is performed in a statistical way.

After the predicted value is set, a random error, within the above limits, is input into every measured parameter. Five hundred such random choices were made and the error bars represent the maximum errors obtained in this process. As indicated by the length of its error bars, the most sensitive result is the particle phase viscosity.

Figures 3.2.5.8 and 3.2.5.9 show the inferred values of the derivatives of the particle drag law with respect to the relative velocity and void-fraction ϵ . These are compared with the corresponding values predicted by popular drag laws, Foscolo-Gibilaro (Foscolo & Gibilaro, 1987), Richardson-Zaki (R_Z) and the Ergun equation (the last two were taken from Shook & Roco, 1991). Note that the theoretical predictions are plotted as discrete points; this is because they are functions of the fluidizing velocity as well as the void fraction and the plotted points assume the same superficial velocity as the experimental values. In all cases the inferred values agree reasonably well with the Richardson-Zaki law and lie below those predicted by the Ergun equation. The derivative with respect to the relative velocity (Figure 3.2.5.6) lies close to the Foscolo-Gibilaro prediction, but their prediction for the derivative with respect to voidage (Figure 3.2.5.7) lies well above the measured values.

Figures 3.2.5.10 and 3.2.5.11 show the predictions for the particle phase elasticity and the viscosity (i.e. the viscous resistance to voidage growth): E_{p0} and η_p . Again, the elasticity falls far below the predictions of the Foscolo-Gibilaro model, the only such prediction in the literature. The viscosity shown in Figure 3.2.5.11 is of the order of 10 poise and is orders of magnitude larger than would be expected from the suspension literature (e.g. Thomas, 1965). However, they are of the same order as those measured by Schügerl et al. (1961) in a concentric cylinder containing a gas-fluidized bed, and as inferred from the motions of bubbles by Grace (1970). (Unfortunately, none of these studies used particles as large as 1mm, so that precise comparison will have to await

experiments on smaller particles.) To our knowledge, the current measurements are the first such determinations made in liquid fluidized beds. This may provide some insight into the mechanism of viscosity generation. If one were to assume that the values

should scale with the viscosity of the interstitial fluid, (as one would expect for a suspension) then the relative viscosities, η_{eff}/η_f measured here are off by orders of magnitude from their corresponding values for gas fluidized beds. However, if one assumes that these viscosities are primarily a result of momentum transport induced by particle motion and interactions, the values should be relatively independent of the fluid; in that case, the results in gas and liquid fluidized beds should be similar just as observed in these results.

3.2.6 Proposed Future Work

The plan for the next year, (which should finish this phase of the project,) will require making much the same studies on different, in particular smaller particle sizes. This will require either the construction of a smaller diameter test bed, or the use of higher powered lasers as the current lasers do not penetrate a 2.5cm bed of 0.5mm particles. At present we plan to build a bed of 1.27cm diameter, exactly half that of the current bed. While awaiting completion measurements on intermediate sized particles will be performed in the current bed.

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Figure 2.1.6: The same particles pressures as functions of the position of the bubble's center-of-area.
BUDGET (11/1/94-10/31/95)