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Model predictive control of continuous layering granulation in fluidised beds with internal product classification

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ABSTRACT

Continuous fluidised bed layering with internal product separation is known to possess unstable steady-states, yielding sustained nonlinear oscillations in the particle size distribution, the key product parameter. In this work, the well-known framework of constrained linear model predictive control is applied to stabilise corresponding unstable steady-states. Performance of the controllers is discussed with respect to design parameters and process constraints, as is robustness to overspray generation and size of formed overspray particles.

1. Introduction

Fluidised bed technology has found many applications in solids processing, for instance in particle formation and drying [1–3]. In particle formation, fluidised bed technology is mainly used for agglomeration, layering and coating of particles. The main difference between these formation processes is that in agglomeration new particles are formed by coalescence of primary particles. The coalescence can be initiated in different ways, for example the spraying of a binding agent, molecular or electrostatic forces, or thermal effects, e.g., glass transition, melting or sintering [4].

In coating and layering, a suspension or solution is sprayed on the fluidised bed, creating a liquid film on the surface of the particles. By evaporation of the liquid new solid layers are formed, resulting in an onion-like growth of the particles. Whereas coating aims at functionalisation of particles, e.g., taste or odour masking, and therefore only thin layers are applied, layering aims at larger thicknesses, i.e., the formation of large particles of a uniform solid material.

The aim in all processes is the production of particles with pre-defined properties, for example the particle size distribution which influences many user-properties, e.g., the re-wettability of agglomerates (and thereby the instant behaviour), or the bulk density (via the standard deviation of the size distribution with respect to the mean particle size) which is of huge importance in packaging, transportation and storage of the products [5,6].

Considering layering processes only in the following, from an industrial point of view, continuous operation under steady-state conditions is desired as it allows for a constant product mass flow with constant, user-specified properties.

Layering granulation in fluidised beds is usually performed in one of two configurations: (1) *internal* classification, wherein the product removal is based on a pre-defined mean product particle size by adjusting a gas flow in the outlet tube; or (2) *external* classification, where particles are removed from the apparatus without classification which is done externally using a screen-and-mill cycle.

Both variants can, depending on process parameters which are based on product specifications, show different dynamic behaviour: For some combinations, a stable steady-state is obtained, for others the process is unstable, e.g., yielding sustained oscillations in the particle size distribution in the apparatus. In case of the layering process with external classification, this effect was first described by Heinrich et al. [7], and numerically investigated using bifurcation analysis by Radichkov et al. [8]. Recently, using an advanced process description, the influence of functional zones in the apparatus on process stability was investigated by Dreyschultze et al. [9]. Experimental observation of oscillating behaviour was

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first reported in the patent of Schütte et al. [10] but without detailed information on the experiments. Schmidt et al. [11] were able to confirm these observations repeatedly, for a range of operating conditions.

For the configuration with internal classification, Vreman et al. [12], based on a limited number of observations at an industrial plant, came up with a model which was able to show oscillatory behaviour. They explained the different dynamic behaviour with the counterplay of nuclei formation and particle growth in the bed, depending on the distance between the spray nozzle and the particle bed. Recently, Schmidt et al. [13] could show experimentally the different dynamic behaviour for a large set of operating conditions, also investigating the influence of heat and mass transfer on process stability, showing significant influence of the drying conditions on nuclei formation.

The oscillatory behaviour leads to an oscillating product mass flow which then requires special attention in all post-processing steps, e.g., drying, cooling, packaging, transportation and storage. Furthermore, there is the risk of overloading the fluidised bed or the danger of emptying it completely, as also shown by Schmidt et al.

From the point of process operation there is therefore the need of stabilising these unstable processes in order to achieve the main aim, i.e., operation of the plants at steady-state with a constant product mass flow rate with constant product properties, as well as preventing the drift of the process into dangerous process states as mentioned before.

Although there are some works on control of agglomeration (granulation) processes, for instance in drums [14,15], feedback control of layering granulation in fluidised beds has so far only received limited attention in the literature: the works of Cotabarren et al. [16], Palis and Kienle [17–19] and Bück et al. [20] are currently the only focussing on this class of processes. However, most of these works refer to the continuous process with external classification, with the exception of Palis et al. [18] and Bück et al. [20] in which H_∞-loop shaping and robust PI controller theory were employed. In these cases, involved mathematical theory had to be used to derive the feedback law and to provide required robustness properties. Although the resulting controllers can be implemented at a plant, the used theory cannot be considered user-friendly with respect to the plant operator, possibly resulting in permanently switched-off controllers in case of experience of counter-intuitive controller action.

In this contribution, the well-studied concept of constrained linear model predictive control (MPC) is applied for the first time for the design of a suitable feedback controller to stabilise open-loop unstable operating points. Furthermore, process constraints are explicitly incorporated in the design, and the performance with respect to practically relevant unmeasurable process uncertainties, overspray generation and size of formed seeds, is studied.

The manuscript is structured as follows: first, the process under consideration is described in more detail and a dynamic process model, based on population balances, is derived. Then the model predictive controller is designed, followed by a presentation and discussion of simulation results. Conclusions and outlook then form the final part of this work.

2. Process description and modelling

In layering processes, a solid containing liquid, e.g. a solution or suspension, is sprayed onto a bed of fluidised seed particles (Fig. 1). Fluidisation, i.e., a fluid-like behaviour of the particles, is achieved by a heated gas flow which enters the fluidised bed from the bottom through a distributor plate. The heat is used to evaporate the liquid from the particle surface, where the droplets

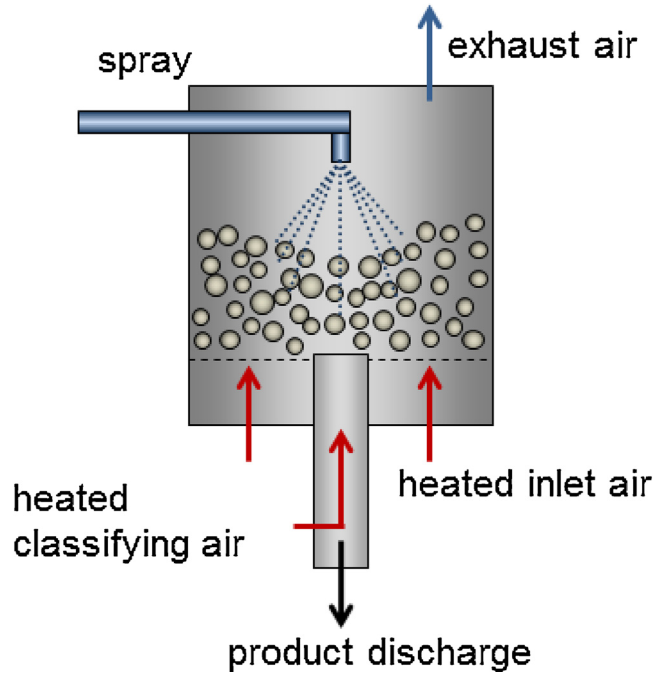

Fig. 1. Simplified process scheme of fluidised bed layering granulation with internal classification.

have spread after deposition, so that over time a new solid layer is formed.

Particles having achieved the desired product size ξ_1 are discharged via a classifying tube which is inserted centrally into the distributor plate. This tube is supplied with a separate gas flow that is adjusted such that the stationary sinking velocity of the particles in the tube corresponds to the product particle size ξ_1. Ideally, all particles having a size smaller than ξ_1 are blown back into the fluidisation chamber for further growth; in real applications, however, also fractions of the particles with $\xi < \xi_1$ are discharged and with $\xi > \xi_1$ are blown back, i.e., the classifying tube possesses a separation function.

New particles can be supplied in two different ways: externally by adding pre-produced seed particles of a given size, or internally by overspray generation. External production requires a separate process and is in most cases used in coating applications. Overspray is made of seed (nuclei) particles that are produced by pre-drying of sprayed droplets before they come into contact with the particle bed, thus forming individual albeit very small particles. The amount of overspray depends on the drying conditions, e.g., the gas-side conditions, and on the bed characteristics, for example the distance between the bed surface and the spray nozzle and the porosity of the fluidised bed which determine the probability of a droplet-particle collision.

Instability of continuous operation in the form of self-sustained oscillations is a counter-play between the discharge of particles and the supply of new particles by overspray generation, as shown by Vreman et al. [12] and Schmidt et al. [13].

Modelling of the layering granulation process follows closely the development given in Vreman et al. [12]—but with several, practice-related comments, modifications and extensions.

On a macroscopic scale the particle formation process can be conveniently modelled within the population balance framework [21]. Alternatively, CFD-DEM and Monte-Carlo modelling is applied to particle formation processes [22–32]. They allow investigation of effects on micro- and mesocale, fully resolving single particle interaction. Although powerful, especially to obtain information on process kinetics, they are still too expensive in terms of online com-