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MECHANICS/HEAT-TRANSFER RELATION FOR PARTICULATE MATERIALS

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SUMMARY

The major emphasis this quarter has been in two areas. The first is to continue working the bugs out of the new particle pressure transducer. The second was to try and measure the particle pressures generated in a bed of FCC catalyst that is undergoing particulate fluidization. The results indicate that the stabilization of fluidized beds in that regime cannot be explained in terms of particle pressure generation. Instead, consistent with other recent observations, the observations can be explained by a material is that not completely fluidized but, instead, retains much of the properties of a solid and, in particular, can transmit particle pressure like a solid.

Also, in this quarter, one of my students, David Wang, successfully defended his PhD thesis: his research was sponsored by this grant and concerned both the thermal conductivity measurements and the early work on particle pressures in fluidized beds. The particle pressure work was also presented at the IUTAM Symposium on the Mechanics of Fluidized Beds, held at Stanford in the early part of this month.

PARTICLE PRESSURE TRANSDUCER

The purpose of the particle pressure transducer is to measure the normal force exerted on the sidewall of a fluidized bed. Essentially, the design is a differential pressure transducer. A diaphragm is flush mounted in the sidewall of the bed, one side of which is exposed to particle and fluid forces while the other is exposed only to fluid forces: consequently, the deflection of the diaphragm reflects the forces applied only by the particles. There have been two designs developed and used under this grant. The design of the newest particle pressure transducer is shown in Figure 2. Here, instead of a solid diaphragm, the design uses a porous screen which is tensioned, much like a drumhead.

Figure 1: Schematic of the new particle pressure transducer

over the probe. Instead of passing through small holes surrounding the diaphragm, the gas pressure is equalized by simply leaking through the screen. The major advantage of this design is that the large diaphragm area applies a much smaller resistance to the passage of gas across the diaphragm, thus reducing concerns about the response time of the probe to an applied particle pressure. This allows us to measure the instantaneous particle pressures, some of which were presented in previous reports.

However, a problem with this design became apparent in the last quarter. It started with the design of a construction transducer. This model had a diaphragm, one half inch in diameter, instead of the one-inch diameter probe used previously. This modification was made in order to provide better spatial resolution. However, when the probe was calibrated in a static water tower, it was found that the output varied in a nonlinear fashion with the applied pressure. We considered many possibilities and found

that great improvement was obtained if the screen was securely fastened to the "tensioning", preventing any slippage of the screen. For these tests, the screen was fastened using glue. A new design is underway to perform the same function using a mechanical clamp that can be released so that the screen may be relaxed and re-tensioned.

PARTICLE PRESSURES IN GAS-FLUIDIZED BEDS UNDERGOING PARTICULATE FLUIDIZATION

Our previous studies¹ indicated that the particle pressures generated in a gas-fluidized bed were primarily a byproduct of the motion of bubbles in the bed. However, the materials used in that study fell into types B and D on the Geldart classification and, consequently, the beds bubbled immediately after minimum fluidization. However, small, lightweight material undergo an intermediate stage of "particulate fluidization", in which the pressure drop across the bed is large enough to support the weight of the bed, but no bubbles appear. All early stability studies of fluidized beds predicted that the bed should be unstable under all circumstances and much of fluidization modeling has been concerned with explaining the stability of the bed in this region.

Early on, it was shown that the particle pressure could be a stabilizing mechanism. Essentially, the particle pressure introduces a compressibility into the solid phase of the bed. The compressibility resists the voidage instabilities that grow into bubbles and stabilize the beds. On a microscopic level, it was speculated that the particle pressure reflected the random, almost thermal, fluctuation of individual particles. The velocity

¹Campbell, C.S. and Wang, D.G., Particle pressures in gas-fluidized beds, *Journal of Fluid Mechanics*, **227**, (1991) 495-508

fluctuations, in turn, are generated by the randomness of the gas flow to which a particle is immediately exposed. Locally, the direction of the gas flow that a particle experiences is determined by the tortuous path the gas follows as it works its way upward through the bed and may change with time as neighboring particles move around.

However, in the past few years, there have been indications that a completely different mechanism is at work. Such small particles are naturally cohesive. Consequently, a bed could remain stable as long as the disturbances are not large enough to break down the interparticle bonds. The earliest indications that this might be the case were presented by Rietema and his coworkers^{2 3}. These describe experiments in which a bed of homogeneously fluidized material was tilted with respect to the vertical. If the bed were truly fluidlike, the free surface of the bed would move to remain horizontal as the angle was changed. But the observations showed that the free surface tilted with the bed and could maintain a substantial angle with respect to the horizontal. This indicated that the bed material could withstand a yield stress. They speculated that the source of this yield stress was the unbroken contacts between particles. Recently this idea has received support from some experiments by Jackson⁴ in which he made extremely detailed density measurements across a particulate fluidized bed. These showed significant void fraction variations within an apparently homogeneous bed that were stable over time scales on the order of hours. Interestingly, the void fractions variations were nearly sinusoidal in shape as if a void fraction wave was frozen in place as it passed upwards through the bed. Jackson speculated that such

²Mutsers, S.M.P and Rietema, K., 1977. The effect of interparticle forces on the expansion of a homogeneous gas-fluidized bed. *Powder Technology*, **18** 239-248

³Rietema, K., 1973. The effect of interparticle forces on the expansion of a homogeneous gas-fluidised bed. *Chem. Eng. Sci.*, **28**, 1493-1497

⁴Jackson, R. Personal communication, also his presentation at the IUTAM Symposium on the Mechanics of Fluidized Beds, Stanford, July 1-4, 1991

structures could only be maintained if there were strong interparticle forces.

Obviously, some insight into this phenomenon could be had by examining the particle pressures generated in the homogeneous regime. This is easier than it sounds, largely because materials may only be homogeneously fluidized with great care. Of particular concern is the design of the distributor as any inhomogeneities there will grow into bubbles. After much trial and error, we discovered that a distributor could be built from multiple sheets (ten is a good working number) of chemical filter paper. The results of test performed on FCC are shown in Figure 2. This shows the gas pressure drop across the entire bed and the particle pressure. Here the particle pressure probe was placed 3 inches above the distributor in an FCC bed that was initially $8\frac{1}{2}$ inches deep. The experiments were started with the bed bubbling lightly and the points show what happens as the gas velocity is reduced. Bubbles disappeared from the free surface at a superficial gas velocity of 0.606cm/s (although it is likely that no bubbles are seen at significantly higher velocity at the depth where the probe it placed.)

The results show that the particle pressure is a continuously decreasing function of the fluidizing gas velocity even throughout the region of particulate fluidization. This is incompatible with the idea that particle pressure in that regime is generated by the thermalized motion of particles. Under those conditions, one would expect that the larger the gas velocity, the larger the disturbances that a particle experiences and the larger the particle pressure that would be generated. Consequently, if such a mechanism were at work, one would expect that the particle pressures would rise as the superficial gas velocity is increased. This indicates that some other mechanism, perhaps strong interparticle forces are the stabilizing mechanism. Furthermore, notice that the particle pressures do not fall to zero, even when the bed is fully supported. This indicates that there is still some structure, most likely the yield stresses between the particles that

can support a particle stress. Consequently, these observations support the notion that such a bed is not truly fluidized and, instead, retains many of its solid characteristics.

Figure 2: Measurements of the particle pressure in a homogeneously fluidized bed of cracking catalyst.

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