NMRI MEASUREMENTS OF FLOW OF GRANULAR MIXTURES

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ABSTRACT

We investigate complex 3D behavior of granular mixtures in shaking and shearing devices. NMRI can non-invasively measure concentration, velocity, and velocity fluctuations of flows of suitable particles. We investigate origins of wall-shear induced convection flow of single component particles by measuring the flow and fluctuating motion of particles near rough boundaries. We also investigate if a mixture of different size particles segregate into their own species under the influence of external shaking and shearing disturbances. These non-invasive measurements will reveal true nature of convecting flow properties and wall disturbance. For experiments in a reduced gravity environment, we will design a light weight NMR imager. The proof of principle development will prepare for the construction of a complete spaceborne system to perform experiments in space.

INTRODUCTION

Particle technology is a science in its infancy and models capable of predicting the behavior of dry granular systems over the range of observed phenomena are generally unavailable. Consequently, engineers are forced to design systems based only on experience and this sometimes leads to failure and breakdown of systems at a tremendous economic cost. There is a clear need to obtain an understanding of the fundamental physics governing these complex materials in order to advance the science of particle technology so that predictive models and scaling laws can be developed.

One of the most intriguing and ubiquitous phenomenon which occurs in particulate mixtures is segregation. When subjected to various mechanical disturbances which typically occur in industrial handling processes, a bulk solid tends to segregate and this is generally an undesirable effect which could have serious implications on the integrity of end products. While several mechanisms of segregation have been proposed, a clear relationship between them has not been established. Convective motions of particles due to vertical vibration has captured some of the great minds including Faraday (ref.1). Furthermore, convection flows due to wall-shear have recently attracted researchers from different disciplines (refs. 2, 3, 4, 5).

Traditionally, granular flow properties have been measured non-invasively from outside the flow by optical methods or high performance video cameras, or invasively by electronic sensors. All non-invasive methods fail when the particle concentration is high. In the proposed experiment we employ Nuclear Magnetic Resonance Imaging (NMRI) which does not suffer concentration related opacity problems and can measure concentration and velocity anywhere and in any orientations in the flow. Emphasis will be placed on ground based experiments to lay the groundwork for future microgravity experiments. In parallel with ground-based NMRI experiments, we will design/construct a light weight NMRI device which can be transported into a reduced gravity environment.

NUCLEAR MAGNETIC RESONANCE IMAGING

NMRI Basics

An atomic nucleus with a magnetic moment, for example, protons, the nuclei of hydrogen atoms, processes around the magnetic field like a spinning top processes about the direction of gravity. There is a unique precession frequency called the Larmor frequency for each atomic nucleus in a particular strength of magnetic field. A known spatial variation of the magnetic field will cause the nucleus at each point to precess at a different Larmor frequency. MRI measures the distribution of signals as a function of this frequency and relates it to the spatial distribution of nuclear spins. This technique is now widely used for non-invasive diagnosis in clinical medicine.

The use of MRI for studying flowing samples is more complex than it is for measuring static samples but it offers a unique technique for non-invasively studying the detailed concentration and flow behavior anywhere in the flow regardless of optical or acoustic opacity. For the evaluation of velocities, we use the so-called phase method in this work. It works on the principle that the phase of the macroscopic magnetization comprised of the aggregate nuclear moments in an element of volume evolves in a manner depending on its motion in the presence of a magnetic field-gradient. We obtain the velocity information from the measured phase behavior of the magnetization in each image voxel. By applying the magnetic field gradient in a certain sequence, we make the phase shift proportional to the average velocity in the voxel with the proportionality factor an experimentally controllable parameter called the first moment of the gradient. This is in addition to phase-encoding which is a procedure to encode a spatial dimension in the image. Basics of MRI for studying flowing fluids have been described elsewhere (refs. 6 and 7).

Previous NMRI Flow Measurements of Granular Flow

Granular Flows in a Rotating Cylinder

In our rotating horizontal cylinder experiment, we demonstrated the feasibility to measure steady-state granular flows by MRI (ref.7). The cylinder is half-filled with particles, inserted into the bore, and rotated with the long nonmagnetic shaft which is required to keep the motor far from the magnet. Most of the particles undergo solid body translation with the cylinder without slipping while the shear flow takes place along the free surface which is inclined at the dynamic angle of repose. At these rotation rates, no transient effects, such as wave propagation, were seen through the acrylic cylinder or end caps and this was supported by MRI evidence as discussed below.

Protons are best suited for MRI because of their strong signal as well as their abundance in nature. We have used mustard seeds which yield excellent proton NMR signals from their oils. Based on measurements of a few hundred representative seeds, their average diameter is 1.5 mm, the average density is 1.3 g/cm^3, and the average coefficient of restitution is 0.75 when they are dry and at room temperature.

An acrylic cylinder of length 300 mm with an inner diameter of 70 mm was half-filled with mustard seeds and inserted into a larger cylinder with an inner diameter of 88 mm. The gap between the concentric cylinders was packed with mustard seeds which formed a ring undergoing rigid body rotation with uniform concentration and predictable velocity profiles. These profiles could then be used as velocity and concentration references at each rotation speed.

Our MRI experiment, the Cartesian components of the velocity, V_x and V_y, were measured in two independent experiments with a total measurement time of approximately 15 minutes. MRI measures average flow properties over this time within each voxel averaged over the 8mm thick slice. Figure 1 shows NMR images of velocity components parallel and perpendicular to the free surface of particles flowing at different rotations speeds. Figure 2 shows a schematic view of particle motion in a rolling mode at 17 rpm with the corresponding velocity profile along a line A-B. f is at the free surface and r at the cylinder wall. F is the sliding layer consisting of a constant shear portion f-f' and a variable shear portion r'-f'. The particles from r' to r do not flow but rotate as a solid body.

Proposed NMRI Research

NMRI experiments

We propose to investigate the origins of segregation due to external shearing disturbances, first on the ground and then in space. It has been observed that the radial segregation occurs very quickly and axial segregation occurs in a much longer time scale under the influence of gravity. In a reduced gravity environment, however, other mechanisms may amplify and segregation phenomena may take different forms. By decoupling gravity effects, we hope to investigate mechanisms of segregation which are important in a reduced gravity environment where, in future, many materials are expected to be handled in particulate forms.

NMRI experiments will be conducted using non-magnetic shaking and shearing devices inside the limited bore space of the magnet. Figures 3 and 4 show possible construction designs for shaking and shearing devices, respectively. For the ground experiments, various variations of the shaking design shown in fig.3 will be used to investigate convection flow, the propagation depth of wall disturbances, and the effects of the vertically shaking bottom wall. Some of the same designs will be used to investigate transverse and longitudinal shaking in the basket. The inner walls are roughened to provide enough shearing effects on the flowing particles.

In the above experiments, we first use monosize particles in order to establish a link between boundary conditions and convection flows with and without gravity effects. Measurable flow properties include concentration, mean velocity, and fluctuation velocity anywhere in the sample, near and far from the boundary. Control parameters include the solid volume fraction, particle properties (size, elasticity, and shape), wall roughness, shaking amplitudes and frequencies, and shearing rates. Since particles' motions in a convection flow are influenced by both the mean flow and velocity fluctuations, the above results provide, for the first time, non-invasive information connecting particle fluctuations due to shaking/wall-shearing to global convective motion. For the Couette shearing experiments, we will also measure the slip velocity by detecting the difference in the average velocity of the particles glued on the inner wall and that of flowing particles adjacent to the wall. We will then use a mixture of two different size particles to investigate conditions where convections cause size-segregation. We will make an effort to find particles whose mechanical properties are identical but NMR signals are not. For example, particles encapsulated with different liquids with distinguishable NMRI signals will be sought. As stated earlier, segregation processes are essentially nonsteady and their time durations depend on many parameters. For the slower segregation process, NMRI will provide concentration, mean velocity and fluctuation velocity continuously. For the faster evolving processes, we stop the flow periodically to image dynamically induced static structures of each segregating constituent. With distinguishable particles, it will be possible to investigate spatio-temporal distribution patterns of each segregating component.

Development of Spaceborne NMRI Components

We propose a proof-of-principle project to demonstrate the feasibility of a spaceborne NMRI apparatus. The proposed ground based laboratory NMRI represents necessary preludes to spaceborne experiments and the demonstration of a low-power, light weight, magnet capable of making NMR images must precede the actual spaceborne unit. After our success with the proposed magnet, it will be easy to predict how to scale it up for any experiment with particular utility and space limitations. The requirements for such an apparatus are: 1) relatively light weight; 2) low electrical power consumption; 3) no cryogenic fluids; and 4) adequate sample space, signal to noise ratios and spatial resolution.

Non-imaging NMR apparatus, based on permanent magnets, have been known but such magnets were unsuitable for NMR imaging or too massive for spaceborne uses. We will design and build a cylindrical permanent magnet system (ref.8) with an opening of roughly 5 cm and a field strength of around 0.4T. That would give a respectable proton Larmor frequency of 17 MHz. The best candidate for the material is NdFeB which, in addition to its superior magnetic properties, is more than 10% lighter than SmCo. A 6 inches od, 2 inches id, and 6 inches long NdFeB Halbach magnet will weigh 40 pounds.

Figure 5 is a sketch of the proposed magnet. It consists of axial segments of magnetic material with their transverse magnetizations rotated between segments as shown. The magnetic field is transverse and the return flux is confined to the volume of the magnet, eliminating the need for a separate iron return path. The homogeneity depends on the number of segments used as well as the quality of each segment of magnetic material.The Halbach magnet has several advantages:

- Its cylindrical shape with a transverse magnetic field is ideal because efficient longitudinal solenoid rf coils can be used for the NMRI experiment.
- The magnet will be fairly light because of the lack of an iron field-return path.
- There will be little or no stray magnetic field.
- No electrical power is required.
- Fast and accurate Fourier images will be possible because of the switching gradients will not induce eddy currents in the poorly conducting magnetic material.

One of the problems to be solved is how to optimally shim such a magnet with the least weight including that of the shim/gradient current supplies. The best results may require ferromagnetic shims together with basic current shimming with auxiliary coils. Take the cylindrical axis to be z, the field along y, and the mutually perpendicular direction to be x. The geometry for the shim/gradient coil providing the gradient along y (the magnet field) can be a simple quadrupole type with four axial wires (ref.9). The four wires are placed 90 degrees apart so, for example, in the 8-segment Halbach magnet, they can be in the centers of the four segments located 45 degrees off axis, as shown in fig.5.

The transverse gradients are more difficult. The x coils can be some variant of the longitudinal wire coil like the quadrupole but with different symmetry of the wire placement which will create a field that is odd with respect to x with a field that vanishes at center. The currents and the wire placements must be adjusted for the best field linearity. The y coils can be a variant of axially displaced saddle coils which create a field that is odd with respect to z. Again, the wire placement must be optimized for best effects.

In order to save weight, we will make a dedicated image sequencer "on a board" with a computer (ref.10). Imaging parameters for density and velocity images will be preset for the experiments. Because this will be a dedicated proton imager with no need for other frequencies, the rf transmitter and receiver circuits can be narrow-banded at the Larmor frequency to save weight.

The NMRI apparatus will be developed as a hybrid of portable and laboratory components. The portable components, i.e., the magnet assembly and the NMRI electronics including the microprocessor, which are the truly novel items, will be developed by us while standard items such as power supplies and audio amplifiers for driving the magnetic field gradients will be of the ready-made laboratory variety.

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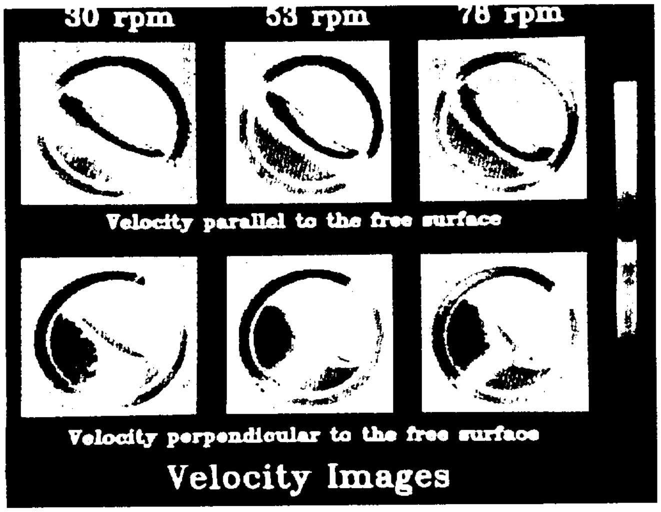

Figure 1. NMR velocity images.

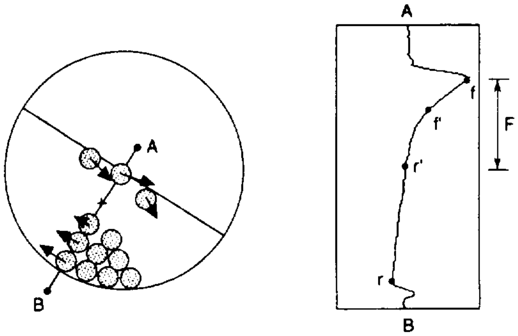

Figure 2. Schematic view of particle motion and velocity profile.

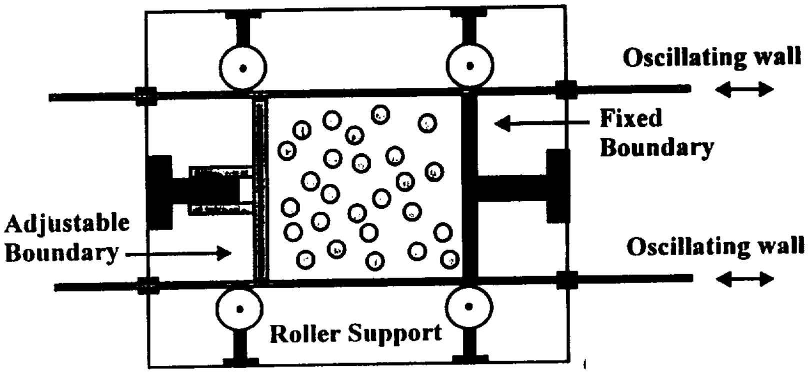

Figure 3. A schematic drawing of the shaking apparatus. Parts colored in black are non-moving components. Parts colored in gray are moving components including particles. Oscillating walls are roughned by gluing particles that are identical to flowing ones.

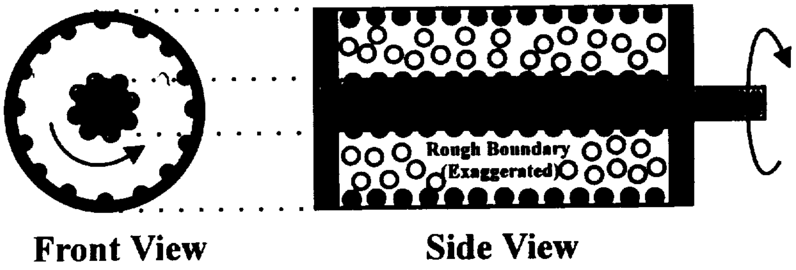

Figure 4. A schematic drawing of the Couette shearing device. Moving partis are shown in gray. Inner walls are roughned by glued particles in order to assure rigorous interactions between the walls and flowing particles.

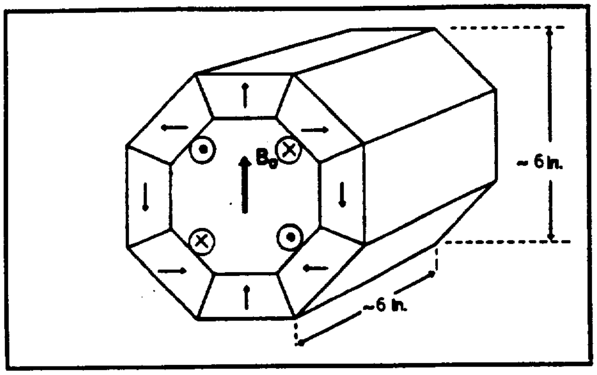

Figure 5. A sketch of the proposed magnet.

Pattern Formation, Flow Instability, and Thermocapillary Flows