Powder Technology 270 (2015) 575–583

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Model-based control of particle properties in fluidised bed spray granulation

Andreas Bück [a,*], Stefan Palis [b], Evangelos Tsotsas [a]

[a] Thermal Process Engineering, Otto von Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany
[b] Automation and Modelling, Otto von Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany

ARTICLE INFO

Available online 26 July 2014

Keywords:
Fluidised bed
Spray granulation (layering)
Feedback control
Population balance modelling

ABSTRACT

In this contribution different control approaches, ranging from standard linear control to non-linear model predictive control, are applied to fluidised bed spray granulation processes with internal and external product classification. These processes exhibit sustained non-linear oscillations in the particle property distribution, i.e. size distribution, that have negative influence on steady-state operation, for example a constant product mass flow with constant properties. The controllers are applied to stabilise these open-loop unstable steady-states.

1. Introduction

Particulates processes play an important role in various fields of application: There are many examples of particulate products in everyday-life, for instance milk powder, milled and roasted coffee, instant cacao powder, and sugar, to name just a few. Additionally, particulate products play an important role in other fields: health-care (e.g. in the form of an active pharmaceutical ingredient pressed into a tablet), in agriculture in the form of fertilisers, or in the chemical industry as catalyst powders. It is reported that approximately three quarters of all industrially processed goods are in solid state — either in their final state or in intermediate production stages [1].

The product properties can often be characterised by the particle properties, or rather the particle properties affect the properties of the product. Important particle properties are for instance the particle size and form, the porosity of the particle, the moisture content, and the enthalpy (temperature).

The particle size and form determine for instance the flow-ability of a powder: If the particles in the powder are too small, then cohesive forces between the particles prevent a free flow. This can be observed by comparison of sugar powder and crystal sugar: Although both products consist of the same material, sugar powder flows less freely because of the increased cohesive forces between smaller sized particles.

For the production of particulate substances from liquid starting material (solutions, emulsions, or suspensions) various processes exist: e.g. crystallisation, granulation, and spray drying. These can be further specialised depending on the characteristic effect that is used for the transformation, for example cooling crystallisation or spray granulation. Crystallisation and granulation are complex dynamic processes, involving multiple phases (fluid and solid), heat and mass transfer between these phases, as well as particle formation processes, e.g. layer formation.

One process that is often used in industries, e.g. in pharmaceuticals, foods, and fertilisers, is fluidised bed spray layering granulation. It allows for the production of dustless, free-flowing particles from liquid raw materials: The suspension (or solution) is sprayed onto particles in the process chamber and due to drying – the bed is fluidised by hot air – the liquid evaporates. The remaining solid builds up a new layer of solid material on the particles.

Fluidised bed spray granulation can be run in batch as well as continuous mode (Fig. 1), and drying and particle formation processes can be coupled and run simultaneously in one apparatus. The structure of the apparatuses is simple, and due to the high heat and mass transfer between the phases induced by the fluidisation, compact plants – compared to other technologies – can be designed. In both modes, a suspension or solution is sprayed leading to particle growth by layering as explained before (centre of Fig. 1). Additionally, in continuous operation, several ways exist to remove the product from the fluidised bed, for example by an external classification circuit which is depicted in Fig. 1 or by an internal classification. Both cases will be described in detail in later sections.

In the practical realisation of particle formation processes the following problem arises: The particles are not uniform, i.e. they differ in their properties, for instance in size, form or colour. This means that the particles in the powder do possess a distribution with respect to their properties, and therefore the product also possesses a property distribution. Given a product specification requires that the distribution lies within the limits posed by the specifications to be accepted by a customer.

The product specifications can be very strict, for instance in processes with expensive raw materials or where the product is a hazardous good,

---

[*] Corresponding author. Tel.: +49391 6718319; fax: +49391 6718265.
E-mail address: andreas.bueck@ovgu.de (A. Bück).
URL:E-mail addresses:E-mail address: http://www.nawitec.org (A. Bück).

http://dx.doi.org/10.1016/j.powtec.2014.07.023
0032-5910/

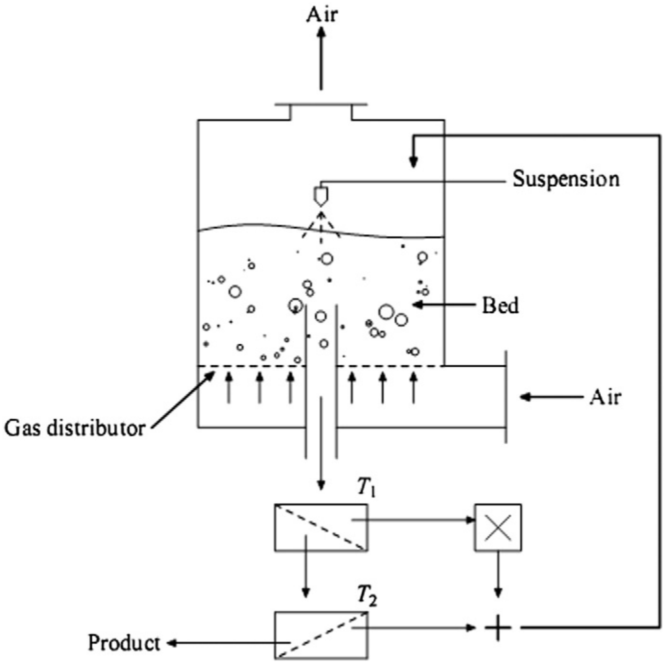

Fig. 1. Schematics of a continuous spray granulation process with external classification and particle recycle.

and the requirements are further increasing. The need to guarantee that the product complies to the specification motivates the use of process control systems in particle processes. This becomes especially important if the process designed according to the product specifications turns out to be unstable [2,3], i.e. even small process disturbances yield an undesired drift in the product properties. The necessary compliance of the product to specifications motivates the use of model-based feedback controllers.

One well-established framework for the macroscopic modelling of particulate processes, which are from a systems-theoretic point of view infinite-dimensional processes, that is well-suited for the modelling of industrial-scale processes, is the population balance approach, introduced for problems in statistical mechanics by Hulburt and Katz in the 1960s [4]. To the field of particulate processes it was transported by the work of Randolph and Larson [5] (with a focus on crystallisation); it was advertised and established in the field by D. Ramkrishna and coworkers [6].

In the literature, many successful applications of population balance modelling to particulate processes can be found, for instance in crystallisation [7–9], granulation [2,3,10–12], drying [13–15], or aerosol processes [16,17].

The main obstacle in the analysis and development of general control design methods for distributed parameter systems is the complex mathematical theory due to the infinite-dimensional character of the processes.

In the case of nonlinear distributed systems the treatment is restricted in most cases to practically important process structures, see for instance [18–20]. Nonetheless, control schemes are successfully designed for distributed parameter systems, for applications to spatially-distributed systems, see for instance [20–22].

There are also contributions in the field of property-distributed processes available, for instance Kalani and Christofides [17] who proposed nonlinear controller design for an aerosol process on the basis of a reduced model, and Chiu and Christofides [23] who applied a nonlinear controller to a crystallisation process on the basis of a reduced model. Pottmann et al. [24] designed a model-predictive controller for a drum granulation system; Vollmer and Raisch [25] and Palis and Kienle [26] designed a stabilising controller for an unstable crystallisation process using H_∞-theory and discrepancy-based control; Shi et al. [27] designed a model-predictive controller for a batch crystallisation process; Dueñas Díez et al. [28] controlled inventories of a property-distributed process by passivity-based control. Villegas et al. [13] presented a distributed control scheme in a batch fluidised bed dryer and Glaser et al. [29] presented the design of a model-predictive controller for continuous drum granulation.

Recently, Palis and Kienle [30–32] presented results on stabilisation of unstable steady-states in continuous fluidised bed spray granulation using H_∞-theory and discrepancy-based control in continuous granulation with internal product classification, assuming that the size distribution of particles can be measured. Apart from these publications, the control of particle size distributions in fluidised bed spray granulation has not received much attention, so that today, practically implemented control systems mainly concentrate on the regulation of heat and mass transfer (e.g. temperature), integral values (e.g. total mass of product) or mean values (e.g. mean particle size) of the particles in the stable process regime. Although the control schemes are for most part sufficient for their tasks, they cannot guarantee that the property distribution as a whole complies to the specifications. This means that in light of the increasing strictness of product specifications the control schemes have to be improved.

In this contribution two industrially appealing process control schemes for the important cases of continuous fluidised bed spray granulation with internal product classification and external classification and particle reflux are presented that allow for the stabilisation of unstable operating points and particle size distributions in these processes.

2. Process modelling

Limiting the scope to a purely macroscopic modelling, which is well-suited for the description of large-scale processes, population balance modelling is often applied [5,6].

The state of a particle is characterised by its properties. In general, two types of coordinates are distinguished: external coordinates $\mathbf{x}$ (the spatial position in the system), and internal coordinates e (particle properties, e.g. the size ξ). In total, these properties span a property state-space (denoted by $\Omega \times E$): Usually, during the process the properties of a particle will change; this corresponds to a movement

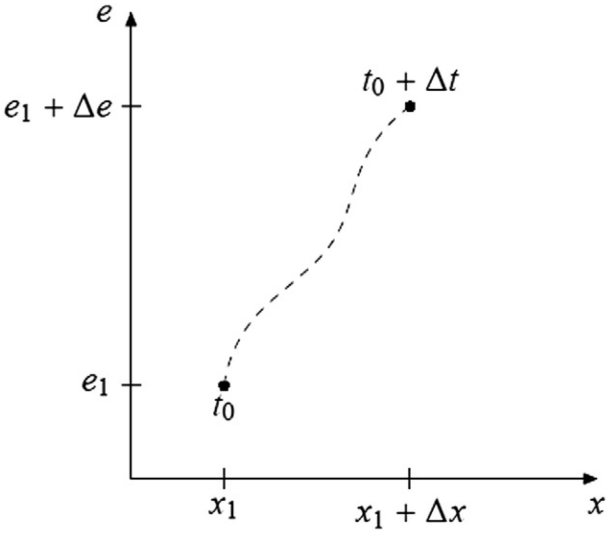

Fig. 2. Movement of a particle in property state-space.