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A particle pressure transducer suitable for use in gas-fluidized beds

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Abstract. This paper describes a device that can resolve the average pressure exerted on a solid wall due to interactions with particles independently of the pressure exerted by fluid forces. The device has been used to measure the average particle pressures exerted on the walls of a gas-fluidized bed.

1. Introduction

Particle pressure may be thought of as the force per unit area exerted on a surface 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 analogue 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 with a surface (e.g. the weight of a particle, or an assembly of particles, resting on a surface).

A term involving particle pressures often appears in theoretical models of multiphase flows. Typically, such flows are modelled as individual phase equations, in which each phase, solid or fluid, is represented by its own set of equations, each with its own associated mass, energy, pressure. The individual phase equations are then coupled together through interaction terms with the other phases in the mixture. So, in such a description of the motion of a solid–fluid mixture, one of the equations would describe the motion of the particulate phase and contain terms involving the particle pressure and other forces describing the interactions within, and the body forces acting on, the particle mass. The interactions between the particle and fluid phases typically appear as separate force terms in the equation. Modelling the particle pressure term has always presented a problem—in extreme cases, some theorists have ignored it as physically unsound, others have taken it to equal the fluid pressure. However, neither of these arguments seems correct in light of the picture drawn in the last paragraph. Such extremely different viewpoints are excusable because there were no experimental measurements of particle pressure available. Nonetheless, the behaviour of the particle pressure can have significant effects on the behaviour of multiphase systems. For example, Jackson (1985) shows that the stability of a fluidized bed is affected by the dependence of the particle pressure on the void fraction, reflecting the possibility that instabilities may grow through the forces transmitted within the particle phase itself.

As the particle pressure represents the forces applied by particles, its measurement may also be of importance in industrial processes. The obvious cases would be those processes that are concerned with attrition of particles where the attrition rate would be determined by the forces applied by other particles and by the wall—and thus should be reflected in the particle pressure. Furthermore, even if they do not cause particle breakage, the forces that particles experience may work to harden their surfaces and change their physical, and possibly their chemical, attributes. Obviously, regions of largest particle pressure would be those that do the most damage and are either to be avoided or sought after depending on the desired outcome.

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 mount 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 (for example, fluidized beds or slurry flows) in which the motion is driven by fluid pressure, the particle pressure may be a small fraction of the total. This paper describes a transducer that is capable of resolving the particle pressure independently of the fluid pressures. It has been used to make particle pressure measurements on the vertical side walls of gas-fluidized beds (although it could be used in many other flow situations). The device 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. The importance of this device lies in the fact that these measurements have never been previously taken. A detailed set of particle pressure measurements in gas-fluidized beds using this probe are presented by Campbell and Wang (1990).

The only other attempt to measure the particle pressure is in the recent study by Kumar et al (1990) for liquid-fluidized beds. They inserted a hydrophone into the wall of the bed and listened to the impacts of the particles. They calibrated their instrument by relating the output signal of the hydrophone to the impact velocity of test particles. Thus, the primary measurement was the 'thermal' velocity of the impacting particles from which the particle pressure can be inferred. Their method had several drawbacks. The first was that the probe calibration was very difficult and showed a great deal of scatter which led to much scatter in their results. Secondly, summing all the collisions on the hydrophone was very time consuming and consequently very few points appear in the data. Lastly, the hydrophone could only record the thermal-like motion of the particles and could not detect long duration contacts. Hence it could only determine a portion of the particle pressure. (This may also be an advantage as it allows the particle pressure to be decomposed into its constituent parts.) This might be perfectly fine for liquid-fluidized beds, but would probably not work for gas-fluidized beds where the particles are agitated en masse by the passage of bubbles. Still, it represents the only other attempt to measure the particle pressure.

2. The particle pressure transducer

The particle pressure is measured using a differential pressure transducer which is illustrated in figure 1. Basically, the transducer consists of a diaphragm, flush mounted into the side wall of the fluidized bed, the front surface of which is exposed to both particle and gas forces. Small passages about the circumference of the diaphragm admit air, but no particles, through to the back side. Thus, the front of the diaphragm experiences both gas and particle pressure and the back experiences only gas pressure, so that the net deflection of the diaphragm reflects the pressure exerted on the surface by particle interactions. Note, however, that due to the time it takes for enough gas to pass from the front to the rear of the diaphragm, the instantaneous diaphragm deflection will not necessarily correspond to the instantaneous particle pressure. However, it can be easily seen by temporal averaging the equation of motion of a diaphragm, that the average displacement of the diaphragm will correspond to the average net force exerted on the surface. Thus, the signal from the pressure transducer is averaged over long time periods to yield the average particle pressure.

Preliminary experiments showed that the placement of the fluid ports surrounding the diaphragm could be critical. In a quiescent fluid this does not present a problem as the fluid pressure is uniform across the face of the probe. Difficulties arise, however, if there is a pressure gradient tangential to the diaphragm surface (exactly as there would be if the probe were mounted in the side wall of a fluidized bed). In that case, fluid would tend to enter a pressure port where the pressure is large and leave through another pressure port where the pressure is lower, inducing a flow through the cavity behind the diaphragm. This could present a particular problem when the external pressure drop is large (as it would be if an airflow was driven through a bed of particles) so that the path through the transducer is easier than that on the outside. To avoid this difficulty the current version of the transducer has only two pressure input ports located on opposite sides of the diaphragm along a diameter oriented perpendicular to the pressure gradient. In this way, the pressure difference between the ports is zero and no flow is induced across the interior of the transducer.

The design of the probe has gone through many iterations. The current probe is constructed of stainless steel and has a 38 mm diameter by 0.2 mm thick diaphragm. The diaphragm and its mounting structure were machined out of a solid piece of stainless steel. (This is not necessarily the best or the easiest way to manufacture such a probe, but it seems to be the best choice given the shop resources available.) The displacement of the diaphragm is measured by a MTI Accumeasure capacitance probe with a 0–0.13 mm range, although the displacement could also be measured by mounting strain gauges or by other means. The diaphragm is thickened directly in front of the displacement transducer so as to always present a flat surface to the transducer. The holes that permit the passage of gas to the back side of the diaphragm were covered with a fine screen to keep them clear of particles. During the experiments on the fluidized bed, the signal from the probe was sampled by a Scientific Solutions Labmaster data acquisition card mounted in an IBM AT computer and averaged over many bubbling periods. (Samples take from 45–300 s to converge to stable averages of the particle pressures.)

3. Testing of the particle pressure transducer

Unfortunately, there is no particle pressure standard against which to calibrate the probe. As these are the first particle pressure measurements, there is no way to create a known particle pressure and use it to evaluate...
the behaviour of the probe. Consequently, the basic calibration of the particle pressure transducer was performed in a static water column in much the same way as would be employed for a conventional fluid pressure transducer. A thin latex sheet was used to cover the gas ports and then the transducer was covered with various depths of water to simulate a static pressure loading. The output from the capacitance probe was found to vary linearly with the applied pressure.

The static calibration is somewhat troublesome because it is conceivable that the particle pressure transducer design is dynamically very active. First of all, the diaphragm behaves as a circular plate pinned at the edges and consequently possesses natural modes of motion. But also, as mentioned previously, it is not expected that the transducer will react to the instantaneous particle pressure due to the time delay for the gas pressure behind the diaphragm to equilibrate to that in the gas outside. Because of this, one might consider the gas pressure behind the diaphragm as the response of an equivalent RC low pass filter. The resistance to air motion is imposed by the pressure drop in the gas moving through the narrow channels, the protecting screen and the particle mass outside as it enters or leaves the chamber behind the diaphragm. The capacitance is imposed by the volume behind the diaphragm which determines the quantity of gas that must be moved through the resistance to change the pressure. As an RC circuit acts as an analogue averaging circuit, the higher the imposed frequency, the smaller the amplitude of the pressure fluctuation that is induced behind the diaphragm. But also, the capacitance induces a phase shift into the signal due to the time it takes the pressure behind the diaphragm to equalize. One might then expect some interaction between the diaphragm motion and the RC circuit that determines the pressure difference and it was not immediately clear that this would not have an effect on the output of the transducer. Therefore, the dynamics of the system had to be tested to be certain that the probe itself does not interfere with the particle pressure measurement.

The system shown in figure 2 was devised to test the dynamic response of the pressure transducer. A pressure source was provided by a standard audio speaker connected to a signal generator through an amplifier. An enclosed space was made by sealing the open end of the speaker with a flat plate. Into this flat plate were mounted the particle pressure transducer and a gas pressure transducer. The gas pressure transducer provided the reference signal for the pressure generated by the speaker which could then be compared with the output of the particle pressure transducer. The output from both systems was sent to a dual trace oscilloscope from which the relative magnitude of the two signals and the phase shift between them could be determined. Note that as the particle pressure transducer ideally should not respond to changes in gas pressure (at least in an averaged sense), its time averaged output should be zero and indeed this was found to be the case. No non-zero time averaged output of the particle pressure transducer was measured for any of the test cases we were able to generate with this configuration. Thus, any output of the probe under these conditions is due to the time it takes the gas pressure behind the diaphragm to equilibrate to that outside.

The results of the relative amplitude and phase shift experiments are shown in figures 3 and 4, respectively. When the test bed is fluidized the particle pressure will come about from the bed motion induced by bubbles and slugs. It might then be surprising to notice that the

![Figure 2](image2.png)

**Figure 2.** The experimental set-up used to test the dynamic response of the particle pressure transducer.
range of frequencies shown here is really quite large compared with the bubbling and slugging rates that are observed in fluidized beds (which are typically of the order of 1 Hz). This is because at these low frequencies (below about 10 Hz) the output of the particle transducer is so small that it lies within the noise band of the system and cannot be discerned, indicating that the fluid pressure behind the diaphragm was capable of equilibrating the inside and outside pressures rapidly enough to keep up with the forcing signal. This was particularly encouraging as it showed that the transducer could be relied upon within the range of frequencies dominant in these experiments.

Figure 3 shows the ratio of the amplitudes of the peak-to-peak gas pressure and particle pressure outputs as a function of the driving frequency. The results show that at 10 Hz the probe could equalize all but about 2% of the gas pressure and that the ratio $P_{\text{particle}}/P_{\text{gas}}$ increases monotonically with frequency from then on. The rise in the ratio reflects the slow approach towards a system resonance which occurs at about 500 Hz (well outside the range of this figure). This is somewhat interesting as the fundamental mode of the diaphragm lies around 80 Hz. (The 80 Hz resonance was found by venting the rear of the diaphragm to the atmosphere to eliminate the filtering effect.) This indicates that the low pass filter characteristics of the probe are sufficient to damp not only the fundamental frequency, but the first harmonic which occurs at about 240 Hz as well. Three different peak-to-peak pressure amplitudes (115, 230 and 460 Pa) were studied. (As will be later apparent in figure 5, this covers the approximate range of average particle pressures observed in a fully fluidized bed.) A simple analysis indicates that the actual pressure difference across the diaphragm should not be a function of the applied pressure difference, and indeed this appears to be the case at low frequencies. An increase in the pressure ratio is apparent at high frequencies probably because the larger the applied pressure the more gas that must be moved across the ports, and the higher the frequency, the less time there is available to complete the task.

Figure 4 shows the phase shift between the imposed signal and the response from the particle pressure transducer. The phase shift can be seen to vary strongly with the applied pressure, varying at 10 Hz from 0° at 115 Pa applied pressure to about 15° at 460 Pa. The phase shift then drops monotonically as the frequency is increased. However, the strong effects occur at much higher frequencies than are likely to be encountered in fluidized beds, and, as the time-averaged output of the transducer is zero there should be little or no effect on the output of the transducer when it is used to measure the average particle pressure in gas-fluidized beds.

4. Particle pressure measurements

In closing, we would like to give an example of the particle pressure transducer in use. Figure 5 shows a typical plot of particle pressure measured in the side wall of a gas-fluidized bed. For comparison, the plot also shows the gas pressure drop between the top and bottom of the bed. These particular results were taken with the probe positioned 76 mm from the distributor for a test bed composed of 1.2 mm glass beads. The particle pressures were followed during an entire cycle of increasing the superficial gas velocity to the maximum value that the apparatus could support and then reducing it to zero. The gas pressure points represent the pressure difference measured between the top and bottom of the bed and shows the characteristic of most such measurements. That is, the gas pressure difference initially rises rapidly from zero until it reaches a value equal to the weight of the bed per unit area. At this point, the gas pressure difference is large enough to support the weight of the bed and the bed is said to be 'fluidized'. (Up to this point the bed is said to be 'packed'.) Further increases in velocity no longer change the pressure drop. The gas pressure curve gives a useful point of reference from which to understand the behaviour of the particle pressure curve. (The reader might note that the behaviour of the particle pressure is totally unlike that of the gas pressure.)

With zero fluidizing gas velocity, the particle pressure is large as the entire bed is supported only across inter-particle contact points. Turning on the gas flow causes a drop in particle pressure (and a corresponding increase in gas pressure) as progressively more and more of the bed is supported by fluid forces. The particle pressure reaches a minimum at just about the velocity where the bed is fully supported by gas pressure. Almost immediately after this point the bed begins to bubble and the particle pressure begins to rise—presumably due to the agitation of the bed caused by bubble passage—after which it seems to asymptote to a constant value at the higher velocities. The results of Campbell and Wang (1990) show that in this region the particle pressure scales with the mean bubble size within the bed and that the asymptote to a constant value for large fluidizing gas velocities is explained by the size of the bed limiting the size of bubbles. (Those results show that the measure-
ments scale with properties peculiar to the fluidized bed and material and thus give confidence that the probe is accurately assessing the particle pressures generated within the bed.) Decreasing the fluidizing gas velocity causes the particle pressure initially to return along the same path. However, after the minimum in the curve, in the region where the bed is packed, the particle pressure returns along a lower path than it followed on loading. At first, this caused great consternation that there might be hysteresis in the particle pressure probe but we found that this was a real phenomenon that represented an internal redistribution of the weight of the bed. In fact, we found that tapping the side of the bed would cause the bed to settle, altering the internal distribution of forces and changing the path followed by the particle pressure. Note also that the loading and unloading paths are not unique as they depend on the initial and final structure of the particle bed.

5. Conclusions

This paper has described the design and testing of a simple probe for measuring the average pressure exerted on a solid surface by the impacts of solid particles. The probe essentially consists of a diaphragm, flush mounted into a wall, one side of which is subjected to the pressure exerted by particles and fluid while the other side is subject to only fluid pressures. From the test results, it appears that any dynamic anomalies the probe might introduce into the particle pressure measurement occur only at frequencies that are large compared with those found in the fluidized beds to which the probe has been applied. Furthermore, when excited with only an oscillating gas pressure the time averaged signal was zero. Collectively, these give us great confidence in the results.

One final word of caution. This type of probe is probably not useful in dynamic systems that are liquid-fluidized or composed of very small, light particles. Problems arise because strong lubrication forces can build up between the particle and a solid surface that can slow or even halt the particle depending on the Reynolds number of the particle (i.e. that based on the particle velocity and diameter). For example, McLaughlin (1968) has shown that steel balls dropped onto a flat wall will not rebound below a Reynolds number of about 20. Thus, while the force on the diaphragm may be representative of the forces on the solid walls, it may not be an accurate reflection of what is happening internally to the fluid–solid mixture. An alternative design that overcomes these difficulties is currently being tested.

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