*Refereed Proceedings*

*The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering*

Engineering Conferences International *Year* 2007

# Multiple Particle Tracking in a Fluidised Bed

A. Ingram* Z. Yang† S. Bakalis‡
D. J. Parker** X. Fan††
P. J. Fryer‡‡ J. P.K. Seville§

*University of Birmingham, a.ingram@bham.ac.uk
†University of Birmingham
‡University of Birmingham
**University of Birmingham
††University of Birmingham
‡‡University of Birmingham
§University of Birmingham

# MULTIPLE PARTICLE TRACKING IN A FLUIDISED BED

A. Ingram[a], Z. Yang[a, b], S. Bakalis[a], D.J. Parker[b], X. Fan[b], P.J. Fryer[a] and J.P.K. Seville[a]

[a] Department of Chemical Engineering, [b] School of Physics and Astronomy
University of Birmingham
Birmingham, B15 2TT, UK

## ABSTRACT

Positron Emission Particle Tracking (PEPT) is a versatile method for following the motion of a single radioactive tracer particle in a fluidised bed. However, there are many applications in which it would be useful to be able to follow the motion of two or more particles simultaneously in cooperative motion. The tracers are labelled with different intensities of radiation and located by converging sequentially on centres of activity. Two 600μm polyethylene particles have been followed in a 15 cm diameter bed and their contact events studied.

## INTRODUCTION

Positron Emission Particle Tracking (PEPT), invented at the University of Birmingham in the 1990s, is a non-invasive technique for tracking the rapid movement of small particles in opaque systems and is one of the most powerful techniques available for visualising and quantifying granular flow.

Certain radionuclides decay by positron emission: each decay releases a positron, which, within a very short distance, annihilates with a free electron to produce two back-to-back 511keV gamma photons. Positron Emission Tomography (PET) is a medical diagnostic tool which has been used for several decades. PEPT is a extension of PET in which the positron emitting radionuclide is concentrated on a single tracer particle. The key difference between PET and PEPT is that PET generates a three-dimensional image of the concentration distribution of the radionuclide during an exposure time of several minutes; PEPT locates the tracer particle in three dimensions many tens or hundreds of times per second.

The PEPT camera at Birmingham is an ADAC Forte medical PET camera. This consists of a pair of parallel detector heads facing each other 300-800mm apart. Each head contains a 16mm thick single crystal sodium iodide scintillator, with a useful active area of 510x380 $mm^2$, backed by an array of 55 photomultiplier tubes.

The volume between the heads is the field of view. The temporal and spatial resolution of the camera is such that the gamma photons corresponding to single decay events are paired and co-ordinated to provide "lines of response" that will pass through the point of emission. In PEPT the point of emission is the tracer particle so all detected lines will pass through the tracer location. Triangulation of successive lines therefore gives the location of the tracer. By limiting the sample period to short periods (a few milliseconds for example), it is possible to generate the trajectory of a moving particle. Tracer location by PEPT is illustrated in Figure 1.

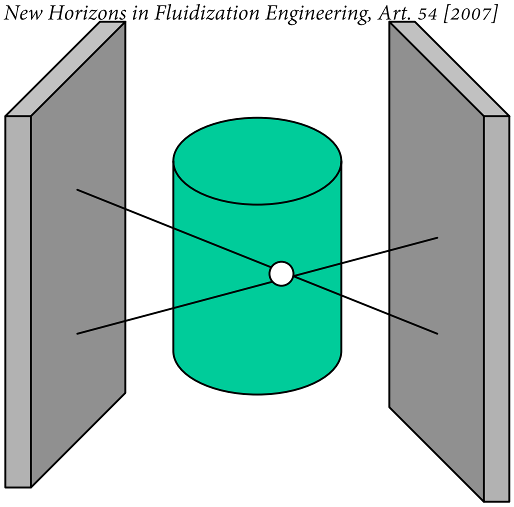
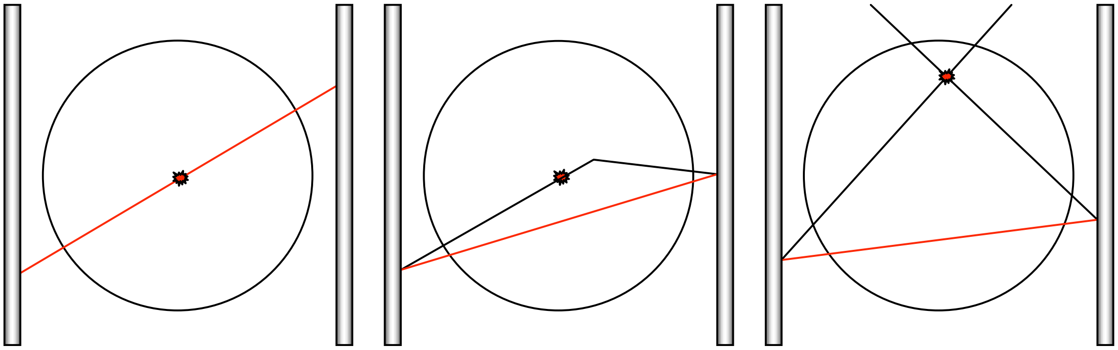


Figure 1. Principle of PEPT. Particle location from triangulation of lines from two photon pairs

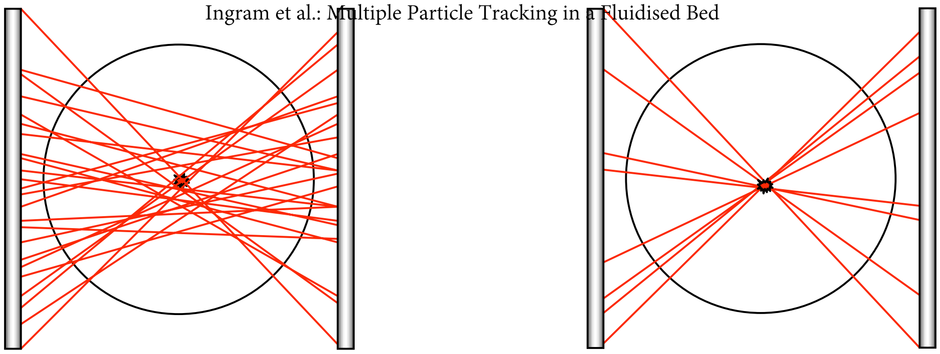
In practice a proportion of the gamma trajectories will be invalid or corrupt due to scatter of one or both photons or random pairing of photons that do not derive from the same event (Figure 2).



True Pairing Scattered Pairing Random Pairing

Figure 2. Categories of valid and invalid gamma pairs

This gives two populations of gamma trajectories: the corrupt ones which are randomly distributed in the field of view and the valid ones which meet, to within the camera resolution, at a point in space. The PEPT algorithm identifies and eliminates the invalid lines by a statistical process in which the location is first approximated by the point that minimises the sum of perpendicular distances to all trajectories. Those trajectories that are furthest from this point are removed and the location recalculated. This proceeds until only valid lines remain and a reliable location is obtained, as in Figure 3.



All events recorded by camera during sample time interval

Algorithm removes outliers (random and scattered pairs) to leave only true events

Figure 3. Elimination of invalid gamma pairs

The rapid emission of gamma photons and their penetrability means that the location of a moving particle can be recorded in three dimensions in otherwise opaque systems; even steel pressure vessels [1]. The frequency and accuracy of particle location depends on the application (mass and distance to be penetrated by gammas, activity of tracer, the velocity of the tracer): typically a particle moving at 1m/s can be located 250 times per second with an accuracy better than ±1mm.

PEPT is now widely established as the most powerful means of probing flow processes in opaque systems: particulate systems in particular but also liquid systems. It has been applied with great success to a range of processes in the chemical industry (rotating drums [e.g. 2], stirred tank catalytic reactors [e.g. 3], fluidised beds [4]), the food industry [e.g. 5,6] and the pharmaceutical industry [e.g. 7,8].

While tracking a single particle has not significantly limited the applicability of PEPT, there are circumstances when the ability to track two or three particles simultaneously would be advantageous. One consideration, discussed in [9], is how multiple tracer spots on the same large particle could be used to determine its rotation. In that case, the sources are rigidly fixed in known positions relative to each other. In the example reported here, two labelled particles are free to move independently in a fluidised bed. The interest is in following the trajectories during periods where the particles are close to each other in order to throw further light on the location, mechanism and duration of contact.

## MULTIPLE PARTICLE TRACKING

If more than one particle is labelled, it is not possible to distinguish the particles by labelling with different isotopes, since the gamma photons from positron emission are emitted at 511keV regardless of the isotope. Instead we have developed an approach in which particles are distinguished by different levels of activity. The conventional PEPT algorithm is used to home in on the most active tracer first, then the second most active and so on. Consider the case of three labelled tracers. There will be four populations of gamma trajectories: invalid randomly distributed pairs as described above and three valid sets that converge on separate points representing the locations of the three particles. The size of these valid sets should be approximately proportional to the activities of the three particles. We have found that the optimum activity ratio is 4:2:1. The algorithm homes in on the location of the strongest particle, treating the true events associated with the other particles as corrupt and eliminating these along with the truly corrupt events. Having located the strongest particle, the trajectories associated with this particle location are removed and all the eliminated trajectories are restored. The process is repeated to find the second location, then the third.

It is well established that granular flow in bubbling fluidised beds is driven by the movement of the bubbles. These set up convective currents that, on average, draw the particles upwards towards the centre of the bed, and push them outwards and downwards at the wall. This is not to imply uniform steady motion: the presence of many coalescing and, perhaps, splitting bubbles all moving erratically upwards results in random, tortuous particle trajectories, as shown in Figure 4.

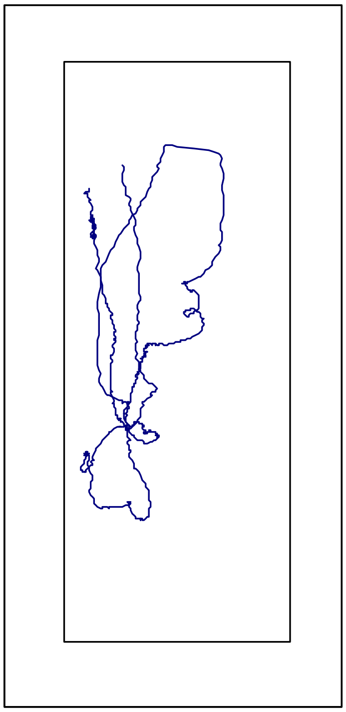


Figure 4. Typical particle trajectory in fluidised bed.

An important question is: how long do particles remain together before agitation separates them? One context where this may be important concerns the phenomenon of sintering in which particles close to their melting point can fuse together to form large agglomerates that disrupt or even terminate fluidisation [10]. This is particularly important in fluidised bed polymerisation where operating conditions are often a compromise between achieving high productivity (high temperature) and avoiding sintering (low temperature). Work by Seville et al. [1] showed that the temperature at which the onset of sintering occurs is increased by increasing the bed turnover frequency. This was attributed to a reduction in the mean “quiescent” time (periods during which particles are not agitated by bubbles and thus do not move relative to each other).

## MULTIPLE PARTICLE TRACKING IN A FLUIDISED BED

### Experimental Details

The work reported here was carried out as a demonstration of principle, the aim being to see whether it was possible to use PEPT to track 2 or more particles simultaneously in a bubbling fluidised bed. The experimental conditions are given in the table below:

| FLUIDISATION | |
|---|---|
| Column Diameter | 150mm |
| Distributor | Multi-orifice plus multilayer filter paper |
| Fluidising gas | Air |
| Bed material | Polyethylene particles |
| Mean size | 600μm |
| Temperature | Ambient (circa 20°C) |
| Pressure | Atmospheric |
| Gas velocity ($U-U_{mf}$) | 0.25 $ms^{-1}$ |
| | |
| TRACER | |
| Tracer particle | Polyethylene particles taken from bulk and labelled by adsorption of 18F following chemical modification of the surface |
| Tracer diameter | 600μm |
| Number of tracers | 2 |
| Activity ratio | 2:1 (774μCi and 388μCi) |

## PEPT

The bed, containing the bulk material and the two tracer particles, was positioned between the flat gamma detector heads of the PET camera. The particles were tracked in the fluidised bed for 45 minutes. The PEPT algorithm was then employed, as described above, to obtain the trajectories of each particle.

## Trajectory Analysis

The PEPT algorithm generates an ASCII formatted data file in the form of a list of time stamped x, y and z Cartesian co-ordinates of the particle trajectories. The frequency of the data depends on user selected parameters and the experimental conditions: the tracer activity, the bed geometry and the location of the tracers relative to each detector head. In this case the frequency ranged from about 50 to 250Hz giving a time interval between locations of 4 to 25ms. For the purposes of this initial study the interest is in the relative motion of the two particles when they were in close proximity to each other in order to study the nature and location of the flows that bring the particles together and separate them. Through a process of trial and error, a minimum separation criterion of 15mm was selected as a trigger to identify the periods of proximity. During the 45 minutes, there were 107 occasions when the two tracer particles were within 15mm of each other. Figure 5 shows two sets of locations in the x (horizontal) direction obtained simultaneously from the two tracers, demonstrating that the location principle works. Figure 6 shows the distribution of interparticle distance for 5 minutes of the run, which peaks at approximately 2/3rds of the bed diameter. Figure 7 shows a typical cooperative movement between particles.

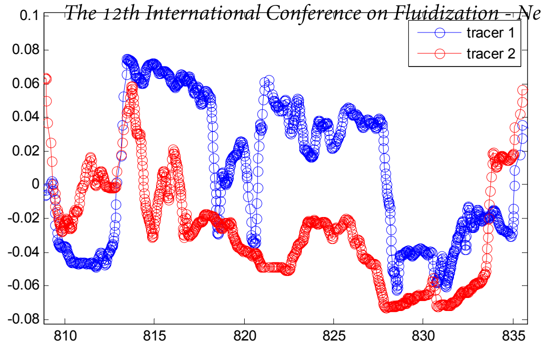


Figure 5. x coordinates for 2 tracer particles

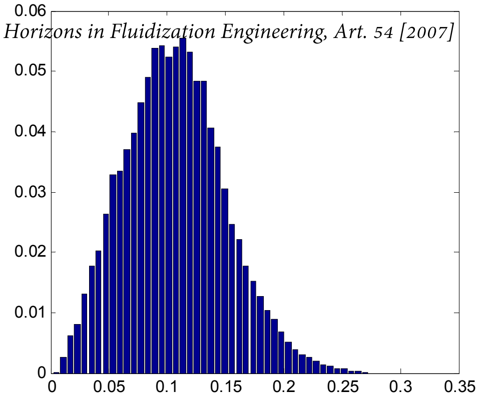


Figure 6. Distribution of tracer separation.

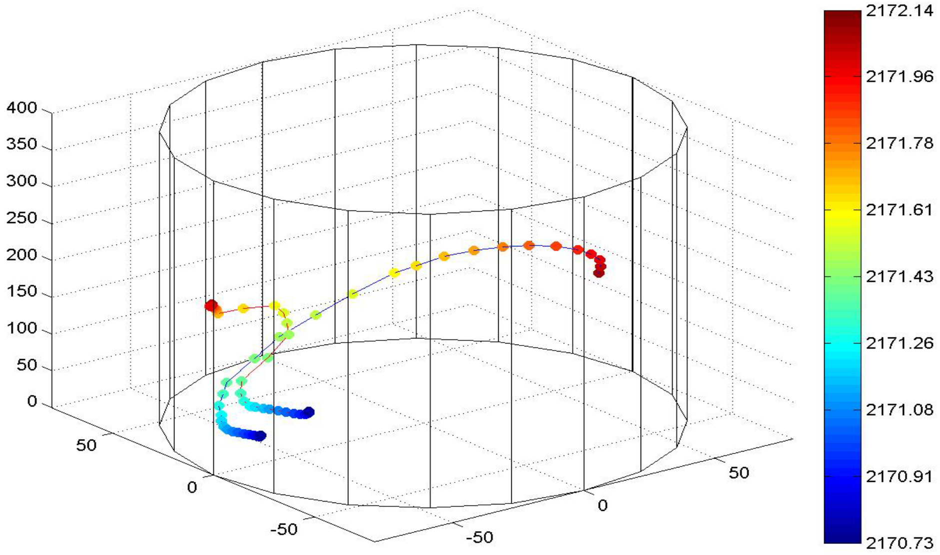


Figure 7. Extended close pass in which particles meet and separate during upward trajectory (colour code indicates time in seconds within pass).

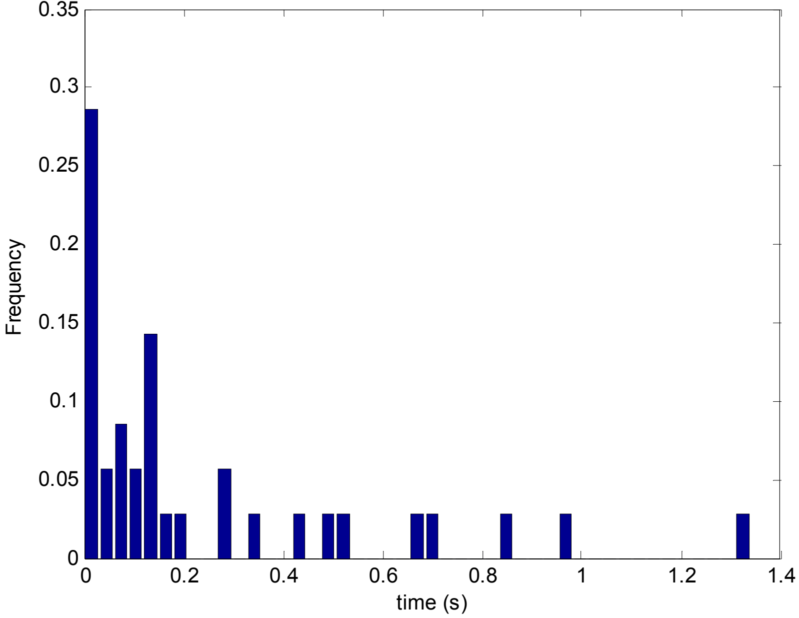


Figure 8. Distribution of durations of near-contact events (separation less than 15mm)

About 2/3rds of the recorded close contacts were extended passes (Figure 8). A typical particle trajectory during one of these extended passes would proceed as follows: the particle would start low in the bed, moving predominantly upwards and inwards, away from the wall; the trajectory becoming progressively more vertical until, at the top of the flight, it flattens out and the particles move horizontally towards the wall for a short distance before descending. Of these upwardly converging trajectories, 20% of subsequent separations would occur during or at the top of the upward movement (as in Figure 7), 35% during the horizontal phase and 45% during the descent. There were no instances of the particles completing a cycle of the bed together, but there were some very interesting and complex trajectories where the particles remained close to each other in parallel motion for some distance.

## DISCUSSION

Simultaneous tracking of two particles in a fluidised bed has been demonstrated. In general terms, this is a very useful extension of an already powerful technique and there are likely to be other applications where the movement of particles relative to each other is important. Note that application of the technique is complicated compared with straightforward single particle PEPT both in terms of particle preparation (control of activity) and in application of the tracking algorithm. The rate of detection of gamma photons from a single gamma particle is a function of its position in the field of view as well as the activity of the particle. It possible therefore to confuse particles. Furthermore, the quality of the individual trajectories will be less good than a single particle PEPT trajectory due to the increased “random” pairs arising from the presence of the other particles. Particular complications also arise if one of particles leaves the field of view. For these reasons, this technique would only be employed if single particle PEPT were unsuitable. Note for example that the preferred choice of method for segregation studies may still be single particle PEPT in which repeat runs with different sizes of tracer are used.

The accuracy of the technique has been reported elsewhere [9,11]. Generally speaking it is not possible to reliably distinguish particles within less than 5mm of each other. Beyond this, resolution is very good: stationary particles of 600µm diameter, can be located to within 1mm giving a separation accuracy of about 2mm. Depending on speed (100-500 mm $s^{-1}$ individual velocity), the separation distance of moving particles can be resolved to within 2-10mm.

Application of the technique has been revealing about the nature of flow in fluidised beds. It has been possible to visualise and categorise the approach and separation of particles as bubbles pass and draw them into their wakes. Between approach and separation, the particle trajectories are surprisingly parallel and cooperative even while some distance apart. It is reasonable to assume that the particles in the bulk between the tracers are also flowing in parallel with the two tracked particles.

## REFERENCES

1. Seville J P K, Salleh A M, Ingram A, McCormack A, Greenwood R W and Reiling V (2004), *Fluidization XI*, ECI, Ischia, Italy, 211-218
2. Parker D J, Fan X F, Forster R N, Fowles P, Ding Y L and Seville J P K (2005), *Can.J.Chem.Eng*, 83, 83-87
3. Fishwick R P, Winterbottom J M and Stitt E H (2003), *Chemical Engineering Science* **58**, 1087-1093
4. Stein M G, Ding Y L, Seville J P K and Parker D J (2000), *Chemical Engineering Science* **55**, 5291-5300
5. Cox P W, Bakalis S, Ismail H, Forster R N, Parker D J and Fryer P J (2003), *Journal of Food Engineering* **60**, 229-240
6. Bakalis S, Cox P W, Wang-Nolan W, Parker D J and Fryer P J (2003), *Journal of Food Science* **68**, 2684-2692
7. Palmer S, Seville J P K, Ingram A, Fitzpatrick S, Fan X F (2006), *5th World Congress on Particle Technology,* AIChE, Orlando, Florida (on CD ROM)
8. Kuo H P, Knight P C, Parker D J and Seville J P K (2005), *Powder Technology* 152, 133-140
9. Yang Z, Parker D J, Fryer P J, Bakalis S and Fan X F (2006), *Nuclear Instruments and Methods in Physics Research, A* **564**, 332-338
10. Seville J P K, Silomon-Pflug H and Knight P C (1998), *Powder Technology,* 97, 160-169.
11. Yang Z, Bakalis S, Fan X F, Parker D J, Seville J P K and Fryer P J (2006), Paper submitted to Partec 2007.