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A dynamic two-zone model of continuous fluidized bed layering granulation with internal product classification

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ABSTRACT

A dynamic two-zone model is proposed to address the formation of granulation and drying zones in fluidized bed layering granulation processes with internal product classification. The model assumes a constant volume for the granulation zone, but a variable overall volume for the fluidized bed to account for classified product removal. The model is used to study the effect of various process parameters on dynamics and process stability. Stability is shown to depend on the separation diameter of product removal and the flow rate of the injected liquid. A lower and upper range of separation diameters with stable process behavior are found. In an intermediate range instability in the form of self-sustained oscillations is observed. The lower stability boundary is in qualitative agreement with recent experimental observations (Schmidt, Bück, & Tsotsas, 2015); the upper boundary was reported in a theoretical paper by Vreman, Van Lare, and Hounslow (2009) based on a single zone model.

Introduction

Fluidized bed layering granulation (FBLG) processes play an important role in chemical, pharmaceutical, and food industries. They are used to generate dust-free and free-flowing granules, which are usually more durable and easier to handle than their liquid equivalents (Heinrich, Peglow, Ihlow, Henneberg, & Mörl, 2002; Mörl, Heinrich, & Peglow, 2007). Despite their importance, the dynamics of these processes remain poorly understood; a fundamental understanding is a prerequisite for stable process operation and the production of particles with tailor made properties.

In FBLG processes a suspension or solution is sprayed into a process chamber. The process chamber contains a large number of particles which are fluidized by a heated gas flow. The surface of the particles is wetted by the injected material, which leads, after drying, to an 'onion layer-wise' particle growth.

Industrial FBLG processes with high production rates are operated continuously. This requires a continuous supply of new nuclei to the granulation chamber. Besides an external supply of nuclei, two different mechanisms can lead to the generation of new nuclei. In processes with external product classification, this can be achieved by a continuous separation of oversized particles, which are ground with a mill and then recycled to the granulation chamber with the undersized particles (Heinrich, Peglow, Ihlow, et al., 2002). These kinds of processes are usually operated with constant bed mass inside the granulation chamber.

In processes with internal product classification, an outlet tube is installed in the lower area of the process chamber (see Fig. 1). By means of an adjustable counter-current classification gas flow, the size of particles, which are withdrawn from the granulation chamber, can be adjusted. Internal formation of new nuclei can be achieved by suitable injection of liquid suspension leading to overspray, which after drying gives rise to new nuclei. As the outlet parameters are fixed to achieve a product size spectrum, bed mass and volume usually vary during operation (Vreman et al., 2009).

Both process configurations tend to be unstable for certain operating conditions. While the particle size distribution of the outlet remains almost constant, these instabilities can lead to self-sustained oscillations of the outlet mass flow, and therefore to variations of the hold-up in the apparatus. Although this problem was already known to practitioners for some time (Schuette, Ruhs, Pelgrims, Klasen, & Kaiser, 1998), a rigorous experimental validation was given only recently by Schmidt, Rieck, Bück, and Tsotsas (2015) for processes with external product classification, and by Schmidt, Bück, and Tsotsas (2015) for processes with internal product classification.

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Notation

A	cross sectional area (m^2)
b	overspray fraction
b_∞	minimum overspray fraction
G	growth rate (m/s)
h_{bed}	bed height (mm)
h_{nozzle}	nozzle height (mm)
K	gain of the withdrawal
L	particle size (mm)
L_0	average size of nuclei (mm)
L_1	average separation diameter (mm)
n_i	particle size distribution in zone i (1/mm)
q_i	normalized particle size distribution in zone i (1/mm)
t	time (s)
T	separation function
$\dot{V}_{Inj}$	solid fraction of injected suspension (dm^3/s)
V_i	volume of zone i (m^3)
V_Σ	total bed volume (m^3)

Greek letters

α	relative size of granulation zone
ε	bed porosity
$\mu_i(\cdot)$	ith order moment of argument
Π_i	parameter sets
σ_0	standard deviation of nuclei size (mm)
σ_1	standard deviation of separation diameter (mm)
τ_i	residence time of particles (s)

A preliminary model based analysis of the instability of FBLG processes with external product classification was given by Heinrich, Peglow, and Mörl (2002) and Radichkov et al. (2006), and for processes with internal product classification by Vreman et al. (2009). In these models, uniform particle growth was assumed. However, this is in contradiction to more recent experimental findings for batch processes where a widening of the particle size distribution over time has been observed. This phenomenon can be explained by zone formation (Hoffmann, Peglow, & Tsotsas, 2011; Peglow et al., 2014; Silva, Tamiozzo, Duarte, Murata, & Barrozo, 2011).

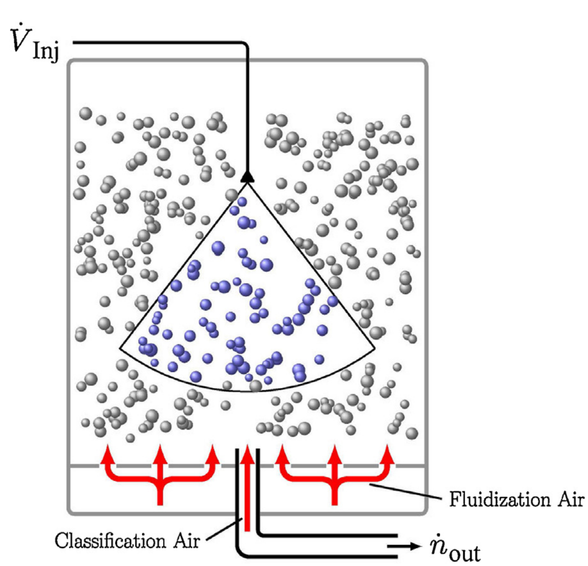

Fig. 1. Simplified scheme of fluidized bed layering granulation with internal product classification. The granulation zone is represented by the blue particles, the drying zone by the grey particles.

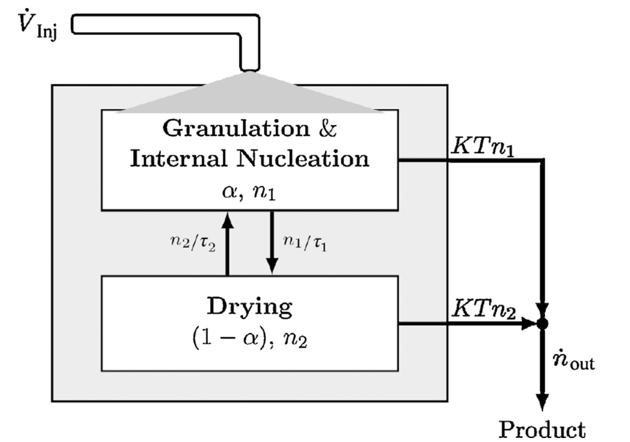

Fig. 2. Nomenclature and model structure of the fluidized bed layering granulation with internal product classification.

Fig. 1 illustrates that only part of the particles in the granulation chamber are wetted by the injected solution, giving rise to distinct granulation and drying zones. The influence of zone formation on the dynamics and stability of FBLG processes with external product classification was recently investigated by Dreyschultze et al. (2015), and further analyzed by Bück et al. (2016). The present study reveals the effect of zone formation on the dynamics of FBLG processes with internal product classification. A mathematical model is developed. In contrast to the external product classification process, variable bed mass has to be accounted for and combined with the effect of zone formation. The model is used for numerical bifurcation and stability analysis, and the results are compared with previous theoretical results (Palis & Kienle, 2013; Vreman et al., 2009) and experimental findings (Schmidt, Bück, et al., 2015).

Mathematical model

The nomenclature and model structure of the FBLG process with internal product classification, as illustrated in Fig. 1, are introduced in Fig. 2.

According to Figs. 1 and 2 the process chamber is divided into two functional zones. In the first zone, the granulation zone indicated by index 1, the spherical, non-porous particles, n_1, are sprinkled with a liquid suspension or solution (with a volume flow rate $\dot{V}_{Inj}$) and growth of the particles takes place. The second zone, indicated by index 2, is the drying zone. Within this zone, the particles are not in contact with the spray, and drying particles, n_2, appear. Exchange rates between the granulation and the drying zones in Fig. 2 follow from the amount of particles in the respective zones and characteristic time constants τ_1 and τ_2.

Following the arguments in Vreman et al. (2009) for the single zone model, it is assumed that the spray injected into the granulation zone $\dot{V}_{Inj}$ gives rise to two different effects. The fraction b of $\dot{V}_{Inj}$ is converted into internal nuclei via overspray; the remaining fraction (1 – b) of $\dot{V}_{Inj}$ leads to the layer-wise growth.

Assuming that the fraction of injected spray contributing to particle growth is equally distributed on the surface of all particles in the granulation zone, by following Mörl et al. (2007) and Vreman et al. (2009), the growth rate can be calculated as:

$$G(\dot{V}_{Inj}, b, n_1) = \frac{2(1-b)\dot{V}_{Inj}}{\pi \mu_2(n_1)}, \qquad (1)$$

where $\mu_i(n) = \int_0^\infty L^i n \, dL$ represents the ith order moment of the number density n.