Particle transport in fluidized beds
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Summary

Fluidization is a process in which solids are caused to behave like fluid by blowing gas or liquid upwards through the solid-filled reactor. The behavior of a bed of particles within the reactor during the process is very complex and difficult to predict. To make sure that a fluidized bed reactor is optimally efficient, normally a pilot model of the proposed reactor is made and tested before an actual reactor is built. Alternatively, a mathematical model can be used to investigate performance of the planned reactor. Physical modeling using a pilot reactor can be expensive, time consuming, and its accuracy may suffer from scaling problems. On the other hand, mathematical modeling is economical, convenient, but accuracy of the performance prediction is the primary concern.

There have been numerous research projects aimed at modeling the physical phenomena governing the transport of particles in fluidized bed. Most of these models are based on the deterministic approach. The deterministic model approaches the problem by macroscopically investigating the evolution of densities of a pulse of marked particles. However application of this approach to a complex system such as transportation of particles in fluidized beds does not always lead to soluble models. Microscopically fluidization entails a strong element of random motion of the particles. The process itself is complex, but yet can be attributed to discrete events. Modeling the fluidization process with stochastic approach is therefore intuitive and preferable.

A stochastic modeling approach may be advantageous also when the processes in question, through the law of large numbers, in practice behave deterministically, leading to soluble models even where traditional modeling techniques are not tenable. An example is the complex case of a slugging fluidized bed discussed in this thesis.

The stochastic model employed in this research is based on a discrete Markov process. The modeling starts with a partitioning of the reactor into a finite number of horizontal cells in which a single particle is located at a certain discrete time of the process. Movement of particles in fluidized beds can be attributed to convective upward and downward transport and to dispersion, all associated with fluidization bubbles or slugs. The possible transitions of particles are: staying in the same cell, moving to the next cell, moving back to previous cell, and being caught up in a bubble wake and deposited at the top of the bed. The probabilities of these transitions are quantified in accordance with the particle transport processes. The probability distribution of the position of a single particle is, by the law of large numbers, the basis for an analysis of the evolution of the density of a
pulse of infinitely many marked particles over time. Since the process is Markovian, the probability distribution of the axial position of the particle at a given time step depends only on its position at previous time step and a set of transition probabilities.

In this study, three types of fluidized bed reactors were investigated by experiments and results were compared to the predictions from the stochastic model. The three types of reactors were: freely bubbling fluidized beds, bubbling fluidized beds with baffles, and slugging fluidized beds.

The motion of individual particles and the dispersion of a pulse of particles in a freely bubbling batch fluidized bed reactor were studied in a series of experiments performed in the Academic Hospital Groningen using Positron Emission Tomography (PET). This experimental technique, which was used here in connection with fluidization, allows direct non-invasive monitoring of physical processes. The main goal of the experiments was to gain insight into particle transport processes in fluidized bed reactors and to validate the concepts behind the stochastic model.

Both PET and Positron Emission Particle Tracking (PEPT) techniques were used to study the particle motion. In order to obtain data with high temporal and spatial resolution, a PET camera equipped with state-of-the-art hardware, normally available only in medical sectors, was used here to study the dynamic behavior of the fluidized particles. The dynamics of both tracer pulses and single particles were investigated in the experiments. The results of the pulse experiments are presented as bitmaps showing the marked particle concentration in the bed in a succession of one second time frames, and in the form of 3-D plots and contour plots of the marked particle concentration as a function of position in the bed and time. The results of the single particle experiments are shown as 2-D and 3-D plots of particle paths and plots showing the distribution over the bed cross-section of upward and downward paths.

The results show that the model, which is based on the notions of upward material transport with the fluidization bubbles and material descent with dispersion in the bulk, capture the essential features. This confirms the validity of the basic modeling assumptions. However, the downward movement is shown to be at least an order of magnitude faster than expected. This discrepancy is attributed to “gulf streaming”, a feature which is not accounted for in the model, but is often encountered and unavoidable in industrial fluidized bed processes. The gulf streaming phenomenon is clearly seen in both single particle and pulse experiments. This phenomenon occurred due to a non-uniform bubble distribution over the bed cross section, regions where, in addition to the wake material, also
bulk material, interstitial between the bubbles, is dragged up with the bubble stream. This flow of bulk material can be considerably more than the wake flow, causing also a considerably faster downward bulk flow in the rest of the bed. Fundamental investigation of the gulf streaming mechanism is needed for future incorporation to the model.

The model for freely bubbling fluidized beds was based on the single type of particle with uniform properties. However, the models for the other two types of system described below, namely bubbling fluidized beds with baffles and slugging fluidized beds, are formulated for binary mixtures with different densities. In such systems, the heavy particles (jetsam) tend to sink and the light particles (flotsam) tend to float during fluidization, thus segregation takes place. The transition probabilities for the freely bubbling fluidization process were modified to take into account segregation effects.

As mentioned, the stochastic model has also been applied to predict the dynamics of particle mixing and segregation in a baffled batch fluidized bed. The possible transitions of a particles in mixing and segregation problems are the same as those mentioned previously for a freely bubbling conventional bed, except that here a particle caught in a bubble wake may be deposited not only at the bed surface, but also under a baffle. Two new aspects feature in this mathematical model: modeling of segregation by increasing the probability of a down-transition for the jetsam particles, giving an extra downward drift, and modeling the effect of baffles.

Experimental data from bubbling fluidized beds with baffles for binary mixture, in which the superficial velocity and number of baffles are varied, were collected and compared to the predictions from the stochastic model. The comparison shows good agreement for the profiles of segregation in baffled batch fluidized bed. The modified Markov chain model for this type of problem still retains the advantages of clarity, intuitiveness, and short calculation time. The results also called for future revision of the model to include particle to particle interference and the effects of local jetsam concentration.

Finally, the stochastic model was applied to yet another type of fluidized bed system: mixing and segregation in slugging fluidized beds containing a binary mixture. A slug is a bubble whose size is nearly equal to the bed diameter and normally occurs in narrow bed reactors. Slugs reduce the efficiency of the reactors but are often unavoidable in practice. This model is based on a description of the particle displacement in the system resulting from the formation and rise of a single slug. It disregards any interaction between successive slugs in the bed. To formulate the model, the entire process was broken up into two distinct phases,
slug formation and slug rise. The segregation effect is simulated as described above for the baffled bed. The cumulative effect of consecutive slugs is found by superposition. The model is validated with experimental data for the particle mixing pattern in time. The predicted axial particle concentration profiles from the stochastic model are compared graphically with the experimental results. This simple and intuitive modeling approach is shown to be successful even for a complex process like slugging fluidized beds, where conventional modeling using conservation equations is untenable.

The basic assumption of independence of the particles' motion is justified as long as the proportion of the marked particles is rather small. As long as this is the case, the single particle modeling proves to be successful in predicting the experimental results. However when there is substantial fraction of marked particles in the reactor, interaction among particles become significant and must be taken into account. A preliminary study of a particle transport model that includes interaction effects was also carried out.

In the course of the work to develop and validate the stochastic models, work on enhancing particle segregation in fluidized bed was also conducted. A fluidized bed equipped with a set of vibrating baffles was designed and built to enhance the fine and cohesive powder classification. Vibration was applied to enhance the capability of the baffles to break the inter-particle bonds. Experimental trials were performed to test the efficiency of the new set up to separate different metallic powders. The results showed that the reactor could separate different metallic powders according to their size and, more importantly, their density. This unconventional fluidized bed technique showed the potential of improving the segregation and fluidization. However, in order to determine optimal conditions, more experiments are recommended.