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A basic population balance model for fluid bed spray granulation

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ABSTRACT

A basic population balance approach is developed for a granulation process in a fluid bed spray granulator. The particle size distribution predicted by the model is confirmed by plant data. Hence this model is considered to be useful to describe and optimize an industrial process. The model depends on a limited number of parameters (most of these factors can be measured or are known): the spray volume flux, the nucleation fraction (the fraction of the spray volume flux which leads to new particles formed), the nucleation particle diameter, the product withdrawal threshold diameter, and the product withdrawal rate. Analysis of the model reveals a steady-state constraint; a steady state does not exist if the nucleation fraction is too large. For cases where the steady state does exist, the steady-state particle size distribution is solved analytically. A numerical implementation of the model is used to illustrate the transient evolution of the process. The steady-state solution appears to be stable for a constant nucleation fraction. However, if the nucleation fraction depends on the bed height the steady state can be unstable. Such a situation may occur if the spray inlet is near the height of the bed surface. Instead of convergence towards a steady state, the transient solution displays ongoing oscillatory behavior with an oscillation period of a number of hours. A linear stability analysis is performed to confirm the findings on the stability of the steady state.

1. Introduction

Product quality is related to the particle size distribution for many particulate products. Particulate products can be manufactured in various processes such as spray drying, mechanical granulation, and fluid bed granulation. The present work concerns processes where a fluid bed granulator is used. In a fluid bed granulator, a liquid is sprayed onto an already existing powder bed that is fluidized with air. The liquid partially evaporates, leaving a dry material and particles that have grown. Such particle growth can be the result of aggregation, where the liquid acts as a binder (e.g. Tan et al., 2006), or it can be the result of so-called onion growth, where the material is deposited onto the particles layer by layer (e.g. Heinrich et al., 2002). It is obvious that these processes influence the particle size distribution. The particle size distribution is a key function, which controls final product properties such as bulk density, powder flowability, and dustiness. It is the aim of this work to link process conditions to the particle size distribution via a basic model that can readily be applied in an industrial environment for process improvement and optimization.

To model the particle size distribution, the so-called population balance approach can be quite helpful (Randolph and Larson, 1988; Hounslow et al., 1988; Ramkrishna, 2000). The present paper considers a basic population balance model, which was developed to describe the process dynamics of an AkzoNobel fluid bed granulator for a certain chemical species. The aims of the project were to formulate a simple model description of the particle size distribution and to obtain knowledge about how unsteady and unstable behavior of the industrial process can be controlled. The early literature on population balance models focussed on crystallization (e.g. Randolph and Larson, 1988; Sherwin et al., 1969; Lie et al., 1971; Randolph et al., 1973). The present model is quite similar to the so-called mixed reactor mixed product or mixed reactor selective product concepts in older works. However, there are subtle differences in the present model (such as a nonzero nucleation diameter), which leads to a previously unknown nucleation constraint for the existence of a steady state. The application of population balance models to fluid bed spray granulation processes has received some attention in literature before (Heinrich et al., 2002; Drechsler et al., 2005; Radichkov et al., 2006; Peglow et al., 2007). For example, milling of coarse particles and reintroducing the milled material into the granulator was found

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to produce oscillatory behavior (Heinrich et al., 2002). Compared to the existing models of fluid bed granulation processes, the present model has deliberately been made more simple. The advantage of a simple model is that it is more accessible for mathematical analysis, and in this way important properties of the model can be revealed. It appears that a population model can be stripped down to basic ingredients and nevertheless be able to describe important features of particulate industrial processes.

The contents of the paper is as follows. In Section 2 we describe the relevant parts of the industrial process and show available plant data. The population balance model is formulated in Section 3. The steady-state solution and the corresponding existence condition are derived in Section 4, in which the solution of the model is also compared with the plant data. In Section 5 we argue that the nucleation parameter in some cases depends on the bed height, and we formulate a corresponding expression for this parameter. Results of numerical simulations are presented in Section 6, to show the transient behavior of the model, both for constant and height dependent nucleation. The linear stability of the model is analyzed in Section 7. Finally, the conclusions are summarized in Section 8.

2. Plant data

In this section relevant information of the granulator is specified and measured particle size distributions are shown. A sketch of the granulator is shown in Fig. 1. The main compartment of the granulator is cylindrical and contains a fluidized bed of height h. The bottom of the bed is cylindrical with area $A = 5\,\mathrm{m}^2$. The bed is fluidized by a vertical hot air flow (arrows 2 in Fig. 1) through a perforated bottom plate. The superficial air velocity equals 2.5 m/s, which is somewhat higher than the minimum fluidization velocity of 1.75 m/s. The granulation is a continuous process, as material is removed via a centrally positioned air sifter.

A solution enters at the side of the bed in the form of droplets through various nozzles (arrow 1), spraying in the horizontal direction and positioned at a height of $h_{noz} = 0.44\,\mathrm{m}$ above the bottom. In the granulator the water content of the spray droplets quickly evaporates because of the high bed temperature, and the solute is

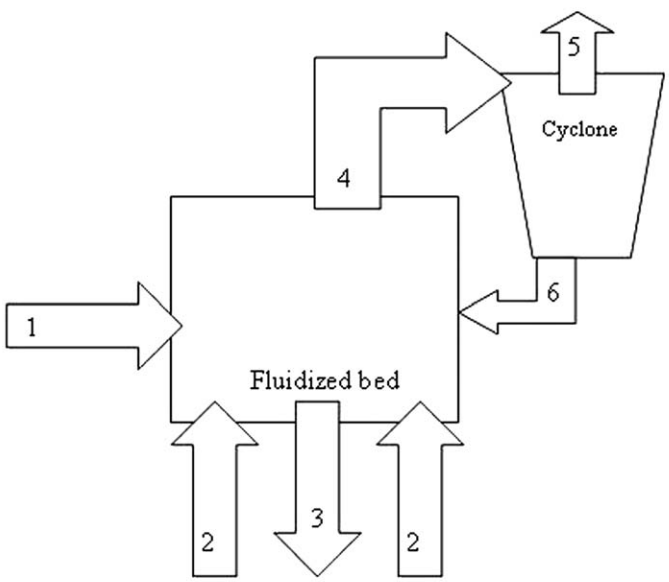

Fig. 1. Sketch of the granulator. Arrows: (1) injection of the suspension, (2) injection of hot air, (3) product removal, (4) flow to the cyclone, (5) air outlet, and (6) fine particles reentering the bed.

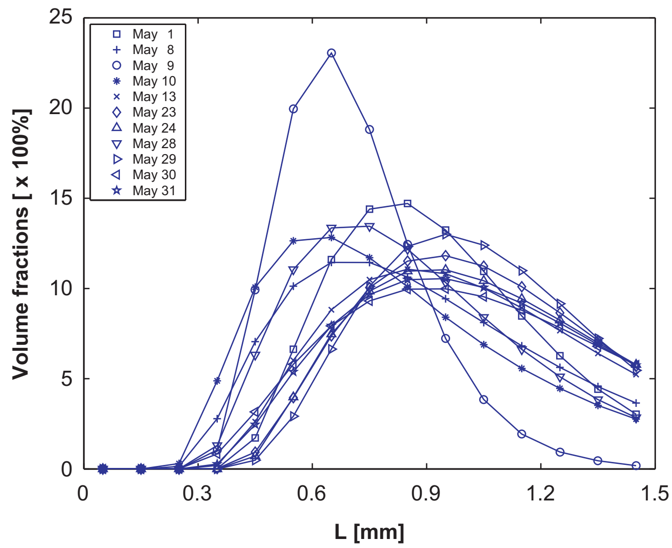

Fig. 2. Volume fractions (×100%) in the bed as a function of particle size. The samples were taken on May 1, 8, 9, 10, 13, 23, 24, 28, 29, 30, 31 (2008).

transformed into a new granule (nucleation) or adds to existing granules (growth). The granules are spherical solid particles.

Dividing the spray solute mass flow by the material density of the solid particles, we obtain an effective spray inflow volume flow, Φ, which equals $1.67 \times 10^{-4}\,\mathrm{m}^3/\mathrm{s}$. It is emphasized that Φ does not refer to the entire suspension but to the solute content only. The typical hold up of the granulator corresponds to a solid volume of $V = 1.1\,\mathrm{m}^3$. Thus the bed height can be obtained from

$$h = \frac{V}{(1-\varepsilon)A}, \qquad (1)$$

where ε denotes the bed porosity. If the porosity were 0.5, the bed height would be just the nozzle height. It was not possible to measure the actual bed height or porosity, but the operation staff believes that the spray inlets are just below the bed surface. To stimulate particle growth, the spray inlets should not be high above the bed height, while, to avoid particles sticking together, the inlets should not be placed much below the bed surface.

The product particles are withdrawn from the center of the granulator (arrow 3). The withdrawal apparatus contains an air sifter with countercurrent flow to separate small from large particles. The large particles are transported to a storage location, while the small particles are reblown into the fluidized bed to continue granulation.

Because the terminal velocity of the fine particles in the bed is smaller than the superficial air velocity, fine particles flow with the air into the cyclone (arrow 4). The cyclone serves as a recycler for the particles to limit material losses; filtered air escapes through the roof (arrow 5), while the fine particles are brought back to the bed (they are injected below the bed surface, arrow 6).

Particle size distribution measurements taken at the plant are shown in Fig. 2 for the granules in the bed. The figure shows results for samples taken on more or less random days within one month. Each sample from the bed corresponds to 1 l of solids, taken out of the bed and subsequently subjected to size analysis by a laser diffraction technique, using particle size classes with a width of 0.100 mm each. Since we do not know the start-up times of the runs from which the samples were taken, nor the hour in which they were taken, we cannot precisely deduce the history of a single run from the present experimental data. Nevertheless, the variation of the measurements shown in Fig. 2 does indicate that the granulation process is unsteady. Since the residence time of particles in the granulator is about 2 h