

Positron Emission Tomography Applied to Fluidization Engineering

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ABSTRACT

The movement of particles in fluidization processes in a model test reactor has been studied using an imaging technique from medical healthcare: Positron Emission Tomography (PET). With this non-invasive technique, tracer particles were followed on their way through the fluidized bed. Experiments were performed with pulses of tracer particles in different alignments. The results give a good impression of both axial and radial distribution of particles in fluidized bed. In this paper, the experimental results confirm the basic assumptions of the model. Our stochastic model captures the dynamic movement of particles qualitatively, but indications are that the system exhibits 'gulf-streaming', a feature which is not accounted for in the model, but is common in fluidized beds in practice.

Keywords Fluidization; Fluidized bed; Stochastic model; Positron Emission Tomography.

1 INTRODUCTION

During the last decade a number of techniques, pioneered and used in the medical sector, have been applied to monitor the dynamics in opaque processes, such as fluidized beds, including X-rays, Positron Emission Particle Tracking (PEPT), Electrical Capacitance Tomography (ECT) and direct visualization by endoscopes. Advanced techniques for better results are continually being pioneered.

Cooperation made it possible to use the Positron Emission Tomography (PET) facility at the Groningen University hospital (AZG), and thus to follow the dispersion through the fluidized bed of a pulse of marked particles in real time. To do this, particles were labeled with an ¹⁸F isotope, and experiments were done inside the PET (ECAT EXACT HR+) camera's cylindrical ring of 83 cm diameter and 15 cm depth as shown in Figure 1.

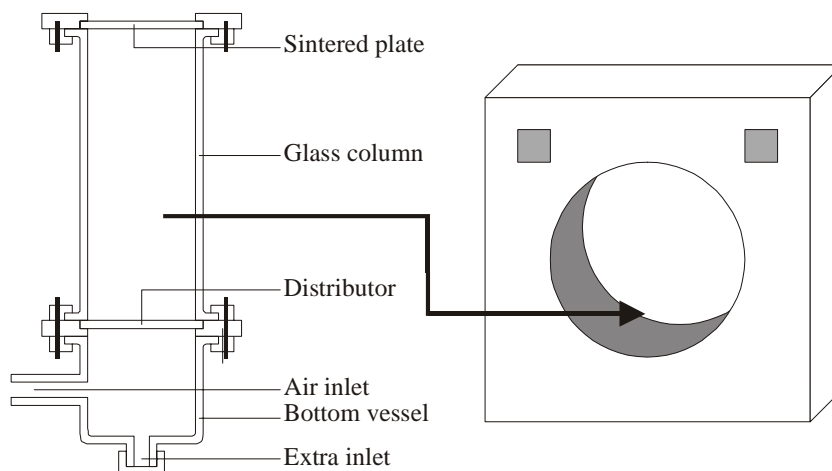


Figure 1: A fluidized bed construction used in the experiments.

The final result of the radioactive decay of the ¹⁸F isotope is the 'back to back' emission of two photons of 511keV. Two photons detected by the scintillation crystal detectors within a certain time window are deemed to originate from the same decay event, and define one 'line of response' (LOR). The camera

output is either in the form of sinograms – 2-dimensional arrays of the angle and the distance to the sensing zone center of LORs – or in the form of 'list mode data', which is discussed in Hoffmann et al. (2003).

Image reconstruction from the raw PET-scan data is a statistical problem, due to the inherent randomness of positron emission and detection. Analysis of such data is discussed for instance in the Poisson emission model by Vardi, Shepp and Kaufman (1985).

2 Background on Fluidization

The fluidized bed is one of the best known contacting methods used in the processing industry, for instance in oil refinery plants. Among its chief advantages are that the particles are well mixed leading to low temperature gradients, they are suitable for both small and large scale operations and they allow continuous processing. The fluid used to fluidize the solid particles can be either liquid or gas. Gas-solid fluidization is studied here. There are several regimes of gas-solid fluidization e.g. particulate, bubbling and slugging. This paper focuses on a bubbling fluidized bed, which is also the regime most often used in the process industry. When continually increasing the flow rate of a gas flowing through a bed of particles through a porous distributor plate as sketched in Figure 2, a point is reached where the particles are supported in the gas stream, and the particles start to lift up. This point is called minimum fluidization velocity. Increasing the gas flow further the formation of bubbles is visible. A bubbling fluidized bed is shown in Figure 2.

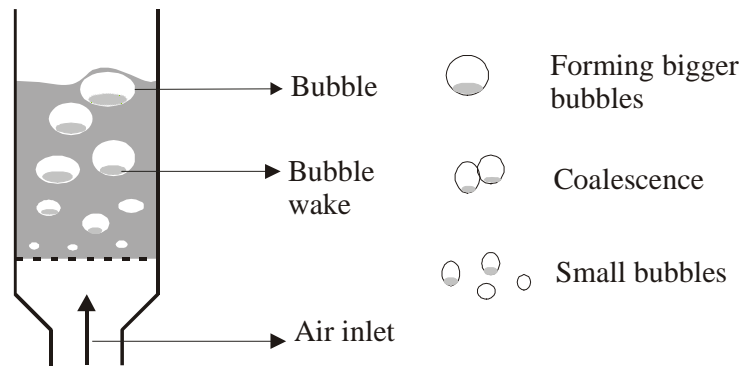


Figure 2: A bubbling fluidized bed.

The underlying explanation of particles transport in fluidized beds is that the bubbles are the cause of circulation, exchange and dispersion of solid particles in the bed. When bubbles are formed at the distributor plate and pass through the bed they collect some particles with them, forming the so-called 'wake' moving with the bubble. During the way upward wake particles exchange with bulk particles in the bed until the wake is deposited at or near the surface of the bed. The bubbles themselves disturb the bulk particles and cause dispersion and mixing of particles throughout the bed. These concepts were pioneered by Rowe and Partridge (1962).

However, also other phenomena may influence the particle motion in fluidized beds. Werther (1973) and Werther and Molerus (1973 a and b) studied the dynamics and cross-sectional distribution of fluidization bubbles using a miniaturized capacitance probe. They found that the bubble distribution is non-uniform over the cross-section, and that this may contribute to determining the solids circulation in the bed. Merry and Davidson described the phenomenon of "gulf-streaming" of solids in shallow fluidized beds, i.e. separate regions of upward and downward solids motion.

3 Experiments

The experiments were carried out in glass columns of 10 and 15 cm diameter equipped with a sintered metal porous distributor plate. Also at the top of the bed a sintered porous plate was placed in order to avoid bed particles escaping into the clean environment. Two types of experiment were carried out: single particle-tracer, where only one particle was made radioactive, and pulse-tracer experiments. The single-tracer experiments are described elsewhere (Hoffmann et al., 2003).

We have performed experiments using pulses arranged both horizontally and vertically, with different materials. We focus here on pulse tracing experiments using FCC catalyst material in 3 different positions, middle, top and bottom layers as shown in Figure 3. The initial bed height was approximately 20 cm in all the experiments. A typical experiment was started by preparing the tracers by soaking the particles in liquid containing dissolved ^{18}F ions. After this, the tracer particles were dried in a separate fluidized bed and then arranged in the test bed in the position wanted. Each experiment was carried out at a fluidization velocity of ~ 10 mm per second, the minimum fluidization velocity of the powder is about 4 mm/s. The fluidizing gas was turned on, and suddenly diverted to the fluidized bed at time $t = 0$. PET measurements were carried out for a total period of about 5 minutes at a constant flow rate.

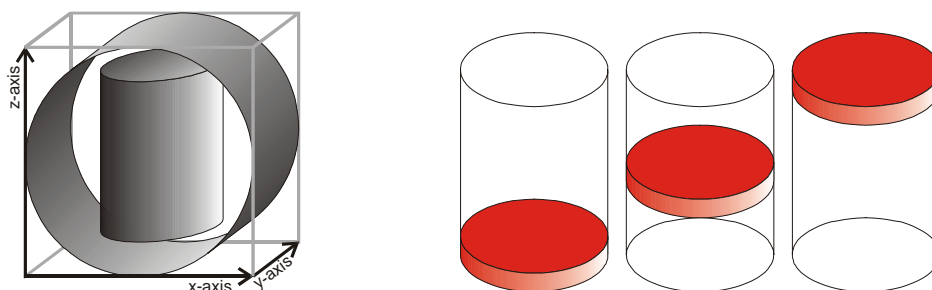


Figure 3: The initial position of the pulse during the pulse experiments and a fluidized bed in PET scanner.

Very informative 3-dimensional images of the evolution of tracer density in time were obtained. Figure 5 and 7 were generated using our own developed software (van der Zwan, 2001), showing the transportation of tracer in time as gray-scale bitmap plots.

4 Stochastic Model for batch bubbling fluidized beds

This model is based on Dehling and Hoffmann's modelling concepts for particle transport in bubbling fluidized beds based on a convection-diffusion process (Dehling et al, 2000). In this paper we study a batch-fluidized bed, where there is no inflow and outflow of the particles during the process. The motion of one particle is considered, and the transport processes are converted to transition probabilities between cells in a discretized bed (see Figure 4). The probability distribution for the particle's position as a function of time reflects the behaviour of a radioactive pulse of tracer particles, such as in the experiment. The model is based on Markov chains, such that the transition probability distribution of a single particle is independent of the past history of the system. For simplicity, we model only the vertical position of the particle, neglecting the horizontal displacement.

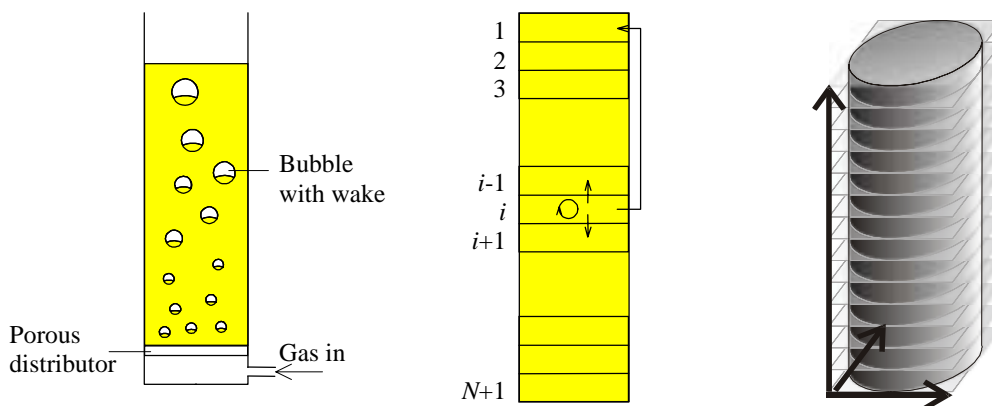


Figure 4: A batch fluidized bed and a discretized bed.

In our discrete Markov model, the reactor is divided into N horizontal cells, and we model the particle's position at discrete times only. The cells are numbered as shown in Figure 4. The model calculates the probability distribution of the axial position of one particle as a function of time. The possible transitions

are: 1) staying in the same cell, 2) moving to the next cell, 3) moving back to the previous cell and 4) being caught up in a bubble wake and deposited at the top of the bed.

We introduce parameters α_i , β_i and δ_i , with sum equal to 1, for the first three probabilities, conditionally on the particle not being caught up in a bubble wake, the latter probability being given by λ_i . The transfer probabilities from cell i to cell j form a matrix, Q , with the elements q_{ij} . The transition probabilities for the interior of the reactor, i.e. for $2 \leq i \leq N-1$, are:

$$q_{i,i} = \alpha_i(1 - \lambda_i), \quad q_{i,i+1} = \beta_i(1 - \lambda_i), \quad q_{i,i-1} = \delta_i(1 - \lambda_i), \quad q_{i,1} = \alpha_i \lambda_i \quad (1)$$

Regarding the boundaries, i.e., $i = 1$ and $i = N$;

$$q_{1,1} = 1 - \beta_1(1 - \lambda_1), \quad q_{1,2} = \beta_1(1 - \lambda_1), \quad q_{N,N} = 1 - \delta_N(1 - \lambda_N) - \lambda_N, \quad q_{N,1} = \lambda_N, \quad \text{and} \quad q_{N,N-1} = \delta_N(1 - \lambda_N)$$

The probability distribution of the position of the particle at the n 'th time step is given by the probability vector $p(n)$, with elements denoted by $p(n,i)$. Knowing $p(n-1)$, one can find $p(n)$ from:

$$p(n, j) = \sum_{i=1}^N p(n-1, i) q_{i,j} \quad \text{or in matrix notation} \quad p(n) = p(n-1)Q$$

After n time steps, we obtain the formula for the probability distribution of position of the particle at time n in terms of its initial probability distribution:

$$p(n) = p(0)Q^n \quad (2)$$

which $p(0)$ is the initial condition of particle distribution in the reactor at time $t=0$.

The model introduced above is a discrete one, but the transfer probabilities will be related to physical parameters describing the particle transport as continuous processes, following Dehling *et al.* We call the time step ε and the cell width Δ . Letting ε and Δ go to 0, we obtain a discrete Markov chain approximation to a continuous limit process.

The vertical distance from the top of the reactor is denoted by x , i.e., $x = 0$ corresponds to the top and $x = 1$ to the bottom, and the convective axial velocity due to circulation by $v(x)$. The dispersion due to the disturbance by bubbles is denoted by a dispersion coefficient, $D(x)$. The probability of returns to the top of the bed is described by the probability rate $\lambda(x)$. The parameters in the transition matrix are defined as follows:

$$\delta_i = \frac{\varepsilon}{2\Delta^2} D(i\Delta) - \frac{\varepsilon}{2\Delta} v(i\Delta), \quad \beta_i = \frac{\varepsilon}{2\Delta^2} D(i\Delta) + \frac{\varepsilon}{2\Delta} v(i\Delta), \quad \alpha_i = 1 - \delta_i - \beta_i \quad \text{and} \quad \lambda_i = \varepsilon \lambda(i\Delta).$$

Both the axial velocity due to circulation of particles as well as the return rate of particles are functions of the particle flow in the wake of rising fluidization bubbles. If Q_w denotes the wake flow and A the

cross-sectional area of the bed, we have: $v(x) = \frac{Q_w(x)}{A}$ and $\lambda(x) = \frac{d}{dx} \left(\frac{Q_w(x)}{A} \right)$.

5 Comparison of model predictions and experimental results

For the comparison of experimental results and model predictions for the dispersion of a pulse of marked particles, the experimental results of 2 different layers of marked tracers are compared with the model predictions as shown below,

5.1 Top layer

This is an experiment placing a tracer layer at the top of the bed. The layer first rose slightly at the onset of fluidization without losing its shape and then sank to the bottom while dispersing. The images from PET show that the top layer dispersed slowly while moving down. The layer of marked particles is still distinguishable as it reaches the lower region, whereafter it is dispersed completely. Figures 5 and 6 show good qualitative agreement between model predictions and experiment.

5.2 Middle layer

Figure 7(Left) shows the experimental results of a layer initially positioned in the middle of the bed. The layer again initially moves up slightly at the onset of fluidization and then down while dispersing. When reaching the bed bottom, the layer seems to be transported to the top before moving down again and dispersing completely. Our model captured the movement of marked particles dispersion qualitatively well as shown in Figure 7.

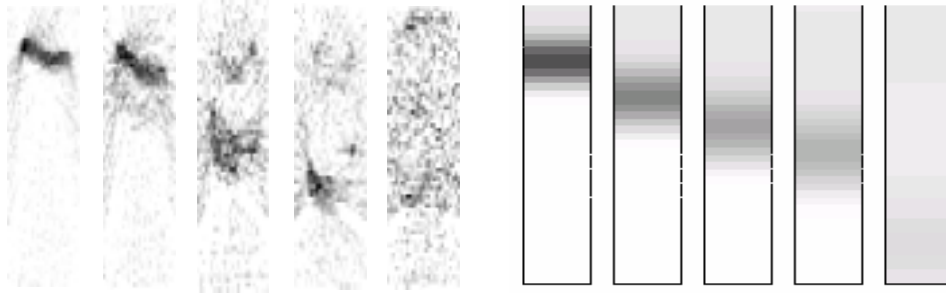


Figure 5: Comparison images from PET and our stochastic model results with the tracer on top of the bed at time 1, 2, 3, 4 and 10 s. (Left: Experimental result, Right: Model prediction)

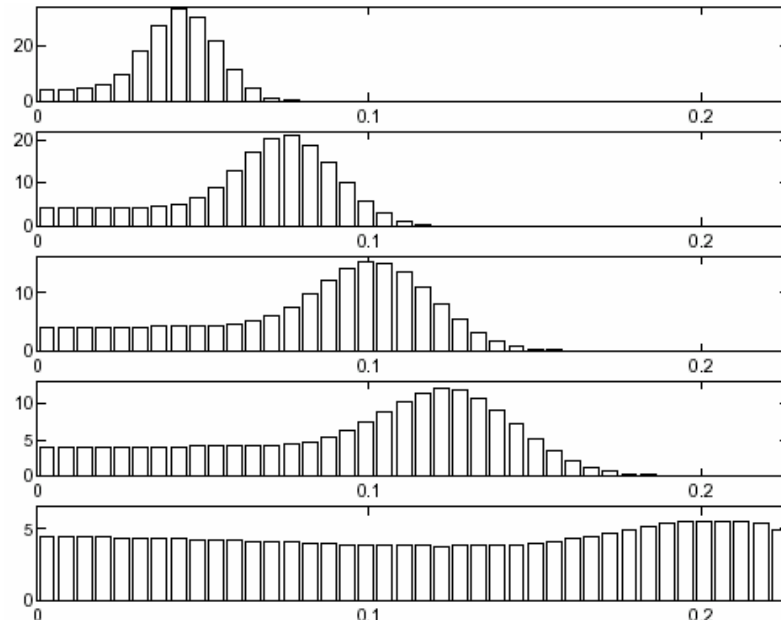


Figure 6: Plots of particle distribution of top layer experiments for $t = 1, 2, 3, 4$ and 10 .

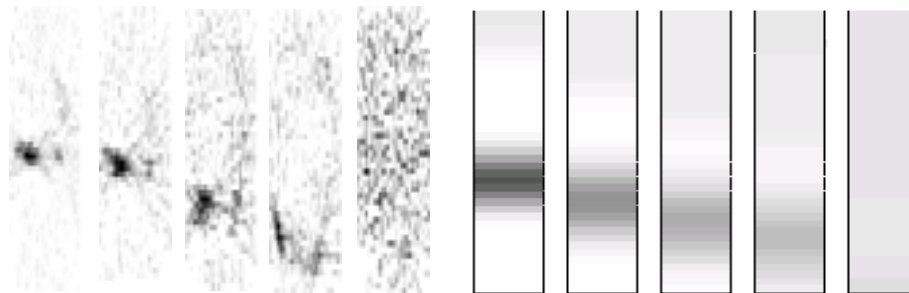


Figure 7: Comparison images from PET and our stochastic model results with the tracer in the middle of the bed at time 1, 2, 3, 4 and 10 s. (Left: Experimental result, Right: Model prediction)

6 Concluding remarks

In previous work, stochastic models developed by our research group were constructed to model the particle dynamics in different types of gas-solid fluidized bed reactors, continuous fluidized beds, binary mixtures fluidized beds with and without baffles and slugging fluidized beds (Dehling et al. 1999; Dechsiri, et al., 2000;2001;2002). Using a PET scanner to obtain the results shown in this paper has shown that the model captures qualitatively the dynamic movement of particles in bubbly fluidized beds and confirm the basic assumptions of the model. The model is relatively easy to apply to different types of fluidized beds with only a few modifications.

A point of concern at this initial stage is that the quantitative comparison of model and experiment was lacking: the downward movement of the layer was considerably faster than could be explained by the wake flow predicted by empirical relationships in the literature, and so we adjusted the parameters in the model to produce the fits in Figures 5 and 7. We think that the difference is caused by 'gulf-streaming' in the bed (Merry and Davidson, 1973). The phenomenon of gulf-streaming is caused by a cross-sectionally non-uniform bubble flow, causing a general upward material flow in one part of the bed, and downward in the other. Due to this effect much more material is brought to the top of the bed by the bubble flow than would be expected on basis of the flow in the wake phase itself, and thus the downward flow in the bulk is also higher. A close inspection of the bitmap charts in Figures 5 and 7 shows that this phenomenon likely takes place, and this is also indicated by the single particle experiments. Gulf-streaming will always take place in a fluidized bed to some extent.

7 References

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