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Design of a Fluidized Drum Granulator for Potassium Nitrate Production

R. Rojas, V. Bucalá, J. Piña
Chemical Engineering Departament, Universidad Nacional del Sur.
Camino La Carrindanga km. 7, Bahía Blanca, Argentina.

The theoretical modeling of fluidized drum granulators (FDGs) represents a great challenge, being the major difficulty the mathematical description of the solids flow pattern. There are many published models for the movement of solids through flighted drums, but mainly for rotary dryers. In this work, the two-phase (airborne and dense phases) model proposed by Sherritt et al. (1993) is extended to predict the granules transport and mean residence time in FDGs. Based on this model and data reported in the open literature, a preliminary design for a potassium nitrate FDG is presented. The drum dimensions, inclination and rotational speed, the geometry and number of lifters and the fluidized bed table dimensions and location are defined. For the designed industrial FDG, the mean solids residence time is estimated.

1. Introduction

Granulation is a widely used process in several industries to obtain products with attractive properties. Particularly, the melt or wet granulation uses a liquid binder that is sprayed onto the particulate phase to form bonds between particles or between the binder drops and solids. This process takes place in an agitated environment to promote the liquid dispersion and the granules growth and consolidation.

Granulation can be carried out in different equipments, among others, high shear units, fluidized beds and rotary drums. The fluidized bed granulator is a relatively new design, which combines the drum and fluidized bed granulation technologies. The FDG is a cylindrical rotating drum with internal lifters and has an inclined fluidized bed inside it where air is blown (Kaltenbach-Thuring, 1999). This special design offers the very good heat and mass transfer rates provided by fluidization but with lower air flowrates.

The FDG modeling is very complex; being the mathematical description of the particles circulation pattern one of the main difficulties. The granules inside the unit are mechanically raised by the lifters, sliding and rolling, up to the upper part of the drum from where they fall onto the fluidized bed for cooling or drying (i.e. melt or wet granulation, respectively). The slope of the fluidized bed surface allows the particles to flow down along the inclined perforated plate and fall into the lower part of the drum after being sprayed with the liquid binder. The lifters raise the granules coated with a new layer to be further cooled or dried. The same cycle is then repeated until the desired particle size is achieved (Thuring et al., 1988).

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Despite its demonstrated success on an industrial scale, there are no many published fundamental studies of this granulation process (Kordek, 1995; Litster and Sarwono, 1996). To the best of our knowledge, there is a lack of research papers involving the design and modeling of FDGs with the purpose of understanding and representing their novel features in order to improve their operation. Currently, considerable trial and error is required to obtain the FDGs operating parameters that would allow stable operations and granules production with the desired attributes.

Potassium nitrate is a premium fertilizer (completely soluble in water and chlorine free) which is used in a wide range of high value agricultural applications (e.g., hydroponic and greenhouse environments). Nowadays, direct soil application is made by dissolution of KNO_3 crystals in water or by spreading prills on the field. However, the KNO_3 granules are harder and more crush resistant than the prills and its production allows certain product granulometry flexibility that makes feasible the physical mixtures of KNO_3 with other granular fertilizers (Kaltenbach-Thuring, 1999). This fertilizer has been selected for this study because it undergoes different allotropic transformations during the granulation.

Aiming to design an industrial FDG for potassium nitrate production, the mass, energy, momentum and population balances have to be solved simultaneously. To correctly account the crystallization and solid-solid phase transitions in the energy balance, the corresponding kinetic rates have to be related with the residence times of the solids as they are axially and transversally transported.

For a given plant capacity (~26-30 TPH, excluding recycle) and a desired granule size enlargement (20 to 30 %), a preliminary design of the FDG is presented. The drum dimensions, inclination and rotational speed, the geometry and number of lifters and the fluidized bed table dimensions and location are defined. For the designed industrial FDG, the solids residence times within the different transport zones are computed.

2. Mathematical Modeling

Two different phases are considered to represent the solids movement through the FDG, as originally proposed by Matchett and Baker (1987) to predict the particles residence time in cascading rotary dryers. An airborne phase (Phase 1) consisting of the falling particles from the lifters and a dense phase (Phase 2) that accounts for the solids that rest in the flights or in the overloaded bed at the bottom of the drum. Sherritt et al. (1993) described the movement of solids through flighted rotating drum driers by means of fundamental equations instead of correlations. Here, this model has been adapted to represent the solids motion in a FDG.

2.1. Solids Residence Time

The solids mean residence time τ, the total mass holdup per unit length M and the total axial solids flowrate F are calculated as follows:

$$\tau = ML/F \quad (1)$$

being L the drum length.

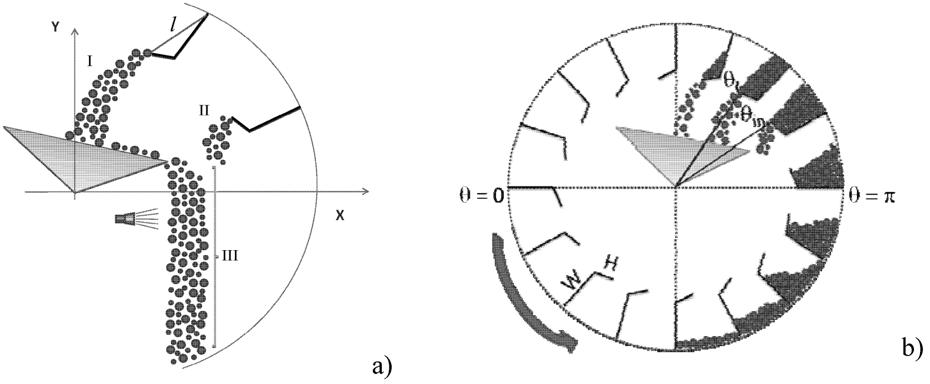
$$F = F_1 + F_2 + F_{melt} \quad (2)$$

$$M = M_1 + M_2 + \left(F_{melt}/L\right)\tau \quad (3)$$

where subscripts 1 and 2 denote the airborne and dense phases, respectively. F_{melt} is the mass flowrate of molten KNO_3 fed along the drum.

2.2. Axial flowrates

Figure 1a and b show cross sectional views of the FDG. Three zones are considered to describe the movement of the granules in the airborne phase (Figure 1a). Zone I and II correspond to the fractions of solids falling from the lifters onto the fluidized table and drum bottom, respectively. Zone III takes into account the solids that flow down along the table and fall into the lower part of the drum.



a)

b)

Figure 1. FDG view in cross-section.

Assuming that all the airborne particles, independently of their sizes, advance axially at the same rate within each zone and following the guidelines proposed by Sherritt et al. (1993), the total axial flowrate of the airborne solids results:

$$F_l = \frac{N \rho_b n}{2} \left[\int_{\theta_l}^{2\pi} l^2 d_z^{I} d\theta + \int_{\theta_{in}}^{\theta_l} l^2 d_z^{II} d\theta + \int_{\theta_l}^{2\pi} l^2 d_z^{III} d\theta \right] \tag{4}$$

where ρ_b is the bed density, θ_l is the angular position at which the solids start to fall onto the fluidized table (see Figure 1b), θ_{in} is the initial discharge angle (i.e., θ equal to the kinetic angle of repose), n is the rotational speed, N is the total number of lifters, l is the length of surface cord on a discharging flight (see Figure 1a) and d_z^m are the axial displacement of the falling granules in the axial directions for zones m = I to III. The angular position is measured in the direction of rotation (see Figure 1b).

Ignoring axial drag and the interference from other particles in the axial direction z, the following force balance for a single spherical airborne particle is solved in order to estimate the axial displacement for each zone m:

$$\left(\frac{\pi}{6}\right) d_p^3 \rho_p \frac{dv_z}{dt} = \left(\frac{\pi}{6}\right) d_p^3 \rho_p \, g \sin(\alpha) \tag{5}$$

where d_p is the particle diameter, ρ_p is the particle density and α is the drum inclination with respect to the horizontal. By integrating twice and assuming a null initial velocity, the axial displacement for each zone m results:

$$d_z^m = g\sin(\alpha)\frac{(t^m)^2}{2} \qquad m = \mathrm{I\ to\ III} \tag{6}$$

being t^m the particles falling time in the corresponding zone.

To determine t^I, the following force balances in the vertical and horizontal directions (i.e, y and x) that consider the drag of the fluidization air are solved:

$$\frac{dv_y}{dt} = -g\cos(\alpha) + \frac{3}{4}\frac{\rho_{air}C_D}{d_p\rho_p}\left[v_{air,y} - v_y\right]^2 \tag{7}$$

$$\frac{dv_x}{dt} = -\frac{3}{4}\frac{\rho_{air}C_D}{d_p\rho_p}\left[v_{air,x} - v_x\right]^2 \tag{8}$$

where C_D is the drag coefficient and ρ_{air} is the air density. The falling time t^I is obtained from the intersection of the vertical and horizontal displacements (calculated by integrating twice equations 7 and 8, respectively) with the linear equation that describes the table location. The initial velocities to complete equations (7) and (8) are computed according to Wang et al. (1995).

To estimate the falling time t^{II}, the drag force in equations (7) and (8) is neglected. The t^{II} value is the one that satisfies the equality between the height computed by the solution of equation (7) and the vertical distance from the tip of the flight to the bottom of the drum. According to the Thuring et al. (1988), the FDG is designed to minimize the flow of solids through zone II.

The time t^{III} is calculated in a similar way to t^{II}, but considering a null initial velocity and the vertical traveled distance denoted as III in Figure 1a. The solids rolling time along the fluidized table is disregarded.

The axial flowrate of the dense phase is computed as suggested by Sherritt et al. (1993) for an underloaded drum.

2.3. Holdup

According to Sherritt et al. (1993), the holdup of airborne particles for zone II is the product of the flight discharge flowrate and the time of fall t^{II}, averaged over one revolution ($\theta_{in} \leq \theta \leq 2\pi$) and multiplied by the total number of flights. Extending this concept to include zones I and III, the total holdup of the airborne solids results:

$$M_I = \frac{N\rho_b n}{2}\left[\int_{\theta_I}^{2\pi} l^2 t^{I} d\theta + \int_{\theta_{in}}^{\theta_I} l^2 t^{II} d\theta + \int_{\theta_I}^{2\pi} l^2 t^{III} d\theta\right] \tag{9}$$

To calculate the holdup of the dense phase, the guidelines proposed by Sherritt et al. (1993) for an underloaded drum are followed.

3. Results and Discussion

The features of a drum can vary greatly (Sherritt et al., 1993). Based on the geometrical data reported by Degrève et al. (2006) for a 26 to 30 TPH NPK flighted drum granulator, a diameter (D) of 4.3 m and equispaced two-segment flights are selected for the KNO_3 FDG. Considering the ratio L/D = 2 proposed by Capes (1980) for fertilizer granulation drums, a length L = 8.6 m is fixed. Lifters of 0.07 m high (H, see Figure 1b) with a fold angle equal to 135° are chosen. Due to the limited available information regarding the fluidized table dimensions and location, the following parameters are specified: wide = 1.75 m, eccentricity = 0.45 m, sloping = 5° (Thuring et al., 1988). This device and the lifters are defined so that most of the granules fall in the vicinity of the fluidized table top end (i.e., zone II is minimized).

For a granulator output of about 14 to 16 kg/s (i.e., a 26-30 TPH plant capacity with a recycle ratio of 1:1; Thuring et al., 1988) and a desired granule size enlargement (20 to 30%, Thuring and Vogel, 1986), the model proposed to represent the solids axial flow and holdup is used to determine the number and width of the flights (W, see Figure 1b), the drum inclination and rotational speed.

For spherical particles characterized by a number-volume mean diameter and assuming growth as the only size enlargement mechanism, the granule growth is described by the following ratio:

$$d_p / d_{p0} = \left[1 + 1/R\right]^{1/3} \tag{10}$$

where d_{p0} refers to the seeds mean diameter and R represents the recycle ratio.

A flight width W of 0.24 m, 20 equidistributed flights, a drum slope of 5° and a 5 rpm rotational speed are established to define a base case. Figure 2, 3, 4 and 5 show the influence of the flights width, flights number, drum inclination and rotational speed, in that order, on the solids axial flowrate, solids mean residence time and growth ratio. As it can be seen, an increase in any of the four studied variables leads to an increase in the solids axial flowrate and decreases in the solids mean residence time and growth ratio.

The shaded areas in Figures 2 to 5 represent regions in which the specified capacity (F = 14 to 16 kg/s) or size enlargement (d_p/d_{p0} = 1.2 to 1.3) can be attained. Thus, the projections of these two areas on the abscissa define the ranges for the independent variables that allow obtaining the targets set for F or d_p/d_{p0}. The intersection of these two ranges determine the feasible values, in terms of desired capacity and size enlargement, for the independent variables W, N, α and n.

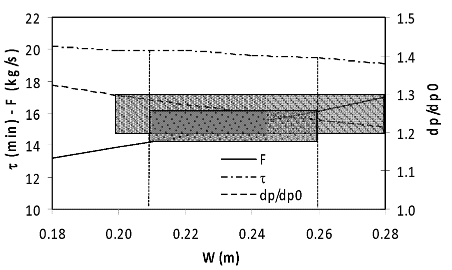


Figure 2. F, τ and d_p/d_{p0} as a function of W.

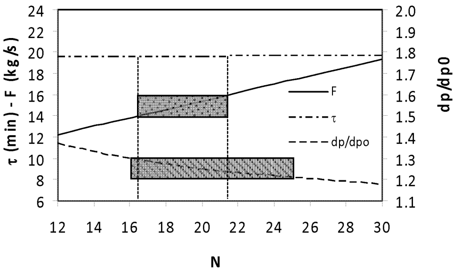


Figure 3. F, τ and d_p/d_{p0} as a function of N.

The simulation results indicate that for a KNO_3 production between 26-30 TPH, a granule growth within 20 to 30 % and an underloaded operating regime, the D = 4.3 m and L= 8.6 m FDG should have between 17 and 21 lifters, each of 0.07 m high and 0.21 to 0.26 m wide. The drum should be inclined about 4.8° and rotate at an average speed of 4.8 rpm. For this preliminary design, τ is approximately 19.6 minutes.

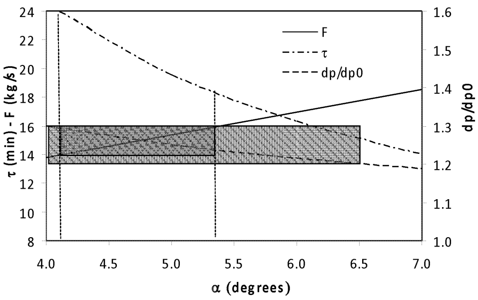


Figure 4. F, τ and d_p/d_{p0} as a function of α.

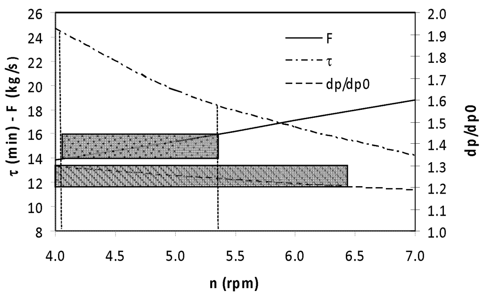


Figure 5. F, τ and d_p/d_{p0} as a function of n.

4. Conclusion.

A preliminary design of a FDG to produce 26 to 30 TPH of granular KNO_3 is presented. Based on data reported in the open literature and using the mathematical model proposed to calculate the solids axial flowrate and holdup, the drum dimensions, inclination and rotational speed, the geometry and number of lifters and the fluidized bed table dimensions and location have been defined. For the designed underloaded industrial FDG, the solids mean residence time has been estimated.

The improvement in the prediction of the axial flowrate of airborne particles, as suggested by Wang et al. (1995) for flighted rotary dryers, and the extension of the implemented procedure to the overloaded and/or extremely overloaded operating regimes deserve further research.

Even though the performed study allowed specifying the flighted drum and fluidized table for its granulation function (production rate and particle growth), the FDG final design requires the solution of the momentum, mass, energy and population balances simultaneously. The crystallization and the phase transition kinetics have to be included to achieve the definitive FDG design.

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