MECHANICS/HEAT-TRANSFER RELATION FOR PARTICULATE MATERIALS

Grant #DE-FG22-88PC88913

QUARTERLY REPORT

October, 1990

Report DOEHT.Q8

Charles S. Campbell
Department of Mechanical Engineering
University of Southern California
Los Angeles, Ca. 90089-1453

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

US-DOE Patent clearance is not required prior to publication of this document

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOV 6 1966

SUMMARY

In this quarter, we have been continuing with the dry granular shear cell experiments and have extended our previous results to different materials. we are also continuing with the development of a new particle pressure probe, but ran into drift problems in the calibration, which we hope have been resolved.

DRY GRANULAR CONDUCTIVITY MEASUREMENTS

Figure 1 shows the measured conductivity for 3.0mm glassbeads, plotted as a function of the shear rate for several values of the solid fraction, ν (the fraction of a unit volume occupied by solid material). The results show that the apparent conductivity varies linearly with shear rate. This may be compared with Figure 2 which shows that the apparent viscosity of the same particles also varies linearly with the shear rate. This comparison underlies the purpose of this investigation which is to establish links between the mechanical and thermal behavior of particulate systems. Computer simulation studies of granular flows indicate that, in a simply shearing flow, the granular temperature varies proportionally to the square of the shear rate. Thus, it appears that both the viscosity and the thermal conductivity of the mixture vary proportionally to the square root of the granular temperature - just as the viscosity and thermal conductivity of a perfect gas depend on the thermodynamic temperature in the kinetic theory of gases. Such behavior is expected in any such system as long as there are no long range forces between the particles and the transport rates are governed by the appropriate temperature. There is, however, a fundamental difference between the internal transport of heat and momentum. Note that the slope of the lines in the conductivity plot seem to be relatively independent of density until a solid fraction of about $\nu = 0.3$, after which a progressive drop in the slope may be observed. (In fact, for certain shear rates, an increase in density may bring about a decrease in the thermal conductivity.) Measurements of the viscosity show exactly the opposite behavior as their slope continually increases with density. This is a reflection of differences in the internal modes of heat and momentum transfer. Now, there are two mechanisms by which momentum may be transported within a granular solid. The first is the "streaming" mode which describes the transport by particles as they diffuse through the system carrying their momentum with them. The other is the "collisional" mode, by which two particles exchange momentum when they collide. Obviously, the streaming mode will dominate at small densities when collisions are infrequent and particles travel long distances between collisions and the collisional mode will dominate at large densities when the free motion of particles is extremely limited. However, heat transfer is a very slow process and collisions occur very quickly, so it is doubtful that a significant amount of heat will be transferred between particles of different temperatures during a collision. Consequently, it appears that the streaming mode is the most important in determining the apparent thermal conductivity. The

Figure 1: The effective conductivity of the shearing particle mixture for 3.0mm glassbeads.

Figure 2: The effective viscosity of the same system.

decrease in the slope of the thermal conductivity lines as the density is increased reflects the fact that increasing the particle concentration restricts the freedom of the streaming particle motions and, consequently, reduces this mode of internal heat transport. Conductivity measurements for two other sizes of glassbeads and for steel shot are shown in Figures 3-5 in an attempt to understand the scaling of the conductivity data. The data is somewhat inconsistent. They all show qualitatively the same behavior as those of the 3.0mm glassbeads and the measured conductivities are generally of the same magnitude. You may notice The slopes of the lines appear to drop off more rapidly for the smaller beads and, surprisingly, the steel shot, which has the largest particle conductivity and heat capacity, shows the lowest conductivities. However, there is no clear trend that is yet apparent to us. Part of the problem is that we are examining a system that depends both on the mechanical and thermal properties of the test material. Thus, even though the thermal properties of the steel shot are large, its mechanical properties may lead to the generation of smaller granular temperatures and consequently to a smaller effective conductivities. We feel that this phase of the grant will be complete when the scaling can be sorted out, although its is quite possible that there is no simple scaling.

If the above argument is correct and the change in apparent conductivity for the mixture is due to the streaming motions of the particles, then the above data still raises some questions. It is a bit surprising, for example, that there is no continuous change in the slopes of the lines through the lower densities and that there is still a significant shear induced conductivity augmentation at the highest concentrations, $\bar{\nu}=0.5$ where the free range of particle motion is negligible. Also, if the internal convection was a reflection of the heat carried by particles, then one would expect a strong dependence on the heat capacity, ρc_p , of the particles, which is missing from the steel shot data. (This may be due to the fact that the heat capacities of both glass and steel are effectively infinite compared to that of the interstitial air.) There is one possibility that is not accounted for above. The physical explanations presented above discount the importance of the interstitial air as all of its thermal properties are insignificant compared to those of the particles. Yet, it is well established that, as the physical contact area between particles is negligible, the majority of the heat exchanged must cross the interstitial air, so, at least in that context, the interstitial air cannot be neglected. The question remains as to whether that is the only role played by the air. Even if the air has little heat capacity, it does have a great deal more mobility than the particles within the mixture - especially at the larger concentrations. It is possible that a great deal of the observed behavior can be accounted for if a major carrier of heat was the turbulence induced in the interstitial air by the random particle motion. To test this possibility, we are currently planning tests at different mean temperatures which will have correspondingly different thermal properties for the air, and, if this is the case, should show results that scale with those changes.

We have also made an improvement to the construction of the dry granular shear cell. Up until

Figure 3: The effective conductivity of the shearing particle mixture for 3.75mm glassbeads.

Figure 4: The effective conductivity of the shearing particle mixture for 1.9mm glassbeads.

Figure 5: The effective conductivity of the shearing particle mixture for 2.2mm steel shot.

Figure 6: (a) Diagram of the old thermocouple circuit. (b) new thermocouple circuit

this time, the temperatures within the rotating disk were monitored by thermocouples through a slipring assembly and referenced to the temperature, T_B of the constant temperature bath that is used to cool the cold side of the shear cell. This configuration is shown in Figure 6a. We began to notice slight inconsistencies in the measurements made from day to day and were finally able to relate the problem to the sliprings. Like thermocouples, the connections made between the thermocouple wires and the sliprings mate dissimilar materials and, consequently, act somewhat as thermocouples themselves. As the sliprings were heated by friction or by changes in the ambient temperature of the room, they would slightly throw off the calibration of the thermocouples. We came up with a solution to this problem by using a new thermocouple circuit which is shown in Figure 6b. Please note in reading this figure that we are using Type T or Copper (Cu) Constantan (C) thermocouples. Consider thermocouple 1 as monitoring the temperature of interest. The initial problem arose because the connections between the Cu and C legs and the sliprings would create different junctions and thus generate different voltages at different slipping temperatures. This problem is solved by inserting into

the C leg, thermocouple 2 which is reverse junctioned so that its C leg is connected to the C leg of thermocouple 1. The junction of thermocouple 2 senses the ambient air in the room. This acts as a reference thermocouple which references the temperature of thermocouple 1 to the ambient temperature in the room. It has the added advantage that the connection with the sliprings is now made through the Cu leg of thermocouple 2, which generates the same voltage as the connection of the Cu leg of thermocouple 1. Thus, the two voltages cancel each other and the slipring assembly no longer takes part in the temperature measurement. The disadvantage is that the temperature measured by thermocouple 1 is now referenced to the ambient air which may change during the course of the experiment. This problem is eliminated by the insertion of two additional thermocouples, 3 and 4. Thermocouple 3 is reversed junctioned to thermocouple 2 and, like thermocouple 2, senses the temperature of the ambient air and is held as close as possible to a point of passage of the rotating thermocouple 2 - but on the stationary side of the slipring. Thus thermocouple 3 cancels any voltage generated at thermocouple 2. Finally, thermocouple 4, which is immersed in the constant temperature bath which cools the cold side of the shear cell, is added to the system reverse connected with thermocouple 3 - and consequently, is reversed junctioned to thermocouple 1 - to provide the global reference temperature for the measurement. Note that the output leg of thermocouple 1 is the Cu junction so that no further downstream connections - as long as they are made of the same materials - will create additional junctions. In short, thermocouples 2 and 3 are passive players in this circuit and are used only so that the slipring assembly does not play a role in the temperature measurement. Globally, the output reflects the temperature of thermocouple 1 referenced to the constant temperature bath through thermocouple 4.

PARTICLE PRESSURE MEASUREMENTS

We have also been continuing the development of the new particle pressure transducer, which is shown in Figure 7. This transducer has been described in detail in previous reports. Basically, it consists of a diaphragm, made of a fine screen, which is flush mounted into the side of the channel. The screen traps the particles, but lets the gas pass through so that the net deflection of the diaphragm only reflects particle forces. We have been having drift problems with the calibration that may be attributed to a loosening of tension in the screen. Even though we have been chasing the problem for several months, we have not yet been able to isolate the problem. We thought for a while that it might be due to simple stretching of the screen, but one would expect that the screen, after a sufficient period of working in, the screen would stretch no longer. This does not appear to be the case so that we have been looking at other possible causes. One idea, which we have just ruled out, was that the screws used to tension the screen were becoming loose. The interesting part of the problem is that it seems only to

Figure 7: A schematic of the new version of the particle pressure transducer.

arise for large, heavy particles. One may easily comprehend why the problem is greatest for large particles as these will produce a larger loading on the diaphragm. But our results have shown that particles size is not a factor in the particle pressure generation. Consequently, one would not expect to see an effect of particle size on the rate at which the screen is stretched. This may be an indicator that that particle size does have an effect on the internal mechanics of the bed.

Some indication of this may be seen in Figure 8 which shows the particle pressures measured for 0.5mm and 1.2mm glassbeads. (No significant drift in the probe calibration was seen for these particle sizes.) There, it can be seen that for the larger beads the minimum point, which occurs near minimum fluidization, is much less apparent for the 1.2mm beads. This is somewhat surprising as we have earlier reported results which indicate similar behavior for much smaller beads. There we speculated that the increased pressures near the minimum point were due to individual particle fluctuations induced by interaction with the gas phase. However, one would expect that such an effect would be most significant for small particle sizes as these will be most susceptible to the fluid motion. Should the results in Figure 8 prove to be valid, this indicated that some other mechanism must be at work. One can speculate that this effect is due to particle-particle interactions similar to those encountered in a granular flow. The effect we observe here occurs right after minimum fluidization when, with such large particles, the bed is lightly bubbling. The bubble motion will cause the granular material to shear which may induce dispersive stresses within the material. Now the dispersive stresses should scale with the square of the particle diameter and thus be much more significant for the larger glassbeads. This

Figure 8: Particle pressure measurements for two sizes of glassbeads. Here, the gas velocity, U , has been scaled by the minimum fluidization velocity, U_{mf} .

may mean that the minimum might be expected to disappear for both large and small particles. Only further tests will tell.

There is one further advantage to the new probe. In Campbell and Wang¹ it was shown that the old probe design behaved like an RC low pass filter and consequently filtered the applied signal. Now, it is easy to show that, as long as no nonlinear effects creep into the problem, this will not effect the time-averaged response of the system and, thus, will not affect the results presented in Campbell and Wang², but it will undoubtedly affect the instantaneous response of the probe to changes in the particle pressure. In that design, the resistance to flow is applied by the screen and ports leading to the back of the diaphragm and the capacitance is related to the space behind the diaphragm in which fluid can gather. The new design has both a reduced resistance, due to the relatively large area of the screen and a reduced capacitance due to the almost negligible volume behind the screen. Consequently, it may be

¹Campbell, C.S. and Wang, D.G., A particle pressure transducer suitable for use in gas-fluidized beds, Measurement Science and Technology, in press

²Campbell, C.S. and Wang, D.G., Particle pressures in gas-fluidized beds, J. Fluid Mechanics, in press

expected to react almost instantaneously to the applied particle pressure. This allows us to plot time traces of the particle pressure, three examples of which are shown in Figure 9. The three cases were chosen to represent the pressure distribution just after minimum fluidization when the bed is just barely bubbling (Figure 9a), when the bed is freely bubbling (Figure 9b) and when the bed is slugging (Figure 9c). All are for 0.5mm glassbeads with the probe mounted at the 15.2cm location within a bed that was initially 31.8cm deep. Just past minimum fluidization, the particle pressure is small but nearly constant, reflecting the pressure applied by the thermalized motion of the particles. Bubbles and slugs, however, generate large scale fluctuations, as seen by the peaks in the curves. By comparing with previous results, one can see that the fluctuations are many times the average particle pressure. Notice that the magnitudes of the peaks when the bed is slugging are not greater than the largest peaks when the bed is simply bubbling, although the large peaks occur more frequently in the slugging bed. This information should be useful in determining the maximum forces to which particles are subject and thus provide insight into the attrition of particles within a fluidized bed. We also hope to have time to examine the particle pressure that are generated by the passage of individual bubbles, similar to the fluid pressure measurements made by Littman and Homolka³.

³Littman, H. and Homolka, G.A.J., 1973, The pressure field around a two-dimensional gas bubble in a fluidized bed, Chemical Engineering Science, 28, 2231-2243

(a)

(b)

(c)

Figure 9: Time traces of the particle pressure, measured using the new probe. (a) just beyond minimum fluidization, (b) when the bed is freely bubbling and (c) when the bed is slugging. All of the data is for 0.5mm glassbeads.

END

DATE FILMED

01 / 22 / 91