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PARTICLE GROWTH MODELLING AND SIMULATION IN DRUM GRANULATOR-DRYER

Gediminas Valiulis[1,2], Rimvydas Simutis[1]

[1] Department of Process Control, Kaunas University of Technology
Studentų St. 48, LT-51367 Kaunas, Lithuania
[2] Department of Electrical Engineering, Šiauliai University
Vilniaus St. 141, LT-76353 Šiauliai, Lithuania
e-mail: g.valiulis@tf.su.lt

Abstract. The paper presents a model of the granule growth within the continuous drum granulator-dryer. The developed model is based on the growth-by-layering phenomena considering the process parameters, features and equipment. Simulation has been executed to test the model and the simulation results have shown close agreement with the measured plant data. The model built can be used for the evaluation of plant control methods, such as PID or Fuzzy. Capability to predict the future states of the granulation process makes it also useful for guidance or operator-training.

Keywords: granulation, modelling, simulation, control.

1. Introduction

Drum granulation is a commonly used process in a commercial fertilizer production for particle size conversion. One of essential tasks in the granulation process is to produce particles with a controllable (predictable) mean size and the range of sizes with respect to plant throughput, the operation cost and stability. Large recycle ratios and frequent unstable operations are common in granulation circuits [3]. Unsteady states can last for several hours and significantly hurt the yield of the production. The main sources of disturbances are related to process chemistry, equipment and control problems. The potential unstable behaviour is shown in Figure 1, where the necessity to interrupt the process occurs.

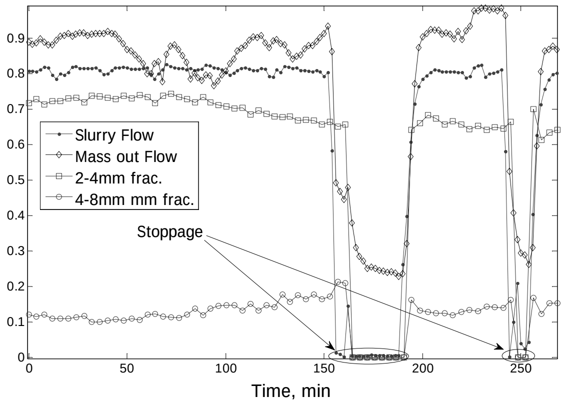


Figure 1. Normalized historical process data

The use of modern model-based control support schemes in connection with methods for process parameter acquisition and estimation can help to avoid such situations and optimize the granulation process.

Diagnostic systems show the potential to apply systems engineering approaches to complex operational problems such that operators are well informed, are able to quickly diagnose abnormal conditions, test quickly possible solutions via detailed simulations and then proceed to apply corrective actions [5].

The studied literature and primary investigation [6] based on process data analysis show that a complex relationship exists between granule size distribution and other process parameters. Plant experiments are too expensive to investigate process relations in detail. So the process control still depends on the experience and skills of technologists and process operators. However, a number of interacting process variables (some of them are stochastic in nature) lead to a complex dynamic system that might be hard to predict and optimize just by intuition, especially for unskilled operators. Fortunately, nowadays it is possible to use granulation process simulations provided by PC for the investigation of such complex problems. But at first, the simulation model must be developed and validated. The main part of the granulation process model, related to granule growth, heat and mass transfer phenomena, is presented in the paper.

2. Main details of the process

Drum granulation is a particle size enlargement process often obtained by spraying a liquid binder or slurry onto fine particles as they are agitated in a rotary drum [7]. The particle circulation is achieved mechanically (by the action of the rotating drum and lifters). Granules are cycled many times through the spray zone and the liquid layer attached is pre-dried before the particle returns to the spray zone again (Figure 2).

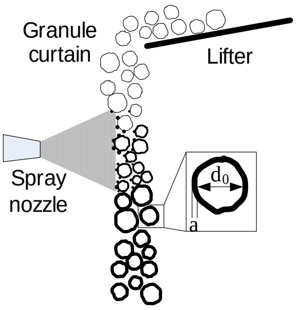


Figure 2. View of the spray zone and a falling particle curtain

The desired mode of granule growth is layering (coating) and in this case very tight granule size distributions can be obtained.

A commercial continuous granulation circuit for granulated diammonium phosphate fertilizer (formed by the reaction of phosphoric acid and ammonia) production consists of these main parts: a pipe reactor, spray nozzle system, drum granulator-dryer, granule classifier (screens), crusher and nuclei feed system (Figure 3).

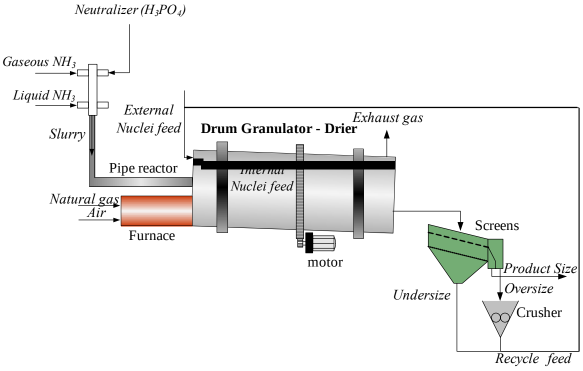


Figure 3. Typical drum granulator-drier circuit utilized in the diammonium phosphate (DAP) production industry

A granulation drum is made of an inclined cylinder with simultaneous drying (there is no separate drying device). Drying is performed by the heat of burned natural gas and/or reaction heat of phosphoric acid and ammonia. Liquid DAP feed (slurry) is sprayed onto the tumbling bed of seeds via spraying nozzles. Drum is tilted lengthwise a few degrees to provide flow of granules through the drum length. By the backward screw a part of the granules (internal nuclei) are sent back to spraying zone. The granules from granulator-drier are transmitted to the classifier to split them into three fractions: undersize, oversize, and marketable product size. Oversize fraction is crushed and together with undersize granules is sent back as seeds (recycle) to the granulator.

The main manipulated input and output process variables are presented in Table 1.

Table 1. Main process variables

Input variables	Output variables
Slurry flow rate	*Granule size distribution*
Slurry viscosity	*Temperature inside drum*
Recycle feed flow rate	*Granule moisture content and mechanical properties*
Natural gas flow rate	
slurry N:P ratio	*granule N:P ratio*
$NH_{3(gas)}:NH_{3(liquid)}$ *ratio*	*Granule mass throughput from granulator*

Fortunately, nowadays some important granule size distribution variables can be measured on-line using advanced particle size analysis systems. The detailed and more accurate information gives the producers of granulated materials more data to improve product quality and to control production processes [8]. Size Guide Number (SGN), related to the median of granule population, and Uniformity Index (UI), which shows the dispersion of population, can be evaluated. A part of important granule size distribution intervals can be also provided.

However, some process variables related to unique material and equipment properties cannot be evaluated and controlled directly. In such a situation the process model can provide information about important process states, such as recycle size flow rate and distribution, drum system jamming factor, granule moisture content, size evolution of single granule inside the granulator-dryer. This information can help to predict future process states and prevent abnormal situations, which can initiate process stoppage and loss of productivity.

3. Modelling

The model presented is essentially based on fundamental conservation principles and it partially accounts for equipment properties and the stochastic nature of the process. For modelling purposes, it is necessary to divide the granulation circuit into several balance areas with the central component of the model – the drum granulator-drier. There are two main processes inside the granulator-drier: the growth of particles and moisture evaporation (drying).

Basic modelling assumptions are:

- granule shape is spherical;
- each granule in the granulation circuit is analyzed;

- stochastic nature of the process is estimated;
- preferred growth is by layering;
- granule agglomeration is an unacceptable mode of operation;
- growth rate is a function of initial granule size, slurry flow rate, temperature inside the granulator, granule position in the drum, number of particles in the granule bed;
- mechanical attrition of granules inside the granulator-drier, defined by attrition function;
- presumable nucleation (formation of new seeds) during slurry spraying;
- external classification of granules into three fractions (undersize, marketable and oversize), defined by classification function;
- external crushing of oversize granules, defined by grinding function;
- residence and transportation delays in the plant;
- internal and external feed of seeds (nuclei for new granules).

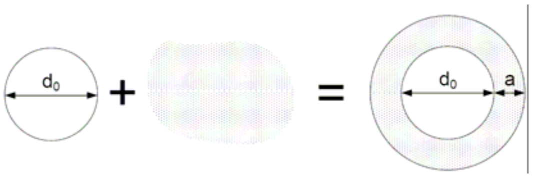
3.1. Basic model of a growth phenomenon

There are two basic granule growth mechanisms that act independently or in combination [4]. A successive layering of binding material on an initial nucleus is termed the layering, coating or ‘‘onion-skin’’ growth mechanism. Another mechanism is an agglomeration or coalescence process that occurs upon particle collision. Whereas growth by agglomeration mostly occurs when a binder is added, layered growth is the result of particle coating by the feed material, followed by solidification of the material on the particle surface [1].

The granulation regime may be defined by the so-called Stokes number, which considers the granule density, the collision velocity, the granule size, the liquid layer viscosity, the liquid layer thickness, the surface roughness, the restitution of the collision.

The design and provided control scheme of the considered drum granulator-dryer normally force layered growth or coating and block coalescence or agglomeration. Sometimes the formation of undesirable agglomerates indicates a shift of granulation regime from layering to coalescence, which is not a normal case of operation and must be avoided.

The granule growth by spraying the slurry onto the previously formed seed is shown in Figure 4.



Initial seed *dispersed slurry* *granule with added layer*

Figure 4. Granule growth by layering

To model the layering phenomenon, the thickness of a new layer applied is determined from the diameter of the initial particle and the volume of the slurry applied. Assuming a spherical primary particle and a uniform distribution of all sprayed slurry applied onto the particle, the volume of the added layer V_l is calculated from the difference in the volumes of the layered particle and the initial particle:

$$V_l = \frac{1}{6}\pi\left((d_0 + 2a)^3 - d_0{}^3\right); \tag{1}$$

here d_0 – initial width of granule (seed), a – thickness of the applied layer.

Equation (1) solved for a gives the thickness of the applied layer:

$$a = \frac{1}{2\pi}\sqrt[3]{\pi^2(\pi d_0{}^3 + 6V_l)} - \frac{1}{2}d_0. \tag{2}$$

The presented growth model is placed in stochastic background, which can better suit the growth phenomenon that actually happens in the real plant. Modern computer and software capabilities can be used to model this real life phenomenon with addition of randomness. The programming code is written to take into account basic assumptions described above and main plant characteristics.

3.2. Mass and energy balance modelling

This subsection presents the mass and energy balance model inside the granulator-dryer. The explicit mass and energy balance model due to its wide and quite complex mathematical and physical features is beyond the scope of this paper. Hence, the following is the simplified version of the model developed.

The overall mass balance inside granulator in liquid phase is:

$$\frac{dM_L}{dt} = F_{L,in} - F_{L,out} - F_e - \dot{m}_c; \tag{3}$$

where M_L – accumulated mass of liquid solution, $F_{L,in}$ – flow of liquid solution into granulator, $F_{L,out}$ – flow of liquid solution out of granulator, F_e – flow of evaporated liquid solution, m_c – mass of crystallized solution (solid material).

The overall mass balance inside granulator in solid phase is:

$$\frac{dM_S}{dt} = F_{S,in} - F_{S,out} + \dot{m}_c + \dot{m}_g - \dot{m}_{att}; \tag{4}$$

where M_S – accumulated mass of solid material, $F_{S,in}$ – flow of solids into granulator, $F_{S,out}$ – flow of solids out of granulator, m_g – mass due to growth, $\mathrm{m_{att}}$ –mass due to attrition.

The overall energy balance inside granulator is:

$$\frac{dE}{dt} = \dot{E}_{in} + \dot{E}_f + \dot{E}_r - \dot{E}_e - \dot{E}_l - \dot{E}_{out}; \tag{5}$$

where E – overall energy, E_{in} – energy provided into granulator, E_{out} – energy removed from granulator, E_f – energy due to gas furnace action, E_r – energy of reaction heat, E_e –

energy for moisture evaporation, E_l – loss of energy from granulator to environment.

This section has presented only a part of the general model, which is in nature a grey box. Complementary models from measured process data have been also built and expert information used to enrich the model presented. These extended models are briefly observed in [6].

4. Results and discussion

To predict fully the behaviour of the system, we would need to follow each particle, understand its state [2]. It is good in the case of increased accurateness and transparency, when less information is lost due to approximation routines, which are common in available models. The bottleneck of the proposed approach is difficulty in modelling granulation in the real plant scale, where the number of granules is dozen times greater than the above methodology can accept. Its main reason is the lack of computing power, due to which simulations can be extremely long or even impossible. This problem can be avoided using some scaling procedures.

Using GrowSim simulation package, two case studies are carried out to test the granulation model presented:

- *start-up of the process;*
- *change of the slurry flow rate.*

These situations are common in the real plant and are used to control process output parameters depicted in Table 1.

The measured process data have been compared with the circuit simulation results. The lack of possibility to perform the planned experiments in the plant gives limited information required to fully validate the system under investigation.

4.1. Start-up of the process

During the process start-up, successive operation requires some conditions to be satisfied:

- appropriate temperature inside the granulator;
- well-established provision of reaction components to the pipe reactor;
- rotation of the granulation drum;
- no hardware malfunctions.

These requirements are vital and should be taken into account in the model.

Figure 5 shows typical process start-up operation, which covers these main stages:

- “no growth no heat” operation;
- “no growth pre-heat” operation;
- “growth and drying” operation.

Some of the stages can be absent and some intercross.

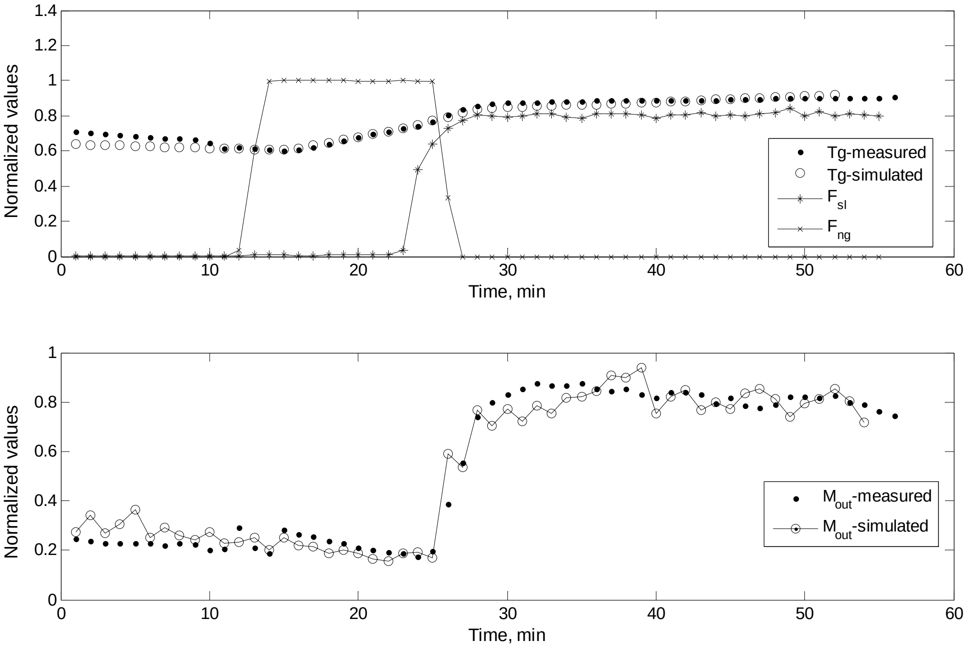


Figure 5. Process start-up measured and simulated normalized data

T_g – temperature inside granulator, F_{ng} – natural gas flow rate, F_{sl} – slurry flow rate, M_{out} – granule mass flow from granulator

During period 1-11 min. no granule growth or heat is produced, so this can be called “no growth no heat” operation. This operation can be divided into smaller counterparts (e.g. fault, repair, cleaning, holdup removal etc.). In our case, the slurry feed rate equals to zero, so no growth happens and temperature inside the granulator gradually drops. The granule mass flow from the drum granulator-dryer is non zero, because it is necessary to remove part of granules from the drum to avoid unacceptable results (e.g. plenty of too large granules). A slight disagreement between measured and simulated data at the beginning of the stage can be observed. It is explained by the fact that the former process state was not precisely defined. So it takes time to reach a new state, which is matched correctly.

During period 12-27 min. “no growth pre-heat” operation occurs. In this stage temperature inside the granulator is increased by heat produced from burned natural gas inside the gas furnace. Granulation by layering requires appropriate temperature to evaporate moisture and to discourage conglutination (sticking together) of particles. When temperature reaches some defined value, natural gas flow is suspended. The process has a delayed temperature reaction and the model assesses this phenomenon pretty well.

Starting with min. 23, the flow of slurry is initiated and the “growth and drying” operation begins. The particles are coated by sprayed slurry and dry. The energy required to evaporate moisture is produced by a reaction heat of phosphoric acid and ammonia. After natural gas flow is removed, the temperature change rate is almost zero. The fair mismatch of measured and simulated data of granule mass flow is explained by imprecisely defined granule mass holdup inside the drum granulator-drier. The oscillations of simulated mass flow occur due to the scaling problem, where a single particle in sparse population can significantly change the overall mass flow.

Now the process start-up procedure is finished and the process comes into a steady state.

4.2. Change of the slurry flow rate

The DAP slurry is fed into the granulator onto a bed of recycled dry material through spray nozzle system. The drum rolling action provides distribution of slurry on the surface of the tumbling granule bed. Change in the slurry flow rate alters the granule growth rate. Increase in the slurry flow rate raises the granule growth rate and a shift of cumulative particle size distribution (PSD) to the right is observed (Figure 6).

In *case A* the process is kept in some steady state, with the median granule size nearly 2.5 mm.

In *case B* the slurry feed rate is increased approximately by 13 %. In this situation, the granule median size is nearly 2.7 mm.

Simulation results match the measured data fairly well.

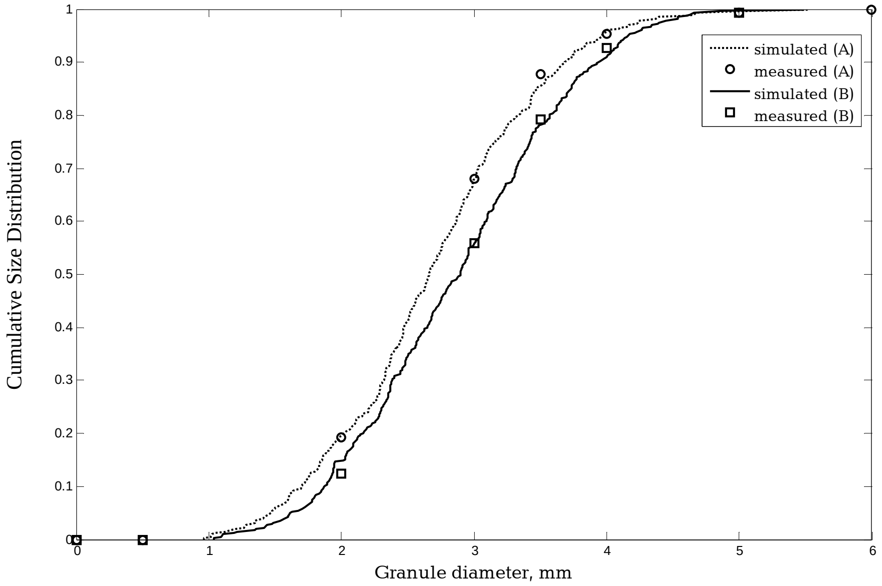


Figure 6. Impact of the change of the slurry flow rate on cumulative granule size distribution

5. Conclusions

A DAP fertilizer granulation circuit has been modelled using basic physical principles such as growth, mass and heat transfer. The mechanism of granulation is the particle growth by layering and subsequent drying. For a better model performance, statistical analysis data of measured process parameters and the experience of process experts have been applied as the extension to the main model. The model has been implemented and simulation executed using GrowSim simulator. The process start-up and the influence of a change in the slurry flow rate as a vital variable have been studied and the results appeared to be in fair accordance with the plant measured data.

The proposed model shows good potential for representing the behavior of the granulation plant and hence can be advised for dynamic simulation leading to improved granulation circuit control and operator training.

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