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Non-identifier-based adaptive control of continuous fluidized bed spray granulation

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ABSTRACT

This paper is concerned with stabilizing control for continuously operated fluidized bed spray granulation with internal product classification. It is well-known that these processes may become unstable for certain operating conditions giving rise to nonlinear oscillations in the particle size distribution. In contrast to previous works, in this contribution a model-free adaptive control is proposed. It is shown that the given fluidized bed spray granulation process fulfills the required structural assumptions. The designed control schemes, universal adaptive and λ-tracking control, are tested in a noise-free scenario and including measurement noise.

1. Introduction

Granulation is an important production process resulting in larger particles and improved product properties, e.g. decreased dust during material handling and increased flowability. Fluidized bed spray granulation involves the injection of an additional liquid, which settles on the particles, dries and thus forms a new solid layer on the particle surface. An important configuration is the continuous fluidized bed spray granulation with internal classification. Here, only particles with a minimum diameter are redrawn from the process by applying a counter-current flow in the outflow. The critical separation diameter can be influenced by the counter-current flow velocity. In order to permanently generate new particles a relative high nozzle height is chosen, such that part of the liquid drops dry before hitting the particle surface. The schematic process scheme is depicted in Fig. 1. As shown in [1–3] qualitative dynamics of continuous fluidized bed spray granulation processes may vary significantly with process conditions. In [1] a detailed bifurcation analysis has been conducted, which, from a practical point of view, gives valuable information in which parameter region to operate the plant at hand. In addition, the derived models can be used for a model-based control design, e.g. robust PI or model predictive control [4,5], H_∞-control [6,7] or nonlinear discrepancy based control [9], to compensate for the undesired losses of stability, i.e. the occurrence of nonlinear oscillations. However, model validation, being the basis of the presented analysis and control design, based on experiments may be often difficult to perform in a production setting due to significant additional costs and undesired set-point changes. Therefore, in this contribution model-free adaptive control approaches [10–12] will be investigated on their feasibility for fluidized bed spray granulation control. The paper is organized as follows: in Section 2 the model of continuous fluidized bed spray granulation with internal product classification as proposed by [3] is stated. In addition, a numerical bifurcation analysis of the process is used to motivate the need for stabilizing control. In Section 3 the universal adaptive and λ-tracking control schemes are introduced together with the main structural assumptions on the process. It is further studied whether these requirements are fulfilled by the given type of process. Some final remarks conclude the paper.

2. Fluidized bed spray granulation

Particles produced during fluidized bed spray granulation processes are of high sphericity and can thus be described by their diameter. Due to the very high number of particles, this leads to the particle size distribution and its dynamical behavior. Applying

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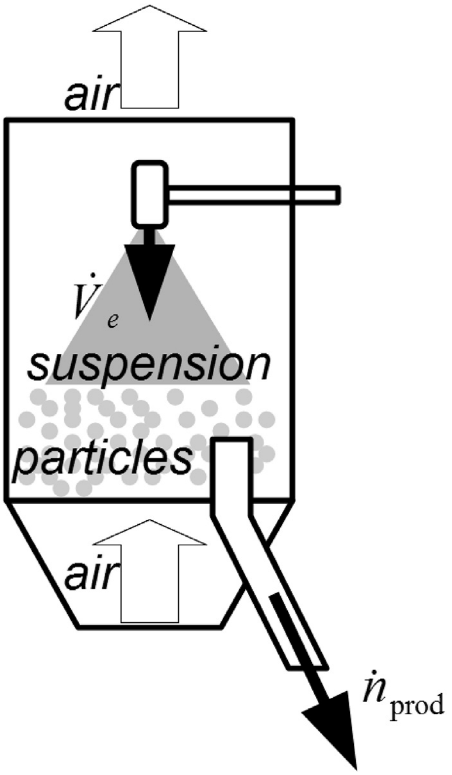

Fig. 1. Process scheme.

population balance modeling [13] for the number density of the particle size distribution leads to the following equation

$$\frac{\partial n}{\partial t} = -G\frac{\partial n}{\partial L} + \dot{n}_{nuc} - \dot{n}_{prod} \tag{1}$$

where the first term is related to the particle growth, the second term accounts for the generation of new nuclei and the third for product withdrawal [3]. Depending on the distance between the particle bed and the nozzle, part of the injected liquid contributes to nucleation and the rest to growth. In [3] it is assumed that the part contributing to nucleation $b(n)$ varies linearly with the bed height between its minimum value b_∞ and maximum value $b = 1$.

$$b(n) = b_\infty + \max\left(0, (1 - b_\infty)\frac{h_{noz} - h(n)}{h_{noz}}\right) \tag{2}$$

The bed height $h(n)$ depends on the overall particle volume $V = \pi\mu_3$, which is proportional to the third moment, and the bed porosity ε, which is assumed to be constant.

$$h(n) = \frac{V}{(1-\varepsilon)A} = \frac{\pi\mu_3}{(1-\varepsilon)A} \tag{3}$$

For the nucleation it is assumed that new particles are uniformly distributed with a medium diameter L_0.

$$\delta(L) = \frac{n_u(L; L_0, \sigma_0)}{\mu_3(n_u(L; L_0, \sigma_0))} \tag{4}$$

where

$$n_u(L; \mu, \sigma) = \exp\left(\frac{-(L-\mu)^2}{2\sigma^2}\right). \tag{5}$$

The classification function of the product removal is given by

$$T(L) = \frac{\int_0^L n_u(L; L_1, \sigma_1)dL}{\int_0^\infty n_u(L; L_1, \sigma_1)dL}. \tag{6}$$

Table 1
Simulation parameters.

$\dot{V}_e$	$1.68 \cdot 10^{-4}\,\mathrm{m}^3/\mathrm{s}$	injection rate
ε	0.5	fluidized bed porosity
A	$5\,\mathrm{m}^2$	granulator cross-sectional area
h_{noz}	0.44 m	nozzle height
b_∞	0.028	minimum nucleation rate
L_0	0.3 mm	medium diameter of nuclei
σ_0	0.05 mm	standard deviation of nuclei diameter
L_1	0.7 mm	medium classification diameter
σ_1	0.05 mm	classification selectivity
K	$1.92 \cdot 10^{-4}\,1/\mathrm{s}$	Product removable rate

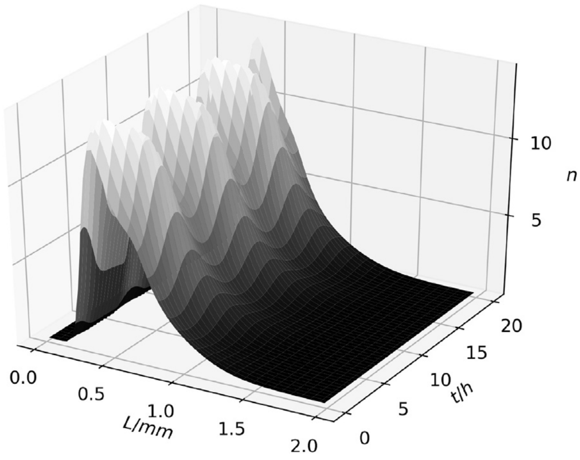

Fig. 2. Time behavior of the particle size distribution $n(t, L)$ for small $\dot{V}_e$.

Therefore, the overall population balance model is given by

$$\frac{\partial n}{\partial t} = -\frac{2(1-b(n))\dot{V}_e}{\pi\mu_2(n)}\frac{\partial n}{\partial L} + \frac{b(n)\dot{V}_e\delta(L)}{1/6\pi} - KT(L)n. \tag{7}$$

For simulation the population balance model has been discretized along the property coordinate L using a finite volume method with an upwind scheme. For the uniform grid of the property coordinate 150 grid points have been used. The parameters are given in Table 1 and are in accordance with [3,7].

It is well-known [3,2,1] that the given process configuration may become unstable depending on the given operation conditions, e.g. the injection rate. The loss of stability results in the occurrence of nonlinear oscillations in the particle size distribution as depicted in Fig. 2. A systematic study of this behavior, in terms of a one-parameter bifurcation analysis, shows that below a certain injection rate $\dot{V}_e$ the steady-state solution becomes unstable and a limit cycle occurs (Fig. 3). This periodic behavior in product quality and availability is in general undesired. It has also been observed in real granulation processes, e.g. [2]. In order to overcome this problem feedback control should be applied. From a practical point of view, one would be interested to control the third moment, as it correlates with the overall bed mass and can thus be derived from simple pressure measurements.

$$y = \mu_3 \tag{8}$$

As the actuated variable the effective volume flow rate $\dot{V}_e$ is chosen, which can be manipulated using the injection pumps.

$$u = \dot{V}_e \tag{9}$$

However, the main difficulties connected with the presented model as a basis for model-based control approaches are: