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Application of Real Time Nuclear Magnetic Resonance Imaging to Studies of Sedimentation and Quick Sand

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Introduction

Many areas of interest to practicing engineers are difficult to study with conventional experimental techniques. Nuclear Magnetic Resonance Imaging (NMRI) has become widely used in medical practice, and recently has been applied to study basic engineering flows of concentrated suspensions, granular flows, and aeration. We wished to determine whether applications of interest to PHRI were practical. We performed two pilot studies on 1) sedimentation of particles and 2) flow induced micro-structural re-arrangements in loosely packed beds. The temporal and spatial resolutions of the NMR images made for these studies are much higher than in medical images, but the region imaged is much smaller.[1]

NMRI

We used the 89 mm vertical bore, 4.7 T, superconducting magnet, the home-built console, and the second generation, home-built, real time nuclear magnetic resonance imaging (RT-NMRI) system in the laboratory of Prof. K. Kose, Institute of Applied Physics, Tsukuba University. A sketch is shown in Figure 1.

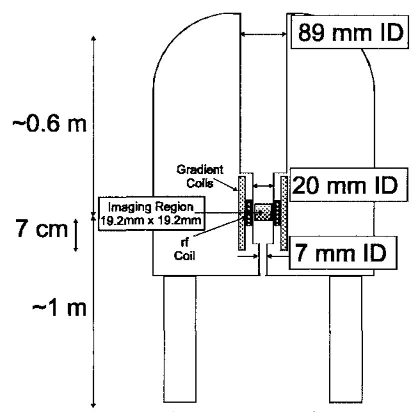


Figure 1. Schematic of magnet used for imaging studies.

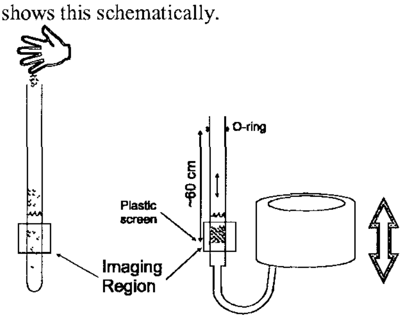
The imaging region for these experiments was a 4 mm thick, square slice, 19.2 mm on a side, oriented vertically, approximately 60 cm below the top of the cryostat. The rf/gradient coil has a 20 mm open bore and there is a 7 mm (ID) port from the bottom of the 20 mm bore to the space below the cryostat. The imaging region is about 7 cm above the point where the opening narrows to 7 mm.

The RT-NMRI system is hosted by a standard Japanese style DOS-PC (PC9821Xa9) which uses a 16 bit PC-9801 bus. The CPU is a 100 MHz Pentium. An A/D board with two sample and hold circuits is installed in the PC and triggered by the NMR sequence. The sampled NMR data stream is Fourier transformed, converted to a magnitude image, scaled to the display range, and copied to a RAM drive and into the dual ported memory of a home-built 256 x 240 Frame Buffer. The Frame Buffer produces NTSC video which is monitored on a CRT and videotaped. The RAM disk allows for storage of over 600 images.

Two types of NMR images were made. The first, sequence (FLASH) had a gradient echo time T_e of 2.7 ms, a repetition time T_R of 4.72 ms, and the data matrix was 128 x 128. The second sequence (EPI) had a T_e of 48 ms, a T_R of 200 ms, the duration of data acquisition T_{DAC} was 40.96 ms, and the data matrix was 64 x 64. The slice thickness was 4 mm and the field of view FOV was 19.2 x 19.2 mm for both sequences, so the voxel dimensions were 150 μm x 150 μm x 4 mm for the FLASH and 300 μm x 300 μm x 4 mm for the EPI.

Experiments

In the first measurement, a 20 mm OD test tube filled with a viscous fluid composed of water thickened with cellulose and doped with $CuSO_4$ was inserted into the rf/gradient coil assembly. A collection of 3.2 mm diameter glass and nylon spheres and 6.4 mm nylon spheres was dropped down a guide tube and imaged at a rate of 1 frame / s. During the experiment, the images of the falling spheres were observed and the test tube was occasionally rotated to bring one of the larger diameter spheres more completely into the imaged slice. Figure 2 a) shows this schematically.



a) b)

Figure 2. The layout of the models inserted into the magnet: a) for the sedimentation experiment and b) for the packed bed experiment.

The second model was constructed from a length of acrylic tube with 20 mm OD and 17 mm ID. A length of 6 mm flexible tubing was threaded up into the bore of the magnet and connected to the lower end of the model. A mixture of 3.2 mm and 6.4 mm nylon spheres was dropped from the open top onto a plastic mesh screen installed approximately 2 cm above the lower end of the model. The other end of the flexible tube was connected to a reservoir. This is shown in Figure 2 b). The reservoir was filled with water doped with $CuSO_4$ sufficient to reduce T_1 to approximately 200 ms. The model was filled by raising the reservoir, and the process of draining and refilling the model was imaged. Then the reservoir was alternately raised and lowered approximately 5-10 cm above and below the loosely packed bed of spheres, producing alternating upward and downward flow. Rearrangements of the spheres were observed with both the FLASH sequence and with the EPI.

Results

Images were recorded on video tape and also digitally processed off-line. Still frames from the gradient echo FLASH sequence are shown in Figures 3 and 5.

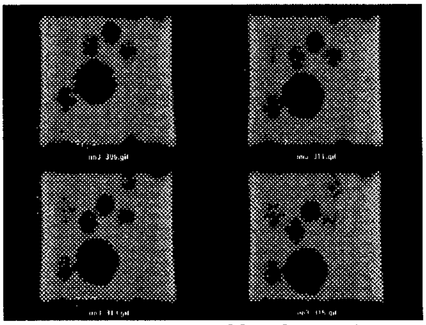


Figure 3. An example of four frames (308, 311, 315, and 318) from the first experiment shows a single 6.4 mm sphere and eight 3.2 mm spheres. This panel of images shows three 3.2 mm spheres traveling with the 6.4 mm sphere, sedimenting at a higher rate than an isolated 3.2 mm sphere.

Positions of the particles were interactively measured in each frame. Gross locations were marked using a cursor, and a region 20% larger than a bead was thresholded at a manually chosen level. The centroid of the pixels with values below the level was calculated and used to estimate the particle location. For sedimentation type experiments, horizontal and vertical velocity components were calculated from the locations and the known frame rate. In Figure 4, the a point is plotted for each of 76 nylon spheres. The x-coordinate represents the horizontal velocity component and the y-coordinate is the vertical velocity component. From analyzing this data we see that the variation of the average V_y is mostly explained by Stokes drag, that there is no average V_x, that the velocity components are not correlated, that the standard deviation of V_y is larger than the standard deviation of V_x but the standard deviation of velocity varies only weakly with velocity.

In the packed bed experiments, the packing fraction and coordination number were calculated before and after each flow induced rearrangement. A sample NMRI frame from these experiments is shown in Figure 5.

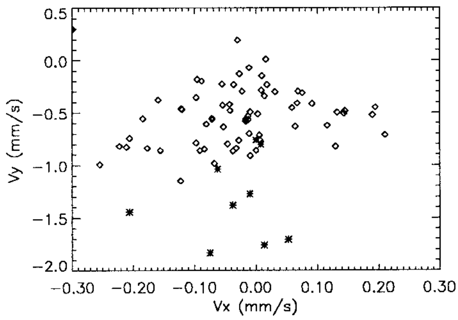


Figure 4. Horizontal (Vx) and vertical (Vy) velocity for 76 nylon spheres are shown. 3.2 mm spheres are shown with open symbols, 6.4 mm spheres with *.

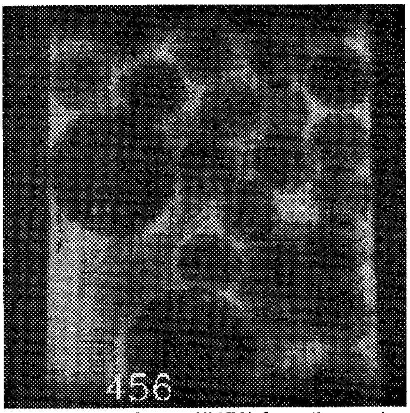


Figure 5. A single frame (#456) from the packed bed experiments. In densely packed regions spheres on both sides of the slice may appear to overlap in the NMR image.

Summary

NMRI imaging is a useful tool for understanding the details of fundamental processes which are of engineering interest. High resolution measurements of the micro-structure of model sedimenting and packed bed systems can be easily produced.

The static field B_0 of the magnet used in these experiments is relatively high for NMR imaging. This favors rapid imaging, because the magnitude of the NMR signal increases with B_0, but it limits materials choice due to increased magnetic susceptibility inhomogeneity.

Acknowledgments

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Reference

1. K. Kose and T. Inouye: A real-time NMR image reconstruction system using echo-planar imaging and a digital signal processor, *Meas. Sci. Technol.* 3 (1992) 1161-1165.