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An improved particle pressure transducer

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Abstract. This paper describes a device that can resolve the portion of the pressure in a multiphase mixture that is applied by particles, independently of the portion exerted by the surrounding fluid. This device has an improved dynamic response to that used by Campbell and Wang.

1. Introduction

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 analogy 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).

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—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. 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. An earlier paper (Campbell and Wang 1990) described a very simple transducer for this purpose. That probe consisted of a solid diaphragm flush mounted into the 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. This probe has been used to carry out particle pressure measurements on the vertical side walls of gas-fluidized beds that were presented by Campbell and Wang (1991) (although it could be used in many other flow situations).

Campbell and Wang (1990) showed that there was room for improvement in the dynamic response of that probe to fast changes in the local fluid and/or particle pressures. The problems arose largely because, fluid dynamically, the probe acted as the equivalent of an RC circuit in the way that it equalizes the fluid pressure across the diaphragm. Ideally, the fluid pressure behind the diaphragm should exactly match the fluid pressure outside. Practically, equalizing the pressures requires that a small quantity of fluid be passed from the test region at the front of the diaphragm, through the small passages, to the cavity at the rear of the diaphragm. The volume of the cavity determines the quantity of gas which must be moved and is the source of the apparent capacitance of the system. The resistance is applied by the small channels through which the fluid must move between the cavity and the outside. An RC circuit has two effects on the signal. Overall, it acts as a low pass filter; for high frequency pressure signals, the pressure behind the diaphragm simply does not have time to equalize with the applied pressure. As a result, the probe may show some response to rapid changes in air pressure, even in the absence of particles. However, even at lower frequencies, it will take some time for the pressures to equalize, resulting in a response that is phase shifted with respect to the applied signal. Campbell and Wang (1990) used an audio speaker attached to a signal generator to apply an oscillating pressure signal to their probe and were able to demonstrate both of these features. Nonetheless, a long time average of the signal will yield the average displacement of the diaphragm so that neither of these problems affect the time averaged results presented by Campbell and Wang (1991).
such a problem was noted with the old probe. Originally, the solid diaphragm was surrounded by a ring of fluid passage ports that permitted a flow behind the diaphragm, but, eventually, all the holes were covered except for two located on diametrically opposite sides. The probe was then placed in the wall so that the diameter connecting the two ports was perpendicular to the external pressure gradient. Thus, there could be no mean pressure difference between the ports and no net flow behind the diaphragm. This change had a demonstrable effect on the measured pressures. In the original configuration, a maximum was observed in the average particle pressure at moderate fluidizing gas velocities which disappeared once all but the two fluid passage ports had been blocked. Making the cavity behind the diaphragm as narrow as possible, not only minimizes the capacitance but also maximizes the pressure drop that a fluid will experience when passing behind the diaphragm, making such a passage less attractive to the fluid. This appears to work as the particle pressure maximum referred to above is absent from the measurements taken with the new probe. Further improvements might be had by reducing the diameter of the diaphragm as much as possible so as to minimize the fluid pressure difference across the probe.

The construction of the probe should be quite evident from figure 1. The screen that forms the diaphragm is tensioned and attached to a stainless steel ring by spotwelding. We have built several versions of the probe with various diaphragm diameters. The one used in the tests presented at the end of this paper had a 12.7 mm diameter. The displacement of the diaphragm is measured by an MTI Accumeasure probe with a 0–0.13 mm range that determines the displacement of the diaphragm by sensing the capacitance across the air gap between the probe and the diaphragm. Of course, the displacement could also be measured by mounting strain gauges or by any other means, but this seemed to be the easiest scheme for us to implement. (We are testing a version of this probe for use in liquid fluidized beds that will use the use the change in fluid resistance between the probe and the diaphragm to carry out the same measurement.)

The composition of the screen turned out to be very important to the success of this design. In the first attempt to build this probe we used a standard woven wire screen. But we found that spotwelding the screen to the ring broke many of the wires and the diaphragm could not retain sufficient tension. We then tried various designs that tensioned the screen like a banjo or drum head. In this case, the screen was attached to a outer metal ring which held the screen tightly over an inner ‘tone ring.’ Screws attached to the outer ring allowed the tension of the screen to be varied in much the same way as a drumhead is tuned. This design was also discarded as it showed a small nonlinear response, which we were able to attribute to slipping of the screen over the tone ring. Eventually we abandoned the idea of using a woven screen altogether. Instead, we discovered that one could obtain stainless steel sheets, into
which an extremely uniform pattern of circular holes had been etched by a manner akin to the manufacture of printed circuit boards. The screen we used in the current probe is manufactured by the Buckee-Mears Precision Etched Products Group (model no. 2-2-8). The holes are approximately 70 μm in diameter and are arranged in a hexagonal pattern on a 0.05 mm thick sheet. Because the screen is etched from a continuous sheet, spotwelding cannot cause enough structural damage (such as breaking the wires that make up a woven screen) to make the screen unable to sustain tension. This allowed us to return to our original, and extremely simple, design shown in figure 1.

Problems might arise in using this design in situations that contain fines that are small enough to pass through the screen that serves as the diaphragm. If enough particles leak through, they can fill the gap behind the diaphragm and restrict its motion. This could be a large problem for test materials that either have a wide size distribution or have been subject to sufficiently violent handling to cause a significant amount of particle attrition. In such a case, the probe would have to be disassembled and cleaned unless some other provision is made (such as a port allowing the gap to be vacuumed clean). How often such cleaning is required depends on the material type and the flow conditions. We are currently attempting to use this probe to study the fluidization of a fluid cracking catalyst which is largely composed of particles that are smaller than the holes in the diaphragm. In that case, the leakage problem is avoided by loosely attaching a sheet of filter paper over the diaphragm.

Dynamically, the probe behaves as a simple diaphragm responding to the pressure difference between the interior and exterior. If both pressures are applied by the fluid only, the two should balance and there should, ideally, be no response. However, as mentioned previously, it will take some time for the pressure behind the diaphragm to balance that outside; the probe is the hydrodynamic equivalent of an RC circuit, where the resistance is the pressure drop needed to force the required flow across the screen and the capacitance is related to the volume of the cavity behind the screen, which determines the amount of fluid which must be moved. Any dynamically interesting response must be induced by this 'RC' circuit. The new probe was tested in the same audio speaker apparatus used by Campbell and Wang (1990), which applies an oscillating air pressure to the probe. However, with the new design, the matching of the fluid pressures across the diaphragm occurs so quickly, that we were unable to detect any response of the probe to the applied pressure signal at any frequency tested (up to 1000 Hz). We conclude that this new design has eliminated the resistance and capacitance problems associated with the old probe.

3. Particle pressure measurements

Figure 2 shows a typical plot of time-averaged particle pressure measured in the side wall of a gas-fluidized bed. The measurements obtained using the new probe are compared against nearly identical measurements made with the old probe. 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 15.2 cm from the distributor for a test bed composed of 0.5 mm glass beads. The gas pressure points show 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 interparticle 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 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. Beyond that point, the particle pressure seems to tend asymptotically to a constant value where the bed is slugging. The results of Campbell and Wang (1991) show that, in the fluidized 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 as the size of the bubbles becomes limited by the dimensions of the bed. (Those results show that the measurements scale with properties peculiar to the
Figure 3. Instantaneous measurements of the particle pressure exerted on the side wall of the gas fluidized bed that were taken with the new probe: (a) just beyond minimum fluidization, (b) a steadily bubbling bed, (c) a slugging bed.

fluidized bed and material and thus give confidence that the probe is accurately assessing the particle pressures generated within the bed.)

Figure 2 compares measurements taken with the new probe to similar measurements taken with the old. As can be seen, the two measurements are nearly identical. The major deviation between the two measurements occurs when the bed is packed. The results of Campbell and Wang (1991) showed that the particle pressures measured in the packed bed region were dependent on the structure of the bed and that changing the structure (e.g. by tapping the walls and forcing the bed to settle) strongly altered the particle pressure measurement. As both measurements, shown in figure 2, could not be taken at exactly the same time, we could not guarantee the same structure in the packed bed and, consequently, exact agreement of the results in the packed bed region should not be expected. The important observation to be made from this figure is that the two measurements are nearly identical in the fluidized region.

But remember that the purpose of this new probe was to allow better resolution of temporal events, not to make time averaged measurements. When the bed is fluidized, Campbell and Wang (1991) found that the majority of the particle pressure is attributable to the passage of bubbles. Consequently, the actual particle pressure cannot be uniform, but instead must be applied in an unsteady manner as the bubble crosses the surface of the probe. With this in mind, figure 3 shows measurements of the instantaneous particle pressures measured on the sidewalls of the bed. Figure 3(a) shows that the particle pressures measured just beyond minimum fluidization are nearly uniform with time. However, the unsteady manner in which the particle pressure is applied is very apparent when the bed is freely bubbling (figure 3(b)). Finally, when the bed is slugging, it can be seen that the particle pressure is applied in tall sharp peaks which are of surprisingly short duration (of the order of several milliseconds).

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