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# Feedback control strategies for a continuous industrial fluidized-bed granulation process

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ABSTRACT

This paper focuses on enhancing the operation of industrial granulation circuits via the design and performance evaluation of different control strategies. Particularly, the control strategies were implemented on a urea flowsheet simulator based on the Uhde fluidized-bed granulation technology (UFT), previously developed in the gPROMS modeling environment (Process System Enterprise) and validated against experimental data by our research group. First of all, an effective strategy for variable pairing in MIMO systems through Relative Gain Array analysis was tested. Continuing with the control system design, the controller parameter tuning was performed coupling an integral of time absolute error method with an optimization strategy. Afterward, the ability of single-loop feedback controllers (PI) to reject operational disturbances and track desired set-points was analyzed. Multiple-loop feedback strategies, such as cascade control were also implemented to improve controller performance. All the studied control loops were effective to either eliminate disturbances in the granulation circuit variables or to reach new set-points for the controlled variables, although it is demonstrated that the cascade configuration outperforms the single-loop feedback control strategy. Summarizing, this contribution provides granulation process engineers with useful control strategies for solving typical transient operational challenges.

## 1. Introduction

Within particle technologies, granulation is a fundamental operation of widespread use. It converts fine particles and/or atomizable liquids (suspensions, solutions or melts) into granular material with desired properties [1]. Typically, three components are needed to produce granules: initial seeds or nuclei, mixing and a binder. The seeds are always agitated to achieve a good distribution of the binder. Depending on the mixing principle, granulators are often classified into mechanical (e.g., pan, drum, high shear granulators) or pneumatic (fluidized-bed granulators) agitated units [1]. Fluidized-bed granulators (FBGs) offer some advantages, with respect to other granulation systems, since they allow us to integrate spraying, size enlargement, drying and/or cooling stages in one single unit [2–4].

Granulation processes are usually also classified according to the binder nature as wet, dry or melt. In wet granulation, the liquid binder (a solution or dispersion) is distributed on the seeds and, subsequently, the granules are dried to evaporate the solvent. In dry granulation, fine solid particles are added to the agitated seed bed; the powder adherence is promoted by Van der Waals or electrostatic forces [5]. In melt granulation, powders are enlarged by using meltable materials. These last binders are added to the systems either as powders that melt during the granulation process or as atomized molten liquids [6].

In general, not all the particles that leave the granulation unit meet the marketable granule size distributions, being necessary other unit operations such as crushing and size classification. The combination of all the involved process units (i.e., granulator, crusher, screens, etc.) constitutes the granulation circuit [7]. 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 the process units [8,9]. Furthermore, the design and operation of these circuits are often performed by trial and error and based on previous experiences [4]. To mitigate this situation, it becomes critical the design and control of granulation circuits under an integrated approach, aided by the progress in numerical techniques and computer resources [10]. It is widely accepted that for processes that handle liquid and gases the development of computing tools to simulate, optimize and control large-scale processes has been one of the most important engineering advancements. Nonetheless, many difficulties arise when process system engineering tools are intended to be applied to processes that handle solids due to their complex nature. While engineering processes involving fluids require relatively few variables to describe the system behavior completely (e.g. temperature, composition, pressure), solid process streams involved lumped variables as well as distributed properties (e.g. particle

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size, porosity, moisture distributions) [11–13]. The mathematical representation of powders transformations is not a trivial task. One well-established framework for the macroscopic modeling, and well-suited for industrial-scale processes, is the population balance equation (PBE). This tool was first introduced in the field of statistical mechanics by Hulburt and Katz [14] and later applied to the field of particulate process, among many others, by Randolph and Larson [15], Hounslow et al. [16], Ramkrishna et al. [17], Peglow et al. [3] and Li et al. [18]. In fact, the population balance equation allows predicting the change of distributed selected particle properties (e.g., size) by different mechanisms, although it is commonly defined by a complex partial integro-differential equation [9,19].

Even though particulate processes are involved in approximately three quarters of all industrially processed goods [20] and despite their imperious necessity of controllability, the analysis and development of general control design methods remain a difficult task. This is due not only to the distributed nature of the PBE (i.e., infinite number of internal states) and the nonlinear and multivariable input–output behavior of such processes, but also to the lack of reliable sensors for the in-line monitoring of distributed properties (e.g., particle size, moisture, porosity), the insufficient degrees of freedom or manipulated variables, and the current batch or semibatch operation of many processes, especially in the pharmaceutical industry [19,21].

In the last few years, several attempts have been made towards the control of particulate processes. Probably, the greatest advances regarding the design of nonlinear controllers have been performed by Christofides' group at the University of California [22–29]. Specifically, their approach consisted in reducing the order of the PBE by different techniques (i.e., method of weight residuals combined with approximate inertial manifold or method of moments) to subsequently design robust nonlinear controllers with stable closed-loop responses and relatively low computational cost [22,25]. Afterwards, the design also incorporated uncertainty in model parameters and unmodeled actuator/sensor dynamics and constraints on the capacity of control actuators [23,24]. The proposed methods have been developed to control the particle size distribution (PSD) in batch and continuous crystallizers, aerosol and thermal spray processes.

Regarding wet granulation technology (in rotary drums, high shear mixers and pan granulators), where particles mainly grow by agglomeration, several control strategies have also been proposed. Particularly, Zhang et al. [30] implemented on a di-ammonium phosphate (DAP) drum granulation pilot plant a simple proportional–integral (PI) controller to control the oversize fraction of the recycle stream, by manipulating the water flowrate to the drum. Pottmann et al. [31] introduced Model Predictive Control (MPC) strategies to control the granule PSD (by tracking the particle diameters corresponding to 5 and 90% of the mass cumulative curve) and density by manipulation of the binder flowrate of a generic granulation circuit (presenting either a pan, rotary drum or high shear granulation unit with agglomeration as the main size enlargement mechanism). Gatzke and Doyle III [32] extended Pottmann et al. [31] study by the formulation of soft constraints and a prioritized control strategy to avoid unattainable set-points. By using a model validated against data from a laboratory-scale high-shear granulator, Sanders et al. [33] compared the use of a proportional–integral-derivative (PID) controller with a MPC strategy to control the granulation unit. As the model did not include the complete circuit, the manipulated and control variables were only related with the high-shear granulator operating conditions. Glaser et al. [34] developed a robust MPC control strategy for a drum continuous granulation plant. They used, for the different circuit units, models validated against experimental data from a pilot-scale plant to analyze the process controllability with the aim of extending it to the industrial scale. These authors considered either the fresh solid feed or the feed moisture to solid ratio as manipulated variables for controlling the mean size of the granulator product. Finally, Ramachandran and Chaudhury [10] extended Glaser et al. [34] study by considering a novel PBE formulation and implementing PI controllers to the multiple-input multiple-output drum granulator system.

Concerning continuous fluidized-bed granulators, Heinrich et al. [35,36], Drechsler et al. [37] and Radichkov et al. [38] studied circuits including this type of technology. In those systems, the corresponding FBG is constituted by one chamber where wet granulation processes occur (i.e., the binder agent is a liquid suspension). Besides, constant granulator mass holdup or hypothetical particle size distributions for the outlet crusher stream were assumed. Considering that the PSD can be measured, Palis and Kienle [39–41] studied the stabilization of unstable steady-states detected by Radichkov et al. [38] in the abovementioned FBG circuit applying $H_\infty$-theory and discrepancy-based control. Finally, Bück et al. [20] applied a standard linear PI structure and a non-linear MPC to stabilize the operation of the fluidized-bed system studied by Heinrich and coworkers with internal and external product classification, respectively. For the PI controller, a linear transfer function relating the manipulated (suspension spraying rate) and controlled variable (PSD third moment, i.e. proportional to the total mass of particles in the bed) was derived after linearization of the mathematical model. The MPC controller manipulated the speed of the mill to control the average size of the milled particles by measuring the PSD second moment (i.e., proportional to the surface area of the particles exiting the mill), which required the PBE linearization around the steady-state (discretization with respect to the particle size by a finite volume method) and time discretization.

It is also worth to mention the recent advances in control of continuous pharmaceutical process performed by the Engineering Research Center of Rutgers University. In-silico closed feedback control has been tested in tablet manufacturing processes via direct compaction [42], roller compaction [43] and wet granulation [44] with advances in MPC implementation for the same configurations [45].

It is important to note that the granulation process is considered as one of the most significant developments in the fertilizer industry, providing products with higher resistance and lower tendency to caking and lump formation. In particular, granular urea is the most-consumed nitrogen-based fertilizer, being critical in the modern agriculture scenario [46]. Industrial urea granulation is mainly performed in fluidized-beds [7], which use a very concentrated urea solution as binder (basically molten urea) sprayed from the bottom. Due to the required industrial high production rates, high urea melt to seed mass ratios (about 50%) are employed. In the industrial practice, short granulation times are used and coating (i.e., layered growth) is the preferred size enlargement mechanism [9,47,48]. Unfortunately, and as granulation circuits in general, this process is usually operated by trial and error [49]. Among others, typical dynamic operational problems of the urea granulation circuits are: undesired plant shutdowns due to the formation of lumps in the granulation unit (which can be triggered by several causes, e.g. too-high operating temperatures and low fluidization air flowrate); and continuous oscillations of product quality due to the cycling nature of the granulation circuits and changes of the desired product mean size to meet particular market demands. Furthermore, as exposed in the literature review, control of continuous industrial fluidized-bed melt granulation processes has not received much attention. Consequently, this work focuses on the design and performance evaluation of different single-loop feedback control and cascade strategies implemented on a urea flowsheet simulator based on the Uhde fluidized-bed granulation technology (UFT), which was previously developed and validated against experimental data by our research group [13]. As well, it is the aim of this contribution to provide granulation process engineers with control strategies for solving typical operational challenges.

## 2. Simulation environment and mathematical models

Fig. 1 shows the operation units typically encountered in the UFT urea granulation process, which are: (1) a multichamber fluidized-bed granulator for the particle growth, (2) a cooling unit to diminish