

A STUDY OF PARTICLE MOTION IN ROTARY DRYER

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(Received: January 13, 2006 ; Accepted: May 23, 2007)

Abstract - The purpose of this work was to study the performance of a rotary dryer in relation to number of flights. In this work an equationing was proposed to calculate the area used by the solids in two-segment flights of with any angle between the segments. From this area, the flight holdup and the length of fall of the particles were calculated for different angle positions and the results obtained were compared to experimental values. The results show an increase in dryer efficiency with the increase in number of flights up to a limit value, for ideal operational conditions. The experimental data on average residence time were compared to results obtained by calculations using equations proposed in the literature. The equation proposed for predicting flight holdup and length of fall of particles generated very accurate estimations.

Keywords: Rotary dryer; Flights; Dynamic coefficient of friction.

INTRODUCTION

Rotary dryers are a class of dryer commonly used in industry to dry particulate solids (Keey, 1972). They are made of a long cylindrical shell that is rotated. The shell is usually slightly inclined to the horizontal to induce solids flow from one end of the dryer to the other. In direct heat rotary dryers, a hot gas flowing through the dryer provides the heat required for vaporization of the water.

To promote gas-solid contact, most direct heat dryers have flights (see Figure 1), placed parallel along the length of the shell, which lift solids and make them rain across the dryer section. The transport of solids through the drum takes place by the action of the solids cascading from the flights, each cascade comprising the cycle of lifting on a flight and falling through the air stream. Thus, good flight design is essential to promote the gas-solid

contact that is required for rapid and homogeneous drying (Revol et al., 2001).

Schofield and Glikin (1962) derived an equation to evaluate the dynamic angle of repose (ϕ) of a powder as a function of its dynamic coefficient of friction (μ). If a powder is poured onto a flat surface, it will form a pile whose angle with the horizontal plane is called the static angle of repose. This angle of repose is affected by the powder cohesivity. Particles within a flight will also display an angle of repose with a horizontal plane, which will depend on the angular position of the flight. Since the angle of repose is affected by the drum rotation speed, it is called the dynamic angle of repose.

Kelly and O'Donnel (1977) developed a procedure for measuring the dynamic coefficient of friction (μ). They also reviewed the equations that relate the drum loading to the flight loading. Baker (1988) showed how the dynamic angle of repose

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could be used to calculate the solids holdup of a flight at any angular position. He developed equations for different types of flight geometries.

The purpose of this work was to analyze the influence of the flights on the drying rate and to evaluate the validation of an equationing proposed for the prediction of load and length of fall of the particles for two-segment flights. Another purpose was to verify the prediction of some equations in the literature for the residence time of the rotary dryer.

EQUATIONING

Flights

A dryer may incorporate one or more different types of flights. A sufficient number of flights must be distributed across the drum in such a way that the volume of material transported by the flights is between 10 and 15% of the total material volume inside the dryer (Perry and Green, 1999). The

number and format of flights influence the amount of material present in the rotary dryer. Perry and Green (1999) suggest that the volume occupied by the load of solids in the rotary dryer should be between 10 and 15% of the total dryer volume.

Figure 2 presents a scheme of the flights with two segments, indicating the main dimensions and variables that will be used in the equationing accomplished in this work.

The flight, presented in Figure 2, can be characterized by the lengths of segment 1 (l') and segment 2 (l), the angle between the two segments (α_A) and the circle radius (R_o) formed by the line between the edge of the flight (O) and the center of the rotary drum. Two sets of Cartesian coordinates are considered. The origin (x,y) of the set is at the flight lip, the x axis is located along the first segment and the y axis, perpendicular to the x axis. This set of coordinates moves as the flight rotates. The origin of the stationary (X,Y) set is on the drum axis with the X axis being horizontal (Figure 2).



Figure 1: Solids cascading inside the dryer

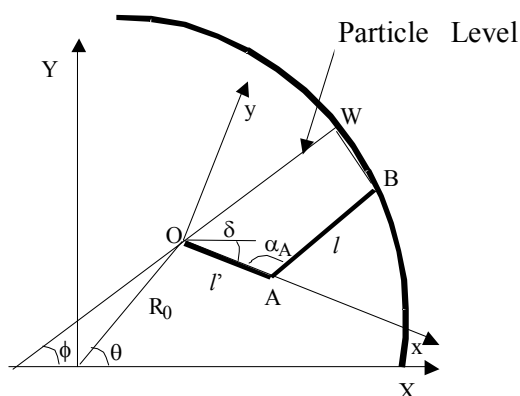


Figure 2: Scheme of a two-segment flight

Schofield and Glikin (1962) linked the dynamic angle of repose, ϕ (the angle formed by the level of material in the flights and the horizontal line, see Figure 2) to the dynamic friction angle of the material (μ), the angular position of the flight edge (θ), the radial position of the flight edge (R_0) and the drum rotation speed (ω), using the following equation:

$$\tan \phi = \frac{\mu + R_0 \frac{\omega^2}{g} (\cos \theta - \mu \sin \theta)}{1 - R_0 \frac{\omega^2}{g} (\sin \theta - \mu \cos \theta)} \quad (1)$$

In order to calculate the area occupied by the material in the flights, the coordinates of points A and B are first calculated (see Figure 2), the angle δ between the two sets of coordinates is evaluated and the volume of material is finally obtained.

Equations for the two-segment flights may be obtained this way:

Segment coordinates: 1 ($y_1 = 0$) and segment 2 ($y_2 = a_2 + b_2x$); with: $a_2 = x_A \tan(\alpha_A)$ and $b_2 = -\tan(\alpha_A)$.

The coordinates of points A and B are given by

- Point A: $x_A = l'$ and $y_A = 0$.
- Point B: $x_B = x_A - l \cos(\alpha_A)$ and $y_B = l \sin(\alpha_A)$.

In the stationary set of coordinates, the position of point B must satisfy the following equation since it is located on the wall of the drum of radius R :

$$X_B^2 + Y_B^2 = R^2 \quad (2)$$

The two sets of coordinates are related by the following equations:

$$X_B = X_0 + x_B \cos(\delta) - y_B \sin(\delta) = \quad (3)$$

$$R_0 \cos(\theta) + x_B \cos(\delta) - y_B \sin(\delta)$$

$$Y_B = Y_0 + y_B \cos(\delta) - x_B \sin(\delta) = \quad (4)$$

$$R_0 \sin(\theta) + y_B \cos(\delta) - x_B \sin(\delta)$$

Substituting Eqs. (3) and (4) into Eq. (2), a new equation is obtained, which can be solved for δ , for any angular position (θ).

The equation for the powder level line is given by

$$y = x \tan(\gamma) = x \tan(\phi - \delta) \quad (5)$$

Its intersection with the line tracing the second segment has the following abscissa:

$$x_2 = \frac{a_2}{\tan(\gamma) - b_2} \quad (6)$$

with

$$y_2 = a_2 + b_2 x_2 \quad (7)$$

as ordinate.

The intersection of the solids level line with the drum wall has the following abscissa:

$$x_w = -\frac{B_w \pm \sqrt{B_w^2 - 4A_w B_w}}{2A_w} \quad (8)$$

with $A_w = 1 + [\tan(\alpha)]^2$,

$B_w = 2X_0[\cos(\alpha) - \tan(\gamma)\sin(\delta)] + 2y_0[\tan(\gamma)\cos(\delta) + \sin(\alpha)]$ and $B_w = R_0^2 + R^2$, and its ordinate is given by

$$y_w = x_w \tan(\gamma) \quad (9)$$

Three types of powder fills can occur:

- The particles reach the dryer wall. This will occur if $\gamma > \arctan\left(\frac{y_B}{x_B}\right)$, since the section area occupied by dust is given by

$$S = \frac{R^2}{2} [\beta - \sin(\beta)] + \quad (10)$$

$$\frac{1}{2} |x_A y_B - x_B y_A + x_B y_w - x_w y_B|$$

with

$$\beta = 2 \arcsin \left[\frac{\sqrt{(x_B - x_w)^2 + (y_B - y_w)^2}}{2R} \right]$$

- The particles that do not reach the wall, but reach the second segment. This will happen

$$\text{if } \gamma < \arctan\left(\frac{y_B}{x_B}\right), \sqrt{(x_2 - x_A)^2 + (y_2 - y_A)^2} < l'$$

and $y_2 > 0$, since the area of the transversal section occupied by the material is given by

$$S = \frac{1}{2} |x_A y_2| \quad (11)$$

- The flights are empty. This will happen if:

$$y_2 < 0 \quad (12)$$

The ratio between the area occupied by the solids in the flights (S) and the load of solids in the flights (h^*) may be given by the following equation:

$$h^*(\theta_i) = S_i L \rho_s \quad (13)$$

Glikin (1978) proposed the following equation for calculation of the length of particle fall of the flight (the length of fall determined here is the straight-line distance of the particles from the edge of the flight, where the fall begins, to the particle bed in the lower part of the dryer):

$$Y_d = \frac{Y_o + \sqrt{R^2 - X_o^2}}{\cos \alpha} \quad (14)$$

where $Y_o = R_0 \cos \theta$ and $X_o = R_0 \sin \theta$.

The equation just presented was used for estimation of load variation in the flights with their angular position (θ) and for calculation of the length of particle fall. The predictions obtained with these equations were compared with experimental data obtained for a rotary dryer operating with fertilizers.

Residence Time

Particle motion in rotary dryers is one of the greatest challenges in theoretical modeling of dryers (Sherrit et al., 1993). The complex combination of particles being lifted in the flights, sliding and rolling, then falling in spreading cascades through an air stream, and reentering the bed at the bottom, possibly with bouncing and rolling, is very difficult to analyze (Kemp, 2004).

There are four components of particle movement along the drum: a) gravitational, due to the slope of

the drum; b) drag of the gas on the particles (for countercurrent flow, this is negative); c) bouncing of the particles on impact with the bottom of the dryer and d) rolling of the particles in the bed at the bottom of the dryer, especially for overloaded dryers. The last two components are almost impossible to predict theoretically and are therefore evaluated experimentally for each type of material (Kemp and Oakley, 1997).

Numerous equations have been proposed for residence time in rotary dryers (Kelly and O'Donnell, 1977). In many of these studies, only average holdups (H^*) and solids feedrate were considered. The average residence time for the particles ($\bar{\tau}$) in these cases is given by

$$\bar{\tau} = \frac{H^*}{W} \quad (15)$$

The holdup H^* is usually determined by suddenly stopping the drum and subsequently weighing its contents. W is the solids feedrate. The previous ratio is for a void axial dispersion.

One of the most frequently used empirical equations for residence time estimation was proposed by Friedman and Marshall (1949):

$$\bar{\tau} = L \left(\frac{0.3344}{\alpha N_R^{0.9} D} \pm \frac{0.6085G}{W_d^{0.5}} \right) \quad (16)$$

The second term in the Friedman and Marshall (1949) equation expresses the air drag on the solids. The negative sign in this equation is used for concurrent flow and the positive sign is used for countercurrent flow.

Saeman and Mitchell (1954) were the first to break away from the empirical approach to calculating rotary dryer holdups adopted by previous researchers. They analyzed material transport through the dryer in terms of incremental transport rates associated with individual cascade paths to yield a transport-rate distribution function. By assuming a linear relationship between the horizontal displacement of the particles due to the air flow and its velocity, they derived the following equation for the average residence time:

$$\bar{\tau} = \frac{L}{f(H^*) D N_R (\tan \alpha \pm m'v)} \quad (17)$$

Where $f(H^*)$ is a “cascade factor” with values typically between 2 and π that increase as solids holdup increases, and m' is an empirical parameter (dimensional) for a given material. The positive sign in Equation (17) indicates the concurrent flow and the negative sign indicates the countercurrent flow.

Schofield and Glikin (1962) derived the following residence time equation by considering the drag exerted by the air flowing countercurrently to the particles:

$$\bar{\tau} = \frac{L_t}{\bar{Y}_q \left(\sin \alpha - \frac{kV_f^2}{g} \right)} \left(\left(\frac{2\bar{Y}_q}{g} \right)^{0.5} + \frac{\bar{\theta}}{\pi N_R} \right) \quad (18)$$

with $k = 1.5f\rho_a / d\rho_s$ where $f = \frac{12}{Re}$ for $Re < 0.2$ and

$$f = \frac{12(1 + 0.15 Re^{0.687})}{Re} \text{ for } 0.2 < Re < 1000.$$

Through analysis of a large amount of data found in the literature on the operation of rotary dryers, both on a pilot and an industrial scale, Perry and Green (1999) proposed the following general correlation for calculation of the average residence time:

$$\bar{\tau} = \frac{k_p L}{DN^{0.9} \tan \alpha} \quad (19)$$

where k_p is a parameter that depends on the number and format of the flights.

The predictions of residence time using the above-mentioned equations from the literature under different operational conditions were compared with experimental data obtained for a rotary dryer operating with fertilizers, and the results are presented in the Results section.

MATERIALS AND METHODS

Materials

The fertilizers (simple superfosfate) used in the drying experiments were obtained from Fertibras, a company located in Uberaba-MG, Brazil. The solids had a Sauter average diameter of 2.76mm, a density of 1.1 g/cm³ and a specific heat of 0.245kcal/kg°C.

Experimental Apparatus

In the experimental apparatus, shown in Figure 3, the air was impelled by a 4-HP blower (1) and passed through a duct with a 0.2 m diameter (3), its flow was measured with a hot wire anemometer (2) and it was heated by a set of electrical resistances (4) coupled to a voltage oscillator (5) and finally entered the dryer in countercurrent flow with the solids (6). The air outlet was opposite to the solids inlet (7). The solid was fed by a container (8) with a worm gear in its lower part (9) and was removed on the side opposite to the solids inlet (10). The air (dry and wet bulb) and solids temperatures were measured with copper-constantan thermocouples, linked to a digital display (11). The dryer cylinder was 60 cm long with a diameter of 25 cm.

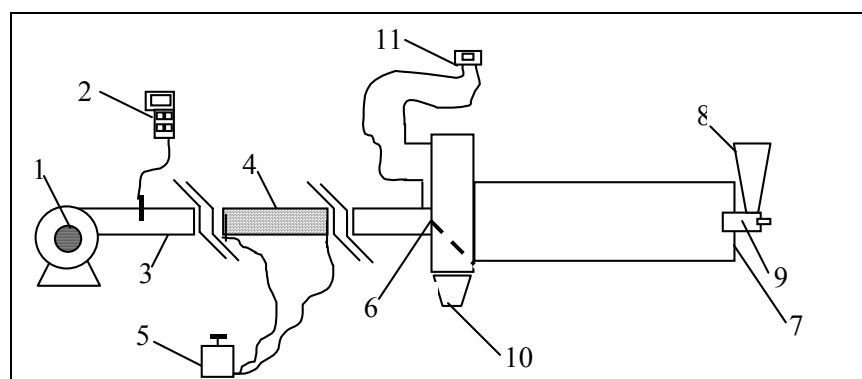


Figure 3: Scheme of the experimental apparatus

Experimental Procedure

a) Evaluation of the Number of Flights

To study the influence of flow, rotation and number of flights over the drying rate, a factorial design with three variables at two levels was elaborated (Box et al., 1978). The values of independent variables were as follow: solids flow (W), 0.33 and 0.67 kg/min; rotation (N_R), 2.65 and 5.55 rpm; and number of flights (N), four and seven. Eight other experiments were also done: four with two flights and four with no flights, at the levels of solids flow and rotation mentioned previously.

b) Residence Time Study

To measure the residence time, experiments were done using tracers. The number of flights for this study was seven. This number was chosen based on the results of the dryer performance analysis.

c) Measurement of the Dynamic Friction Coefficient

In order to measure the characteristic angle (which is used to calculate the friction coefficient in Eq. 1), pictures were taken of the inside of the equipment in operation. For each image obtained, the angular position of the flight (θ) and the dynamic angle of repose (ϕ) were measured using the Global Lab Image 2 software.

d) Measurement of Flight Holdup and Length of Particle Fall

In order to measure the flight load in each angular position, the equipment was stopped and the material was collected from the flight for weighing on an analytical scale. In order to measure the length of

particle fall for a flight, the dryer cylinder was started up and shut down many times, in such a way that the flights would operate in different angular positions.

RESULTS

Evaluation of the Number of Flights

Figure 4 shows the variation in fertilizer drying rate in relation to number of flights, solids flow and dryer cylinder rotation.

Analyzing the results in Figure 4, it can be verified that, for the same feed and rotation conditions, both residence time and drying rate increase with number of flights. When rotation is increased, maintaining the other variables constant, drying rate also increases and residence time decreases.

The ideal number of flights must be enough to carry 10 to 15% of the total volume of product in the dryer (Baker, 1988). This fact is related to optimum dryer load. Values below this range result in a waste of energy and values above this range produce heterogeneity of the final product. For the dryer with seven flights, the volume of loaded material corresponded to 16.0% of the total volume of material in the dryer. For other numbers of flights, the loading was lower than the recommended range.

Evaluation of the Residence Time Equations

Figure 5 shows the experimental results on residence time and the ones calculated using the following equations: load ratio (Eq. 15), Perry and Green (Eq. 19) and Friedman and Marshall (Eq. 16). Figure 6 shows the experimental data and the ones calculated with the Saeman and Mitchell's (Eq. 17) and Schofield and Glikin's (Eq. 18) equations.

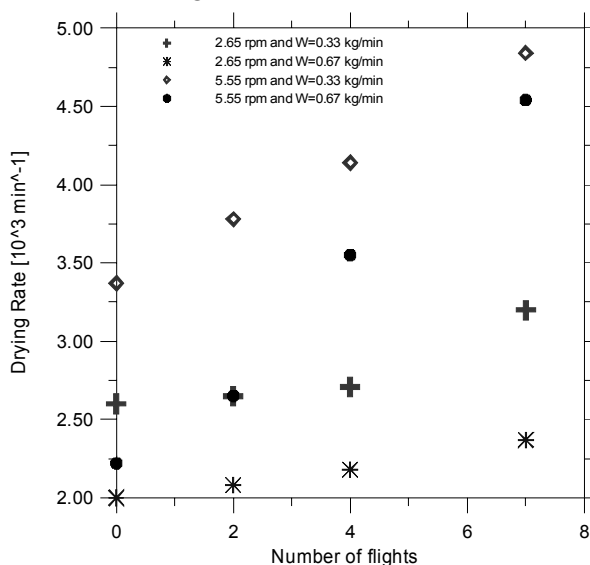


Figure 4: Variation in drying rate with number of flights

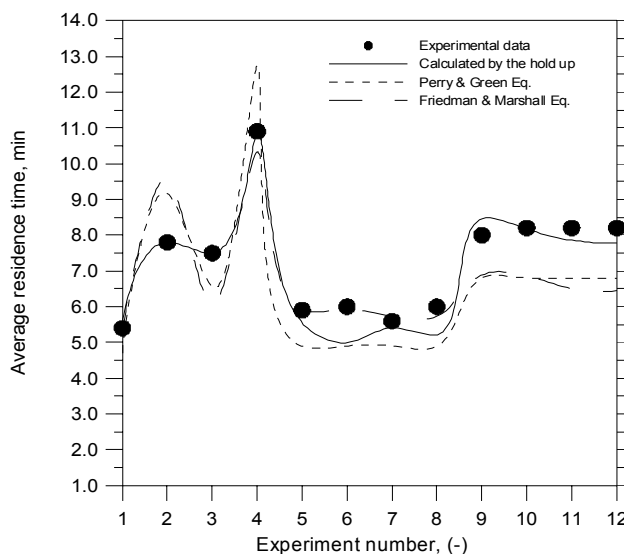


Figure 5: Experimental and calculated residence times (Eq. 15, 16 and 19)

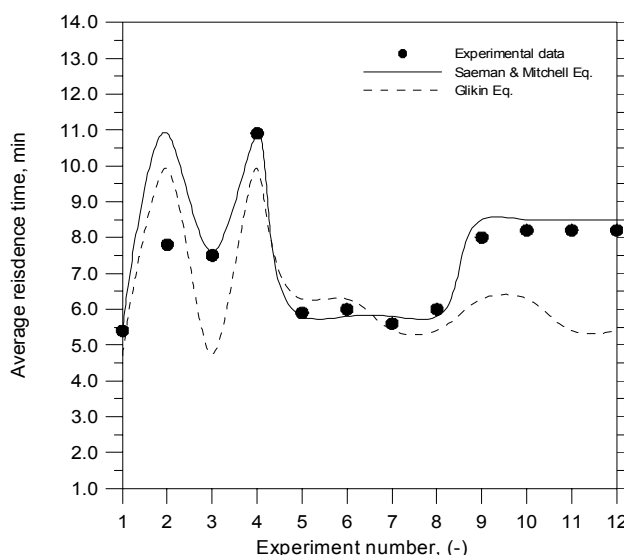


Figure 6: Experimental and calculated residence times (Eq. 17 and 18)

It can be observed in the results presented in Figure 5 that Eq. (15) (load) had a good fit with the data. However, use of this equation for the project is not feasible, because it is not related to any process variable. Perry and Green's and Friedman and Marshall's equations had good fits for experiments 1 to 8. In these experiments, the value of solids flow was 0.67 kg/min. When the solids flow had been lowered (experiments 9-12), the values predicted by these equations did not represent well the experimental data. This is explained by the fact that these equations do not take into account either the load effect on the flights or the particle drag by the air flow.

Figure 6 shows that Saeman and Mitchell's equation is in good agreement with the experimental

data. This equation has interesting characteristics for the project, performance and scale-up of rotary dryers, since it takes into consideration the load in the flights and the particle drag.

Dynamic Coefficient of Friction (μ), Holdup and Length of Fall

Figure 7 contains the results calculated by experimental measurement and with Eq. (1) for the simple superfosphate dynamic friction coefficient (μ) as a function of flight angular position and solid moisture (0.08 and 0.12 kg of water/kg of dry solids) and Figure 8 contains the data on the dynamic friction coefficient (μ) for these two values of solids moisture.

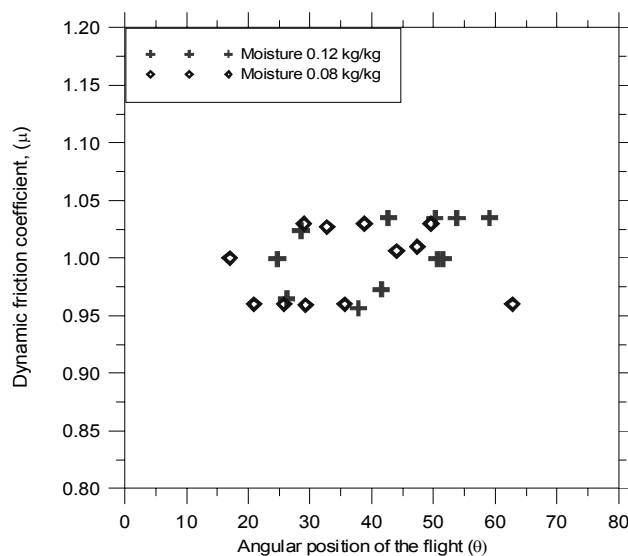


Figure 7: Dynamic friction coefficient for the simple superfosphate as a function of angular position

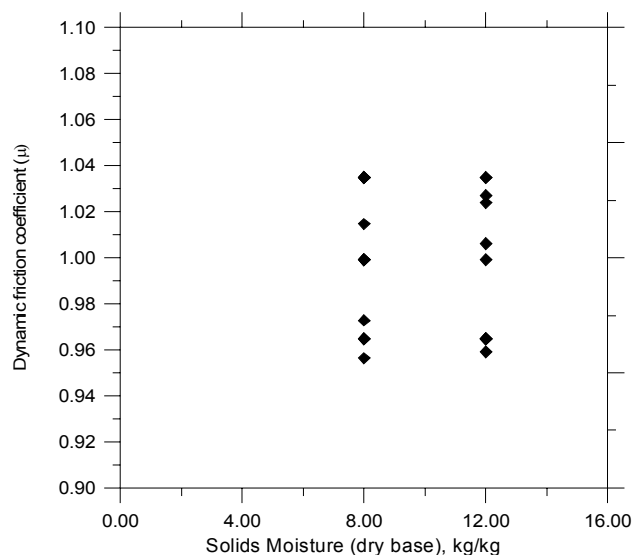


Figure 8: Effect of solids moisture on the dynamic friction coefficient

In the results in Figure 7, it can be observed that the dynamic friction coefficient is independent of the angular position of the flight. This result is in agreement with those found in other literature (Revol et al., 2001). For the results presented in Figure 7, the dynamic friction coefficient reached a confidence interval of 95%, between 0.974 and 1.015, with an average value of 0.994.

The results presented in Figure 8 show that the dynamic friction coefficient (μ) remained in a constant range, when the fertilizer moisture was increased from 0.08 to 0.12 kg of water/kg of dry solids. Therefore, for this material, an average value of 0.994 can be used to calculate the flights load and

average length of particle fall, in the moisture range studied.

Figure 9 contains the comparison between the holdup measured experimentally for each flight angular position and the results obtained with the proposed equationing (Eq. 2 to Eq. 14) for the prediction of holdup for the two-segment flights. Figure 10 contains the same for the length of particle fall for a flight. The results in Figures 9 and 10 show that the equations for load prediction in the flights and the length of particle fall generated very precise estimations. This confirms its potential use for the prediction of solids cascading inside the rotary dryer.

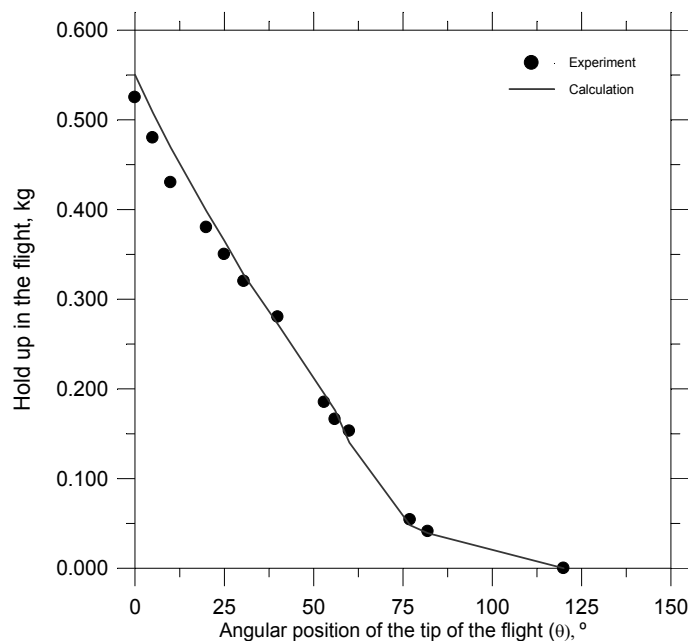


Figure 9: Variation in flights solids holdup with angular position of the flight tip

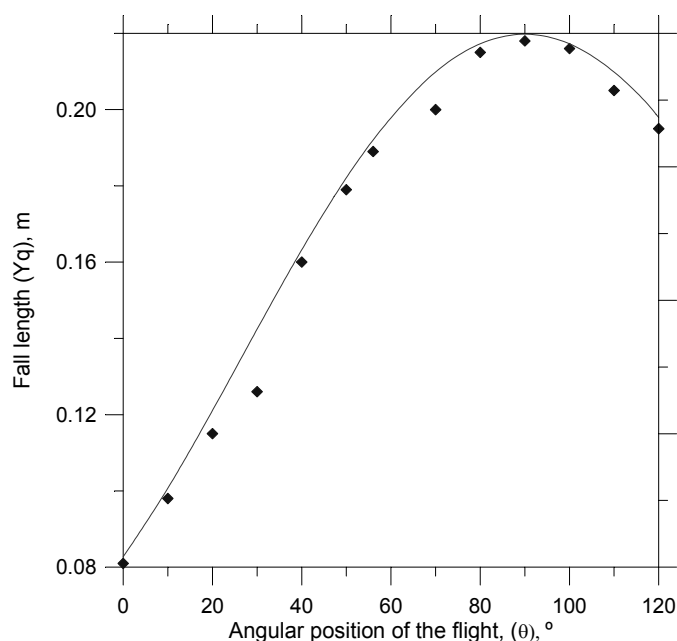


Figure 10: Variation in the average length of particle fall in the flight with angular position.

CONCLUSIONS

The results obtained in this work allow the following conclusions to be made:

- Efficiency of the dryer studied increased with number of flights up to a limiting value, for the optimum loading range. For the dryer studied, seven was the number of flights that showed the best results, with at least 16.0% of the volume occupied.
- The calculations with the Saeman and Mitchell (1954) equation showed good agreement with the experimental results on residence time. Since this equation has a good theoretical fundament, it can be used for project studies, performance and scale-up of rotary dryers.
- In the experiments, a friction coefficient of 0.994 was obtained for the simple superfosphate. With calculation of the dynamic friction coefficient,

important information, such as the flights holdup for different angular positions and the average length of cascading particle fall, was obtained on the material cascading characteristics in the dryer

▪ The proposed equations for prediction of the load in two-segment flights and the average length of particle fall generated very precise estimations from the experimental data. Therefore, these equations may be used in projects for the prediction of the solids cascading behavior inside a rotary dryer.

NOMENCLATURE

d_p	average particle diameter,	microns
D	dryer diameter,	m
f	dragging factor,	considering one particle only
$f(H^*)$	parameter related to dryer load,	-
G	gas flow,	m^3/min
h^*	flight material load,	kg
H^*	dryer material load,	kg
l	length of the second segment,	M
l'	length of the first segment,	M
L	dryer length,	M
N	number of flights,	-
N_R	rotation speed,	rpm
R	dryer radius,	M
R_0	distance from the edge of the flight to the dryer center,	M
S	transversal section area, occupied by the flight solids,	m^2
v_r	relative gas-particle velocity,	m/s
W	solids flow,	kg/min
x	abscissa,	m
X	abscissa in the coordinate set centered on the drum axis,	m
y	ordinate,	m
Y	ordinate in the coordinate set centered on the drum axis,	m
\bar{Y}_q	average length of fall,	m
α	dryer inclination,	rad

$\bar{\tau}$	average residence time,	min
θ	angular position of the flight edge,	rad
$\bar{\theta}$	average angle of particle fall of the flights,	rad
ρ_s	particle density,	kg/m^3

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