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A SINGLE PARTICLE VIEW OF FLUIDIZATION

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ABSTRACT

Radiation-based single particle tracking approaches have distinct advantages in investigating opaque particle systems such as fluidized beds. The principles of one of these – positron emission particle tracking (PEPT) – are summarised here, together with recent developments in the use of the technique. Applications in bubbling beds, circulating beds, in heat transfer and in coating are illustrated. PEPT is beginning to be used in validation of computational methods for simulating fluidized beds, such as discrete element methods.

INTRODUCTION

Both fundamental understanding and practical design of fluidized beds requires the solids motion to be understood, preferably on a single particle level. While many single particle tracking methods have been used, radioactive tracers have distinct advantages in opaque systems.

It is important to distinguish between the two basis types of single particle radiation tracking techniques: “proximity” techniques such as CARPT (computer automated radioactive particle tracking technique), developed at the University of Washington, St Louis, and the École Polytechnique, Montréal; and PEPT (positron emission particle tracking) developed at the University of Birmingham, UK. In CARPT, a gamma emitter is placed within the system of interest and its position found by measuring the relative count rates in an array of detectors. In PEPT, each emitted positron (positive electron) annihilates with a nearby electron to produce a pair of back-to-back gamma rays, so that multiple annihilations produce a forest of lines which cross at the particle position. That position can then be found by triangulation, allowing for a certain percentage of erroneous data due to scattering. Both techniques are used to image solids flows in industrial processes and both have advantages and disadvantages. An advantage of PEPT is that no precalibration is required. In both techniques it is desirable to use the actual particles of interest as tracers, and advances in radioactive labelling allow this in many cases (1).

EXPERIMENTAL TECHNIQUE DEVELOPMENT

PEPT (2) is derived from the commonly-used medical diagnostic technique of positron emission tomography (PET). Whereas in PET a distribution of radioactivity is imaged in a relatively long time (some minutes), in PEPT a single small source of radioactivity is located very frequently (normally up to several 100 times per second). As mentioned above, the basis of positron emission techniques is that positrons emitted from the tracer annihilate with electrons very close to their point of emission to produce pairs of "back-to-back" γ-rays, which travel along the same line in opposite directions (Fig.1). These are then detected using two large position-sensitive detectors (the "positron camera"), from which, in PEPT, the tracer position can be found by triangulation. Normally at least 100 γ-ray pairs are used to find the tracer.

The PEPT tracking algorithm discards the outlying γ-rays in order to find the most probable position, on the basis that outliers normally result from scattering events. The precision, Δ, of a PEPT location is then given approximately by

$$\Delta \approx \frac{w}{\sqrt{fN}} \qquad (1)$$

where w is the intrinsic spatial resolution of the positron camera (roughly 10 mm in a conventional camera), N is the number of events detected during the location interval and f is the fraction of these actually used for location. Therefore, at a data rate of 50 k s^{-1} with f = 0.2 (typical of a challenging application such as imaging through a steel-walled vessel) location is possible to within about 1 mm every 10 ms using the existing camera. During this time interval a tracer moving at 1 m/s will move 10 mm, so that for faster moving tracers it is necessary to locate more frequently and with slightly lower precision.

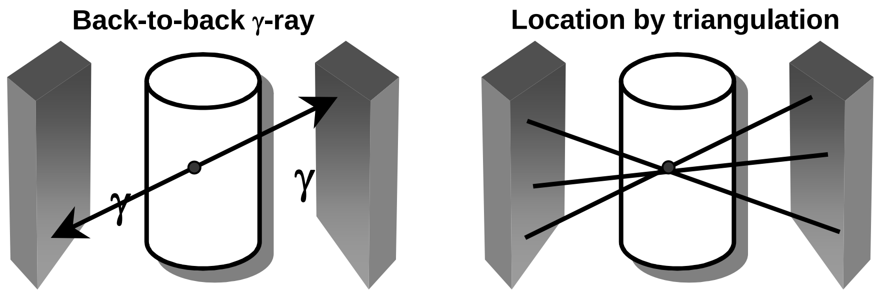

Figure 1: Principles of PEPT

At its most basic level, PEPT measurement yields a continuous trajectory, consisting of a large file of x,y,z,time values, plus any chosen continuously-recorded user-defined parameters. Velocity values can then be obtained from this data file, in practice by a multi-point weighted averaging technique, and time averaged velocity profiles can then be derived, as shown for a bubbling fluidised bed in Fig. 2. It is also possible to obtain values of “occupancy”, which is equivalent to time-averaged density.

In fluidized beds the most common analysis methods have included measurements of circulation times and solids fluxes (in which upward and downward moving particles can be distinguished) and residence times in defined parts of the bed, including close to surfaces.

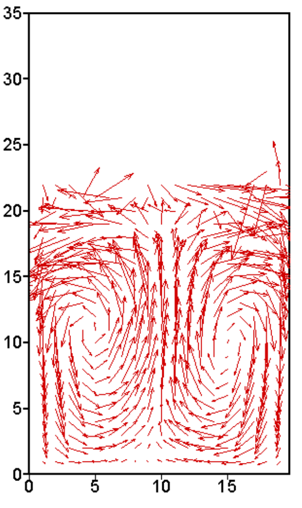

Figure 2: Typical time-averaged PEPT output for a bubbling fluidised bed (length of arrows is

proportional to speed) showing bubble-driven motion, upwards in the centre and down at the walls.

Parker *et al*. (3) describes the medically-related positron camera used for much of the early work on PEPT carried out at the University of Birmingham. More recently, it has been possible to construct customised camera geometries using mobile modular detectors, as described by Ingram *et al*. (4). This approach allows on-site investigations and when configured in a compact geometry it achieves a count rate of over 300k events per second, allowing very accurate high speed tracking. The original PEPT algorithm relies on *a priori* knowledge that only a single labelled particle is present in the field of view. This algorithm has been extended to enable several particles to be tracked simultaneously (2).

APPLICATIONS

Applications of PEPT in fluidization (2) have included: solids circulation and scaling studies in bubbling beds; motion around in-bed obstacles such as heat-exchange surfaces; the effect of cohesion in fluidization due to surface liquid layers and of sintering at high temperature; heat transfer to in-bed tubes; segregation; solids motion in circulating fluidized beds; coating in top-spray fluidized beds, bottom-spray Wurster coaters and spouted beds; and validation of computational approaches to the modelling of fluidized beds.

Stein *et al*. (5), studied the trajectories of single tracer particles in bubbling fluidized beds. Particles move upwards in a series of discrete fast movements ("jumps"), punctuated by periods of relative inactivity ("idle time" or "quiescent time"). It is during these idle times that the particles are potentially able to react and form bonds, which can lead to defluidization. Clearly, vertical jumps are associated with bubble motion. This aspect has been further studied by Cheun U (6). Figure 3 shows a typical history of vertical particle motion, from which bubble velocities can be successfully estimated.

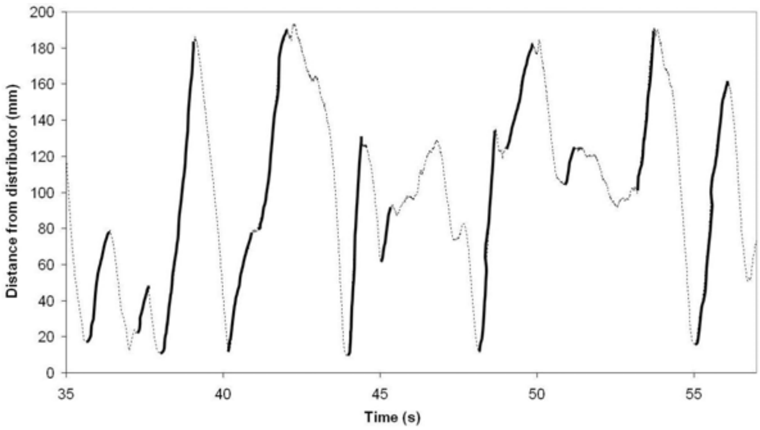

Figure 3: Vertical motion of a tracer particle with time, in a bubbling fluidized bed. The full dark lines indicate the location of jumps where the particle is moving upwards with a bubble (Cheun U; 6).

Fluidised beds are particularly favoured as chemical reactors because of their ability to exchange heat through immersed heat exchange surfaces. However, little is known about how the heat exchange process works on a single particle level. Wong (7, 8) used PEPT to follow the trajectory of a single tracer particle in a fluidised bed containing heat exchanger tubes (Fig. 4). The residence time of particles in the vicinity of the heat exchange surface was determined directly for the first time, allowing the observed heat transfer variations to be interpreted mechanistically.

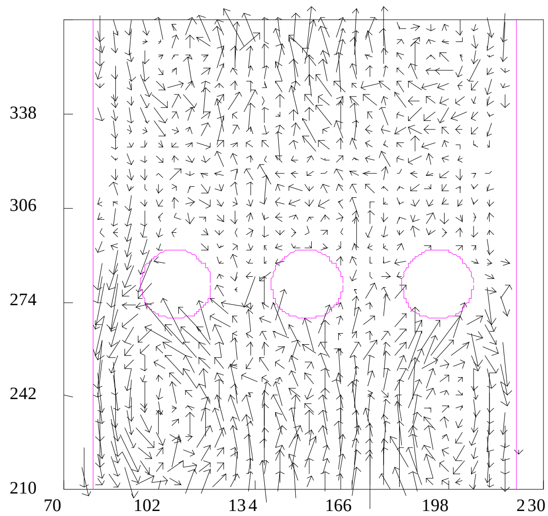

Figure 4: Time-averaged particle motion around heat exchange tubes (3 parallel horizontal tubes, showing how tube layers disrupt overall circulation); Wong (7)

Circulating fluidised beds (CFBs) are used for both gas-solid and gas-catalytic reactions; however, the operating modes in these two cases are completely different. In modelling and designing CFBs as reactors, the solids residence time is an important parameter. Previous studies mostly assess operations at moderate values of the solids circulation rates (≤ 100 kg/m²s), whereas gas-catalytic reactions and (for example) biomass pyrolysis require completely different operating conditions.

Van de Velden *et al.* (9) used PEPT to study the movement and population density of particles in the CFB-riser. The PEPT results were used to obtain: (i) the vertical particle movement and population density in a cross sectional area of the riser; (ii) the transport gas velocity required in order to operate in a fully established circulation mode; (iii) the overall particle movement mode (core flow *versus* core/annulus flow); and (iv) the particle slip velocity. Figure 5 shows an example of PEPT data for the two principal flow regimes. Using these results Van de Velden *et al.* (9) were able to recommend design rules for operation of such reactors in terms of the gas velocity/solids loading parameters.

Chian and co-workers (10-13) used PEPT to study all parts of a circulating fluidized bed separately: the riser, cyclone, downcomer/standpipe and L-valve, obtaining separate design equations for each. Figure 6 gives some examples of trajectories of particles injected into the base of the riser under different conditions.

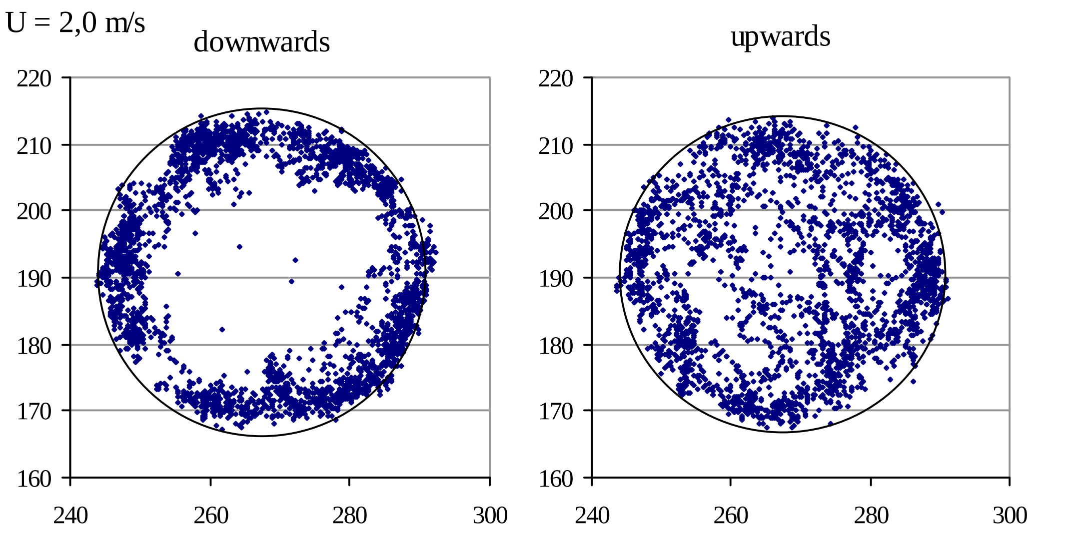

Figure 5: Cross-sectional view of the riser with (left) only downward-moving particles shown, and (right) only upward-moving particles shown; at G = 260 kg/m²s and superficial gas velocity 2.0 m/s. The plots show all the particle locations over the height of the viewed section, integrated over the time of the run (9).

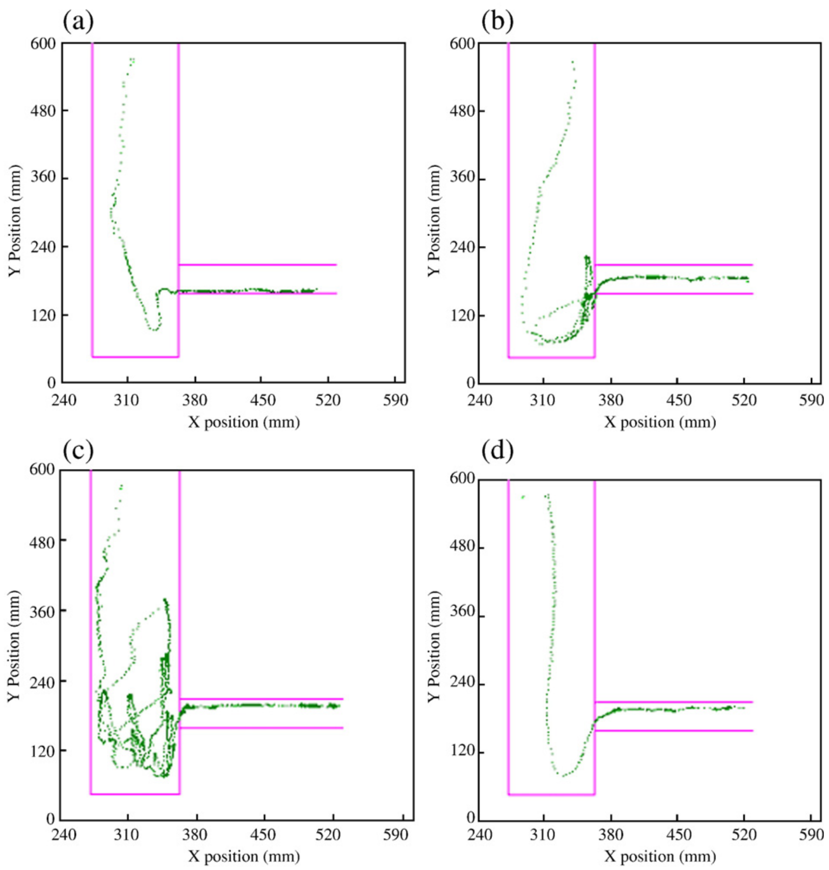

Figure 6: PEPT view of the bottom of the riser (10), at $U-U_{TR}$=2.1 m/s, for values of G (kg/m^{2}s) of: (a) 5.5 (b) 20.1 (c) 55.5; and (d) 210.

PEPT has also been used to investigate particle motion in fluidized bed agglomeration and coating processes (14); Fig. 7 shows an example of motion in a Wurster coater. In this type of device, it is the variation in the coating per pass through the spray zone which dominates the overall particle-to-particle coating variation. PEPT has been used to follow the particle trajectory in the spray zone in order to predict the evolution of coating mass distribution (14, 15).

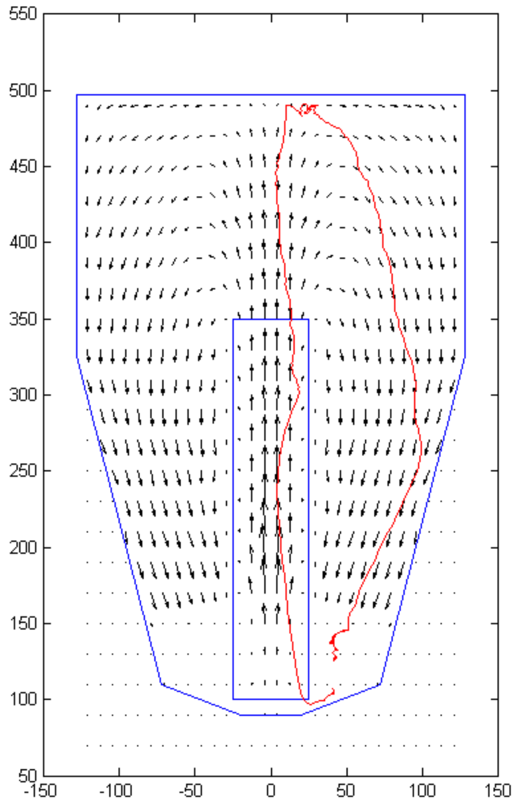

Figure 7: Solids motion in a Wurster coater – time-averaged solids motion (black arrows) & a single particle trajectory (red line). The figure shows an internal draft tube (14).

Validation of Discrete Element Method codes

Discrete element methods (DEM) have grown in popularity for simulation of particulate systems including fluidized beds. Just as PEPT can be used to follow single particle trajectories in experiments, DEM can be used to construct trajectories in simulations. Clearly, other measures such as particle velocity and time-averaged bed density can also be used as comparators. As a method for testing and validating DEM, this approach is in its infancy, but is exemplified by the work of the Twente group (16, 17)

SUMMARY AND FUTURE PLANS

Positron emission techniques have developed rapidly in recent years, now enabling the tracking of realistic tracer particles down to approximately 50μm in size, at speeds up to 10 m/s, in real process equipment. Algorithm development has enabled multi-particle PEPT. The technique has been demonstrated in novel fields such as pharmaceutical and food engineering, minerals processing and metals casting. A mobile version of the technique has been used *in situ* at industrial scale.

It is likely that over the next few years there will be an increasing use of multimodal studies, combining complementary measurement techniques such as impedance and x-ray tomography on the same system.

Work on validation of computational approaches to simulating fluidized beds is growing; PEPT represents one of very few ways of doing this convincingly.

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