J | P | S | T

http://jpst.irost.ir

Journal of Particle Science and Technology

IROST

Drying of calcium carbonate in a batch spouted bed dryer: optimization and kinetics modeling

Sadegh Beigi[1], Mohammad Amin Sobati[*,1], Amir Charkhi[2]

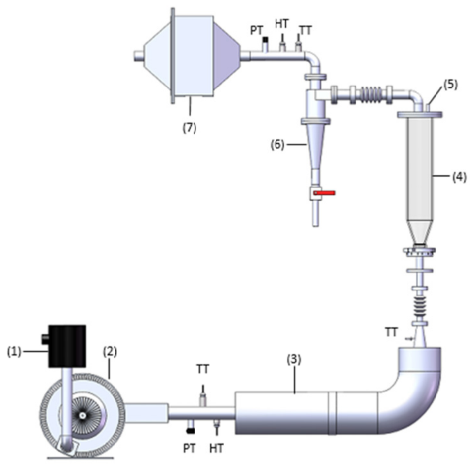
[1] *School of Chemical Engineering, Iran University of Science and Technology (IUST), Tehran, Iran*

[2] *Material and Nuclear Fuel research school, Nuclear Science and Technology Research Institute, Tehran, Iran*

HIGHLIGHTS

- A new batch spouted bed dryer was investigated for drying calcium carbonate.
- A new criterion has been introduced to measure the effective efficiency of the drying process.
- The drying kinetics have been modelled using semi-theoretical approaches.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 June 2017
Revised 12 July 2017
Accepted 23 July 2017

Keywords:
Spouted bed dryer
Drying kinetics
Taguchi method
Drying effective efficiency
Modeling

ABSTRACT

In the present work, the drying of calcium carbonate in a batch spouted bed dryer with inert particles has been investigated experimentally. The effect of several operating parameters including air temperature (90, 100, and 110 °C), air velocity (U_{ms}, 1.2 U_{ms}, and 1.5 U_{ms}), and dry solid mass (5, 10, 20 g) has been studied. The Taguchi method has been applied to determine the optimal parameters and also to reduce the number of required experimental runs. It has been found that the dryer performance was affected by all parameters. It has also been found that drying with 5 g dry solid at a temperature of 100 °C and a velocity of 1.2 U_{ms} leads to maximum drying efficiency. Additionally, the effect of air inlet velocity and temperature on the drying kinetics of calcium carbonate has been investigated. Several semi-theoretical models with temperature and velocity dependent parameters have been selected to estimate the drying kinetics. The performance of all fitted models was acceptable but the logarithmic model was the best model in terms of the statistical analysis.

* Corresponding author: Tel.: +9821-77240496 ; Fax: +9821-77240495 ; E-mail address: sobati@iust.ac.ir
DOI: 10.22104/jpst.2017.2257.1087

1. Introduction

Calcium carbonate is applied in different industries such as chemical [1], pharmaceutical [2,3], food [4], plastics [5,6], paper [7], paints [8], ceramic materials [9,10], etc. Hence, the demand for calcium carbonate has been growing quickly in recent years.

Calcium carbonate is produced in powders, granules and slurries form by two general methods: (1) ground calcium carbonate, commonly referred to as GCC, which is produced by intensive milling or grinding of natural calcium carbonate and (2) precipitated calcium carbonate (PCC) which is produced by the reaction of aqueous calcium hydroxide suspension with carbon dioxide. Generally, the product should be conventionally dewatered and dried [11-13]. For instance, PCC has four processing steps including (1) calcination, (2) lime slaking, (3) carbonation, and (4) drying [14]. Accordingly, drying is required in order to prepare the final calcium carbonate for market. Also, nanoparticles of calcium carbonate are required in some of the above-mentioned applications [6,15].

Different dryers, such as spray dryers, fluidized bed dryers, and spouted bed dryers, have been proposed for drying slurries and pastes. Spouted bed dryers with inert particles are a relatively new technology with a number of advantages such as high drying rates, uniform temperature distribution, uniform size particle production, and low drying cost for solution, slurries, and pasty materials [16-20].

Gishler and Mathur applied a spouted bed dryer in 1954 for drying wheat in Canada [21]. The spouted bed is a gas-solid contactor in which the fluid jet is introduced through a nozzle located at the center of the conical bottom of the bed. Intensive interaction between the solid particles and gas occurs in this dryer. Three regions are distinguished for gas-solids flow in a spouted bed: (1) a spout zone located in the center of the bed (2) an annulus zone located between the spout and the column wall and (3) a fountain zone located above the spout [22]. The particle flow with respect to the gas flow is co-current and counter-current in the spout and annulus zones, respectively.

Regardless of the hydrodynamic configuration of the dryer, the principle behind this technology is based on the drying of a thin layer of slurry that coats the surface of the inert particles. Depending on the type of dryer, these particles can be vibrated, fluidized, or spouted either by a hot air or combination of hot air and a mechanical device installed inside the dryer, such as an agitator or a conveyor screw [23].

In the spouted bed dryer with inert particles, the slurry is directly sprayed onto the bed and is deposited as a thin-film layer on the surface of the inert particles. The bed of particles is spouted with the hot gas causing the film on the particles' surface to dry and become fragile due to the large surface area of inert particles and intensive spouting. Then, particle-particle and particle-wall collisions lead to the conversion of the dried film to a dried powder. In the final step, the dried powders are entrained by the exit stream and are recovered using suitable solid separation equipment. It should be noted that the required energy for water evaporation is supplied via (1) a direct method through the hot air and (2) an indirect method through the inert particles heated by the hot spouting air [24]. The bed temperature is approximately uniform due to rapid circulation. The main operational parameters influencing the drying rate are the inlet air flow rate and temperature which in turn control the heat transfer and solids circulation rates [25].

Kudra and Mujumdar [26] have reviewed the application of the inert particles in different dryers. Schneider and Bridgwater [27] have investigated the drying of inorganic suspensions in a spouted bed using different inert particles. The effect of liquid injection on the spouting velocity, stability of the spouting regime, fountain height, and bed pressure drop was examined in their studies. The drying of a micro-particle slurry and a salt-water solution using a powder-particle spouted bed have been investigated by Guo et al. [28]. According to their results, the agglomeration of particles was observed when the drying efficiency was above 60%. Passos et al. [25] have investigated the drying performance for pastes in a conical spouted bed. Their study was focused on the investigation of the effect of column dimensions, fluid flow characteristics, and paste properties on the drying performance. Based on their study, a criterion is provided for the design of conical spouted bed dryers used for suspensions drying.

Nakazato et al. [29] have applied a powder-particle spouted bed to the production of fine calcium carbonate with a mean particle size around 1 μm. They have investigated the effect of operating conditions, such as superficial gas velocity and static bed height, on the particle size of the product (i.e., $CaCO_3$ powder). Benali and Amazouz [30] have proposed a jet spouted bed dryer to substantially reduce the stickiness of meat-rendering slurry (MRS). They examined the effects of calcium carbonate as drying-aid agents on the reduction of slurry stickiness. Arsenijevic et al. [31,32] have studied the drying of calcium carbonate and calcium stearate in a draft tube spouted bed and investigated the effects of the operating conditions on the dryer throughput and product quality. Moreover, they proposed and verified a model for predicting the particle circulation rate. Almeida et al. [33] have experimentally analyzed the fluid dynamic, thermal and mass transfer behavior of pasty materials, such as calcium carbonate, sewage sludge, and skimmed milk, during transient drying in spouted beds.

Calcium carbonate drying is influenced by parameters such as hot inlet air velocity, inlet drying temperature, dry solid mass, and so on. These parameters do not have the same effect on the drying process and their simultaneous impacts are very complex and debatable. Therefore, the Taguchi method has been used to determine the influence of each of these parameters and quantifiy their influence on the drying efficiency [34,35]. Taguchi techniques have been widely used in engineering design for the optimization and identification of critical parameters [36,37].

In the present research, the objectives are to investigate the drying kinetics of calcium carbonate slurry in a spouted bed dryer and to optimize the drying using the Taguchi method. The spouted bed dryer was selected and designed among different types of dryers. In this regard, experimental runs were conducted in a laboratory-scale spouted bed dryer with inert particles. Then, the effects of drying conditions, such as air temperature, hot air velocity, and dry solid mass, were discussed and optimized using the Taguchi method. Afterwards, an experimental run was carried out in optimal conditions. Finally, several semi-theoretical models were applied to model the drying kinetics.

2. Theory

2.1. Taguchi method

Taguchi has introduced a robust design method for ordered categorical response data. This method uses the cumulative frequencies of each category and each parameter setting to analyze data, determine optimal levels and apply the analysis of variance (ANOVA) [38]. Taguchi methodology proposes a particular method using an orthogonal array (OA) to reduce the number of experimental trials [39].

In the Taguchi method, the signal-to-noise ratio (S/N) is used to express the variability and it is calculated from experimental data by a loss function [40]. In the Taguchi method, the signal-to-noise (S/N) ratio is applied as an objective function for the optimization [36,41]. There are three categories of performance characteristics to analyze the signal-to-noise ratio (*SNR*) which are given by the following equations:

Larger is better:

$$SNR = -10 \log_{10}\left[\frac{1}{n}\sum\frac{1}{y^2}\right] \tag{1}$$

Nominal is the best:

$$SNR = -10 \log_{10}\left[\frac{1}{n}\sum\frac{\bar{y}}{{s_y}^2}\right] \tag{2}$$

Smaller is better:

$$SNR = -10 \log_{10}\left[\frac{1}{n}\sum y^2\right] \tag{3}$$

Where n, y, $\bar{y}$, and s_y^2 are the number of observations, the observed data, the average value of the observed data, and the variance of observed data, respectively.

2.2. Mathematical modeling of the falling period of drying rate

There are several models available in the literature to estimate the drying kinetics. The developed models of drying can be categorized into three categories: empirical, semi-theoretical, and theoretical models [42,43]. In the present study, the drying kinetics of calcium carbonate in the spouted bed is evaluated using some of the semi-theoretical correlations. These methods are proposed based on Fick's second law using a number of additional exponent terms [44]. These models are summarized in Table 1.

Table 1. Semi-theoretical models for drying kinetics.

No.	Model	Equation		Ref.
1	Lewis	$MR= exp(-kt)$	(4)	[45]
2	Page	$MR= exp(-kt^n)$	(5)	[46]
3	Henderosn and Pabis	$MR= a.exp(-kt)$	(6)	[47]
4	Logarithmic	$MR= a.exp(-kt)+b$	(7)	[48]
5	Balbay and Sahin	$MR= (1-a).exp(-kt^n)+b$	(8)	[49]

MR, dimensionless solid moisture, is calculated as follows:

$$MR = \frac{X - X_{eq}}{X_0 - X_{eq}} \tag{9}$$

It should be noted that X_0, X, X_{eq} are the initial moisture content, the moisture content, and the equilibrium moisture content on the dry basis, respectively. It should be noted that X_{eq} was assumed to be zero because the values of equilibrium moisture content, X_{eq}, are small in comparison with X and X_0 [50,51].

The k constant in the above-mentioned correlations can be assumed as a function of temperature, and inlet air velocity [52]:

$$k = k_0\, U^m exp\left(\frac{-E}{RT}\right) \tag{10}$$

where, U, m, E, k_0, and R are the gas superficial velocity, power constant, the activation energy of process, the pre-exponential factor, and the universal gas constant, respectively.

It should be noted that a derivative-free method, such as the simplex search method of Lagarias et al., was used to determine the model parameters [53].

2.3. Statistical analysis

The estimation capability of the fitted models was evaluated in terms of some statistical criteria such as root mean square error (E_{RMS}), the coefficient of determination (R^2), and Chi-square [54]:

$$R^2 = 1 - \frac{\sum_{i=0}^{N}\left(M_{exp,i} - M_{pre,i}\right)^2}{\sum_{i=0}^{N}\left(M_{exp,i} - \bar{M}_{exp,i}\right)^2} \tag{11}$$

$$\mathrm{E}_{RMS} = \left[\frac{1}{N}\sum_{i=0}^{N}\left(M_{exp,i} - M_{pre,i}\right)^2\right]^{1/2} \tag{12}$$

$$\chi^2 = \frac{\sum_{i=0}^{N}\left(M_{exp,i} - M_{pre,i}\right)^2}{\mathrm{N-Z}} \tag{13}$$

It should be noted that $M_{exp,i}$, $M_{pre,i}$, $\bar{M}_{exp,i}$, N and Z are the experimental data, the estimated data, the mean value of the experimental data, the number of experimental data, and the number of constants in the drying correlation. The best fitted correlation is the one with the lowest values of E_{RMS} and χ^2 close to zero, and the highest value of R^2 close to 1.

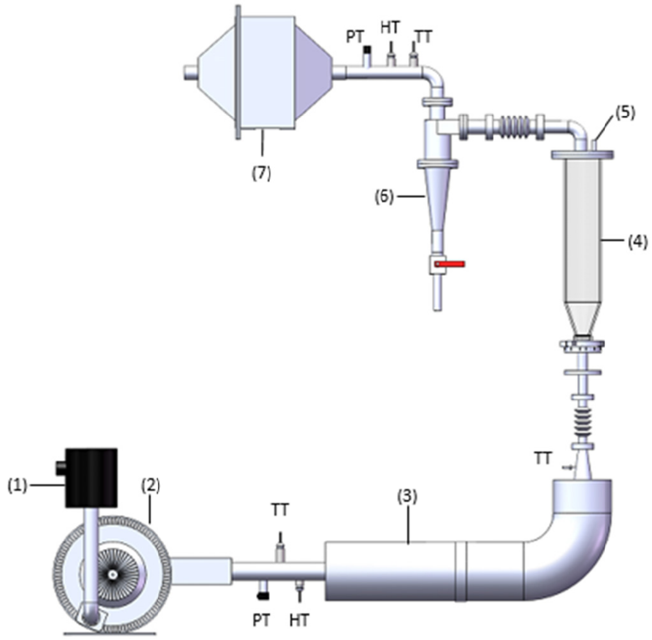


Fig. 1. Experimental setup, (1) pre-filter, (2) side-channel blower, (3) heater, (4) spouted bed dryer, (5) the feed port, (6) cyclone , and (7) HEPA filter; TT: temperature transmitter; HT: humidity transmitter; PT: pressure transmitter.

3. Experimental

3.1. Experimental Setup

A schematic view of the experimental setup is shown in Figure 1. The main drying equipment was made of an upright cylindrical column (inside diameter: 9 cm, outside diameter: 10 cm) and a base conical section (cone angle of 45°). A 1.5 cm nozzle was also located at the center of the lower end of the conical section. The height of the cylindrical and the conical sections were 40 cm and 9.5 cm, respectively. Glass beads (diameter: 1 mm, density: 1602 kg/m^3) were used as inert particles. The air inlet port was equipped with a stainless steel screen in order to avoid the glass particles discharging into the air duct.

The spouting air was supplied through a side channel blower (2RB 420-7HH46, GREEN-CO). The maximum air flow rate was 140 m^3/h at a pressure of 50 mbar. Some auxiliary accessories including an inlet vacuum filter, relief valve, and silencer were also applied along with the side channel blower. A 3 kW electrical heater was used for heating the air before it was introduced into the drying chamber. A cyclone and HEPA filter (Camfil Ireland Co.) were used to separate the dried powder from the outlet air stream.

The rotating speed of the blower was changed to adjust the inlet air flow rate. A digital thermo-anemometer mounted at the entry point of the blower was used to measure the air inlet velocity. Three K-type thermocouples (accuracy of ±0.1°C) were used to measure the air temperature at the inlet, middle, and the outlet of the drying chamber. In addition, two temperature-moisture transmitters (HTemp-wire, HW groups s.r.o) and two pressure transmitters (KM11-ASHCROFT, Japan) were also installed after the blower and before the cyclone to detect the inlet and outlet air moisture and pressure with an accuracy of 1% R.H. and 1 mbar, respectively. A human-machine interface (HMI: the model of MT-6070IE, Weintek) was applied to collect and monitor the measured data.

3.2. Experimental design

The main function in this study is to improve the drying of calcium carbonate in a spouted bed dryer and the side effect is the variation in the effective efficiency. The considered factors affecting the drying process are inlet air temperature, inlet air velocity, and dry solid mass. It should be noted that the initial moisture content, ambient temperature, and operator skill have been considered as noise factors in this study.

The quality characteristic (response) in this study is the effective efficiency because energy consumption is generally considered the most important parameter in all industrial processes. The effective efficiency is defined as the ratio of the power consumption to the total input power.

The whole input power during the process includes the blower and the heater powers:

$$P_{in,tot} = \dot{m}C_p(T_{out} - T_{in}) + \frac{\rho g Q \Delta P}{\eta} \tag{14}$$

The first term on the right side is the heater power which is consumed to increase the air temperature from the ambient temperature to the dryer inlet temperature, and the second term is the blower power. $\dot{m}$, C_p, ρ, Q, ΔP, and η are the mass flow rate of air (kg/s), specific heat capacity of air (kJ/kg.K), air density (kg/m^3), volumetric flow rate (m^3/s), dryer pressure drop (pa), and blower efficiency, respectively.

It should be noted that the specific heat capacity and density of the air are considered as dry air because of the low inlet humidity of the air (lower than 5%) and the use of the same inlet air in all experiments.

The amount of energy consumed to evaporate the moisture contained in the wet feed, considering a negligible final moisture content of the solid product, can be calculated as follows:

$$E_{ev} = m_s X_0 \lambda \tag{15}$$

where m_s, X_0 and λ are the mass of dry solid (g), initial moisture content on the dry basis (i.e., g water/g dry solid), and latent heat of vaporization of water at the dryer inlet temperature, respectively.

The amount of power consumed to evaporate moisture is obtained by dividing the evaporation energy to the drying time. Consequently, the effective efficiency can be expressed as follows:

$$\eta_{eff} = \frac{m_s X_0 \lambda / t}{\dot{m}C_p(T_{out} - T_{in}) + \rho g Q \Delta P / \eta} \tag{16}$$

Considering this definition for the effective efficiency, the quality characteristic is established as the maximum as the best. Therefore, the objective function is calculated by Eq. (1).

In order to determine levels, three or more levels should be selected if a factor has a nonlinear or dynamic relationship to the response variable [55]. The examined factors in the drying experiments were the inlet air temperature, inlet air velocity, and dry solid mass mentioned earlier. Before designing the experiments, three levels for each factor, low, medium, and high, are determined for conducting the experiments. The factors and their levels are summarized in Table 2.

Table 2. Factors and their levels for the drying experiments.

Factors	Levels		
	1	2	3
Inlet air temperature (°C)	90	100	110
Inlet air velocity (m/s)	1 U_{ms}	1.2 U_{ms}	1.5 U_{ms}
Dry solid mass (gr)	5	10	20

It should be mentioned that U_{ms} is the minimum spouting velocity which is determined by the Mathur and Epstein method (1974) [21] and its value is 6.06 m/s.

In the Taguchi method, the combination of factors is selected from the orthogonal array (OA). In this study, a L_9 (3^3) orthogonal array is selected which has nine rows and three “3 level” columns. Table 3 shows the required 9 experimental runs.

Table 3. Design of experiments using L_9 array.

Exp. No.	Parameters		
	Inlet air temperature (°C)	Inlet air velocity (m/s)	Dry solid mass (g)
1	90	6.06	5
2	90	7.20	10
3	90	9.00	20
4	100	6.06	10
5	100	7.20	20
6	100	9.00	5
7	110	6.06	20
8	110	7.20	5
9	110	9.00	10

3.2.1. Implementation of the experiments and data collection

Calcium carbonate particles were provided by the Local Corporation (Zagros Powder Co., Iran). Nine drying experimental runs were designed and carried out in a conventional spouted bed (Figure 1) at the selected factor levels according to the L_9 orthogonal array (as seen in Table 3).

In each experimental run, first the conical base of the spouted bed was filled with the glass beads to an initial static bed height of 115 mm. Afterward, the bed was preheated by the hot air at the specified temperature and flow rate for about 30 min. The inlet air temperature was maintained constant with an accuracy of ±1°C. After achievement of steady state conditions, the feed slurry (i.e., 30% w/w calcium carbonate solution) was fed at the top of the bed. During the drying experiments, the temperature and relative humidity of inlet and outlet air were measured and monitored every 0.5 s. The experimental run was terminated when the relative humidity of the outlet air becomes almost the same as the inlet air.

At the end of each experimental run, the glass bead particles were discharged from the bed in order to be washed with water and dried for the next run.

4. Results and discussion

In order to obtain the solid moisture content, the overall mass balance in the bed is used as follows:

$$m_s \frac{dX}{dt} = G_{in} \left(Y_{out} - Y_{in}\right) \tag{17}$$

where X, G_{in}, Y_{out}, and Y_{in} are the solid moisture content, mass flow rate of air, outlet and inlet air humidity, respectively.

So the moisture content at different times is calculated after integration of Eq. (17) as follows:

$$X = X_0 + \int_0^t \frac{G_{in}}{m_s} \left(Y_{out} - Y_{in}\right) dt \tag{18}$$

Relevant data such as the moisture content of air (Y) [56] and saturation vapor pressure of the air (P^{sat}) [57] were described using Eqs. (19) and (20), respectively.

$$Y = 0.62198 \frac{P^{sat}.RH}{P_a - P^{sat}.RH} \tag{19}$$

$$ln\left(\frac{P^{sat}}{P_c}\right) = \frac{T_c}{T} \left(C_1\vartheta + C_2\vartheta^{1.5} + C_3\vartheta^3 + C_4\vartheta^{3.5} + C_5\vartheta^4 + C_6\vartheta^{7.5}\right) \tag{20}$$

$$\vartheta = 1 - \frac{T}{T_c} \tag{21}$$

where RH, P_a, P_c, T_c, and C_i are the relative humidity of air, ambient pressure (mbar), critical pressure (220640 mbar), critical temperature (647.096 K), and coefficients, respectively.

The variation of the moisture content of calcium carbonate versus time in the spouted bed dryer during the 9 different drying experimental runs is shown in Figure 2.

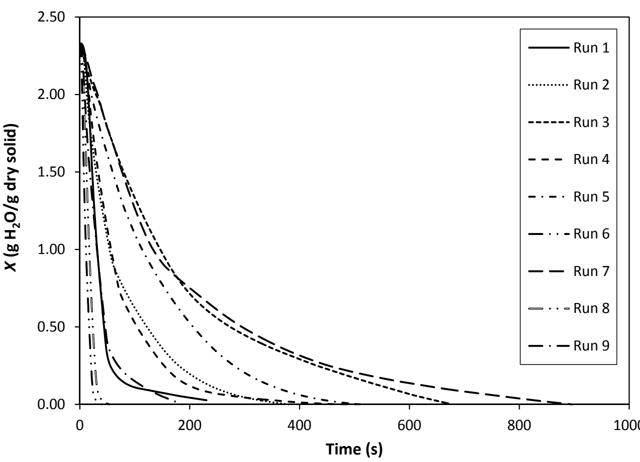


Fig. 2. Variation of moisture content versus drying time using Taguchi experiments

The observed values for drying time, the pressure drop of the dryer, the outlet temperature, and the measured value of effective efficiency are summarized in Table 4.

Table 4. Experimental results for L_9 orthogonal array.

Run	Drying time (s)	Pressure drop (mbar)	Outlet temperature (°C)	Effective efficiency (%)
1	230	0.073	41.1	8.670
2	380	0.101	43.1	7.778
3	667	0.148	44.8	5.818
4	518	0.072	45.6	6.979
5	511	0.099	45.7	10.630
6	40	0.151	54.5	22.504
7	896	0.074	46.6	7.269
8	53	0.106	53.2	22.874
9	186	0.152	57.6	8.946

The results of the analysis of variance (ANOVA) are summarized in Table 5.

Table 5. The ANOVA results.

Factor	DF	Adj SS	Adj MS	F-value
Inlet air temperature	2	66.95	33.475	4.15
Inlet air velocity	2	62.15	31.075	3.85
Dry solid mass	2	204.55	102.273	12.67
Error	2	16.14	8.071	
Total	8	349.79		

As can be observed, the dry solid mass is the main parameter affecting the effective efficiency in the dryer.

4.1. Data analysis and the optimal point determination

The target of the experimental design is to get the optimum parameters of drying by maximizing the effective efficiency using the Taguchi method; therefore, the larger effective efficiency the better type analysis was used in calculation of the S/N ratio. The average S/N ratios for the effective efficiency is shown in Figure 3. According to Figure 3, the highest S/N ratio values were computed when the drying conditions were at the inlet air temperature of 110 °C, inlet air velocity of 1.2 U_{ms}, and dry solid mass of 5 g. When the S/N ratio has the highest value, the corresponding factor level is close to the optimum. The optimum value for each factor was clearly detected from the linear plot. These optimum values for the calcium carbonate drying process are as follows: 100 °C for the inlet air temperature (level 2), 1.2 U_{ms} for the inlet air velocity (level 2) and 5 g for the dry solid mass (level 1).

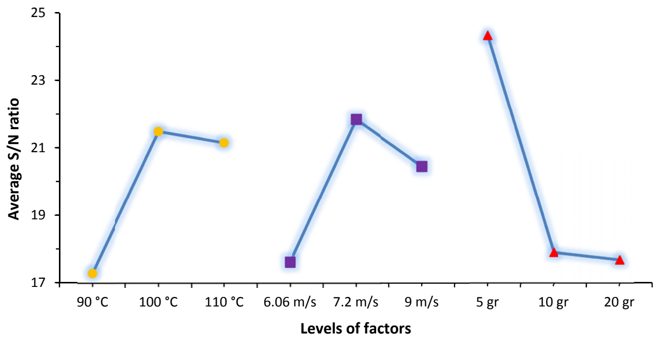


Fig. 3. Plots of factor effects.

4.2. Validation of the experiments

An experiment was carried out at the optimum values of the factors. The results of this experiment is shown in Table 6. As can be observed, the effective efficiency at the optimal point suggested by the Taguchi method is larger in comparison with other experimental runs (Table 4).

Table 6. Experimental results for the optimal point.

Drying time (s)	Pressure drop (mbar)	Outlet temperature (°C)	Effective efficiency (%)
54	0.101	48.4	24.949

The estimation of the response at the optimum condition based on the Taguchi method was 22.599 %. It should be noted that the prediction error is equal to 9.42 %.

4.3. Drying kinetics of calcium carbonate in the spouted bed dryer

The effect of air inlet velocity and temperature on the drying kinetics of calcium carbonate has been investigated. Drying experiments have been conducted at three different temperatures (90, 100 and 110 °C), and three different air inlet velocities (1, 1.2 and 1.5 times the minimum spouting velocity).

The trends of moisture content of calcium carbonate versus drying time at the different temperatures and different inlet air velocities are shown in Figures 4 and 5, respectively. As can be observed, an increase in the

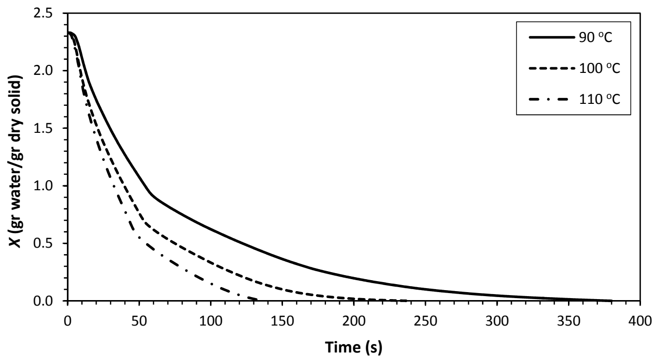


Fig. 4. Variation of moisture content versus drying time at different temperatures (gas velocity = 1.2 U_{ms}).

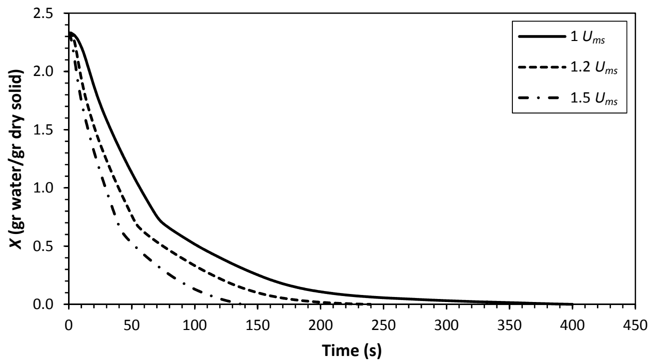


Fig. 5. Variation of moisture content versus drying time at different gas velocities (gas temperature = 100 ºC).

inlet air velocity and temperature results in a decrease in the drying time.

4.4. Performance of the fitted models

An attempt was made to fit the drying correlations introduced in Table 1 to the experimental data. Regression analysis was carried out to determine the values of the correlation parameters. Table 7 shows the values of the fitted parameters and the results of the statistical analysis. It should be mentioned that the experimental data was normalized and applied for the modeling.

As can be observed in Table 7, the logarithmic model with the lowest values of E_{RMS} and Chi-square (χ^2), and the highest value of determination of coefficient (R^2), shows the best fitting capability. Therefore, this model is selected as the best model of the drying kinetics of calcium carbonate in the spouted bed dryer.

The trends of estimated moisture ratio using the Logarithmic model versus drying time are shown in Figures 6 and 7.

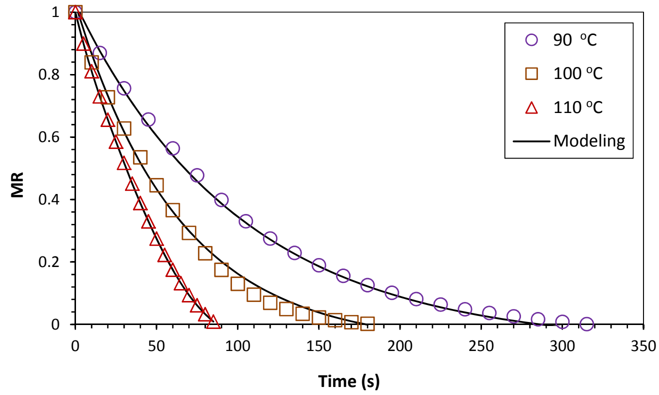


Fig. 6. Estimated moisture ratio by Logarithmic model versus drying time at different temperatures (gas velocity =1.2 U_{ms}).

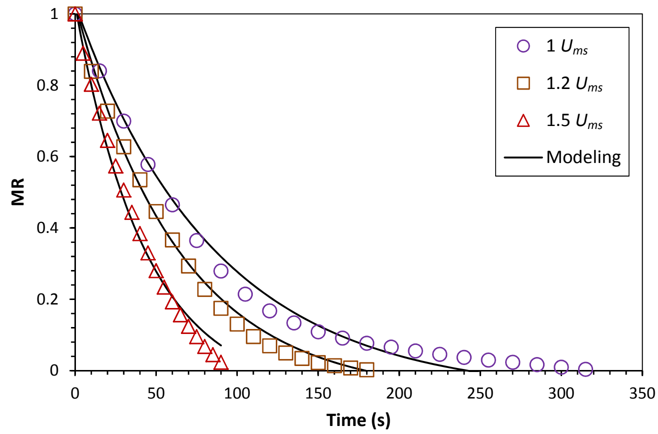


Fig. 7. Estimated moisture ratio by Logarithmic model versus drying time at different gas velocities (gas temperature =100 ºC).

5. Conclusion

In the present work, the optimization of calcium carbonate drying in a conventional spouted bed with inert particles was implemented using experiments designed based on the Taguchi method. Inlet air

Table 7. Statistical results and parameters of the examined drying models for calcium carbonate drying in the spouted bed dryer.

Model	k_0 (s^{-1})	m	E (J.mole^{-1})	n	a	b	R^2	E_{RMS}	χ^2
Lewis	9367.1	1.6278	50854.2	—	—	—	0.9839	0.0795	0.0014
Page	80997.0	2.0231	64990.2	1.2126	—	—	0.9943	0.0483	0.0005
Henderson and Pabis	10041.0	1.6378	50994.7	—	1.0459	—	0.9865	0.0727	0.0012
Logarithmic	12958.0	1.7454	52954.4	—	1.0917	-0.0669	0.9966	0.0114	0.0002
Bablay and Sahin	99196.0	2.0686	63996.2	1.2286	0.0098	-0.0103	0.9948	0.0460	0.0005

temperature, inlet air velocity, and dry solid mass were selected as the control factors. Effective efficiency was considered as the criterion to optimize the drying process. Effective efficiency was defined as the ratio of the total energy consumption for water evaporation to the total input energy.

According to the orthogonal array, 9 experiments were carried out. Signal to noise ratio analysis was used to find the influence of the control factors on the drying effective efficiency. Optimization of drying was performed using the "larger is the better" criterion. It was found that when the S/N ratio has the highest value the corresponding factor level is optimum. These optimum values for the calcium carbonate drying process were as follows: 100 °C for inlet air temperature, 1.2 U_{ms} for inlet air velocity, and 5 g of dry solid mass. An experiment was performed under the optimal conditions and the effective efficiency value was found to be 24.95%. It should be noted that this value was larger in comparison with the calculated efficiency of all previous experiments.

The effect of air temperature in the range of 90-110 °C and air velocity in the range of 1-1.5 times of the minimum spouting velocity (i.e., 6.06 m/s) were determined. According to the results, the moisture ratio of the calcium carbonate decreases exponentially with time. Moreover, a shorter drying time was obtained using a drying air temperature of 110 °C and an air velocity of 1.2 U_{ms}.

Several available drying models with temperature and velocity dependent constant were examined to estimate the drying kinetics of calcium carbonate in the falling rate period. The fitted models were compared on the basis of the coefficient of determination (R^2), root mean square error (E_{RMS}), and Chi-square. The coefficients of the models for each experimental run were calculated. Among the proposed models, the Logarithmic model was found to be the best one to describe the drying behavior of calcium carbonate.

References

[1] G. Zhu, H. Li, S. Li, X. Hou, D. Xu, R. Lin, Q. Tang, Crystallization behavior and kinetics of calcium carbonate in highly alkaline and supersaturated system, J. Cryst. Growth, 428 (2015) 16-23.

[2] T. Stirnimann, S. Atria, J. Schoelkopf, P.A. Gane, R. Alles, J. Huwyler, M. Puchkov, Compaction of functionalized calcium carbonate, a porous and crystalline microparticulate material with a lamellar surface, Int. J. Pharm. 466 (2014) 266-275.

[3] C. Bacher, P. Olsen, P. Bertelsen, J. Kristensen, J. Sonnergaard, Improving the compaction properties of roller compacted calcium carbonate, Int. J. Pharm. 342 (2007) 115-123.

[4] T. Paseephol, D.M. Small, F. Sherkat, Lactulose production from milk concentration permeate using calcium carbonate-based catalysts, Food Chem. 111 (2008) 283-290.

[5] H. Zhang, J. Chen, H. Zhou, G. Wang, J. Yun, Preparation of nano-sized precipitated calcium carbonate for PVC plastisol rheology modification, J. Mater. Sci. 21 (2002) 1305-1306.

[6] M. Di Lorenzo, M. Errico, M. Avella, Thermal and morphological characterization of poly (ethylene terephthalate)/calcium carbonate nanocomposites, J. Mater. Sci. 37 (2002) 2351-2358.

[7] J. Gullichsen, C-J. Fogelholm, Papermaking science and technology book 6A: chemical pulping, Finish Paper Engineers Association and TAPPI, Finland, 1999.

[8] C. Petersen, C. Heldmann, D. Johannsmann, Internal stresses during film formation of polymer latices, Langmuir, 15 (1999) 7745-7751.

[9] F. He, J. Zhang, F. Yang, J. Zhu, X. Tian, X. Chen, In vitro degradation and cell response of calcium carbonate composite ceramic in comparison with other synthetic bone substitute materials, Mater. Sci. Eng. C. 50 (2015) 257-265.

[10] L. Simão, R. Caldato, M. Innocentini, O. Montedo, Permeability of porous ceramic based on calcium carbonate as pore generating agent, Ceram. Int. 41 (2015) 4782-4788.

[11] C. Nover, H. Dillenburg, US Patent No. 0276897A1, (issued Dec. 15, 2005).

[12] J.B. Foster, EP Patent No. 1790616A1, (issued May 30, 2007).

[13] J.B. Foster, EP Patent No. 1790616B1, (issued Mar. 9, 2011).

[14] S. Teir, S. Eloneva, R. Zevenhoven, Production of precipitated calcium carbonate from calcium silicates and carbon dioxide, Energ. Convers. Manage. 46 (2005) 2954-2979.

[15] T. Vehmas, U. Kanerva, E. Holt, Spray-dry agglomerated nanoparticles in ordinary portland cement matrix, Mater. Sci. Appl. 5 (2014) 837-844.

[16] M. Markowski, I. Białobrzewski, A. Modrzewska, Kinetics of spouted-bed drying of barley: Diffusivities for sphere and ellipsoid, J. Food Eng. 96 (2010) 380-387.

[17] N. Epstein, J.R. Grace, Spouted and spout-fluid beds: fundamentals and applications, Cambridge University Press, 2010.

[18] A.D.A. Araújo, R.M. Coelho, C.P.M. Fontes, A.R.A. Silva, J.M.C. da Costa, S. Rodrigues, Production and spouted bed drying of acerola juice containing oligosaccharides, Food Bioprod. Process. 94 (2015) 565-571.

[19] Z.L. Arsenijević, Z.B. Grbavcić, R.V. Garić-Grulović, Drying of suspensions in the draft tube spouted bed, Can. J. Chem. Eng. 82 (2004) 450-464.

[20] S. Tia, C. Tangsatitkulchai, P. Dumronglaohapun, Continuous drying of slurry in a jet spouted bed, Drying Technol. 13 (1995) 1825-1840.

[21] K. Mathur, N. Epstein, Spouted Beds, Academic Press, New York, 1974.

[22] F.G. Cunha, K.G. Santos, C.H. Ataíde, N. Epstein, M.A. Barrozo, Annatto powder production in a spouted bed: an experimental and CFD study, Ind. Eng. Chem. Res. 48 (2008) 976-982.

[23] Z.B. Grbavcic, Z.L. Arsenijevic, R.V. Garic-Grulovic, Drying of slurries in fluidized bed of inert particles, Drying Technol. 22 (2004) 1793-1812.

[24] M. Passos, A. Mujumdar, Effect of cohesive forces on fluidized and spouted beds of wet particles, Powder Technol. 110 (2000) 222-238.

[25] M. Passos, G. Massarani, J. Freire, and A. Mujumdar, Drying of pastes in spouted beds of inert particles: Design criteria and modeling, Drying Technol. 15 (1997) 605-624.

[26] T. Kudra, A.S. Mujumdar, Advanced drying technologies, Second Ed. CRC press, 2009.

[27] T. Schneider, J. Bridgwater, The stability of wet spouted beds, Drying Technol. 11 (1993) 277-301.

[28] Q. Guo, S. Hikida, Y. Takahashi, N. Nakagawa, K. Kato, Drying of microparticle slurry and salt-water solution by a powder-particle spouted bed, J. Chem. Eng. Jpn. 29 (1996) 152-158.

[29] T. Nakazato, Y. Liu, K. Sato, K. Kato, Semi-dry process for production of very fine calcium carbonate powder by a powder-particle spouted bed, J. Chem. Eng. Jpn. 35 (2002) 409-414.

[30] M. Benali M. Amazouz, Effect of drying aid agents on processing of sticky materials, Dev. Chem. Eng. Min. Process. 10 (2002) 401-414.

[31] Z.L. Arsenijević, Ž.B. Grbavčić, R.V. Garić-Grulović, Prediction of the particle circulation rate in a draft tube spouted bed suspension dryer, J. Serb. Chem. Soc. 71 (2006) 401-412.

[32] Z.L. Arsenijević, Ž.B. Grbavčić, R.V. Garić-Grulović, Drying of solutions and suspensions in the modified spouted bed with draft tube, J. Therm. Sci. 6 (2002) 47-70.

[33] A. Almeida, F. Freire, J. Freire, Transient analysis of pasty material drying in a spouted bed of inert particles, Dry. Technol. 28 (2010) 330-340.

[34] S.M. Tasirin, S.K. Kamarudin, J.A. Ghani, K. Lee, Optimization of drying parameters of bird's eye chilli in a fluidized bed dryer, J. Food Eng. 80 (2007) 695-700.

[35] R. Moreno, G. Antolín, A. Reyes, Thermal behaviour of forest biomass drying in a mechanically agitated fluidized bed, Lat. Am. Appl. Res. 37 (2007) 105-113.

[36] K. Uday, J. Prathyusha, D. Singh, P. Apte, Application of the Taguchi method in establishing criticality of parameters that influence cracking characteristics of fine-grained soils, Dry. Technol. 33 (2015) 1138-1149.

[37] S.K. Karna, R. Sahai, An overview on Taguchi method, Int. J. Eng. Math. Sci. 1 (2012) 1-7.

[38] S.M. Tasirin, I. Puspasari, L.J. Xing, Z. Yaakob, J.A. Ghani, Energy optimization of fluidized bed drying of orange peel using Taguchi method, World Appl. Sci. J. 26 (2013) 1602-1609.

[39] S. Athreya, Y. Venkatesh, Application of Taguchi method for optimization of process parameters in improving the surface roughness of lathe facing operation, Int. Ref. J. Eng. Sci. 1 (2012) 13-19.

[40] H.-H. Chen, C.-C. Chung, H.-Y. Wang, T.-C. Huang, Application of Taguchi method to optimize extracted ginger oil in different drying conditions, IPCBEE May, 9 (2011) 310-316.

[41] J. López-Cacho, P.L. González-R, B. Talero, A. Rabasco, M. González-Rodríguez, Robust optimization of alginate-carbopol 940 bead formulations, Sci. World J. (2012) 1-15, Article ID 605610.

[42] M. Perea-Flores, V. Garibay-Febles, J.J. Chanona-Perez, G. Calderon-Dominguez, J.V. Mendez-Mendez, E. Palacios-González, G.F. Gutierrez-Lopez, Mathematical modelling of castor oil seeds (*Ricinus communis*) drying kinetics in fluidized bed at high

temperatures, Ind. Crops Prod. 38 (2012) 64-71.

[43] E.K. Akpinar, Determination of suitable thin layer drying curve model for some vegetables and fruits, J. Food Eng. 73 (2006) 75-84.

[44] S. Azzouz, A. Guizani, W. Jomaa, A. Belghith, Moisture diffusivity and drying kinetic equation of convective drying of grapes, J. Food Eng. 55 (2002) 323-330.

[45] W.K. Lewis, The rate of drying of solid materials, Ind. Eng. Chem. 13 (1921) 427-432.

[46] G.E. Page, Factors influencing the maximum rates of air drying shelled corn in thin layers, M.Sc. Thesis, Purdue University, West Lafayette, 1949.

[47] S. Hendreson, S. Pabis, Grain drying theory. I. Temperature effect on drying coefficients, J. Agr. Eng. Res. 6 (1961) 169-174.

[48] A. Yagcioglu, Drying characteristic of laurel leaves under different conditions, In: A. Bascetincelik (ED.), Proceedings of the 7th International Congress on Agricultural Mechanization and Energy, Adana, Turkey, (1999) 565-569.

[49] A. Balbay, Ö. Şahin, Microwave drying kinetics of a thin-layer liquorice root, Dry. Technol. 30 (2012) 859-864.

[50] G. Dadalı, D. Kılıç Apar, B. Özbek, Microwave drying kinetics of okra, Dry. Technol. 25 (2007) 917-924.

[51] O. Yaldýz, C. Ertekýn, Thin layer solar drying of some vegetables, Dry. Technol. 19 (2001) 583-597.

[52] A. Magalhães, C. Pinho, Spouted bed drying of cork stoppers, Chem. Eng. Process. Process Intensif., 47 (2008) 2395-2401.

[53] J.C. Lagarias, J.A. Reeds, M.H. Wright, P.E. Wright, Convergence properties of the Nelder-Mead simplex method in low dimensions, SIAM J. Optim. 9 (1998) 112-147.

[54] J. Stoer, R. Bulirsch, Introduction to numerical analysis, Second Ed., Springer-Verlag New York, 2013.

[55] M. Satter, Optimization of copra drying factors by Taguchi method, 4th International Conference on Mechanical Engineering, Dhaka, Bangladesh (ICME2001) (2001) III 23-27.

[56] A.S. Mujumdar, Principles, classification, and selection of dryers, Handbook of Industrial Drying, Fourth Ed, CRC Press, 2014.

[57] W. Wagner, A. Pruß, The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use, J. Phys. Chem. Ref. Data. 31 (2002) 387-535.