Refereed Proceedings

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

Engineering Conferences International — *Year* 2007

Portable Positron Emission Particle Tracking (PEPT) for Industrial Use

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PORTABLE POSITRON EMISSION PARTICLE TRACKING (PEPT) FOR INDUSTRIAL SCALE USE

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ABSTRACT

Positron Emission Particle Tracking (PEPT) has become an established technique for studying the motion of particles in granular and fluid systems. Until recently, this technique was confined to use with medically-derived detectors, which places constraints on the geometry and scale of process equipment that can be viewed. Demand for greater flexibility in the use of the PEPT technique - in imaging larger process equipment and, more importantly, industrial equipment *in situ* - has led to the development of a modular PEPT camera. This comprises a set of individual detectors, which can be arranged around the equipment in whatever configuration is appropriate to enable particle tracking. This paper reports the use of the modular camera to track particle motion on a 750mm diameter pressurised fluidised bed reactor under industrially relevant conditions. The results show how the technique can be used reliably on large scale equipment to measure quantities such as circulation time.

INTRODUCTION

Positron Emission Particle Tracking (PEPT) is derived from the commonly-used medical diagnostic technique of Positron Emission Tomography (PET). The main difference is that in PET, a distribution of radioactivity is imaged in a relatively long time (some minutes), whereas in PEPT a single small source of radioactivity is located very frequently (about 100 times per second). In PEPT (1, 2), positrons emitted from the tracer particle annihilate with free electrons very close to their point of emission, resulting in the formation of two "back-to-back" γ-rays (Fig. 1), which travel along the same line in opposite directions. These are then detected using two large position-sensitive detectors (the "positron camera"), from which a line can be constructed on which the tracer must lie. In theory, two such γ pairs (or "events") are sufficient to locate the tracer in three dimensions; in practice, 50 to 100 are used. Features of particular benefit to study of fluidised beds include the fact that the actual particles of interest may be used as tracers, rather than dissimilar materials of unknown behaviour, and that γ-rays are sufficiently penetrating that location is unimpaired by the presence of metal walls, for example.

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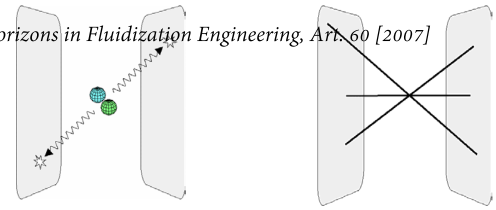
Figure 1: The basis of PEPT : two large position sensitive detectors are used to detect pairs of back-to-back γ-rays, then the particle location is determined from a number of such events



Recent PET and PEPT studies at Birmingham have used a "positron camera" consisting of a pair of digital γ camera heads, each consisting of a single sheet of sodium iodide scintillator of dimensions 60x40 cm^2, operating in coincidence to detect the pairs of back-to-back γ-rays. The characteristics of this camera have been fully described elsewhere (3). A significant fraction of the detected events are invalid as either they correspond to a "random coincidence" between two unrelated γ-rays or else one or both of the γ-rays has been scattered prior to detection. The PEPT algorithm attempts to discard these invalid events, using an iterative procedure in which the centroid of the events is calculated, the γ-rays passing furthest from the centroid are discarded, and this process is repeated until a specified fraction *f* of the original events remains. The optimum value of *f* depends on the mass of material between the tracer and the detectors, which adds to the number of scattered events. For example, when studying flow inside a vessel with 15mm thick steel walls, 80% of the detected events must be discarded, so that the fraction *f* of useful events is 0.2. The precision Δ of a PEPT location is given approximately by

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

where *w* is the intrinsic spatial resolution of the positron camera (roughly 10mm 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. Assuming a data rate of 50k s^{-1} with *f*=0.2 one expects to be able to locate the tracer to within about 1mm every 10ms using the existing camera. This is typical of the tracking achieved for relatively slow moving tracers. During this time interval a tracer moving at 1m/s will move 10mm, so that for faster moving tracers it is necessary to locate more frequently and with slightly lower precision.

A PROTOTYPE MODULAR POSITRON CAMERA

As discussed above, the present Birmingham positron camera consists of a single pair of large area detectors. In contrast, most medical PET scanners consist of rings of hundreds of small detectors. By distributing the events over many detection elements the problems of dead-time and random coincidences are reduced so that higher overall count rates can be achieved. Since count rate is critical for tracking at high speed, it is of considerable interest to investigate extending this approach to PEPT. An important additional benefit of constructing a positron camera from a number of detector modules is that it becomes possible to consider adapting the detection geometry to suit the individual system under study.

A redundant medical PET scanner, a CTI ECAT931/08, was acquired. This comprises 128 detector blocks (Fig. 2(a)), each consisting of four photomultiplier tubes viewing a 30mm thick crystal of bismuth germanate scintillator approximately 49 x 56 mm^2 in area, which is cut into an array of 8x4 elements (each approximately 5.6x12.9 mm^2, separated by slots 0.6mm wide). By comparing the light intensities measured in the four photomultipliers a γ-ray interaction can be unambiguously assigned to a particular element out of the 32.

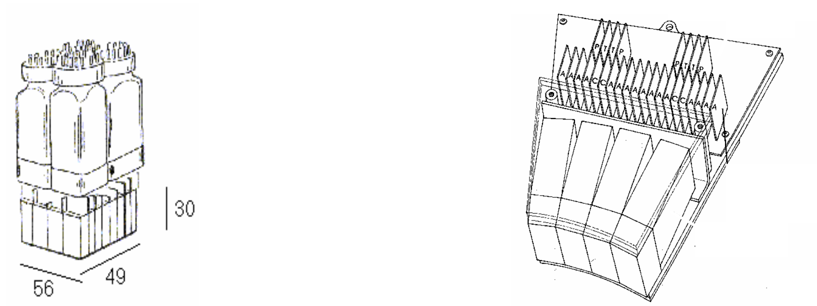


Figure 2: Components of the ECAT931 scanner:
(a) detector block (dimensions in mm), (b) 4 blocks mounted on bucket

The blocks are grouped in sets of four into "buckets" (Fig. 2(b)) on which are mounted the appropriate electronics (preamplifiers and discriminators under microprocessor control). The buckets can thus be considered as detector modules (each with an active area 200x56mm^2), and the scanner consists of 32 of these buckets. As originally configured they were mounted in two adjacent rings (16 buckets in each ring), so that in terms of the individual detection elements this corresponded to 8 rings each containing 512 elements.

The scanner is designed to recognise coincidences where events occur in two opposing buckets within a resolving time of 12 ns. In normal operation, only coincidences between two elements in the same ring or adjacent rings (of the 8) were accepted, but for PEPT use this restriction was removed. The data acquisition system of the scanner was also modified so that coincidence data is recorded in list mode with time stamps at 1ms intervals.

The buckets were removed from the original gantry and reconfigured for trials as two rectangular arrays to mimic the geometry of the conventional positron camera. In considering the optimum layout of buckets, there is a trade-off between sensitivity and field of view. Because it is necessary to detect pairs of back-to-back γ-rays, tracking is only possible when the tracer lies directly between a pair of buckets. Taking into account the overlapping cones of detectable rays, the sensitivity is highest when the tracer lies on the centre line between the two buckets and drops to zero at the edge of the volume between (Fig. 3). The same variation is found regardless of whether the buckets are directly opposite each other or inclined at some angle, though the absolute sensitivity will depend on the orientation and separation. Maximum sensitivity will occur in regions which are in line between several pairs of buckets. On the other hand, to cover an extended field of view it is necessary to spread out the buckets.

To investigate the ability of the system to operate at high count rate, a point source of ^{11}C (half-life 20.4 min) was produced and was mounted approximately centrally between the arrays. Figure 4 shows the count rate recorded as a function of source activity as the source gradually decayed. At low activity the

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relationship is linear and the sensitivity consistent with the previous results, but at higher activity the count rate begins to level off due to a dead-time of over 1μs per pulse in each individual detector block. A feature of this scanner is that each pulse is tested twice by the coincidence circuitry, once with the normal timing and once with a delay introduced, and by measuring the number of delayed coincidences occurring, the contribution of random coincidences (pairs of unrelated γ-rays which just happen to be detected within the resolving time) can be measured. The filled squares in Fig. 4 show this contribution and the open triangles the net true coincidence rate obtained by subtracting the random contribution from the total. This true coincidence rate peaks at about 250k events/s.

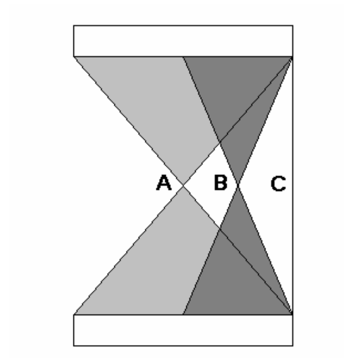


Figure 3: Schematic showing geometrical variation in sensitivity along the centre line between two detectors: at A a wide cone of back-to-back gammas can be detected, at B a narrower cone, and at C the sensitivity drops to zero

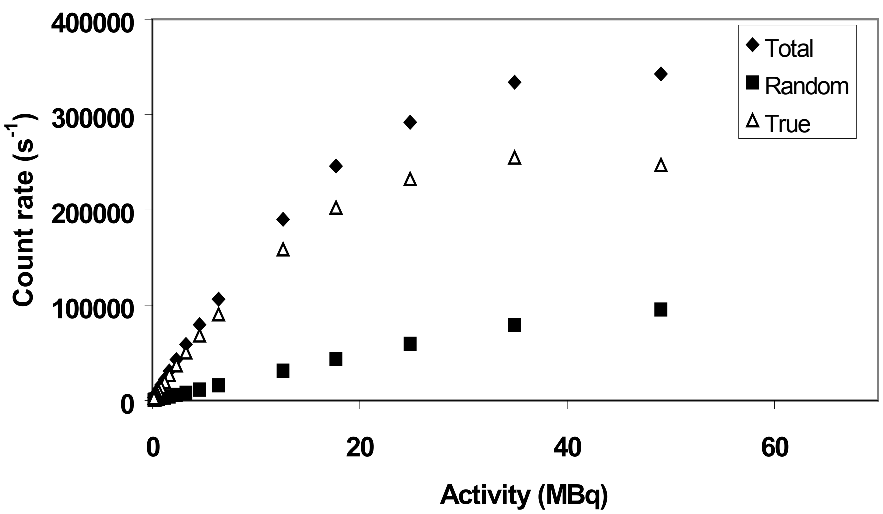


Figure 4: Count rates achieved from the prototype positron camera for a central ^{11}C source

In order to test the quality of data produced, the software used to generate PEPT locations from positron camera data has been modified to recognise the geometry of the modular camera. Testing the performance for data from a stationary tracer, the optimum value of *f* in equation (1) was found to be approximately 0.4, and using N=100 events gave locations consistent to within 1mm in 3D. In a laboratory test, a tracer mounted on a turntable rotating at approximately 12 rev/s, corresponding to a tracer speed of almost 6 m/s, gave rise to an average count rate of approximately 120k events/s, and the locations were derived using *f*=0.3 and N=100 so that the tracer was located on average once every 850μs.

Deviations from the best-fit trajectory were around 4mm. With some refinement to the PEPT algorithm it should be possible to achieve significantly better tracking.

INDUSTRIAL APPLICATION

The principle described above was first tested on the 154mm inside diameter stainless steel pressurised fluidised bed described by Seville *et al*. (4), using the geometry shown in Fig. 5.

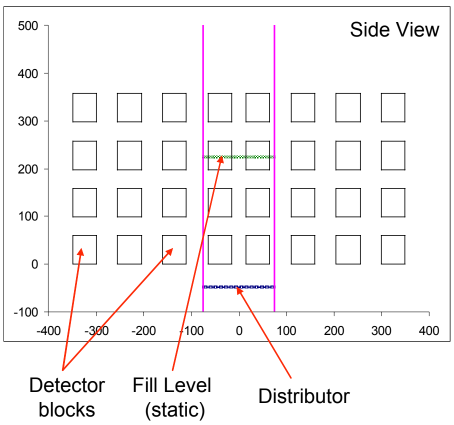


Figure 5: Arrangement of detector blocks around 154 mm column (dimensions in mm)

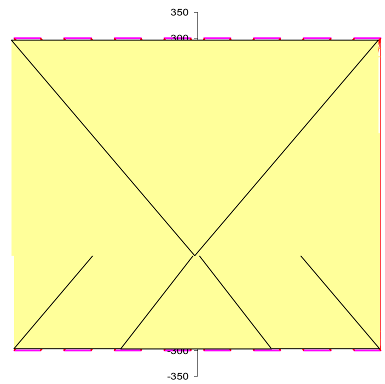
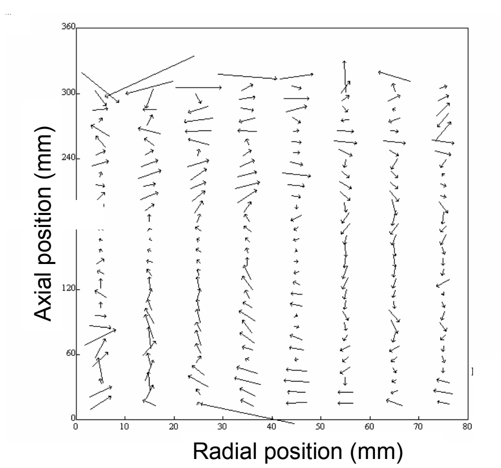


Figure 6: Detector arrangement and field of view for 154mm fluidised bed (dimensions in mm)

The field of view is shown in Fig.6. It can be seen that the separation of the blocks does not lead to gaps in the field of view in the region of interest. This arrangement resulted in excellent location accuracy. An example of a time-averaged particle velocity vector plot is given in Fig. 7.

The first *in situ* industrial test was carried out at BP's Hull Research and Technology Centre in spring/summer 2006 on a 750mm diameter pilot scale fluidised bed with a central baffle plate and asymmetric gas injection to promote particle circulation, as shown in Fig. 8. The fluid bed was operated under industrially relevant conditions of elevated temperature and pressure. Due to the thickness of the lagging, the minimum detector separation was 1150 mm.

Figure 7: Time-averaged velocity vectors for 154 mm fluidised bed



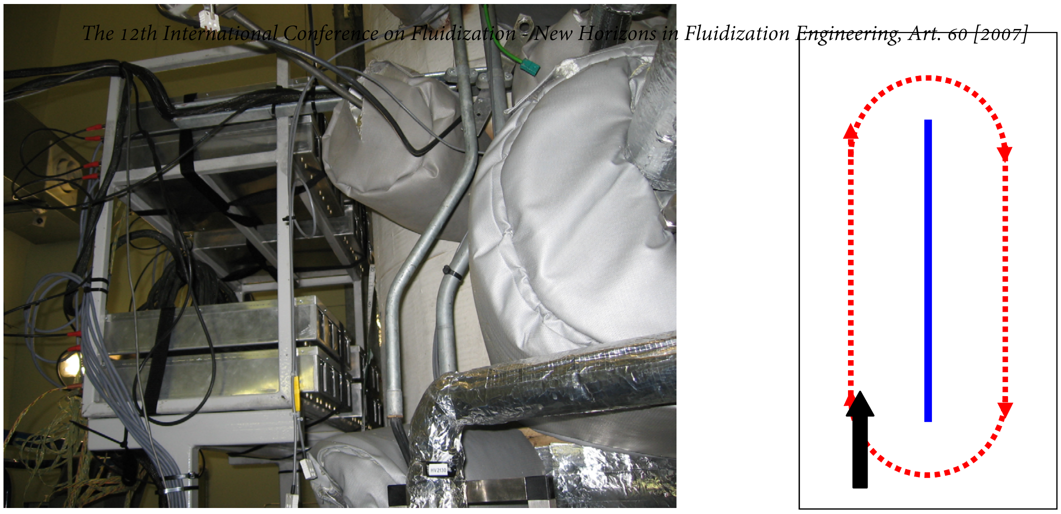


Figure 8: (left) detector arrangement in situ next to lagged bed; (right) circulation arrangement, with central baffle; arrow shows additional gas injection.

In this application, the portable camera is capable of imaging motion over the full width of the fluidised bed but not the full height. Because the main aim of the work was to quantify circulation, it was decided to form the camera elements up into lower and upper banks, intended to follow the flows under and over the baffle, respectively.

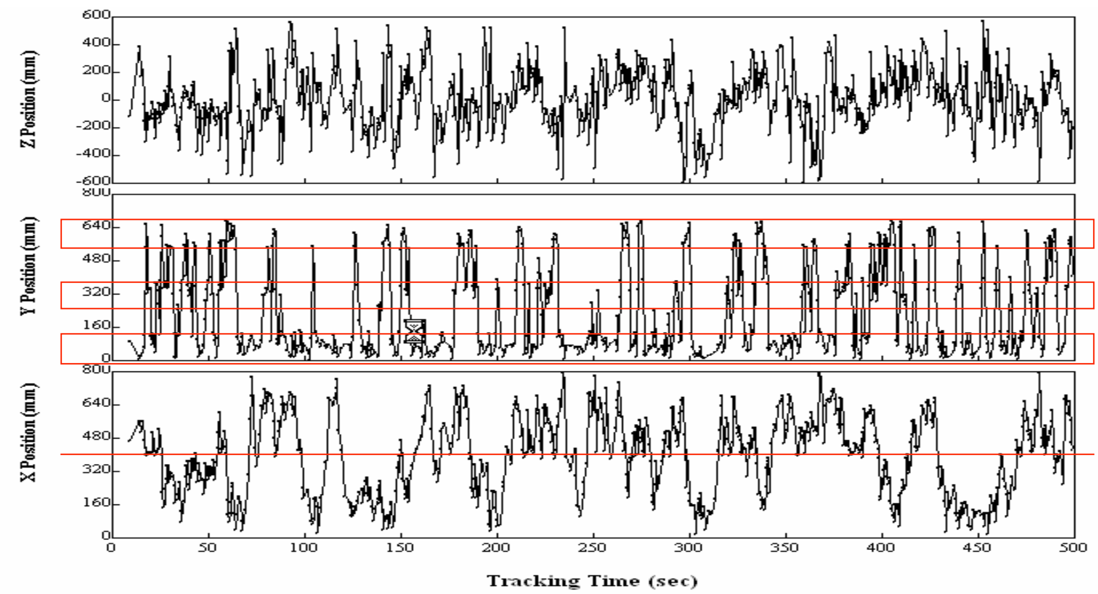


Figure 9: Tracer particle coordinates in 750 mm diameter bed

Figure 9 shows the tracer particle coordinates over a few seconds for this bed. The y coordinate in this case indicates height and the three strips indicate the upper, middle and lower parts of the bed that are in the field of view. The x coordinate indicates which semi-cylindrical half of the bed the tracer is in. In general, particles were found to move up and down on each side of the central baffle, with occasional movement between semi-cylindrical sections, either under the baffle within the dense bed or over the baffle within the freeboard space. Since tracking of complete trajectories was impossible because of the split nature of the detector field, a different method of circulation measurement was devised.

The least ambiguous measure of tracer movement is the location. The bed was therefore divided into sections as shown in Fig. 10, so that locations could be attributed to upper left and right and lower left and right, as shown. Clearly the sequence LL, UL, UR, LR then indicates a single clockwise rotation.

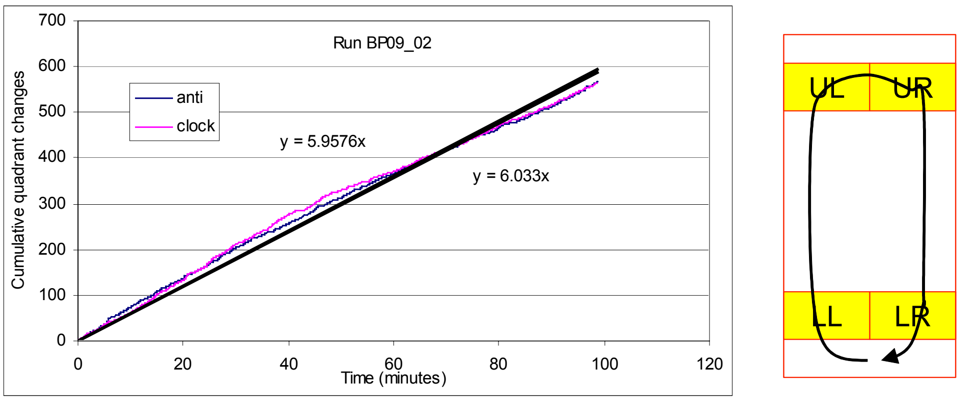
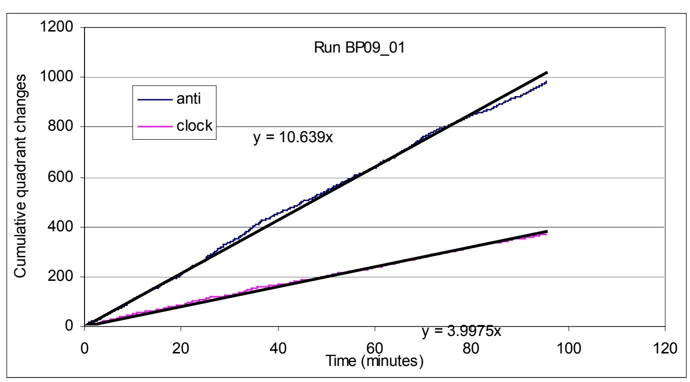


Figure 10: Circulation within the fluidised bed: (left) quadrant changes versus time for no circulation enhancement; (right) arrangement of location quadrants

This arrangement was employed to assess circulation with symmetrical (uniform) gas flow, with the result shown in Fig. 10 – clockwise and anti-clockwise rotations each grow approximately linearly with time but at the same rate, so that their cumulative effect is zero. Figure 11 shows the effect of introducing extra gas to one side of the bed: the anticlockwise rate of movement is now about twice that of the clockwise rate, so that the net effect is an anticlockwise solids circulation of about 1.7 rpm.

Figure 11: Circulation within the fluidised bed: quadrant changes versus time with circulation enhancement



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CONCLUSIONS

A prototype portable positron camera has been constructed, based on γ-ray detectors from an ex-medical PET scanner. Using 14 multiple-detector "buckets" configured so as to cover a field of view of approximately 60x30x45 cm^3, a maximum useful count rate of 250k events/s was achieved, which is significantly better than a conventional PEPT camera previously used to study fluidised beds. This flexible arrangement has been used *in situ* on a BP site to image particle movement within a 750mm diameter pilot scale pressurised bed, enabling circulation rates to be determined. Higher count rates will be possible if more buckets are used and are configured so that the tracer remains between several pairs at all times. Alternatively, the modular construction allows for a larger field of view to be covered, but possibly at the expense of some regions of low sensitivity, and more consideration will have to be given to optimising the PEPT algorithm to accommodate these. Further *in situ* industrial trials are planned.

ACKNOWLEDGEMENTS

We acknowledge the support of Yorkshire Forward (Yorkshire & Humber Regional Development Agency). This project received funding from Yorkshire Forward through their Industrial Research and Development Award Scheme which was part financed by the European Regional Development Fund. The development of the Mobile PEPT camera is also supported by an EPSRC Platform Grant.

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