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Invited paper

Application of magnetic resonance imaging techniques to particulate systems

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Abstract—Magnetic resonance imaging (MRI) is a well-established technique in the medical field, typically for imaging liquid water in the human body, but it is increasingly being used in the field of engineering and materials science. A particular section of this is in the area of particulate systems and granular material flows. MRI is being used to provide a unique insight into particle distribution and motion with *in situ* measurements. In this paper we discuss how judicious choice and development of imaging technique applied to various different granular systems can provide us with valuable new data on the processes occurring in granular flows. Experimental results focus on rotating bed segregation, velocity imaging in vertical fluidized beds and phase-resolved velocity distributions within vertical vibro-fluidized beds. A discussion of the various imaging techniques used to acquire these data is also given.

Keywords: Magnetic resonance imaging (MRI); flow imaging; rotating kilns; fluidized beds; vibro-fluidized beds.

1. INTRODUCTION

Granular materials and granular flows play an important role in a wide variety of industrial processes, including rotary kilns, mixing, fluidization and flows of particles. These processes are industrially important in many areas, including reaction engineering, pharmaceuticals, food processing and materials processing. There is therefore much research and interest in advancing the understanding of granular flows. Despite their importance, the understanding of granular flows is relatively undeveloped compared with fluid flows for several reasons; in particular, the complex and numerous particle interactions, and the difficulty of making measurements inside these opaque systems. Magnetic resonance imaging (MRI) has long been utilized in medicine for non-invasively imaging structure and transport

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in the human body, and more recently has been extended for use in other science and engineering fields where the ability to probe local molecular environments and motion in opaque samples can be extremely valuable. Most work to date has focused on the imaging of liquid flows rather than gas or solid flows, but there is an increasing interest in these systems. Gas imaging is less common simply because of the low concentration producing low signal-to-noise (SNR) images, although interesting results can be obtained with suitable averaging [1] or the use of hyperpolarized gases [2]. In solids this is often not the case, but the lifetime of the signal from rigid materials is very short and usually makes MRI of solid materials impossible with standard techniques. Imaging of solids can sometimes be done with single-point techniques such as SPRITE [3] and STRAFI [4], but these techniques present significant limitations on spatial and temporal resolution, and for the measurement of motion. The most common approach to imaging particulate systems with MRI has therefore been to identify particles that have a hard outer shell and so behave like solid particles in motion, but have liquid or liquid-like centers and so can be observed with MRI techniques. Mustard and poppy seeds are often used [5], although porous particles soaked in liquid and other particles filled with a liquid core have also been used. A detailed introduction to nuclear magnetic resonance (NMR) and MRI can be found elsewhere [6, 7].

In this work we focus on the MRI techniques which we have used and developed to obtain a wide range of information about moving particulate systems, specifically rotating kiln segregation, gas fluidized beds and vibro-fluidized particles. Results shown are predominantly for rotating bed segregation as further results for the fluidized bed studies can be found elsewhere [8–10]. In each case, there are MRI challenges to be overcome as they are all transient systems where we wish to image the ‘solid’ particles and it is by the application of several techniques that we can begin to build up a greater understanding of the underlying processes.

2. MATERIALS AND METHODS

2.1. Rotating bed

All rotating bed experiments are performed in a Perspex® tube of 49 mm internal diameter and approximately 2 m in length, with roughened interior walls. The tube ends used were a smooth plastic with a tight fit within the tube and their position along the length of the tube can be moved in order to select an appropriate bed length to study. Figure 1 shows a schematic view of the experimental apparatus. The tube is supported using several rollers above and below the tube, and the motor could be operated in the range 0–30 r.p.m., such that the centripetal acceleration was always small relative to gravitational acceleration. Poppy and millet seeds in the ratio 25:75 were mixed and placed into the cylinder before rotations were started. Physical properties of the particles (poppy seeds and millet, respectively) were as follows: density 1000 and 1150 kg/m^3, average diameter 1.1 and 2.3 mm, and angle