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Granule size distribution for a multi-chamber fluidized-bed melt granulator: Modeling and validation using process measurement data

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HIGHLIGHTS

- We model a multi-chamber fluidized-bed granulator used for urea production.
- The model has mass, energy and population balances for all the fluidized beds.
- The model including coating and elutriation is consistent with industrial data.
- A method is proposed to reduce the errors in the population balance solution.
- The fines are removed almost completely in the first and second chambers.

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ABSTRACT

In this work, a steady-state model of a multi-chamber fluidized-bed granulator used for urea production is developed and validated. To this aim, mass, energy and population balances are solved for all the fluidized beds. Regarding the population balance equation (PBE), pure coating or the combined mechanisms of coating and elutriation are taken into account. Both PBE formulations are analytically solved and a new solution methodology is proposed to handle inlet solid streams distributed in different size grids and to minimize the solution errors propagation expected when a set of PBEs in series has to be solved. By comparison with experimental data, it is found that the model including coating and elutriation gives a better representation of the particles size distribution with respect to the results found when pure coating is assumed. Besides, the results indicate that the fines are removed almost completely in the first and second chambers, being the amount of fines in the subsequent chambers negligible.

1. Introduction

Flowsheet simulation of industrial processes has nowadays become essential to take advantage of new and cost effective software tools for plant design, troubleshooting, control strategies improvements, optimization, workforce education, etc. (Dosta et al., 2010; Reimers et al., 2009). Therefore, there is need to develop modern simulation packages capable to integrate accurate equipment models. In large-scale plants, reliable simulators can help to identify optimal operating conditions that allow increasing industries benefits significantly (Werther et al., 2011).

Although 60% of industrial chemical products are particulate in nature and a further 20% use powder intermediates (Ennis, 1997), simulation tools for plants that handle particulate systems are not as well developed as those for liquid/gas based industries. The modeling of processes involving powders or granules is difficult because, among other reasons, they have to be described as distributed systems. Consequently, the mathematical representation of powders transformations is not a trivial task. In fact, these models called population balance equations (PBE) are described by a set of complex partial integro-differential equations (Dosta et al., 2010; Reimers et al., 2009; Werther et al., 2011).

Within the operations that handle solids, granulation is considered as one of the most important advances. It is a key particle size enlargement process, widely used in the pharmaceutical, food, mining and fertilizer industries, which converts fine particles and/or atomizable liquids (suspensions, solutions, or melts) into granular material with desired properties (Adetayo et al., 1995; Tan et al., 2006). Even though granulation is accepted as an overwhelming particle size enlargement unit operation, not all the particles that leave the granulator meet the marketable granules size distributions. To this end, other unit operations are necessary (such as crushing and size classification stages). Therefore, the granulator along with

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crushers and screens constitute the granulation circuit. The operation of granulation circuits is not simple and often presents operational challenges, which force them to work with a capacity less than the nominal one and with high recycle ratios that overload all process units (Balliu, 2005; Cotabarren et al., 2011; Wang and Cameron, 2007). In particular, the recycle characteristics greatly influence the granulation unit operation. This stream represents a continuous feedback of mass, energy and a certain particle size distribution to the granulator, producing frequent oscillations in the process variables. Depending on the operating conditions, these oscillations are damped or generate increasing instabilities that may cause undesired plant shutdowns. The oscillations, in turn, lead to a granular product with properties that vary in time (Radichkov et al., 2006). In view of the operational complexity associated to processes that handle particulate systems, research related to process modeling for the development of robust simulators applied to the solids industry has been intense in recent years (Adetayo, 1993; Balliu and Cameron, 2007; Dosta et al., 2010; Gatzke and Doyle, 2001; Sanders et al., 2009; Werther et al., 2011; Wildeboer, 1998).

Granulation circuit models can be used with confidence to address key design changes only if they are validated against collected data (Balliu and Cameron, 2007). Particularly, the modeling of large-scale industrial granulators requires identifying the main size change mechanisms and consequently formulating and accurately solving the PBE, and finally fitting the corresponding kinetic parameters by taking into account experimental data.

In this context, this article is focused on the mathematical model development and validation of a multi-chamber fluidized-bed melt granulator used for urea production. This particular process has been selected as an interesting case of study because there are many large-scale urea plants around the world operating with fluidized-bed granulation technologies as finishing process (Cotabarren et al., 2012), which require validated simulators to improve process performance and, thus, plant profitability. The main goal of this work is to provide a steady-state model of a multi-chamber fluidized-bed granulator, accurate enough to be reliably applied in industry for process simulation, optimization and control purposes. To this aim, pure coating and the combined mechanisms of coating and elutriation were proposed. The different PBE formulations were analytically solved and a new solution methodology was proposed to handle inlet solid streams distributed in different size grids and to minimize the solution errors propagation expected when a set of PBEs in series is required to be solved. Finally, based on data collected from a large-scale urea plant, a kinetic parameter are given.

2. Description of the multi-chamber fluidized-bed melt granulator

Although urea granulation can be performed in different types of granulators, fluidized-bed units are commonly used for large-scale production due to their versatility and potential to carry out the process at low costs (Mörl et al., 2007). Fig. 1 presents a simplified schematic representation of the urea fluidized-bed granulator. This unit is basically a bed of solids fluidized by air, continuously fed with small urea particles (called seeds) and a urea highly concentrated liquid solution (about 96%) that is sprayed from the bottom (Niks et al., 1980). The bubbling nature of the fluidized bed, which is responsible for the strong solids mixing, promotes the repeatedly circulation of the granules through the spray zone. The unit is designed and operated with the purpose of favoring granules growth through a coating process, which consists in the deposition of tiny liquid droplets onto the seeds followed by cooling and water evaporation that facilitate the solidification of the sprayed urea. The energy for evaporation is provided by the urea solution itself, which is atomized into the granulator at a relatively high temperature (Bertin et al., 2007). In order to increase the granules residence time and to reduce the dispersion of the outlet particle size distribution (PSD), industrial granulators have several growth chambers (where the urea concentrated solution is sprayed) connected through the bottom of the unit. Subsequently, fluidized-bed dedusting/cooling compartments are arranged to meet specific requirements for further granules processing. In particular, Fig. 1 shows a typical configuration of an industrial urea granulator, constituted by 3 growth chambers and 3 cooling ones.

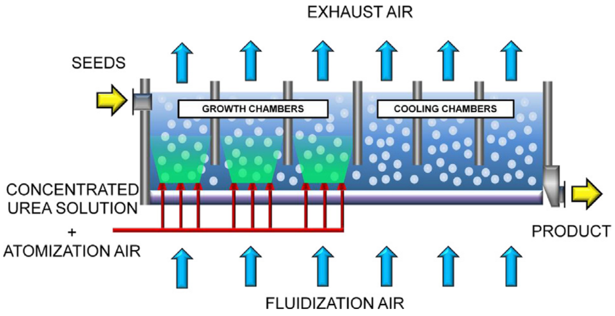

Fig. 1. Schematic representation of a multi-chamber fluidized-bed granulator for urea production.

Even though coating is the preferred growth mechanism, unexpected operating conditions may favor undesired particles size change phenomena. Therefore, it is necessary to identify the main size change mechanisms that may take place within the unit.

3. Fluidized-bed granulator model: pure coating growth

The starting model for the urea fluidized-bed granulator is founded on the assumptions of pure coating growth and a coating efficiency of 100% (i.e., all the urea present in the atomized solution successfully contributes to particles growth).

3.1. Mathematical model

Considering the unit features above described (Fig. 1) and previous simulation results on the steady and unsteady-state operations of the multi-chamber granulator (Bertin et al. 2007, 2010, 2011), the steady-state model of the industrial fluidized-bed urea granulator is formulated on the basis of the following hypotheses:

- The solid phase is perfectly mixed within the fluidized beds. As it is known, the degree of mixing within the granulator has an important effect on the granule size distribution. It has been observed that the experimental PSD greatly broadens along the granulator chambers (from the inlet to the outlet). Moreover, it has been found that the exponential residence time distribution of the particles provided by the assumption of perfect mixing in each fluidized growth chamber was enough to achieve consistency between the real and simulated PSDs.
- In each chamber, all the urea granules have the same density and porosity and are spherical.
- All the urea melt droplets successfully reach the solids surface and contribute to the particles growth (i.e., perfect coating efficiency). The sprayed droplets are distributed proportionally to the fraction of total particles surface area (Litster et al., 2004; Mörl et al., 2007).
- Coating is the only size change mechanism, i.e. the elutriation of fines, formation of nuclei by attrition, agglomeration, breakage and overspray are negligible.