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Summary of Technical Progress:

Abstract:

The objective was to visualize the flow of granular materials in flat bottomed silo. This was done by for dry materials introducing mustard seeds and poppy seeds as tracer particles and imaging them using Nuclear Magnetic Resonance. The region sampled was a cylinder 25 mm in diameter and 40 mm in length. Eight slices containing 128*128 to 256*256 pixels were generated for each image. The size of the silo was limited by the size of the high resolution NMR imager available. Cross-sections of 150mm flat bottomed silos, with the tracer layers immobilized by a gel, showed similar qualitative patterns for both dry and wet granular solids.

Introduction:

Nuclear Magnetic Resonance Imaging can be used to study the flow of granular material noninvasively inside the container. In NMR imaging, a detectable signal is produced by spin-spin (T_2) relaxation. But the T_2 relaxation time is usually very short (less than 1 msec) in the solid state. So the signal from the solid-state particles decays too rapidly to produce a detectable signal. The easiest nuclei to image by NMR are protons in the liquid state because of their strong signal, as well as their abundance in nature. We can avoid the solid state NMR problems by using solid particles containing protons in the liquid state. As a consequence it is convenient to study the flow of solids by observing the liquid state NMR signals given by organic liquids trapped in the solid..

Mustard seeds and poppy seeds were used as tracer particles. Proton spin density images were obtained using a Bruker (Amx 360) Nuclear Resonance Imager. Multi-slice multi-echo pulse sequence was used for all imaging experiments. The imaging probe operated at 360.13 MHz for proton. The gradient strengths were: read gradient $G_x=4.69$ Gauss/cm, phase encoding gradient $G_y=4.69$ gauss/cm, and slice selection gradient $G_z=21.52$ Gauss/cm for a 1.0 mm slice thickness. Typically, 8 slices were acquired with a repetition time (T_r) of 2000 ms and an echo time (T_e) of 20 ms. Spyglass Slicer software purchased from Fortner Research (Sterling, Virginia) was used to analyze images.

A less sophisticated, but still effective method to observe flow patterns that would not be limited by the NMR sampling volume uses colored tracer layers initially laid horizontally. After a certain volume has been discharged, the layers are frozen into place by using an agar solution. The bed is then sliced to observe the layer location.

Results and discussion:

Figure 3.1 shows an NMR image of mustard seeds mixed with glass beads. This is a transverse slice. Glass beads, being in solid state, do not give any detectable signal.

Figure 3.2 shows a schematic diagram of the cylindrical silo used for imaging experiments. The silo was made of polyacrylate and was provided with a slide valve to control the solid discharge.

Stop and flow experiments were done using glass beads. Figure 3.3 shows the flow patterns in glass beads as the material is discharged from the silo. A funnel flow type of flow patterns were observed. The average diameter of the glass beads was 2.5mm. Nine layers of poppy seeds, separated by approximately 1 cm, were used as markers. The poppy seeds layers have been numbered to keep track of their successive positions. The total bed height was 11 cm. The material was discharged from the silo by using the sliding valve. The imaging window was 4 cm long and

2.5 cm in diameter (figure 3.2). Figure 3.3a shows the layers of poppy seeds in glass beads before any discharge of the material. Figures 3.3b-.33f show the successive position of the poppy seeds layers after approximately 0.80 gm of the glass beads were discharged between images. Figures 3.3g-3.3j show the successive position of the poppy seeds layers after the discharge of approximately 2.2 gm of the glass beads between images. In first 6 discharges, there was no wall effect on the flow patterns (Figures 3b-3g). With further discharge, the boundaries of the funnel flow reached the wall (Figures 3.3h-3.3j).

The results indicate that far of the discharge orifice the flow was approximately plug flow with a wall effect layer 3 to 5 particles thick. Funnel flow is observed in the neighborhood of the discharge orifice but the resolution is too low for further mechanism elucidation.

Experiments in 150 mm flat-bottomed silos using both dry and wet material yielded the same qualitative behavior and no distinction could be made of the flow of both types of materials.

Future work:

Mechanical properties of the wet granular materials will be studied next. The surface tension and the contact angle of the wetting liquid are the two main factors that affect the yield loci of the wet granular materials. Therefore, liquids of different surface tensions need to be used. The contact angle will be controlled by modifying the surface of the granular material.

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Figure 3.3: NMR image of 2.5 mm mustard seeds mixed with glass beads of the same size.

Figure 4.2: Schematic image of silo used tracer imaging in NMR flow experiments.

3(a)

3(b)

3(c)

3(d)

3(e)

3(f)

3(g)

3(h)

Figure 3.3: NMR image of the flow patterns of 2.5 mm dry glass beads in a 25 mm flat bottomed-silo.