Process analysis for an alfalfa rotary dryer using an improved dimensional analysis method

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Abstract: All parameters in terms of wet alfalfa input capacity, dry alfalfa output capacity, alfalfa stem length, rotary speed, heated air temperature, air flow velocity and number of lifting flights fixed at the interior wall of rotary dryer were integrated and derived into four π terms based on Jiang's principle. The drying temperature was a significant factor influencing the drying rate and the post-drying quality of alfalfa hay. An improved G. Murphy theorem with high confidence was used to design an experimental program for alfalfa drying in a rotary dryer. A π equation was derived by using the multiplication of component equations involving the drying parameters and most of its correlation coefficients were higher than 0.99. The validation results show that most of the relative errors of π terms were lower than 10% and are acceptable in engineering practice. This empirical equation may be used to investigate the parameter interactive effects on conveyor performance, which may be useful in the design and selection of rotary dryers for drying alfalfa hay.

Keywords: alfalfa, drying, rotary dryer, dimensional analysis
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1 Introduction

Alfalfa (*Medicago satica,* L) -- an excellent source of protein, vitamins and minerals for animals is the most important forage crop species in the world. In addition to being feed for cattle, alfalfa is an important plant for adding nitrogen for improved soil fertility.

If dehydration is delayed, the alfalfa plant may spoil and deteriorate due to the invasion of harmful microorganisms that consume a large quantity of nutrients, such as protein and carbohydrate. The deterioration process in alfalfa is related to the moisture content and dehydration duration. The activity of enzymes in alfalfa increases with the moisture content. Fonnesbeck et al.[1] and Patil et al.[2] studied the effect of rainfall on yield and nutrient losses of field-dried alfalfa hay. Their research results showed that the simulated rain reduced available carbohydrates from 27.3% to 24.3%, and the estimated yield loss of soluble nutrients was 9.7%. Therefore, fresh alfalfa must be dehydrated promptly at a high drying rate to maintain the nutrients in alfalfa hay. Research results from Zheng[3] showed that the fresh alfalfa may be dried to a moisture content of 14%–15% (w.b.) in a short time with a minimum loss of nutrition under hot-air drying treatment, because the microorganisms destroying protein and vitamins appear inactive with the high dehydration rate. Premium quality alfalfa hay obtained by hot-air drying method,

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which improves livestock nutrition and commercial value of the hay, has characteristics of high digestibility, favoritism from animals feed and special hay aroma.

Rotary dryers are widely used in the industrial drying process. Some rotary dryers have been designed based on special material properties, such as chemical materials or food products. These dryers are unfit for drying alfalfa due to the difference of desired product type with respect to material shape, quality and physical-chemical properties[3]. Therefore, it is necessary to design rotary dryers for alfalfa whose performance characteristics are low energy consumption and high alfalfa quality. However, although rotary dryers have been used for drying alfalfa hay, most research focused on the functions of the machinery [4-6] and relatively little attention was paid to the kinetic mechanism of materials processed. It is difficult to quantitatively describe the interaction of numerous variables, such as air velocity, drying temperature, number of lifting flights, rotary cylinder length and diameter in drying process of alfalfa in a rotary dryer. This complicated process involves the alfalfa spiraled with cascading cycles and dried in the gas-solid flow.

Dimensional analysis, as an effective modeling method, has been well documented for a large number of engineering problems and develops the basis for many formulas and dimensionless quantities. This method can be used to predict the performance of a new design based on empirical equations from an existing, similar design.

Srivastava[7], Shafii[8] and Srivastava[9] employed a dimensional analysis method and developed equations to predict the behaviors of corresponding equipment with high confidence.

A dimensional analysis method provides qualitative information about the research, which significantly reduces the amount of experimental data that must be collected. It is based on the premise that physical quantities have dimensions and that changing the dimensional measurement units does not alter physical laws. Thus, the phenomena under investigation can be described by a dimensionless equation among the variables. Dimensional analysis can be considered as a suitable method to simulate the drying process of a rotary alfalfa dryer, which improves the efficiency of an experimental design and extends the optimal results to similar type dryers. Wood and Sokhansanj[10] worked on the optimization and control of several alfalfa dryers. Adapa et al.[11] designed an innovative rotary dryer with a large chamber and three passage drums, which reduced the moisture difference between leaves and stems of alfalfa hay. However, little literature on the analysis of the capacity of rotary dryers with a dimensionless method was found in published materials.

The objective of this study was to develop π terms and an empirical equation describing the effect of clusters of drying parameters on the performance of rotary dryers using an improved G. Murphy theorem method.

2 Jiang's principles

Based on a series of experimental studies and theoretical analyses, Jiang[12-14] disproved the statement advanced by Murphy[15] that the two component equations must have the same form in order to combine them to be a general π equation. Instead Jiang asserted that they may be totally different each other, and so named the improved G. Murphy theorem. This finding results in a significant increase in prediction accuracy if the following principles can be followed:

1) The highest regression coefficient (R^2) should be the sole criteria for selecting the type (form) of component equations, i.e. pursuing best fitness of curve to the plots.

2) The relationship between the dependent π_1 term and the independent π term must be strictly kept constant. And their value should be the same as before if they were selected as a non-variable π term in developing a component equation for other variable independent π terms.

3) It is most desirable that the value of each physical quantity has the chance to be varied, and what's more, in a sufficiently wide range of magnitude.

4) The dimensionless physical quantities influential to the phenomena should be involved in the π item's formation. As soon as these quantify being positioned in certain π items, their positions should not be arbitrarily moved due to their dimensionless characters.

By doing so, their effects on the phenomena will be truly manifested through the generated π equation and empirical equations.

5) For those physical quantities of the same dimension but different physical characters, their physical characters should be identified clearly during the manipulation of π items and experimental tests. Otherwise, erroneous results may be deduced.

These above-mentioned principles were considered as the theoretical basis to select parameters and derive π items for the alfalfa drying in a rotary dryer. And the improved G. Murphy theorem was employed to select the fitting components equations.

3 Experimental procedures

3.1 Experimental design

The variables shown in Table 1 were selected to describe the alfalfa drying process in a rotary dryer [16]

Table 1 Parameters describing the drying process in a pilot rotary dryer

Parameters	Unit	Dimension	Value range
Capacity of wet alfalfa, *G*	kg/min	MT^{-1}	27.67, 20, 15.64
Angle speed of rotary cylinder, ω	Rad/min	T^{-1}	6, 8, 10, 12
Temperature of air, *t*	℃	ML^2T^{-2}	320, 360, 400, 440, 480, 520
Air velocity of air, *U*	m/s	LT^{-1}	1.3, 1.8, 2.30
Alfalfa length, *L*	m	MT^{-1}	2, 4
Flight number, *N*	N/A	L	30, 40, 50, 60
Capacity of dried alfalfa, M	kg/min	MT^{-1}	dependent variable

The following relationship represents a general form to describe the capacity of dried alfalfa depended on variables:

$$M=f(G, \omega, t, U, L, N) \quad (1)$$

A dimensional homogeneous theory [17] was used to arrange these parameters into number groups (π terms), were shown as the following:

$$\pi_1 = \frac{M}{G} \quad \text{Capacity number} \quad (2)$$

$$\pi_2 = \frac{t}{GUL} \quad \text{Temperature number} \quad (3)$$

$$\pi_3 = \frac{U}{\omega L} \quad \text{Velocity number} \quad (4)$$

$$\pi_4 = N \quad \text{Flight number} \quad (5)$$

These π terms divide the process parameters of a rotary dryer into four groups, namely capacity number, temperature number, velocity number and flight number, used to establish empirical models at cluster parameters form, which avoid the analysis of complex interaction between heated air flow and alfalfa crop drying.

The general function on π terms was expressed as follows:

$$\frac{M}{G} = f\left(\frac{t}{GUL}, \frac{U}{\omega L}, N\right) \quad (6)$$

A specific form of function (6) can be determined by experiments of alfalfa drying in a rotary dryer. According to the above-mentioned Jiang's principles and relevant dimensional analysis[17], the experimental procedures were proposed [3].

3.2 Experimental process

The fresh cut alfalfa (variety: Canada #1) was planted at the experimental farm of Northeast Agricultural University, China. A hay harvester was operated to harvest the alfalfa at 10% bloom stage. The alfalfa plants were immediately placed in double-layer plastic bags and tied securely to seal them. These fresh alfalfa samples were stored in a freezer at –4℃. Before experimentation, the alfalfa were taken out from the bag, spread and allowed to thaw for 4–6 h. Heated air was achieved to the desired temperature by a gasoline fueled stove with a solid-state temperature controller. The airflow velocity was controlled manually by an air dampener in the blower with air velocities of 1.3, 1.8, and 2.3 m/s. A variable speed motor controlled the rotary speed of the rotary cylinder.

The moisture content (MC) of fresh and dried alfalfa was measured by the air oven method[3] at 103℃ for 24 h, and initial MC of whole plant alfalfa was 78.5% (w.b.). A rubber hammer was used to manually crush the whole alfalfa plants to destroy the outer layer of alfalfa stems to increase the drying rate, then cut them into segments of 2–4 cm length. In this study, the dimension of the rotary dryer in terms of length (s), rotary diameter (d), and angle of flight (α) were kept at constant values of 4 m, 0.8 m, and 135 degrees, respectively.

4 Results and discussion

4.1 Fitting component equations

The component equations were derived based on the improved G. Murphy theorem. SAS software was used to process the data in Tables 2–4. The results in terms of component equations and reliability (r) are listed in each table.

Table 2 Experimental data and component equations for $(\pi_{1/2})_{\bar{3}\bar{4}}$ and $(\pi_{1/2})_{\bar{3}\bar{\bar{4}}}$

t,℃	π_2	N=60, $\bar{\pi}_3$=0.1125, $\bar{\pi}_4$=60		N=30, $\bar{\pi}_3$=0.1125, $\bar{\bar{\pi}}_4$=30	
		M, kg • s^{-1}	π_1	M, kg • s^{-1}	π_1
320	4.444	11.81	0.5905	8.44	0.422
360	5.000	8.55l	0.4275	6.22	0.311
400	5.556	6.44	0.322	4.68	0.234
440	6.111	5.53	0.2765	3.56	0.178
480	6.667	4.97	0.2485	2.92	0.146
520	7.222	4.65	0.2325	2.68	0.134
Component equation		$\pi_1 = 6.685 - 2.750\pi_2 + 0.395\pi_2^2 - 0.019\pi_2^3$ r=0.9999 (7)		$\pi_1 = 2.127 - 0.558\pi_2 + 3.90\times10^{-2}\pi_2^2$ r=0.9998 (8)	

Table 3 Experimental data and component equations for $(\pi_{1/3})_{\bar{2}\bar{4}}$ and $(\pi_{1/3})_{\bar{\bar{2}}\bar{4}}$

U m • s-	ω rad.min^{-1}	G kg • min^{-1}	L=2 cm, $\bar{\pi}_2$=5.56, $\bar{\pi}_4$=60			L=4 cm, $\bar{\bar{\pi}}_2$=2.28, $\bar{\pi}_4$=60		
			M, kg • min^{-1}	π_1	π_3	M, kg • min^{-1}	π_1	π_3
1.3	6	27.67	8.633	0.312	0.108	12.731	0.461	0.054
1.3	8	27.67	7.000	0.253	0.081	11.060	0.400	0.041
1.3	10	27.67	6.610	0.239	0.065	10.771	0.389	0.033
1.3	12	27.67	6.329	0.229	0.054	9.685	0.351	0.027
1.8	6	20	7.640	0.382	0.150	11.700	0.585	0.075
1.8	8	20	6.441	0.322	0.113	9.586	0.479	0.057
1.8	10	20	5.733	0.287	0.090	8.652	0.433	0.045
1.8	12	20	5.244	0.262	0.075	7.937	0.397	0.038
U m • s^{-1}	ω rad.min^{-1}	G kg • min^{-1}	L=2 cm, $\bar{\pi}_2$=5.56, $\bar{\pi}_4$=60			L=4 cm, $\bar{\bar{\pi}}_2$=2.28, $\bar{\pi}_4$=60		
			M, kg • min^{-1}	π_1	π_3	M, kg • min^{-1}	π_1	π_3
2.3	6	15.64	7.472	0.478	0.192	11.782	0.753	0.096
2.3	8	15.64	6.114	0.391	0.144	9.103	0.582	0.072
2.3	10	15.64	5.424	0.347	0.115	8.000	0.512	0.058
2.3	12	15.64	4.804	0.307	0.096	7.211	0.461	0.048
Component equation			$\pi_1 = 1.295\times\exp(-2.180\times\exp(-4.055\pi_3))$ r=0.9827 (9)			$\pi_1 = 0.269\times\exp(10.682\pi_3) - 0.371\times\exp(-143.765\pi_3)$ r=0.9934 (10)		

Table 4 Experimental data and component equations for $(\pi_{1/4})_{\bar{2}\bar{3}}$ and $(\pi_{1/4})_{\bar{2}\bar{\bar{3}}}$

N	π_4	L=2 cm, $\bar{\pi}_2$=5.56, $\bar{\pi}_3$=0.1125		L=4 cm, $\bar{\pi}_2$=5.56, $\bar{\bar{\pi}}_3$=0.0563	
		M, kg • min^{-1}	π_1	M, kg • min^{-1}	π_1
30	30	3.278	0.164	5.061	0.253
40	40	4.041	0.201	6.169	0.309
50	50	5.018	0.251	7.952	0.398
60	60	6.442	0.322	9.687	0.484
Component equation		$\pi_1 = 0.160 - 2.41\times10^{-3}\pi_4 + 8.5\times10^{-5}\pi_4^2$ r=0.9998 (11)		$\pi_1 = 0.152 - 1.070\times10^{-3}\pi_4 + 7.5\times10^{-5}\pi_4^2$ r=0.9979 (12)	

Equations (7) and (8) in Table 2 describe the relation of drying temperatures on the dryer capacity under two types of fixed lifting flights. Two regression equations with high reliability coefficients were developed to fit the relationship between the π_1 and π_2 terms. The π_2 value increased with the drying temperature, which resulted in the drying rate of wet alfalfa increases. Increased drying temperature obviously improved the working capacity of dryer for alfalfa drying, which causes a decrease in the value of π_1 if other parameters were held at certain levels shown in Table 1. Under the same drying temperature, if the number of lifting flights decreases from 60 to 30, the retention time of alfalfa in the rotary dryer increases due to the decrease of chances of alfalfa segment lifted, this results in an increase of the amount of moisture removed from the wet alfalfa. Thus, the final moisture content of dried alfalfa decreases as the number of lifting fights decrease.

The effect of temperature number π_3 including capacity of wet alfalfa G, air velocity of air U and angular speed of the rotary cylinder ω on the capacity number π_1 is shown in Table 3, where the experimental data and component equations for the terms $(\pi_{1/3})_{\bar{2}\bar{4}}$ and $(\pi_{1/3})_{\bar{\bar{2}}\bar{4}}$ were obtained. Under the drying conditions of U=1.3 m/s, G=27.67 kg/min and t=400℃, the amount of dehydration from fresh alfalfa increases with the increase of angle speed of the rotary cylinder from 6 to 12 rad/min. However, when the ω value exceeds 10 rad/min, the dehydration amount of alfalfa can not increase proportionately due to the increase of centrifugal force, which prolongs the retention time of alfalfa in the rotary dryer, and results in a decrease of the productivity of dried alfalfa. When the alfalfa stem length changes from 2 to 4 cm, the productivity of dried alfalfa significantly increases due to the resistance of water migration inside the alfalfa stems rising under the same drying conditions. Two component equations were developed with r values, 0.9827 and 0.9934, respectively, to describe the relationship between π_1 and π_3 with high credibility. Table 4 displays the experimental data and component equations for the terms $(\pi_{1/4})_{\bar{2}\bar{3}}$ and $(\pi_{1/4})_{\bar{2}\bar{\bar{3}}}$. The lifting flights fixed on the interior wall of a rotary dryer fling alfalfa stems, and heated–air flows stirred the floating stems move forward along the axial direction of the cylinder. Increasing the number of lifting flights may reduce the retention time, which caused dehydration amount of alfalfa hay to decrease, as well as increasing the length of alfalfa hay increased the MC of alfalfa hay discharged from dryer.

A π equation can be proposed by combining all component equations in Table 2–4 using a multiplication form [17] shown in equation (13).

$$\pi_1 = F(\pi_2, \pi_3, \pi_4) = \frac{f_1(\pi_2, \bar{\pi}_3, \bar{\pi}_4)\, f_2(\bar{\pi}_2, \pi_3, \bar{\pi}_4)\, f_3(\bar{\pi}_2, \bar{\pi}_3, \pi_4)}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4)^{4-2}} \tag{13}$$

According to the results in Table 2–4, thus:

$$F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4) = f_1(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4) = f_2(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4) = f_3(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4) = 0.322 \tag{14}$$

The component equations (7), (9), (11) and (14) were submitted into equation (13), a π equation describing the relationship between capacity of dried alfalfa in a rotary dryer (M in π_1 item) and the other independent π items was proposed as following:

$$\pi_1 = F(\pi_2, \pi_3, \pi_4) = (6.685 - 2.750\pi_2 + 0.395\pi_2^2 - 0.019\pi_2^3)(1.295\times\exp(-2.18\exp(-4.055\pi_3))(-0.160 + 2.41\times10^{-3}\pi_4 + 8.5\times10^{-5}\pi_4^2)/0.322^2 \tag{15}$$

4.2 Verification of validation of component equations

Verifiable experiments were conducted to test the validation of component equations. If the determination coefficient R^2 of component equations from measures and predicted values were higher than 0.9 and the relative error from comparison formula was lower than 10%, the component equations were confident in representing a certain process[12-14].

The verified experiments were performed under the other drying conditions and derived corresponding component equations (8), (10) and (12). A comparison method[14] between component equations derived from two kinds of drying conditions for the same π term was employed to test the validation of component equations (7), (9) and (11), respectively. The lesser of the difference between the two component equations, more precise component equation is [14,17].

$$\frac{(\pi_{1/2})_{\bar{3},\bar{4}}}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4)} = \frac{(\pi_{1/2})_{\bar{\bar{3}},\bar{\bar{4}}}}{F(\bar{\bar{\pi}}_2, \bar{\bar{\pi}}_3, \bar{\bar{\pi}}_4)} \tag{16}$$

The component equation and constant value were substituting into equation (16), as shown in equation (17).

$$\frac{6.69 - 2.75\pi_2^2 - 0.02\pi_2^3}{0.322} = \frac{1.75 - 0.45\pi_2 + 2.88\times10^{-2}\pi_2^2}{0.164} \tag{17}$$

The comparative results are described in Figure 1.

$$\frac{(\pi_{1/3})_{\bar{2},\bar{4}}}{F(\bar{\pi}_2,\bar{\pi}_3,\bar{\pi}_4)}=\frac{(\pi_{1/3})_{\bar{2},\bar{\bar{4}}}}{F(\bar{\pi}_2,\bar{\pi}_3,\bar{\bar{\pi}}_4)} \quad (18)$$

Substituting the component equations and data in Table 2 into equation (18):

$$\frac{1.295\times\exp(-2.180\times\exp(-4.055\pi_3))}{0.322}=\frac{0.269\times\exp(10.682\pi_3)-0.371\times\exp(-143.765\pi_3)}{0.479} \quad (19)$$

The comparison result in equation (19) was presented in Figure 2.

$$\frac{(\pi_{1/4})_{\bar{2},\bar{3}}}{F(\bar{\pi}_2,\bar{\pi}_3,\bar{\pi}_4)}=\frac{(\pi_{1/3})_{\bar{\bar{2}},\bar{4}}}{F(\bar{\pi}_2,\bar{\bar{\pi}}_3,\bar{\pi}_4)} \quad (20)$$

Substituting the component equations and data in Table 3 into equation (9):

$$\frac{0.160-2.41\times10^{-3}\pi_4+8.5\times10^{-5}\pi_4^2}{0.322}=\frac{0.152-1.070\times10^{-3}\pi_4+7.5\times10^{-5}\pi_4^2}{0.484} \quad (21)$$

Figure 3 shows the comparison result in equation (21).

Figures 1–3 describe the comparison results with a high correlation coefficient R^2 above 0.92, which showed the higher agreement between the component equations (7) and (8) under different drying conditions. The same trends appear in component equations (9) and (10), (11) and (12), respectively. The component equations can be expressed with different functions according to the above-mentioned improved G. Murphy theorem. Most of the component equations have the reliability exceeding 0.99, except one with 0.9827. Figures 1–3 presented the comparisons between the both sides of expression (17), (19) and (21), respectively, in which most relative errors were below 3% (45 out of 78 experiment points), and among 3%–5% were 15 experimental points, and among 5%–11% were 10 experimental points. Only 8 relative errors of experiment points exceed 10% in all 78 experimental points. The highest error was 20.4%, which occurred at an unexpected experimental boundary where drying temperature was 600 ℃. In general, engineers may accept the relative error below 10% processing in an engineering problem[14]. The results indicate that those component equations developed based on the improved G. Murphy theorem closely expressed the relationship between the π terms, which is helpful to analyze the drying properties of alfalfa hay in the rotary dryer within the experiment range.

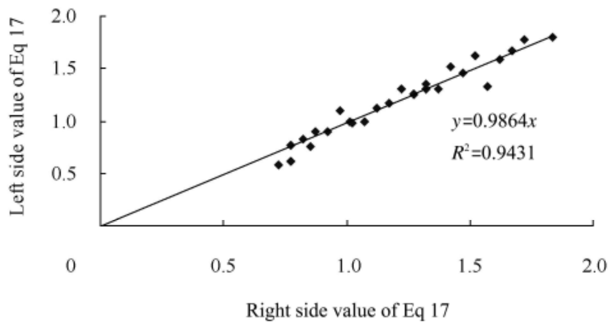

Figure 1 Comparison of the $\bar{\bar{\pi}}_4$ substitute for $\bar{\pi}_4$ for equation 17

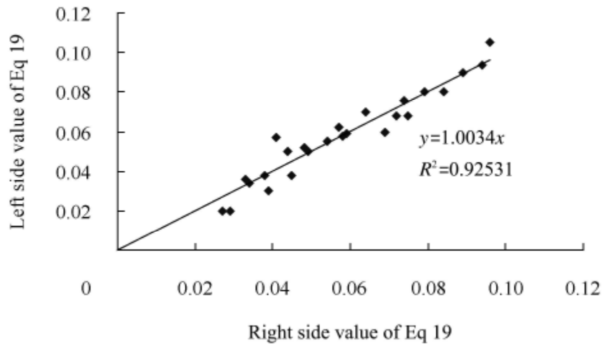

Figure 2 Comparison of the $\bar{\bar{\pi}}_2$ substitute for $\bar{\pi}_2$ for equation 19

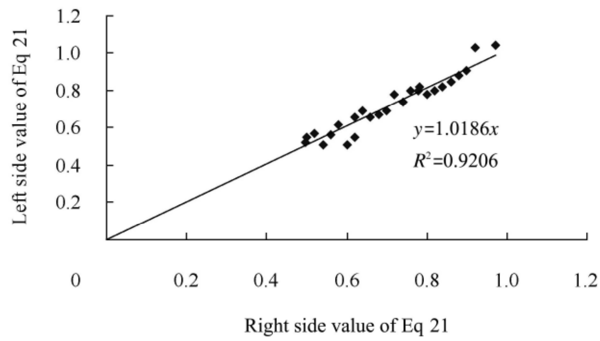

Figure 3 Comparison of the $\bar{\bar{\pi}}_3$ substitute for $\bar{\pi}_3$ for equation 21

5 Conclusions

According to Jiang`s principles and the improved G. Murphy theorem, drying parameters were arranged into number groups (π terms) and the component equations were derived, respectively, which effectively describe alfalfa drying process in a rotary dryer. The verifiable results from theory and experimentation show that there exists a reasonable agreement with the high correlation coefficient. Therefore, the results from this research can be better used to analyze, predict and optimize the performance of rotary dryers for drying alfalfa hay and further extended to design a series of similar dryers.

In all parameters, the drying temperature is a significant factor in the drying rate and the post-drying quality of alfalfa hay. As a potential method, dimensional analysis can be applied to determine the effect of the parameters of rotary dryers.

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