Institution: University of Birmingham

Unit of Assessment: UoA 9 -Physics

Title of case study: Positron emission particle tracking (PEPT) enables a paradigm shift in process design and multi-scale modelling

1. Summary of the impact

The challenge of observing complex industrial processes in optically opaque machinery has limited the potential for optimising efficiency and throughput. The technique of positron emission particle tracking (PEPT), conceived and developed by David Parker and colleagues in Physics, over comes this barrier offering a paradigm shift for studying flows in realistic industrial plant and for validating computational models of flow. As a result of this transformative work, industry has improved the design of key plant for companies such as Procter and Gamble and Johnson Matthey Catalysts. In addition to a continuing programme of studies at Birmingham, PEPT measurements are now performed at the University of Bergen and at the iThemba National Lab in South Africa, where since 2009 a PEPT facility has been developed in collaboration with Birmingham with funding from AngloPlatinum, which has had significant impact on improving mineral processing on an industrial scale.

2. Underpinning research

PEPT was conceived and developed at the University of Birmingham as a tool for studying the fundamentals of flow in physics and engineering. PEPT is an advanced version of the medical imaging technique positron emission tomography (PET). Both rely on detecting the pairs of back-to-back gamma-rays emitted during positron/electron annihilation for localising a positron-emitting radioactive tracer. In PET the concentration of a radioactively-labelled fluid tracer is mapped in 3D, whereas in PEPT a single radioactively-labelled particle is accurately tracked at high speed - making the technique suitable for studying high speed flows. PEPT can be used to study flow in granular material (labelling and tracking a single grain) or viscous fluid flow (using a neutrally-buoyant tracer particle). Because the gamma-rays concerned are highly penetrating, measurements can be made through thick steel walls, enabling non-invasive studies to be performed on realistic engineering systems.

The basic concept was first described by Parker (Professor of Physics) et al in 1993 [1], and the technique has been continuously developed and refined by the Birmingham group in the subsequent years through the development of improved positron cameras, tracer labelling techniques and methods for extracting information from PEPT data [2]. In 1999 the original Birmingham positron camera (initially developed for performing PET studies) was replaced by a commercially-available gamma camera PET system leading to a dramatic improvement in sensitivity and precision of location in PEPT. In recent years further improvements have been achieved by adapting medical PET scanners as transportable modular positron cameras for PEPT as well as allowing PEPT measurements to be performed on larger-scale equipment and at other sites. These PEPT systems offer significantly higher data rates and enable accurate tracking of faster-moving tracers [3, 4 and 5]. Early studies were restricted to labelling and tracking glass spheres several mm in diameter but, thanks to a continuous programme of research and development at Birmingham, a wide range of materials with sizes as small as 50 μm can now be labelled and tracked.

The radionuclides needed for this work are produced using a cyclotron: to this end in 2002 the elderly Radial Ridge Cyclotron was replaced by the MC40 Cyclotron which enables production of a much wider range of positron-emitting radionuclides. In parallel, techniques have been developed for extracting information such as time-averaged velocity fields and dispersion coefficients from the PEPT data. The Birmingham group has applied PEPT to study a wide range of systems of academic or generic interest, ranging from vibrofluidised granular beds to flows of non-Newtonian viscous fluids.

3. References to the research

1. *Positron emission particle tracking - a technique for studying flow within engineering equipment*, D J Parker, C J Broadbent, P Fowles, M R Hawkesworth and P A McNeil
Nucl. Instrum. & Meth. **A326** (1993) 592-607: http://dx.doi.org/10.1016/0168-9002(93)90864-E

2. Positron emission particle tracking studies of spherical particle motion in rotating drums”
D J Parker, A E Dijkstra, T W Martin and J P K Seville, Chemical Engineering Science **52** (1997)

2011-2022: http://dx.doi.org/10.1016/S0009-2509(97)00030-4
3. Positron emission particle tracking using the new Birmingham positron camera, D J Parker, R N Forster, P Fowles and P S Takhar, Nucl. Instrum. & Methods **A477** (2002) 540-545: http://dx.doi.org/10.1016/S0168-9002(01)01919-2
4. Positron emission particle tracking using a modular positron camera, D J Parker, T W Leadbeater, X Fan, M N Hausard, A Ingram and Z Yang, Nucl. Instrum & Methods **A604** (2009) 339-342: http://dx.doi.org/10.1016/j.nima.2009.01.085
5. Characterisation of the latest Birmingham modular positron camera, T W Leadbeater, D J Parker and J F Gargiuli, Measurement Science and Technology **22** (2011) 104017: doi:10.1088/0957-0233/22/10/104017
References 1, 3 and 4 best indicate the quality of the underpinning research.

4. Details of the impact

Prior to PEPT, much of the understanding and optimisation of industrial flow and mixing processes was performed via mathematical modelling without the crucial ability to experimentally validate the models. PEPT is the *only* existing technique capable of imagining complex flow, mixing and comminution (grinding) processes within opaque industrial equipment. Optimisation of these leads to minimisation of processing time, enhanced throughput and in the case of mineral processing a reduction of wear on expensive plant.

The revolutionary development of the PEPT has permitted both the validation and further refinement of process modelling and has been widely used within the industrial processing sector. Companies such as AstraZeneca, Johnson Matthey Catalysts and Procter and Gamble have used the technique for optimization of processes ranging from drug manufacture to understanding washing machines and dishwashers – leading to cost and efficiency savings. In the mineral sector, the technique has been used by Xstrata and AngloAmerican Platinum to reduce wear of key components in their extensive and expensive production plant.

PEPT Impact at Birmingham

The following are a series of examples of the industrial impact of the PEPT approach during the current REF census period (2008-2013) with the PEPT facilities at Birmingham (descriptions adapted from text provided by industrial partners):

Refinement of industrial polymer extrusion: PEPT has been used in an investigation of polymer flow and mixing behaviour within industrial twin-screw processes. The measurements were used to determine the influence of key parameters such as machine design, process operation and polymer system. The results were used to establish knowledge based machine design criteria and operation guidelines, and to develop both new and existing commercial simulation and modelling software – the results were applied to eight different commercial case studies. This EU funded project, called PEPTflow, ran until December 2009 and had a significant impact on the competitiveness of SMEs throughout the plastic supply chain, realising higher added value and improved products and services. The project brought together 25 organisations (research groups, equipment manufacturers and industrial users). [s1]

Pharmaceutical manufacture studies: Continuous processing has recently emerged as an area of interest for the pharmaceutical industry, where potential benefits include faster and lower cost of development, increased process robustness, improved product yields and greater supply chain flexibility. Roller compaction and twin screw wet granulation are two important technologies which can be used to achieve continuous granulation.

The *roller compaction* process involves the compaction of fine powders into ribbons or flakes that are subsequently milled to produce granules. The milling process is critical for controlling the properties of the granules, but an understanding of the governing design and operating factors is still in its infancy. PEPT was employed to examine the kinematics of roll compacted ribbons at various milling speeds using both single tracer and two tracers approaches. The PEPT data revealed that the mill speed plays an important role. At low mill speeds, the milling process is dominated by cooperative motion of the ribbons and the blade, with size reduction occurring primarily by abrasion. At high mill speeds, ribbons move randomly with comminution by impact breakage. This research was funded by AstraZeneca (description adapted from supporting statement from AZ [s2]).

Washing machine and dishwasher design: The work done on the characterisation of internal processing in mechanical washing devices has influenced the design of the cleaning formulations and has led to products that minimise energy and water usage. Procter & Gamble is one of the largest R&D employers' in the North East of England and over the last 10 years have developed a strong relationship with the University of Birmingham – both with Chemical Engineering and Physics. Through the use of PEPT they have been able to quantify mechanical forces within washing machines, allowing them to understand mass transfer limitations in the laundry washing process. These insights are leading to an optimisation of P&G detergent formulations and to significant improvements in energy efficiency and environmental performance. The impact is significant; in Europe alone, about 270 billion washing operations are performed annually, each using about 20L of water and 1KWh of power. In order to realise the full potential of their formulations in reducing the amount of water and energy required during cleaning, careful characterisation of the phenomena occurring during cleaning under real conditions is critical; only PEPT has been able to provide this to-date. In the short term, the use of PEPT has allowed P&G to improve the methods used to evaluate performance of formulations under real conditions, resulting in faster and cheaper testing at their technical centres. (adapted from supporting statement from P&G [s3]). Dr Jose Vega, R&D Director, Procter & Gamble, Brussels Innovation Centre observes "*This has provided information which could not have been obtained in any other known way today."*

Catalyst development: Johnson Matthey Catalysts have used PEPT to understand and improve the behaviour of crystallisation plant used in a wide range of processes, and in validating modelling codes widely used within the company [s4]. Most recently, PEPT has been used to validate a DEM mathematical model of a Turbula® mixer used for powder blending which is now being applied in commercial applications. Johnson Matthey continues to support PEPT through EngD and PhD projects.

PEPT impact on mining and milling in South Africa using Birmingham expertise

The PEPT technique developed at Birmingham has now been established at iThemba Labs in Cape Town (2009). This facility was established with key support by the Birmingham Group and mirrors Birmingham's facility. This has now led to significant impact in the mining and milling sector (*descriptions adapted from supporting statement from the South African Centre for Minerals Research* [s5 and s6]). All Impact is in the period (2009-2013). The commercial nature of many of these developments mean that companies will not release details of direct economic benefit, but as an example of the level; the annual revenue of companies such of AngloAmerican Platinum exceeds £1b [s7] and there has been significant impact on the efficiency of their operations from this research.

Comminution in platinum mining: Xstrata funded a project to study the motion of grinding media in stirred mills used for minerals comminution in platinum mining. The aim was to understand the reasons for high wear rates in certain portions of the mill and come up with options to address the causes. The study was able to provide insights into the causes for high wear rates in some sections of the stirred mill and have used the data to improve the life of the lining material in these mills. Here PEPT studies revealed for the first time that compaction of material occurs in the first chamber of the mill leading to excessive wear in this region.

Performance of tumbling mills: This project was initially funded by the South African Minerals to Metals Research Institute, SAMMRI. SAMMRI was established by AngloAmerican, Lonmin, Impala, AngloGold Ashanti and Exxaro to ensure the growth, sustainability and global competitiveness of South African mining. The initial research was aimed at studying the influence of different liner/lifter designs on the performance of tumbling mills. The PEPT study provided insights on the influence of key design variables on mill performance and the data used to test if the simulation model being developed captured the actual characteristics of the mill. The results have now attracted further follow-on funding from AngloAmerican.

PEPT was used to study the transport of particles in the tumbling mill with a view of isolating the important variables that can be optimised to increase tumbling mill capacity while achieving a relatively fine product size. The PEPT studies showed that when an intermediate grinding media size is used the tumbling mill is able to process more material compared to the smaller or bigger media. This insight was implemented on three Anglo American Platinum plants and resulted in an increase in production on two plants. It was not possible to quantify the influence of changing the grinding media size on the third plant because they changed the shaft where ore was being drawn from at the same time.

AngloAmerican Platinum also funded a project to study the influence of speed on utilisation of energy in tumbling mills, i.e. to establish the optimum speed for various types of mills. A model was developed from the PEPT measurements which showed that operating the mills at very high speeds resulted in transferring energy to the charge (raw materials inside the mills) more than once per revolution. The study showed that very low speeds resulted in transferring energy to the charge less than once per revolution. Having an energy transfer rate much lower than 1, resulted in less breakage and a fine product is predominantly produced. Energy transfer rates much higher than once per revolution resulted in high capacity but very coarse product. The outcomes from this project have assisted in most of the designs where the budget is not sufficient to install variable speed drives on the mills. The model is used to predict the optimum speed for the given conditions and a decision on the speed of the fixed speed motor is taken. The size of the motor is an important design consideration and being able to predict the optimum speed results in significant savings on the capital costs for the plant. This model was developed using data from PEPT experiments and calibrated against pilot plant and industrial plant data. Based on this work AngloAmerican Platinum has agreed to fund PEPT related projects on tumbling mills for another 5 years.

The third project funded by AngloAmerican Platinum involved using PEPT to develop a model for the transport of particulate materials in the tumbling. Grinding in tumbling mills involve transport the material from the inlet to discharge and out of the mill. This process controls the capacity of the mill and there are no models in the literature than can be used to predict the transport of particles in the tumbling mills. The reason for not having reliable models for this important process was due to the lack of a technique for measuring the flow of particulate materials in opaque systems containing slurry and particles. Therefore, all models were developed using many assumptions regarding the influence of slurry. PEPT has provided numerous insights regarding the important variables for this important part of the grinding process. The insights have been implemented on selected operating plants and the results presently look encouraging and will lead to the optimisation of the throughput of the mill and minimisation of cost and energy consumption.

Optimisation of Ball Mill operation: AngloAmerican Platinum are using PEPT to study the behaviour of charge and grinding media in laboratory-scale ball mills in order to optimise operating conditions and reduce energy consumption (typically comminution corresponds to 65-80% of energy used in the mine-milling process). A simple model of mill operation has been developed. To enable results obtained at laboratory scale to be adapted to full scale plant, AngloAmerican Platinum has recently instrumented its full scale mills with sensors for process characterisation. "*The ongoing support from the companies listed above and the outcomes from the PEPT study is a clear indication that it is an important tool in improving the understanding of comminution processes. The results from the projects listed above have also shown that the information has already started contributing to resolving some challenges encountered in Mineral processing comminution plants.*" Head of Comminution Research, Centre for Minerals Research, Cape Town. [s5]

5. Sources to corroborate the impact (indicative maximum of 10 references)

s1. www.peptflow.com
s2 Corroborating statement from Formulation Sciences, Pharmaceutical Development, Global R&D, AstraZeneca, dated 3/12/12
s3. Corroborating statement from R&D Director, Procter & Gamble , Brussels Innovation Centre, dated 7/12/12
s4 Corroborating statement from Scientific Consultant and Chief Chemical Engineer, Johnson Matthey Catalysts, dated 3/1/13
s5. Corroborating statement from Head of Comminution Research , Centre for Minerals Research, University of Cape Town, dated 4/12/12
s6 Corroborating statement from Head of Physics Dept, University of Cape Town, dated 15/7/13
s7 Anglo-American Plc, Annual Report 2012, pp76-81 (available from the University)
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