PEPT Cape Town: a new positron emission particle tracking facility at iThemba LABS

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Abstract. Positron emission particle tracking (PEPT) has become a powerful tool for in-situ characterisation and visualization of particulate flow within aggressive industrial environments, such as tumbling mills and powder mixers. PEPT is based on the tracking of a single tracer particle which has been labelled with a radionuclide that decays via beta-plus decay. The location of the particle is obtained by the triangulation of events associated with the detection of pairs of annihilation gamma rays in a modified "positron camera." One of the challenges facing PEPT is associated with labelling particles smaller than 100 μm which would allow studies in systems of finer particulate flow, such as flotation cells. The Positron Imaging Centre at the University of Birmingham is currently the only operational PEPT facility in the world. PEPT Cape Town will shortly become operational at iThemba LABS, South Africa.

1. Introduction

Medical imaging based on positron emission tomography (PET) continues to have wide-ranging clinical impact, particularly in cancer diagnosis and management, cardiology and neurology [1]. At the basis of PET is the decay of particular isotopes which emit a positron, the anti-particle of the electron, first postulated by Dirac in 1928, and observed by Anderson in 1932. A positron produced in a nuclear decay will rapidly annihilate with an electron, resulting in a pair of 511 keV gamma rays which are emitted almost back-to-back. If both of these gamma rays are detected at two points in space, thereby defining their line of response (LOR), then the origin of these gamma rays must have occurred somewhere along this straight line. A three dimensional image may be constructed from a collection of such LORs, measured at many angles, using the analytical methods of tomography. Positron-emitting radionuclides are nowadays easily produced using particle accelerators, with the majority of medical PET facilities making use of the radiopharmaceutical [18F]-fluorodeoxyglucose (FDG).

An extension [2] of PET imaging is to label a *single particle* with a positron-emitting radioisotope. The position of this tracer particle can be determined within the field of view of a PET camera using only a small number of measured LORs. In principle only two LORs are necessary, but practical concerns such as the detection of gamma rays after undergoing Compton scattering between creation and detection, and the coincident detection of two gamma rays which were not associated with the same annihilation event, mean that a larger number of measured LORs are required. However, since many thousands of coincidence events can be detected in a PET camera and processed each second, the possibility of tracking the position of a fast moving particle may be realised. This provides the basis of a Lagrangian

technique, called “positron emission particle tracking” (PEPT) as developed in the early 1990s by a group at the University of Birmingham [3, 4, 5], which may be used to map the flow of dry particles and fluids in a wide range of engineering systems.

Most industrial systems that process rheologically complex materials, such as in the minerals industry, employ empirical models to describe and control their operations. The ever increasing emphasis on energy efficiency and sustainability is demanding improved fundamental understanding of mechanisms governing engineering operations. PEPT is currently the only non-invasive technique capable of mapping flow fields in robust, industrial systems to the level of detail that is demanded for tests of both analytical and computational mechanistic and flow models. The Positron Imaging Centre [6] at the University of Birmingham is the only PEPT facility in the world today. PEPT Cape Town is set to become the second operational PEPT laboratory.

2. The Positron Imaging Centre (University of Birmingham, UK)

In a response to the need to develop a PET camera having a wide field of view at reasonable cost for non-medical studies, the original Birmingham Positron Camera [7] was designed and constructed at the Rutherford Appleton Laboratory. It consisted of a pair of multi-wire proportional chambers, each having a sensitive area 600 x 300 mm^2, operated in coincidence. It was completed in 1984 and operated reliably for over 15 years. In 1999 it was replaced by a Forte gamma camera (figure 1) manufactured by ADAC Laboratories, consisting of two heads, each containing a single crystal of NaI(Tl) scintillator, 500 x 400 mm^2 and 16 mm thick, optically coupled to an array of 55 photomuliplier tubes, each channelled through a separate ADC [8]. Each head can operate at a singles rate of over 2 million counts per second with the dead-time per pulse less than 170 ns. The detector heads have an energy resolution of better than 15% (FWHM of the 511 keV photopeak), sufficient to discriminate against photons scattered by more than 30°. With a point source of gamma rays from electron-positron annihilation, a coincidence rate of over 100k events per second can be achieved with a coincidence resolving time of 7.5 ns. The spatial resolution of the camera (FWHM of the back projected image of a point source) is approximately 6 mm. The data are recorded event by event on computer for subsequent processing. The heads are mounted on a motorised gantry which permits rotation about a horizontal axis, and adjustment of the face-to-face separation of the detectors from 250 to 800 mm.

FIG. 1. A Forte PET camera consisting of two NaI(Tl) detector heads in parallel geometry.

Using the Forte camera, a tracer labelled with a positron-emitting radioisotope moving with speed around 1 m s^{-1} can be located to within 0.5 mm at over 250 times per second [9]. This allows the distribution of the instantaneous velocity of the tracer to be calculated with 10% uncertainty. Tracking is possible over the volume between the two front faces of the detectors, giving a maximum field of view of 800 x 500 x 400 mm^3, although accurate tracking is not possible near the edges of the field of view. The camera was thus mounted on rails with a motorised drive under computer control so that a slowly moving tracer can be followed in real time. Recently the Positron Imaging Centre has also developed a flexible and transportable positron camera based on detector modules from redundant clinical PET scanners [10]. Over the last decade a wide range of PEPT applications have been explored at the Positron Imaging Centre, in particular, powder mixing [11], and particle and fluid behaviour in granular beds [12], rotating drums [13], stirred tanks [14] and flotation cells [15].

3. PEPT Cape Town (iThemba LABS, South Africa)

PEPT Cape Town [16] is due to become the second operational PEPT facility in the world during 2009. The laboratories of PEPT Cape Town are situated at iThemba LABS, Faure, South Africa, which operates a $k = 200$ separated sector cyclotron, and a 6 MV van de Graaff accelerator. The cyclotron facility routinely produces both light and heavy particle beams for nuclear physics research, radiotherapy and radioisotope production. The situation of the new PEPT laboratory at iThemba LABS has all the obvious advantages with respect to radioisotope production, handling and licensing.

The conception of PEPT Cape Town received a critical boost when it became possible for Imperial College London to facilitate the relocation of the ECAD 'EXACT3D' (Model: CTI/Siemens 966) positron emission tomography camera (figure 2) from Hammersmith Hospital to iThemba LABS. The 'EXACT3D' was originally designed with the aim of achieving high sensitivity and resolution using available detector technology [17]. The camera consists of 48 rings of standard bismuth germinate detector elements (each 4.39 mm transaxial x 4.05 mm axial x 30 mm deep, grouped in blocks of 8 x 8) with a ring diameter of 82 cm, producing an axial field of view of 23.4 cm. This is significantly larger than other 'standard' ring geometry PET cameras. The data acquisition system can maintain a sustained acquisition rate of about 4 million coincidence events per second. The mean spatial resolution is 4.8 ± 0.2 mm FWHM (transaxial, 1 cm off-axis) and 5.6 ± 0.5 mm (axial, on-axis). The scanner has been used for clinical research use at Hammersmith Hospital, London, since 1995, and may still be the most sensitive 3D PET scanner in operation today.

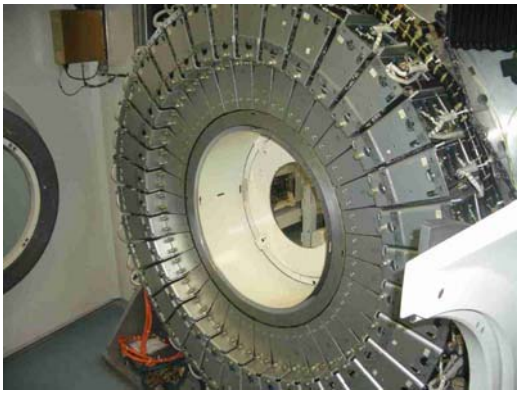

FIG. 2. The ECAD 'EXACT3D' PET camera consisting of 48 rings of BGO detector elements.

4. Radioisotopes for PEPT studies

The analysis of list-mode data from PEPT runs begins with slicing the series of chronological coincidence events into equal groups of pre-determined number (typically between 120 to 200). For each slice of data, the centroid of the set of measured lines of response (LORs) is determined, and an iterative algorithm rejects outlying LORs until the desired fraction (between 5-10%) of original events remain. The uncertainty in the measured position of a tracer particle is inversely proportional to the square root of the number of events used to define the centroid. Therefore the analysis involves optimising the use of measured LORs in order to provide as many positions of the moving tracer as possible, within a given uncertainty. The number of usable coincidence events therefore depends on the activity of the tracer and the mass of the material between the tracer and the detectors. In most PEPT studies it is important to make the tracer size and composition similar to the bulk material. In turn, the activity with which a tracer may be labelled depends strongly on the both the size and composition of the tracer. The activity of the tracer must be sufficiently high so that enough usable LORs are measured to accurately reflect the trajectory of the moving tracer particle. For typical PEPT applications it has been found that the activity of the tracer needs to be between 300 and 1000 μCi (about 10 to 40 MBq).

There are a large number of positron-emitting radioisotopes, with half-lives ranging from minutes to years, which in principle are suitable for labelling PEPT tracers. However, since it is often not realistic to recover the labelled particle from the bulk of the liquid or powder under study, the half-life of the radioisotope should ideally be long enough to enable detection over a reasonable experimental timescale, but short enough for the tracer to be discarded after use. The main radioisotopes used at the Positron Imaging Centre are ^{66}Ga (half life 9.45 hours), ^{68}Ga (half life 68 minutes), ^{18}F (half life 109 minutes), ^{61}Cu (half life 204 minutes) and ^{64}Cu (12.7 hours). The isotope ^{18}F is used most frequently for PEPT experiments since it does not emit any gamma-rays other than the 511 keV annihilation photons. This reduces the singles rates in the detectors thus increasing the live time for coincidence events. In addition, the use of ^{22}Na (half life 2.6 years) is sometimes useful in experiments where the tracer may be recovered.

A number of different techniques have been developed at the Positron Imaging Centre for the labelling of tracers, which involve direct activation, ion exchange and modification to the surface of the tracer material [18, 19]. Ion-exchange techniques based on both weak-base and strong-base anion exchange are used to activate resin tracers with sizes less than 1000 μm, or so. For example, ion-exchange methods using ^{18}F can be used to label strong-base anion exchange resins with an activity greater than 300 μCi on a tracer as small as 60 μm. Since the accumulation of ^{18}F on a resin particle is dependent on both the adsorption rate and the half life of ^{18}F (109 minutes), the optimum time for the labelling process is about 20 minutes. Surface modification techniques [18] based on the introduction of particular metallic ions, e.g. Fe^{3+}, onto the tracer surface help to enhance the adsorption of ^{18}F. Since the ^{18}F in the labelled particles exists within a layer about 0.3 mm deep, degradation during experiments is inconsequential in all but the most aggressive environments.

Direct activation using a 35 MeV ^{3}He beam from the Birmingham MC40 Cyclotron is often used for tracers of size greater than 1 mm. The particles are held by an aluminium target and ^{18}F is produced in the tracer via the reactions ^{16}O(^{3}He, p)^{18}F and ^{16}O(^{3}He, n)^{18}Ne-^{18}F. Generally the other radioisotopes produced in the tracer material are short lived, e.g. ^{10}C (half

life 19.3 s), ^{12}N (half life 11 ms), ^{27}Si (half life 1.16 s), ^{29}P (half life 4.1 s), and ^{26}Al (half life 6.4 s), and thus decay to negligible levels after a "cooling" period of about 20 minutes.

Further research into the labelling of particles is underway both in Birmingham and at iThemba LABS. In order for the reliable applicability of PEPT to be extended to liquid and gaseous systems, such as floatation cells, the state-of-the-art needs to be extended to the routine production of tracers of sizes less than 20 μm activated to more than 300 μCi.

5. Measurements of kinematic distributions via PEPT: an example

In order to illustrate some features of PEPT analyses, a selection of recent results from PEPT experiments using a scaled down tumbling mill (figure 3) undertaken by the UCT group at the University of Birmingham are discussed. The experimental mill (figure 3) had an internal length of 270 mm and internal diameter of 300 mm, with 20 lifters and a grate with open area of about 30%. The mill was rotated axially using a DC drive having a power delivery capacity of 0.55 kW. The mill load consisted of conditioned blue stone with a specific gravity of 2.75, conforming to a Rosin-Rammler size distribution. Results from using labelled blue stone tracers of diameter 2 mm are presented here.

FIG. 3. The tumbling mill positioned between the two detector heads of the Forte PET camera at the Positron Imaging Centre.

Figure 4 shows the measured trajectories of a 2 mm diameter tracer for three mill rotation speeds, with the mill 15% filled with dry rock and no slurry. Each PEPT measurement was undertaken for 40 minutes, and the plots are projections onto the front face of the mill of all data collected for each run. The measured trajectory fields are obtained in the Lagrangian coordinate system of the PEPT unit. The transformation to the Eulerian system of the tumbling mill is achieved by placing location markers (labelled glass spheres) on the front, back and length of the mill. Measurements of the circular traces of the rotating mill shell may be used to reconstruct the outline of the mill. Furthermore, the data are regarded as being ergodic [20], since the trajectory fields of one tracer are measured over a relatively long period of time. Therefore subsequent analyses based on discretisation of the mill volume and time averaging of kinematic quantities may be taken as probabilistic distributions of the true ensemble average for the given particle class (of which the tracer is a typical representative).

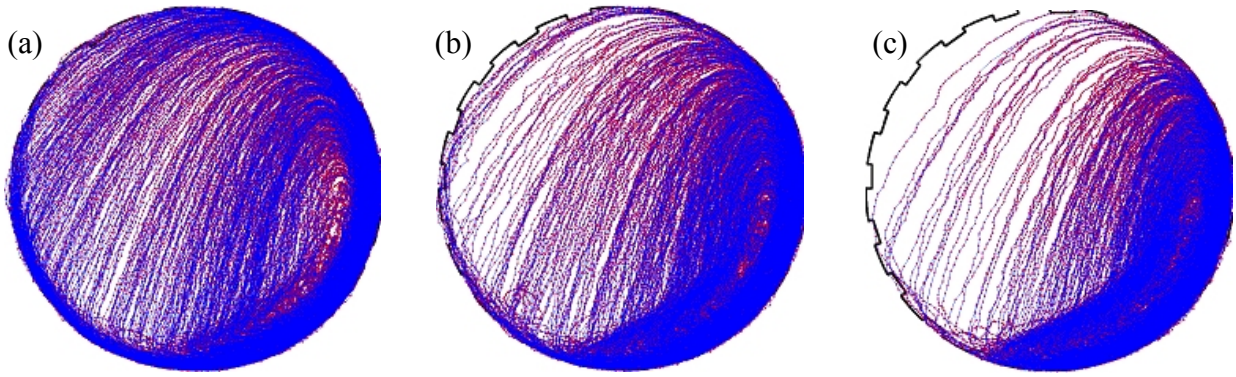

FIG. 4. Front view trajectory fields measured via PEPT for a 2 mm rock particle in a mill charged with a 15% dry load, rotating at (a) 95%, (b) 85% and (c) 75% of critical speed.

Figure 5(a) is an "occupancy plot" derived from the trace data shown in figure 4(c) for the mill rotating at 75% of critical speed. The front view of the mill has been discretised into a rectangular grid and the (projected) occupancy of the particle is calculated for each pixel as a normalised fraction of the total occupancy. Figure 5(b) shows the distribution of the average velocity of the 2 mm particle for the mill rotating at 75% of critical speed. The velocity at each position shown is a projection onto the front face of the mill, and is derived from the raw positional data.

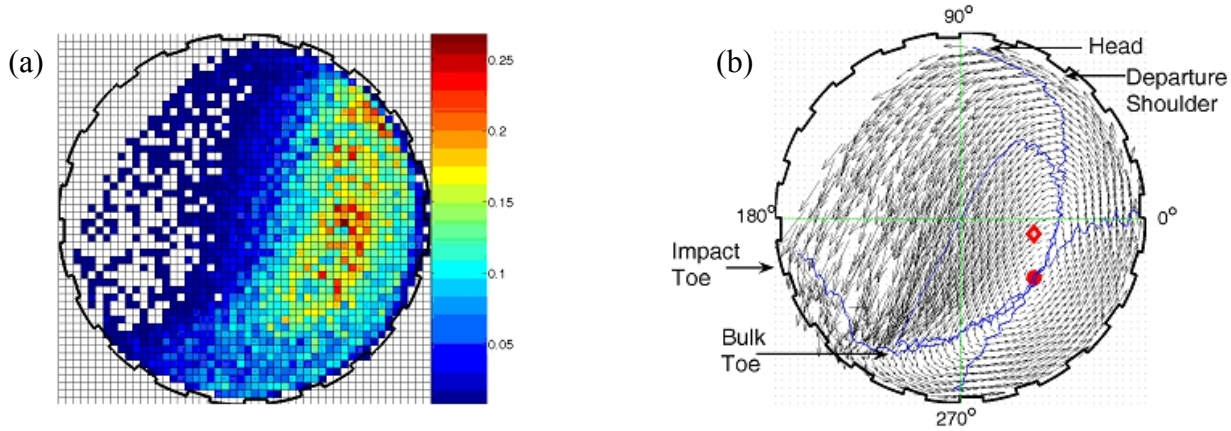

FIG. 5. (a) Percentage occupancy of a 2 mm rock particle for the mill rotating at 75% of critical speed. (b) Distribution of average velocity of the 2 mm rock particle. The three flow equilibrium surfaces (blue lines, see text) allow a number of charge features to be identified.

The characterisation of charge motion in tumbling mills is seldom undertaken without appealing to the notions of a toe and shoulder region. A definition of these regions which is free from subjective judgment has been recently proposed [21] based on three analytically derived equilibrium surfaces. The cross section of the mill is first sectioned using a series of horizontal, vertical and radial planes, termed control surfaces, whose normals lie in the plane of the cross section of the mill. The point of maximum flow of charge along a control surface is termed the flow equilibrium point, and the surfaces generated by linking flow equilibrium points from successive control surfaces are termed the equilibrium surfaces. The three flow equilibrium surfaces (blue lines) determined in this way are shown in figure 5(b) with the centre of circulation (CoC) indicated at the intersection of the surfaces with a red dot. The CoC is the point about which all charge appears to circulate, and is often referred to as the "eye of the charge". The flow count along a control surface passing though the CoC will be a maximum and independent of the orientation of the control surface. The red diamond in

figure 5(b) marks the position of the centre of mass of the charge. Other features [21] may then be identified such as the "departure shoulder" which is the uppermost point at which the charge departs from the shell of the mill, and the "head" at the apex position of the charge. Discussion around the toe region of the charge may be refined using the concepts of an "impact toe" and a "bulk toe." The bulk toe defines the point where the horizontal extension of the horizontal equilibrium surface from the inflection point (defined as the point at which the horizontal equilibrium surface moves in an upwards direction towards the impact toe) intersects the shell. The impact toe is the position where the cataracting charge impacts the shell in the toe region, and is described by the point where the horizontal equilibrium surface intersects the shell of the mill in the toe region.

6. Discussion

In recent years PEPT [8] has allowed researchers an in-situ perspective of particle dynamics in industrially robust systems, using tracer particles of similar composition to the bulk material under study. A few features of PEPT have been illustrated in this paper using data obtained from studies using a realistic, scaled milling environment. These data form part of a larger set which are being used to develop modern mechanistic models of charge transport and breakage. PEPT data also offer opportunities to benchmark numerical models used in DEM and SPH computational environments. In this regard, within the context of tumbling mills for example, careful measurements of charge descriptors (such as the "departure shoulder" and "impact toe") have become important tools for validating numerical models [23]. As the production of smaller tracer particles (10 to 50 μm) becomes possible, the reliable extension of PEPT to study the behaviour of slurry in mills and froth in floatation cells, for example, will become feasible.

PEPT Cape Town will become operational mid 2009 using the ECAD 'EXACT 3D' ring geometry PET camera from Hammersmith Hospital. The geometric constraints of this camera will set scale boundaries on the systems than can be studied using PEPT. On the other hand, the high number of detector elements and excellent timing of the detector system will offer new opportunities to make high resolution PEPT measurements in contexts where the tracers are either slowly moving or confined within the field of view of the camera. Experiments focussing on the dynamics of flotation froth and gaseous systems are anticipated. Collaboration between PEPT Cape Town and the Positron Imaging Centre in Birmingham will provide opportunities for technological exchange. Plans are also well advanced for PEPT Cape Town to acquire a parallel geometry PET camera with a field of view similar to the Forte camera presently in operation in Birmingham.

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