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Entropy-based control of continuous Entropy-based control of continuous Entropy-based control of continuous fluidized bed spray granulation processes fluidized bed spray granulation processes Entropy-based control of continuous fluidized bed spray granulation processes

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 $\overline{\mathcal{M}}$ on the basis of an entropy function a control Lyapunov function will be derived. In order to
facilitate the control design procedure this entropy-based control Lyapunov function will be approximated by its second order Taylor expansion. facilitate the control design procedure this entropy-based control Lyapunov function \mathcal{L} On the basis of an entropy function a control Lyapunov function will be derived. In order to approximated by its second order Taylor expansion. Abstract: This paper is concerned with control of a continuous fluidized bed spray granulation. on the basis of an entropy function and the basis of an entropy-based control Lyapunov function will be dependented. In order to a coorder to the derived. In order to the detail of α and α and α order to the deriv

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1. INTRODUCTION 1. INTRODUCTION 1. International control of the con
1. International control of the con Fluidized bed spray granulation is a particulate process, 1. INTRODUCTION 1. INTRODUCTION

Fluidized bed spray granulation is a particulate process, Principal bod spray grammation is a particulate process, injecting a solid matter solution. Due to high process air temperature, the fluid evaporates and the remaining solid emperature, the fund evaporates and the remaining solid
material either contributes to growth of already existing naterial effect contributes to growth of already existing
particles or forms new nuclei. As product particles should have a certain minimum size an additional product clasration is required. In this contribution a process configuration is required. In this contribution a process con-
figuration applying an air sifter with countercurrent flow inguration applying an air sines with connecturient now
as depicted in Fig. 1 will be studied. Another possibility as depicted in Fig. 1 win be studied. Another possibility
is for example the application of an external classification is for example the application of an external classification
using sieves with corresponding recycle of the overusing sieves with corresponding recycle of the over-
and undersized fraction [2]. In order to allow a continuous process operation part of the withdrawn product particles will be milled and fed back as nuclei to the granulation will be milled and fed back as nuclei to the granulation
chamber. It is well known that continuous granulation processes in general and in particular continuous granuation plying a mill cycle tend to instability and the occurrence of nonlinear oscillations of the particle size distribution. These oscillations give undesired time behavior of product quality [4, 3, 2]. Similar patterns of behavior have been $\left(\frac{1}{2}, \frac{1}{2}, \frac{1}{2} \right)$. Similar particulate processes as e.g. crystallization processes (e.g. [10]). In order to control these mation processes (e.g. [10]). In order to control these
several approaches have been proposed ranging from linear
finite dimensional several (e.g. [0, 7]) to nonlinear lization processes (e.g. $[10]$). In order to control these
several approaches have been proposed ranging from linear
finite dimensional control (e.g. $[9, 7]$) to nonlinear infinite time dimensional control (e.g. [b, η]) to nonimear immediately
dimensional control methods [8]. Especially the later, i.e. the discrepancy based control design, has been successfully and discrepancy stated control design, may been successfully undersized fraction $[2]$. In order to allow a continuous
process operation part of the withdrawn product particles observed for other particulate processes as e.g. crystal-
ligation processes $(a \in [10])$. In order to control these the discrepancy based control design, has been successfully
condict to different particulate processes

applied to different particulate processes.
In this contribution control design exploiting the thermodynamic structure, i.e. the entropy, of the process will dynamic structure, i.e. the entropy, or the process will function will be derived and used for control design. studied. Therefore, an entropy-based control Lyapunov function will be derived and used for control design.

2. CONTINUOUS FLUIDIZED BED SPRAY 2. CONTINUOUS FLUIDIZED BED SPRAY 2. CONTINUOUS FLUIDIZED BED SPRAY GRANULATION GRANULATION OUS FLUIDIZED A continuous fluidized bed spray granulator with an ad-2. CONTINUOUS FLUIDIZED BED SPRAY GRANULATION GRANULATION

A continuous fluidized bed spray granulator with an ad-A continuous nutured bed spray granulator with an additional mill as depicted in Fig. 1 consists of a granuladitional film as depicted in Fig. 1 consists of a granua-
tion chamber, where the particle population is fluidized tion chamber, where the particle population is fluidized
through an air stream and coated by injecting a suspension V_e . The particle growth associated to the layering process has been described in [1]. has been described in [1]. \dot{V}_e . The particle growth associated to the layering process has been described in [1]. has been described in [1].

Fig. 1. Process scheme Fig. 1. Process scheme Fig. 1. Process scheme Fig. 1. Process scheme

$$
G = 2 \frac{\dot{V}_e}{\pi \int_0^\infty L^2 n dL} \tag{1}
$$

It should be mentioned that the particle growth rate is inversely proportional to the overall particle surface area and hence the second moment of the particle size distribution. Product particles are continuously removed through an air sifter with countercurrent flow. Here, due through an an site with countercurrent now. Here, due to the particle size specific sinking velocity, sinal particles
with $L < L_2$ are reblown into the granulation chamber, while large product particles with $L \geq L_2$ pass the air
sifter. The associated ideal separation function T is given as follows. as follows. while large product particles with $L \geq L_2$ pass the air as follows. as follows.

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$$
T(L) = \sigma(L - L_2)
$$
 (2)

The outlet flow is hence

$$
\dot{n}_{out} = KT(L)n.
$$
\n(3)

where K is the drain, depending mainly on the air velocity and the ration between granulation chamber and sifter cross section. In order to guarantee a continuous process operation nuclei have to be continuously supplied. This can be achieved using an additional mill. For simplicity it can be assumed that the mill is mass conserving and generates a rectangular distribution.

$$
B = \alpha(\sigma(L - L_0) - \sigma(L - L_1)) \frac{\int_0^\infty L^3 K T n dL}{\int_0^\infty L^3 n dL} \tag{4}
$$

$$
= \alpha(\sigma(L - L_0) - \sigma(L - L_1)) \frac{\int_0^\infty L^3 K T n dL}{4(L_1^4 - L_0^4)} \tag{5}
$$

To describe the process, a population balance model for the particle size distribution can be stated consisting of the following particle fluxes

- B particle flux from the mill,
- \dot{n}_{out} particle flux due to particle removal,

and size independent particle growth associated with the particle growth rate G.

$$
\frac{\partial n}{\partial t} = -G \frac{\partial n}{\partial L} - \dot{n}_{out} + B \tag{6}
$$

For numerical simulation the model equations are semidiscretized with the finite volume method (1st order upwind flux discretization) with 310 grid points. The model parameters used are given in Table 1.

\dot{V}_e	$1.5 \cdot 10^{5} \frac{mm^3}{\ }$
L_0	0.1mm
L_1	0.2mm
L2	0.7mm
K	$1 \cdot 10^{-3}$ ¹
α_0	$5 \cdot 10^{-3}$ ^s
	T 11 -1

Table 1. Plant parameters

3. ENTROPY-BASED CONTROL LYAPUNOV FUNCTION

In the following a control Lyapunov functional will be derived based on an entropy function for the population balance model. The candidate being proposed in this contribution is strongly related to the one studied recently in [6] for a continuous crystallizer.

$$
S = \int_0^\infty -Cn \ln n dL = \int_0^\infty s(n) dL \tag{7}
$$

Here, C is a positive constant, which will be specified later. As we are interested in deviations from and control design for a desired steady state n_0 the following quantities can be defined

$$
\Delta S = S_0 - S,\tag{8}
$$

$$
\Delta Z = Z_0 - Z,\t\t(9)
$$

where $Z = kn$. The conjugate variable of Z can be calculated as

$$
\omega_0 = \frac{\partial s}{\partial Z}\bigg|_{Z=Z_0} \tag{10}
$$

$$
=-\frac{C}{k}(\ln n_0+1). \tag{11}
$$

Using Z , its conjugate and the entropy S a control Lyapunov function can be derived [6, 5].

$$
V = -\int_0^\infty \Delta Z \omega_0 dL + \Delta S \tag{12}
$$

Using eq. (11) yields

$$
V = \int_0^\infty \Delta n (C(\ln n_0 + 1)) dL,\tag{13}
$$

$$
-\int_0^\infty C(n_0\ln n_0 - n\ln n)dL,\tag{14}
$$

$$
= \int_0^\infty C(\Delta n - n(\ln n_0 - \ln n))dL.
$$
 (15)

In order order to simplify the control design for the continuous fluidized bed granulation process this control Lyapunov candidate will be approximated by its second order Taylor approximation.

$$
V = \int_0^\infty \frac{C}{n_0} \Delta n^2 dL \tag{16}
$$

Choosing $C = \frac{1}{2}n_0$ yields

$$
V = \frac{1}{2} \int_0^\infty \Delta n^2 dL.
$$
 (17)

4. CONTROL DESIGN

In the following the second order approximation of the entropy-based Lyapunov candidate (17) will be used in order to design an appropriate feedback control law. Calculating the time derivative V yields

$$
\dot{V} = \int_0^\infty \Delta n \left(\frac{\partial n_0}{\partial t} - \frac{\partial n}{\partial t} \right) dL \tag{18}
$$

$$
= -\int_0^\infty \frac{G}{2} \frac{\partial \Delta n^2}{\partial L} + \Delta n \left[B_0 - B - KT \Delta n \right] dL \tag{19}
$$

$$
= -\left. \frac{G}{2} \Delta n^2 \right|_0^{\infty} - \int_0^{\infty} \Delta n \left[B_0 - B - KT \Delta n \right] dL \left(20 \right)
$$

Here, the first two terms vanish due to the boundary conditions $n(L = 0) = \lim_{L \to \infty} n(L) = 0$, i.e. there are no particles of size zero and infinitely large particles. Hence, the time derivative of the Control Lyapunov functional V does not depend on the growth rate G and thus all results will be robust with respect to variations in the suspension injection rate.

$$
\dot{V} = \int_0^\infty \Delta n \left[B_0 - B - KT \Delta n \right] dL \tag{21}
$$

Inserting the equations for the particle outlet (3) and the mill flux (5) results in the following

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