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Granular temperature in a liquid fluidized bed as revealed by diffusing wave spectroscopy

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ABSTRACT

We report granular temperature and solid fraction fields for a thin rectangular bed (20×200 mm cross-section and 500 mm high) of glass particles (mean diameter of 165 μm and density of 2500 kg/m^3) fluidized by water for superficial velocities ranging from $0.05U_t$, which is approximately double the minimum fluidization velocity, to $0.49U_t$, where U_t is the particle terminal velocity estimated by fitting the Richardson–Zaki correlation to the bed expansion data. At superficial velocities below $0.336U_t$, the solid fraction and granular temperature are uniform throughout the bed. At higher superficial velocities, the solid fraction tends to decrease with height above the distributor, whilst the granular temperature first increases to a maximum before decaying towards the top of the bed. Correlation of the mean granular temperature with the mean solid fraction and the local granular temperature with the local solid fraction both suggest that the granular temperature in the liquid fluidized bed can be described solely in terms of the solid fraction. The granular temperature increases monotonically with solid fraction to a maximum at $\phi \approx 0.18$ where it then decreases monotonically as ϕ approaches the close-packed limit.

1. Introduction

Flowing dense granular media are ubiquitous—just a few examples include fluidized beds (FBs), screw conveyors, hopper flows, granulators and soils during seismic events. In such granular flows, dissipative granular particle collisions are dominant. These particle collisions produce a random motion of the particles which is quantified by the so-called granular temperature, which is directly related to the mean-square of the velocity fluctuations about the mean flow velocity, $\langle \delta v^2 \rangle$. This quantity, which was first introduced by Ogawa (1978) in the earliest of kinetic theories of granular flows, now underpins many of the current theories (e.g., Lun et al., 1984; Ding and Gidaspow, 1990; Goldhirsch, 2003) and is seeing increasing use in other contexts such as heat transfer (Hunt, 1997), segregation (Yang, 2006), erosion (Lyczkowski and Bouillard, 2002), attrition (Campbell, 1994) and aggregation (Tan et al., 2004) in various particle processing technologies. As validation of these theories at the most fundamental level requires independent knowledge of the granular temperature, its experimental determination is highly desirable.

Much of the experimentally determined granular temperature data is for gas FBs (see Biggs et al. (2008a) and references therein) due to their extremely wide industrial application. However, liquid FBs are of increasing interest as they find application in hydrometallurgy, food technology, biochemical processing, electrochemical reaction, and water treatment (Fan, 1996). In addition, liquid FBs expand homogenously in contrast to gas FBs, which are usually unstable and give rise to bubbling behaviour. This makes liquid FBs particularly suitable for testing nearly-homogenous two-phase flow models across a wide range of solid fractions (Gevrin et al., 2008).

In the last decade, there have been several experimental studies of velocity fluctuations in liquid FBs, although for very limited ranges of experimental conditions. Limtrakul (1996), Kiared et al. (1997) and Limtrakul et al. (2005) used non-invasive radioactive particle tracking techniques to measure velocity fluctuations. Their work was, however, focused on the radial distribution of the granular temperature (amongst other quantities). Segre and McClymer (2004) and Tee et al. (2008) used particle image velocimetry (PIV) to measure velocity fluctuations in a very dilute system at a mean solid fraction of around 0.1. Gidaspow and Huilin (1997) determined velocity fluctuations for a few solid fractions in a two-dimensional liquid FB using a video imaging technique. Also using a video imaging technique, Spinewine et al. (2003) found that the velocity fluctuations decreased monotonically with increasing solid fraction. Using diffusing acoustic wave spectroscopy (DAWS), a method analogous to that used by us here, Cowan et al. (2000) observed on the other hand a weak maximum in granular temperature at intermediate solid fractions.

We report here a detailed study of the granular temperature in a liquid FB. Using diffusing wave spectroscopy (DWS), we determine the spatial variation of the granular temperature along with the

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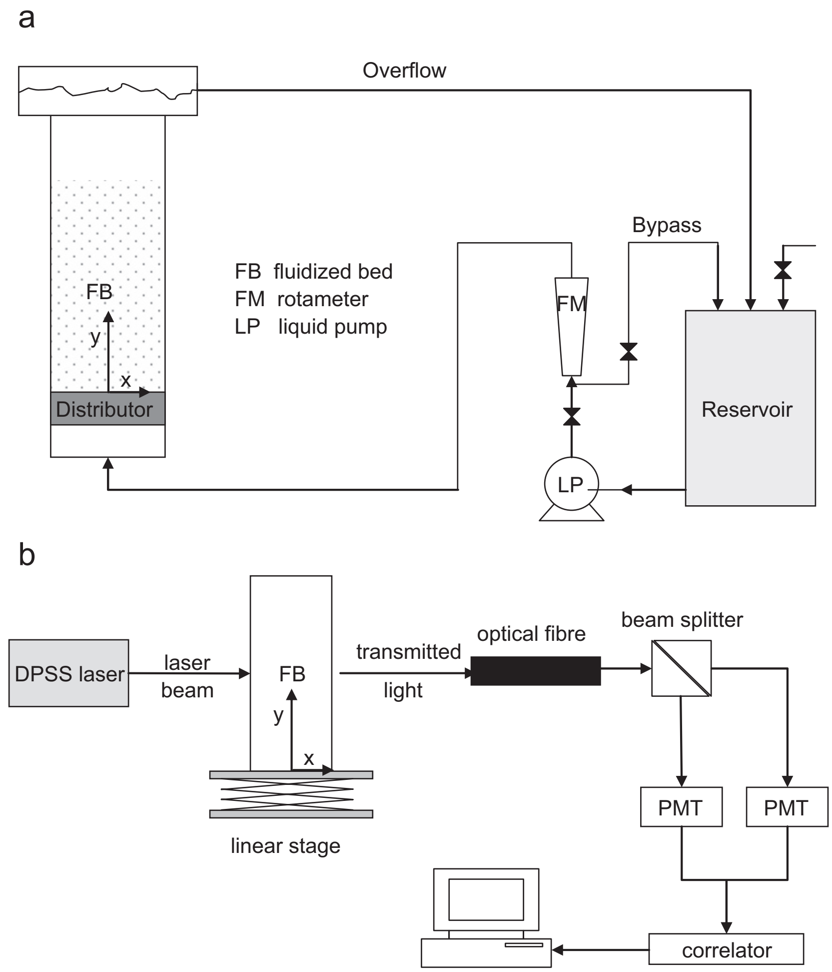

Fig. 1. Schematic diagram of (a) liquid FB apparatus and (b) DWS apparatus.

associated local solid fractions for a thin, rectangular bed of small glass particles fluidized by water across a wide range of superficial velocities (i.e., mean solid fractions). We first outline the experimental details, including an overview of DWS and details pertaining to the apparatus and the particulate material, and the experimental procedures used. This is followed by presentation of the results obtained and their discussion.

2. Experimental section

2.1. Apparatus

2.1.1. Fluidized bed

The FB apparatus is illustrated in Fig. 1(a). A 0.5 m high rectangular bed of 200 mm×20 mm cross-section was mounted on a linear stage so that different points of the bed could be investigated with ease. The distributor, which consisted of a stainless steel mesh of 40 μm apertures and a 5 cm deep packed bed of 1.5 mm stainless steel beads, was designed to provide highly uniform and homogeneous fluidization. Water was pumped by a centrifugal pump from a feed reservoir through the bed before being passed back into the reservoir via an overflow at the top of the bed. The water flow rate was measured by a calibrated rotameter (KDG 2000, KDG flowmeters, UK) and the temperature of the water was maintained at 20 ± 0.5 °C.

The FB material was made up of SiLibeads type S glass particles (Sigmund Lindner, UK) of density $\rho_p = 2500\,\text{kg/m}^3$. The as-supplied particles were carefully sieved between two close meshes to obtain a narrow diameter distribution of $d_p = 165 \pm 15\,\mu\text{m}$. The height of the material in the FB when defluidized was 75 mm.

2.1.2. Diffusing wave spectroscopy

DWS (Weitz and Pine, 1993), which has now been applied extensively in the study of particle dynamics in various dense granular systems (Menon and Durian, 1997a,b; Xie et al., 2006; Biggs et al., 2008a,b; Zivkovic et al., 2008) was used here in the transmission mode as illustrated in Fig. 1b. A 400 mW diode pumped solid state (DPSS) linearly polarized laser (Torus 532, Laser Quantum Ltd., Cheshire, UK) operating at a wavelength of $\lambda = 532$ nm in single longitudinal mode is used to illuminate one side of the bed at the point of interest with an ∼2 mm diameter laser beam. The light passes through the bed, being scattered many times by the particles before exiting the back of the bed as a diffuse spot of ∼20 mm diameter for our bed. The scattered light was collected over time, t, with a single mode optical fibre (OZ Optics Ltd., Ottawa, Canada). The collected light signal was bifurcated and the 50/50 split light signal fed into two matched photomultiplier tubes (PMTs) to reduce spurious correlation due to possible after-pulsing effects of the detector. The intensity outputs $I(t)$ from the PMTs were amplified and fed to a multi-tau digital correlator (Flex 05, Correlator.com, US), which performed a pseudo cross-correlation analysis in real time to give the intensity autocorrelation function (IACF), $g_2(t)$, that was stored on a PC for further offline analysis as detailed below.