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Lagrangian particle tracking in mechanically agitated polydisperse suspensions: Multi-component hydrodynamics and spatial distribution

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ABSTRACT

We investigated the local hydrodynamics and phase distribution of complex polydisperse suspensions 'just-suspended' by a down-pumping pitched blade impeller in a mechanically agitated vessel. The solid–liquid mixtures consisted of five size fractions of coarse glass particles in water, and the total concentration was varied within the range 2.4–23.6 vol% (5–40 wt%). The whole flow field and spatial distribution of the liquid phase and of each particle size fraction were resolved using the Lagrangian technique of positron emission particle tracking (PEPT). For the first time, it has been possible to conduct such a detailed 'pointwise' examination within an opaque polydisperse suspension of this type and complexity. For each component of the two-phase flow, results are presented in the form of maps of local velocity, solid concentration and time-averaged slip velocity, as well as plots of spatial suspension uniformity index. The accuracy of measurements is verified through six-component mass balance and mass continuity calculations.

Introduction

Industrial processing of solid–liquid suspensions such as bio-slurries, minerals, food, crystallisation and catalytic mixtures, is commonly conducted in mechanically agitated vessels. A key aspect of such a process is the achievement of good mixing to ensure a good distribution of all the different phase components and enable an efficient interaction between them. The methods generally used for designing stirred vessels for solid–liquid mixing have tended to follow a global 'black-box' approach, but a more detailed description of the internal flow structure is needed to enable more rational rules to be established for equipment and process design. The advent of powerful measurement and modelling techniques in recent years has revivified interest in this field and increasingly more attempts are being devoted to better understand the mechanisms behind particle suspension and distribution in such systems (Kagoshima and Mann, 2006; Guha et al., 2007; Unadkat et al., 2009; Tamburini et al., 2009).

Homogeneous suspension exists when the solids are practically uniformly distributed throughout the vessel volume, i.e. there are no solids concentration gradients, and for a polydisperse system the particle size distribution should also be approximately the same everywhere. This condition is required when it is necessary to obtain uniform treatment of all the particles, when a suspension must be dispensed at a constant concentration for sampling, for further processing, or for packaging and the process result that the mixing has to achieve is that the discharge from the vessel should enable homogeneous filling of packaging lines, e.g. meat/vegetable pieces in a sauce or fruit particles in yoghurt. Another example would be in a crystalliser where a non-uniform solids distribution may cause high local supersaturation levels and hence non-uniform crystal growth which is undesirable. Therefore, knowledge of the local solid concentration and distribution in polydisperse systems, where multiple particle size fractions are suspended in a liquid phase, would be useful for optimum process design, development and scale-up.

Detailed experimental investigation of these phenomena has remained a major challenge for decades due to a lack of adequate measurement techniques capable of probing such opaque multiphase systems (Barigou, 2004). Among the various flow visualisation techniques, laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) have become the most reliable to examine complex flow fields in optically transparent single-phase systems (Ducci and Yianneskis, 2006; Chung et al., 2007, 2009). Application to multi-phase studies, however, has been confined to dilute suspensions as these techniques fail completely in dense systems which are opaque.

Attempts at local measurements in these complex systems have been chiefly limited to the measurement of mean axial

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solid-concentration profiles at relatively low concentrations, using a single vertical conductivity or capacitance probe traverse or a withdrawal technique (Barresi and Baldi, 1987; Brunazzi et al., 2004). More recent experimental studies using electrical resistance tomography (ERT) demonstrated, albeit mainly qualitatively, how visualisation of gas, solid or liquid distribution can help improve understanding of mixing processes (Wang et al., 2000). However, none of these methods is capable of probing concentrated suspensions in detail to acquire quantitative information on the local flow dynamics of the different phase components or their individual 3-D distributions.

Rammohan et al. (2001) developed a more sophisticated computer automated radioactive particle tracking (CARPT) technique based on gamma-ray emissions. It has been argued for some time that Lagrangian data obtained from a single particle trajectory, where such data can be accurately determined, may unravel valuable mixing information which is not provided by Eulerian observations (Villermaux, 1996; Wittmer et al., 1998; Doucet et al., 2008; Guida et al., 2009; Barigou et al., 2009). The technique of positron emission particle tracking (PEPT) allows non-invasive probing of opaque fluids and within opaque apparatus by using a single small sub-millimetre positron-emitting particle as flow tracer (Parker and Fan, 2008). Being able to examine flow phenomena in three dimensions in dense opaque systems that could not be observed as effectively by using other techniques, PEPT is particularly useful for the study of non-transparent multi-phase or multi-component flows, where one component can be selectively labelled and its behaviour observed (Fangary et al., 2000, 2002).

A number of mixing studies have reported that in stirred solid–liquid systems, variation in the particle size produces significant effects on the fluid dynamics and phase distribution. For example, Virdung and Rasmuson (2007) using LDV measurements showed that the fluid velocity fluctuations due to turbulence in the liquid phase were higher in solid–liquid suspensions than in single phase flow, an effect that increased with particle size. Although their simulations involved particle sizes less than 0.1 mm, Altway et al. (2001) showed that the pattern of solid concentration contours for different particle sizes was qualitatively similar; however, smaller particles showed a more uniform distribution. Using larger particles with 0.1 mm < d < 0.5 mm, Špidla et al. (2005) experimentally confirmed by means of a conductivity probe that smaller solid particles generate a more homogeneous suspension. Their results also showed that the homogeneity of the solid–liquid suspension improved with increasing average solid concentration. We recently observed the same effect using coarse monosized or binary suspensions of glass particles ($d \sim 1, 3$ mm) (Guida et al., 2010a, 2011; Liu and Barigou, 2013).

In this paper, we report on the use of the Lagrangian PEPT technique to study the mixing of dense polydisperse mixtures consisting of glass beads of five different size classes suspended in water. We present for the first time extensive data for these polydisperse systems containing up to 40 wt% (23.6 vol%) solids. Detailed Lagrangian information is obtained on particle and fluid trajectories which is converted to give a 'pointwise' Eulerian description of the flow field as well as the spatial distribution of each of the liquid and solid components of the mixture.

Materials and methods

Experimental conditions

The mixing experiments were conducted in a fully-baffled flat-base Perspex vessel of diameter $T = 288$ mm, agitated by a down-pumping 6-blade 45° pitched-turbine (PBT) of diameter $D = T/2$, as illustrated in Fig. 1. The height of the suspension was set at $H = T$ and the impeller off-bottom clearance was $T/4$. The suspending liquid was an aqueous solution of NaCl of density 1150 kg m^{-3} – NaCl was added to enable the water density to be matched to that of the resin PEPT tracer used to track the liquid phase – and the solid particles used were spherical glass beads of density 2485 kg m^{-3}. Five nearly-monomodal particle size fractions, ($d_p \sim 1.0$ mm; $\sim$1.5 mm; $\sim$2.0 mm; $\sim$2.5 mm; $\sim$3.0 mm) were used to make polydisperse solid–liquid suspensions. The five size fractions were mixed in equal proportions with a total solid mass concentration, X, varying from 0 to 40 wt%, i.e. $X_1 = X_2 = X_3 = X_4 = X_5 = 0.2X$. Experiments were conducted under the 'just-suspended' regime corresponding to the minimum impeller speed for particle suspension N_{js}, which was visually determined in the transparent vessel according to the well-known Zwietering criterion (Zwietering, 1958), i.e. no particle remains stationary on the bottom of the tank for longer than 1–2 s. The experimental mixing conditions are summarised in Table 1.

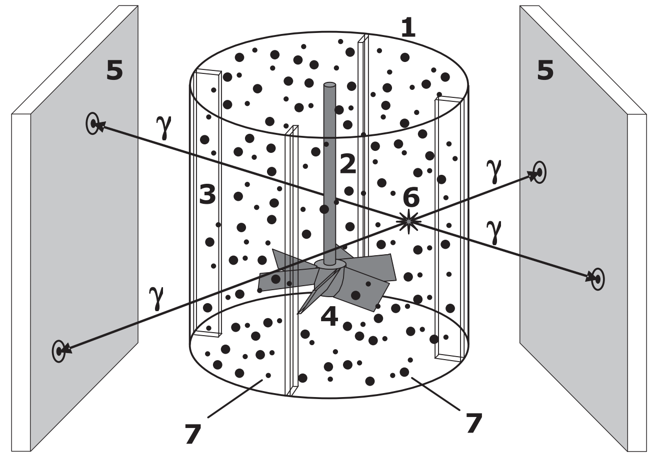

Fig. 1. Experimental set-up for studying the mixing of polydisperse suspensions by PEPT: 1 tank; 2 shaft; 3 baffle; 4 PBT; 5 γ-ray detectors; 6 PEPT particle tracer; 7 polydisperse glass particles.

Multi-component positron emission particle tracking

The multi-component two-phase flow field and spatial phase distribution in the mixing vessel were determined by the technique of positron emission particle tracking (PEPT), as illustrated in Fig. 1. PEPT uses a single positron-emitting particle as a flow tracer which is then tracked in 3-D space and time to reveal its full Lagrangian trajectory. The measurements can be analysed in two different ways: a Lagrangian-statistical analysis exploiting concepts such as residence time, circulation time and trajectory length distribution; or, a Lagrangian–Eulerian analysis used to extract local Eulerian quantities from the purely Lagrangian information contained in the tracer trajectory such as the three velocity components (u_r, u_z, u_θ) of each phase component, its local occupancy or time-average concentration (Guida et al., 2012). PEPT has been validated by comparing its measurements with PIV in water, and has been shown to be an accurate and reliable technique

Table 1
Experimental conditions.

C (vol%)	X (wt%)	N_{js} (rpm)	Re_{imp} (–)
2.4	5	378	1.5×10^5
4.9	10	450	1.8×10^5
10.4	20	510	2.0×10^5
23.6	40	612	2.4×10^5