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Research note

Dynamic Simulation of an Industrial Rotary Dryer

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Abstract
Solid transport phenomena drastically affect rotary drying process. A change in any solid movement variable such as particle hold up or input flow rate results in a significant variation of heat and mass transfer rates. Therefore, in this research dynamic study of these phenomena was conducted both experimentally and theoretically. Several experiments was performed employing an industrial granule dryer. The dryer length and diameter were 5 and 1 m, respectively. In each experiment one of the solid movement variables was changed and the resulting dynamic change on the process was measured. The data was used to estimate the parameters of a dynamic distributed parameter model of the system using dynamic optimization method. The data were also employed to evaluate the model. The model predictions for solid hold up and outlet flow rate were compared with those of the experimental data. The average model error for solid hold up and outlet flow rate were 5.6% and 5.4 %, respectively.

Keywords: *Solid transport, Rotary Dryers, Modeling, Nitrocellulose, Simulation*

1- Introduction
Nitro cellulose (NC) is used in manufacturing lacquer, stencil paper, ink, varnished cloth, sealing cover, binder, leather oil, nail polish and several other materials. The drying process is the last section of the NC production line. In this process the temperature and moisture content of NC particles are tightly controlled to ensure the high quality of the product. Rotary dryers are successfully used for solid particle drying. The main advantages of rotary dryers are their simplicity, flexibility and large capacity. Compared with fluidized and conveyor-belt dryers rotary dryers are the most expensive to construct but have the lowest operating cost [1]. The rotary dryer is superior to the fluidized dryer for continuous treatment of solids. In continuous mode the products of fluidized dryer are not uniform due to the rapid mixing of solids leading to non-uniform residence time of solids in the dryer [2]. Rotary dryers, if equipped for particle lifting flights, are suitable for removing the solvents (mainly water) from solid particles. This dryer can be run continuously, while rotation rate, inlet air temperature and flowrate can be used to

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control solid temperature and moisture. Particular flight design can be used for each material, resulting in a large portion of air born particles. This leads to high mass and heat transfer rates between the air and solid particles.

Process control is very important to drying processes with significant economical impacts. This includes tighter temperature and moisture control of the product to avoid financial penalties as well as associated operational problems such as dusting. Most importantly, a too high temperature of an industrial dryer may result in fire or even explosion. High moisture content of solid particles at the outlet of the dryer has an adverse impact on the quality of those products for which NC is an ingredient such as paint and nail polish. On the other hand, too much drying would result in more brittle particles, leading to more dust in the dryer and in turn increase the chance of an explosion. Since light particles can be blown back and accumulate in the dryer, dusting can cause dryer over-load. When overloaded, the dryer performs badly yielding higher output moisture until it recovers and the cycle reoccurs. Traditional feedback controls have generally proved inadequate in providing stable operation under a range of process disturbances such as changes in inlet air and product moisture. To tackle this challenge, implementation of a model-based control for such processes can be advantageous, with the models capturing the complex dynamic interactions in the system. Furthermore, advanced control strategies can improve the drying because of the large transportation lag in the dryer and significant interactions between the process variables. In a control study reported by Duchesen et al., five control strategies have been evaluated using a dynamic rotary dryer simulator for mineral concentrate [3]. Two control strategies are based on PI controllers and the others use neural network models.

In spite of the indisputable importance, the identified model uncertainties introduced by inaccurate determinations of heat and mass transfer coefficients, as well as solid retention times, have significantly restricted the implementation of a model-based control for rotary dryers. Consequently, it is essential to develop an improved dynamic model with minimized plant-model mismatch for the accurate prediction of rotary drying dynamics and the implementation of model-based control. There have been several attempts to develop models for rotary drying. Sharples et al. [4]; Chandra and Singh [5]; Kamke and Wilson [6], Brasil and Seckler [7], and more recently Shene et al. [8] used mathematical models to study steady state behavior of the process. Douglas et al. [9] proposed a model to study the dynamics as well as the steady state behavior of the process. This model is a discretized form of a distributed parameter model. To use this model for the distributed rotary drying system, the drum was divided into a number of equal segments. A lumped parameter model was then used for each of these segments. In order to compute retention times, the model employed the semi-empirical correlation suggested by Friedman and Marshall [10].

It can be identified in the literature that key issues in the modeling of rotary drying processes are the computation of heat and mass transfer rates, and the determination of solid retention times. The reported works also show that there are two main difficulties in computing heat and mass transfer rates of rotary dryers. First, the contact surface area between the solid and the gas is not constant. This area depends on several variables such as solid hold-up, solid distribution, the stickiness of the particles and the hindered nature of the falling particle curtain. A model that considers all the variables affecting the contact surface area is extremely complicated. Such a model has not been reported in the literature. Second, computations of mass and heat transfer coefficients are not sufficiently accurate. They are commonly calculated using empirical equations whose parameters are estimated by employing a set of experimental data obtained under a specific set of operating conditions. When the operating conditions change, these equations may not estimate the coefficients accurately. Hence, there is a need for an adaptive model that can estimate these parameters on-line. Shahhosseini et al. have developed a model for a rotary sugar dryer that employs on-line experimental data to adapt itself to any operating conditions [11].

Solid particle distribution in the drum affects the amount of contact surface between the solid and the gas. Solid particle retention time influences the time the particles can stay in contact with the gas to transfer heat and mass. Any heat and mass transfer model for a solid particle dryer must be able to reasonably predict solid flowrate and solid hold-up. There have been several reports in the literature regarding the modeling aspects of solid transport in dryers. If the model is developed for model-based control, it must be simple and yet represent the dynamics of the system accurately.

Several researchers have attempted to develop mechanistic solid transport models, Matchett and Baker [12], Sherritt et al. [13], Sherritt et al. [14] and Wang et al. [15]. However, the reported models are not fully mechanistic and still employ some empirical correlations. Earner [16] found these models were more complicated than the Friedman and Marshall model and did achieve satisfactory accuracy. Shahhosseini et al. modified the Friedman and Marshall solid transport model by adding one more parameter to it, resulting in more flexibility and accuracy of the model predictions [17].

The main objective of this study was to obtain a simple and yet accurate model for an industrial rotary dryer. This model was needed for inferential and model based control of the dryer. Such a model has been reported for a pilot sugar rotary drying process by Shahhosseini et al. [17]. Since solid material and particle size in the industrial NC dryer are different from those of sugar dryers, the parameters in solid transport equations of the process model were to be estimated employing the industrial experimental data dryer. In this work, several experiments were conducted to collect the data necessary to estimate solid transport model parameters and to evaluate the model. The model predictions and the experimental data were compared in order to evaluate the model.

2- Mathematical model

The model used in this work, for the industrial dryer was similar to that reported by Shahhosseini et al. [11]. Since the aim of this work was a comparative study on the solid transport aspect of the model, only solid transport equations are presented here. More detailed aspects of the model are given in this reference [11]. The following equation shows the dependency of solid hold up and flowrate on the time and space.

$$\frac{\partial H_s}{\partial t} = \frac{\partial F_s}{\partial z} \qquad (1)$$

Where, H_s is the solid hold-up of the dryer (kg) and F_s is the solid outlet from the dryer (kg/s). One way to solve such a partial differential equation is to use the method of lines, in which the dryer is divided into n sections as shown in Fig. 1.
In this way Equation 1 is discretized and can be written as follows.

$$\frac{dH_{s(i)}}{dt} = F_{s(i-1)} - F_{s(i)} \qquad for\ i = 1,\ldots,n \qquad (2)$$

Where, $H_{s(i)}$ is the solid hold-up in the ith section of the dryer (kg), and $F_{s(i)}$ is the solid outlet from the ith section of the dryer (kg/s).
The following retention-time equations initially proposed by Friedman and Marshall and modified by Shahhosseini are also incorporated into the solid model [8 & 10].

$$R_{t(i)} = L_{(i)}\left[\frac{\alpha}{tan(\delta)R_s^{0.8}D} + \frac{\beta(F_a+\gamma)}{D_p^{0.5}F_{s(i)}}\right] \qquad (3)$$

Where:

F_a is the air flowrate (kg/s)

R_t is the retention time (s)

δ is the drum slope to horizontal (degrees)

R_s is rotation speed of the drum (rpm)

D is the dryer diameter (m)

D_p is weight average particle size (m)

α, β, and γ are parameters which should be estimated using experimental data

The model parameters (α, β, and γ) were estimated using experimental data and an optimization routine written in this study.

$$H_{s(i)} = F_{s(i)}R_{t(i)} \qquad for\ i = 1,\ldots,n \qquad (4)$$

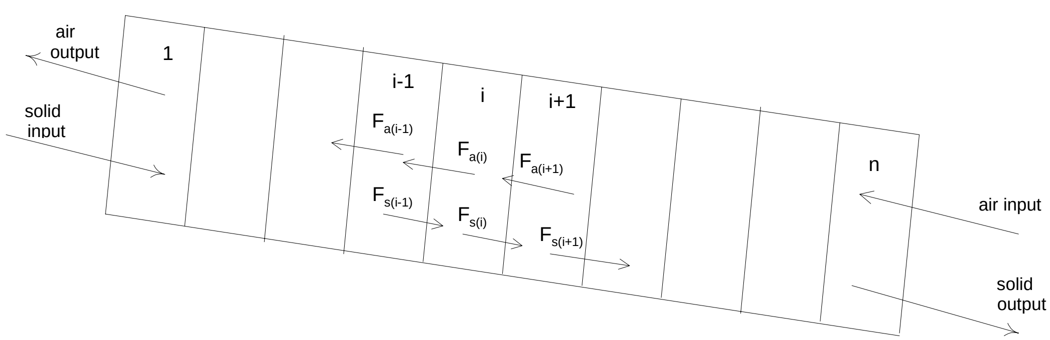

Figure 1. The divisions of the dryer applied to discretize the partial differential equations.

A mass balance equation is also presented in order to demonstrate the importance of the solid transport equations to calculate heat and mass transfer rates. Solid water content mass balance for the ith segment is given by:

$$\frac{dM_{w(i)}}{dt} = \frac{(F_{s(i-1)}M_{w(i-1)} - F_{s(i)}M_{w(i)}) - d_{r(i)} - M_{w(i)}\frac{dH_{s(i)}}{dt}}{H_{s(i)}} \quad for\ i = 1,...,n \tag{5}$$

Where, $M_{w(i)}$ is solid moisture content and $d_{r(i)}$ is drying rate in the ith segment of the dryer. This equation indicates that solid flow rate and hold up of the ith segment, which are calculated from equations 2 and 4, respectively, can be used to compute solid water content of the ith segment. Since the dynamic model is supposed to be used for on-line model-based control of the process, drying rate was computed using the on-line data of inlet and outlet air humilities and flow-rates applying the following equation:

$$d_r = F_{a(out)}W_{out} - F_{a(in)}W_{in} \tag{6}$$

Applying equation (6) needs to assume that drying rate remains constant over a short sampling period. The drying rate in each segment of the dryer $d_{r(i)}$ can be computed if the distribution of the solid water content in the dryer is known. Alternatively, it can be calculated by dividing the drying rate, obtained from equation (6), to the number of the segments (n) as shown below.

$$d_{r(i)} = \frac{d_r}{n} \tag{7}$$

3- Experimental methods

The experiments were designed in order to obtain appropriate data for the estimation of the model parameters (α, β and γ) and to investigate the effects of air flowrate, rotation speed and solid flowrate on the solid retention time in the dryer. The experiments were conducted employing an industrial dryer. The dryer length and diameter were 5 and 1 m respectively. There were 11 flights mounted on the inside of the drum. A conveyer belt was used to feed particles to the dryer in a constant rate. The dryer was equipped to appropriate instruments to keep the rotation speed and inlet air flowrate and temperature at their desired values. Table 1 shows the conditions of the three experiments performed in this study.

Table 1. The conditions of experiments 1 to 3.

Number of the experiment	**1**	**2**	**3**
The specific test	A pulse in solid inlet from 5.3 to 7 kg/min for 20 minutes	A step in solid inlet from 5.3 to 2.75 kg/min	A step in air flow rate from 2500 to 1500 m^3/hr
Air flow rate (m^3/hr)	2500	2500	2500
Inlet solid flowrate (kg/min)	5.3	5.3	2.75
Rotation speed (rpm)	1.1	1.1	0.75
Inlet NC moisture content	31%	31%	31%
Outlet NC moisture content	19.9%	16.7%	18.4%

4- Results and discussions

The steady state and one set of dynamic data were employed to estimate the parameters of the model (α, β and γ). The estimated values were 16.302, 1.012 and .785 for α, β and γ, respectively. The model was then used to predict solid holdup and output flowrate, while estimated parameter values were inserted into the model equations. Another set of experimental data was then compared with the model predictions, produced in the same conditions. Figures 2 to 5 indicate some of the comparisons between mode predictions and the data. On the whole, the model predicted solid hold up and outlet flow rate with average errors of 5.6% and 5.4 % respectively.

Fig. 2 shows the response of the process in terms of solid output flow rate to a pulse input in terms of solid inlet from 5.3 to 7 kg/min, which took 20 minutes. The pulse started 175 minutes after the onset of the experiment. The experimental data in this figure indicate that solid output begins to rise around 25 minutes after the solid input was stepped up, which means there is a death time in the response of the output flow rate to the input flow rate. The simulation results of this figure show the model can predict the death time. The model is able to predict the death time since it is a distributed parameter model so that the sum of the retention times, calculated for all of the segments of the dryer, are equal to the death time that is predicted by the model. However, the predicted death time is much shorter (around 10 minutes). Similar behavior can be observed when the pulse is finished at 195 minutes. The figure indicates that the model prediction profile and the experimental data follow very close trends. Therefore, the model has been able to predict the process response reasonably well.

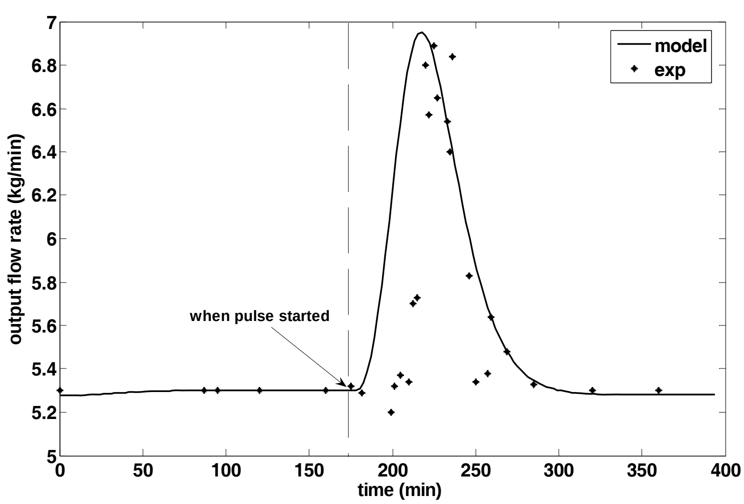

Figure 2. The comparison between solid output data of experiment 1 and the model predictions.

The reason is that Fig. 3 shows the response of the process in terms of solid output flow rate to a step change in solid inlet from 5.3 to 7 kg/min, which occurred 175 minutes after the experiment was started. This figure displays that solid output flow rate has started to respond to the step down around 25 minutes later. This indicates that the model has been able to predict the death time as well. This figure implies high accuracy of the model, since the model prediction profile stays very close to the experimental data.

Fig. 4 depicts model predictions and experimental data in terms of dryer holdup during experiment 2. In this experiment solid inlet rate was dropped down from 5.3 to 7 kg/min 180 minutes after the experiment was started. Since a reduction in the solid inlet does not immediately lower solid outlet, as shown in Fig. 3, solid holdup decreases right after the decrease in the solid input rate. The holdup gradually decreases till it reaches a new level. The figure also indicates a good agreement between the model predictions and the experimental data.

Figure 5 displays the model predictions and the experimental data of experiment 3 in terms of solid outlet. In this experiment air flow rate was dropped down from 2500 m^3/hr to 1500 m^3/hr 275 minutes after the start of the experiment. Since air flow affects the movement of air born particles, a change in its rate almost immediately causes a variation in solid outlet. In this research the dryer worked in counter current mode where the air flow blows back the air born solid particle. Therefore, a decrease in air flow rate means less blowing air, leading to a temporary increase in the solid outlet due to the sudden reduction of air resistance against solid movement. The figure also indicates that the model could predict this phenomenon. The reason for the model ability to predict this phenomenon is conceivable by observing equation 3. This equation implies a reduction in the air flow rate (Fa) causes a decrease in solid retention time, leading to an increase in solid flow rate. However, according to equation (3), these variations happen immediately, while the experimental data display rather gradual changes.

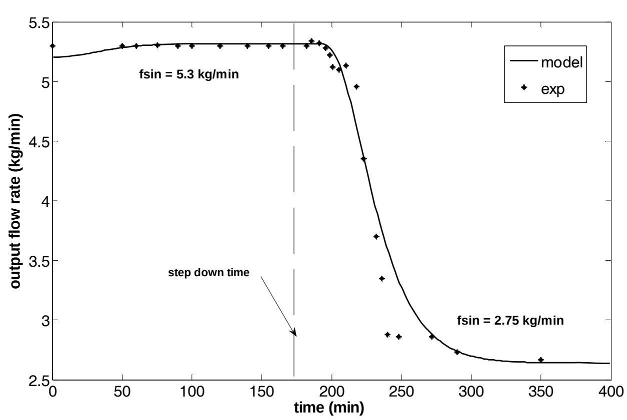

Figure 3. The comparison between solid output data of experiment 2 and the model predictions**.**

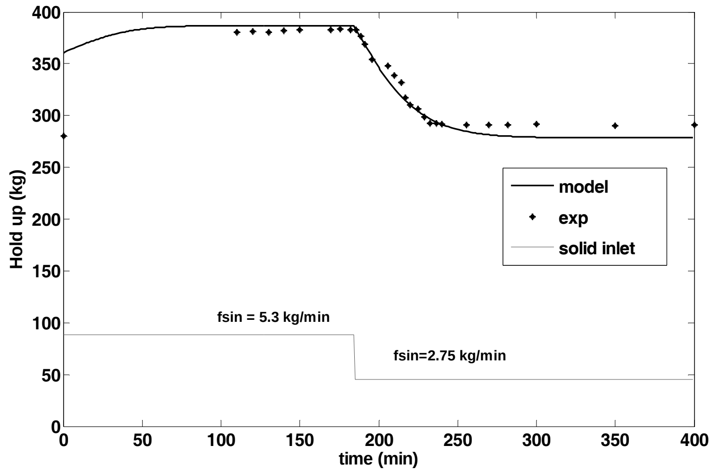

Figure 4. Comparison between solid hold up data of experiment 2 and the model predictions**.**

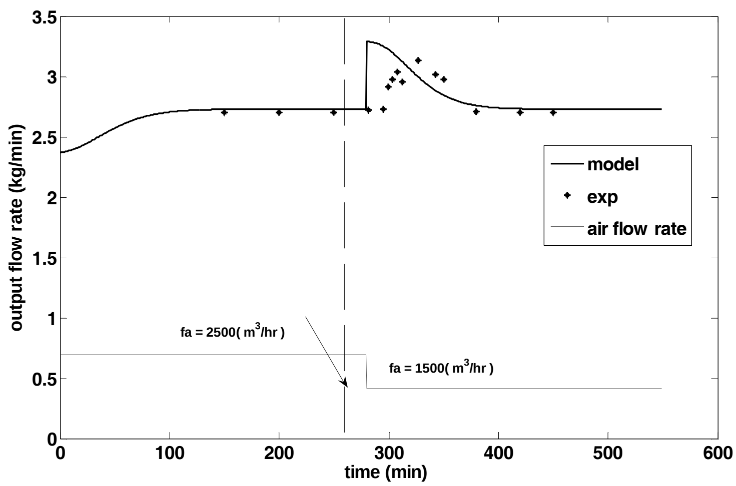

Figure 5. Comparison between solid output data of experiment 3 and the model predictions.

5- Conclusion

A mathematical model that computes heat and mass transfer rates from on-line experimental data was developed for an industrial granule dryer. This model employs modified Friedman and Marshal Equation. Solid transport equations of the model were evaluated against the experimental data. Visualized and quantitative comparisons between model predictions and the experimental data indicated that the model could reasonably represent the solid transport phenomena. The average model error for solid holdup and outlet flow rate were 5.6% and 5.4 %, respectively. Therefore, it can be concluded that the model is sufficiently accurate to be used for the optimization and model-based control of industrial rotary dryers.

6- Nomenclature

D	dryer diameter, m
D_p	weight average particle size, m
dr	drying rate, kg/s
F_a	air flowrate, kg/s
F_s	solid outlet from the dryer, kg/s
$F_{s(i)}$	solid outlet from the ith section of the dryer, kg/s
H_s	solid hold-up of the dryer, kg
$H_{s(i)}$	solid hold-up in ith section of the dryer, kg
L(i)	length of the ith segment, m
M_w	solid water content, kg/kg
R_t	retention time, s
R_s	rotation speed of the drum, rpm
t	time, s
w	air humidity, kg/kg
z	dryer length, m
α , β, γ	parameters which should be estimated using experimental data
δ	drum slope to horizontal, degrees

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