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Optimum energy requirement of fluidized bed dryer for drying of *Khoa*

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Abstract
Drying is an important as well as most energy intensive unit operation in process industry. Drying optimization leads to same quality with minimum energy wastes. Fluidized bed drying is most acceptable process in-terms of final quality of dried product. Compare to other drying process, fluidized bed drying process yield brighter colour, lower moisture content with low temperature in less time. This paper focuses on energy requirement per kg of product, per kg of moisture removed with different values of batch size, air velocity and air temperature. It also concluded the optimum combination of trio.

Keywords: Fluidized Bed Dryer; Energy Requirement; Air Velocity; Air Temperature; Batch Size; Dried *Khoa*

1. Introduction

Indian farmers have led to extravagant achievement by making India world leader in milk production. Milk production in the country is expected to increase at a rate of 4% and it will reach to 127.29 MT. For preparing delicious sweets & preservation of nutritious milk solids, various products from surplus milk are manufactured and one of the best method for preserving this milk solid which is followed all over the world is drying. Drying of milk and milk products is considered to be the best way to preserve the milk solids. It reduces water activity and thus slows down the deterioration in quality. In the chemical, pharmaceutical and food processing industries drying of solutions, suspensions and pastes is an important unit operation. It is the most energy consuming industrial operation. The trends in drying technology are associated with higher energy efficiency, enhanced drying rates, development of more compact dryers, better control for enhanced quality, optimal capacity, developments of multi-processing units etc. Numerous new or improved drying technologies are currently at various stages of development like tray dryers and drum dryers. But these process were more energy intensive and the powder quality was not up to the mark. Also, the most prevalent method which is still ruling the dairy industry is the spray drying. The quality of product obtained, in spray drying, is well appreciated. With the time many advances were made in the process of drying as well as the automation and control of the dryer systems. The advances include wet scrubbers, pneumatic atomizers, bag filters more recently CIP'able bag filters, swirl nozzles, Lenient steam injection (LSI) system, multistage dryers, integrated fluid bed dryers and so on (Hauberg and Krag, 1976; Pisecky, 1985; Refstrup, 2000) [1-3].

There are many and varied requirements for thermal drying of foods throughout the food processing industries. Some involves the removal of moisture or volatiles from various food ingredients or products that differ in both chemical and physical characteristic. Others involve the drying of solutions or liquid suspensions for different approaches to the problem. Three basic methods of heat transfer are used in various types of industrial dryers in varying degrees of prominence and combinations, specifically, convection, conduction and radiation. In present research fluidized bed dryer has been used for drying of *Khoa*. There are a number of reports published for studying the use of fluidized bed dryers in various field. But there are no reports on commercial adaptation of the process for drying of *Khoa*. But definitely, great opportunity lies in use of fluidized bed. So this study is planned to assess the feasibility of fluidized bed dryer with hot air for drying of above products. With the few of reports of successful application of the technology, definitely it is worth studying extensively. Some of the research have shown successful results for drying of Peanuts, Potato chips, casein etc. But its feasibility for dairy industry is still to be demonstrated.

Once the feasibility and advantages of the dryer,for drying of *Khoa* is established, large-scale developments in control and modification according to the product needs can be planned. Thus study regarding performance of the dryer for drying of *Khoa* would help in opening extensive research opportunities in this direction. The versatility of the dryer can be very useful to match the various product needed in a single unit. So the fluidized bed dryer can be used for vegetables (Carrot, Potato) as well as food products (Casein, Tofu).

2. Materials and Methods

2.1 Drying of Foods

Drying commonly describes the process of thermally removing volatile substances (moisture) to yield a solid product. Moisture held in loose chemical combination, present as a liquid solution within the solid or even trapped in the microstructure of the solid, which exerts a vapour pressure less than that of pure liquid is called bound moisture. Moisture in excess of bound moisture is called unbound moisture. When a wet solid is subjected to thermal drying, two processes occur simultaneously:

- Transfer of energy (mostly as heat) from the surrounding environment to evaporate the surface moisture.
- Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to process

2.2 Fluidized bed drying

Batch type fluidized bed drying is one of the most used and successful methods in food, pharmaceutical and chemical industries due to its higher efficiency. When compared with other conventional drying systems, fluidized bed dryer has shorter drying time due to high thermal efficiency and having higher drying capacity. High thermal efficiency and higher drying capacity are the most important advantages of fluidized bed dryers (Emrah and Hacimurat, 2005) [8]. Swanson (1971) [9] reported that compared to the conventional tray method, the fluidized bed method shortens the time required for drying grated Italian cheese. Makarov *et al*., (1972) [10] discussed the use of ultrasonics acoustic vibrations to accelerate the rate of lactose drying in a fluidized bed dryer. Ultrasonic waves with 5000-15000 hz, produced by sirens operating at less than or equal to 7 kg/cm^2 air pressure and less than or equal to 160 dB used in an experimental fluidized bed drier, reduced the time required for drying lactose of 18% moisture content from nearly 80 to 30 min with air at 50 ^{0}C temperature and 1.4 m/s flow. Bentzien (1981) [6] suggested improvements in the rotating disk fluidized-bed drier to facilitate salvage of the product particles as cheese. Tesch and Lavallee (1982) [7] described particle injection system for a fluid bed drier and observed that the particles are immediately surrounded by and suspended in the drying air and do not tend to stick together. This is particularly important for such products as cheese and yeast, which readily agglomerate into lumps. Mukundrao (2006) [5] developed and evaluated performance of inert spouted bed dryer. Energy analysis of the drier was carried out and observed following parameters like thermal efficiency (48.56 – 81.09%), overall volumetric heat transfer coefficient (3.37-8.34 kW/m^{3}K), specific energy consumption (5.839-12.217 MJ/kg), surface heat transfer coefficient (0.0027 – 0.0067 kW/m^{2}K). Wachiraphansakul and Devahastin (2005) [4] investigated experimentally the effects of various drying parameters. Those were inlet air velocity, inlet air temperature, initial bed height and heating duration. The study was on both the drying kinetics and various quality attributes of dried okara viz. percentage changes of the total protein content, color, urease index, as well as the specific energy consumption during drying in a jet spouted bed dryer. Based on the quality and energy consumption the selected drying conditions were those using all drying parameters at their highest levels (air velocity -1.5 m/s, bed height -18 cm, and inlet air temperature – 130 ^{0}C); these conditions yielded the specific energy consumption of 3.69 MJ/kg evaporated water.

2.3 Experimental set-up and procedure for Fluidized bed dryer

The fluidized bed dryer unit used for the research work, consists of the following system components.

1. Damper (outlet air regulator);
2. Electric motor;
3. Blower;
4. Fluidized bed column;
5. Sight glass;
6. Drying chamber;
7. Electric heater;
8. Air filter;
9. Power analyzer;
10. Control panel;
11. Thermocouple;

Figure 1. Illustrating the schematic diagram of fluidized bed dryer with label, which was used in this experiments the components are as follow:

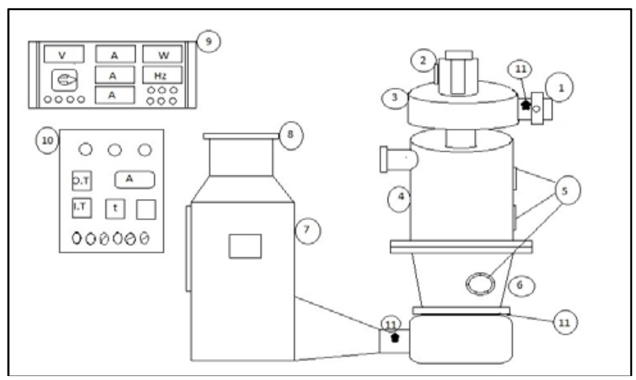

Fig 3.1: Schematic diagram of fluidized bed dryer

Over view of procedure to perform drying with fluidized bed dryer is:

- Manually shredded mass of *Khoa* was kept in drying chamber on perforated plate.
- Turn on blower and then air heater.
- Note down the initial reading of air temperature (thermocouples), air velocity (anemometer), air humidity (hair hygrometer), energy reading from energy meter etc,.
- Now wait for constant reading of outlet air temperature and air humidity for at least two consecutive reading.

2.4 Specific Energy (E_s)

An alternative measure of dryer efficiency is the specific energy consumption (E_s), which is defined as the heat input to the dryer (Q_h) per unit mass of water evaporated. For convective dryers the heat input is given as the power supplied to the heater, so

$$E_s = \frac{Q_h}{W_{ev}}$$

Where, W_{ev} is the water evaporated.

2.5 Production Efficiency (η_{Po})
Production efficiency of single pass convective batch dryer is calculated as:

$$\eta_{po} = \frac{M_{po} x (1-X_{po})}{M_{paste} x (1-X_{paste})} X\ 100$$

Where, M_{po} and M_{paste} are final weight and initial weight respectively. X_{po} and X_{paste} are moisture contents of final and raw product respectively. (Strumillo *et al.*, 2007)

2.6 Energy Efficiency (η_E)
The energy efficiency (η) relates the energy used for moisture evaporation at feed temperature to total energy supplied to dryer.

$$\eta_E = \frac{E_{ev}}{E_t}$$

Where, E_{ev} Calculated from the mass of water evaporated water and the latent heat of vaporization. (Strumillo *et al.*, 2007)

2.7 Thermal Efficiency (η_T)
For low humidity and low temperature convective drying, the energy efficiency can be approximated by the thermal efficiency (η_T) that is based on the inlet air temperature (T_1), the outlet air temperature (T_2) and the ambient temperature (T_a) (Strumillo *et al.*, 2007):

$$\eta_T = \frac{T_1 - T_2}{T_1 - T_a}$$

2.8 Statistical Calculation
To analyse the data obtained from experiment, Response Surface Method (RSM) was used and for that 20 different numbers of combinations were performed and are followed.

Table 1: Combination of three parameters to perform experiment

Khoa			
Run Order	**Quantity (g)**	**Air Velocity (m/s)**	**Inlet air Temp. (ºC)**
1	1250	15	60
2	1250	15	60
3	1000	7	50
4	829.6	15	60
5	1500	23	50
6	1250	28.5	60
7	1500	7	70
8	1000	23	50
9	1500	7	50
10	1670.4	15	60
11	1250	15	60
12	1250	15	76.8
13	1000	7	70
14	1250	15	60
15	1250	15	60
16	1250	15	60
17	1000	23	70
18	1500	23	70
19	1250	1.5	60
20	1250	15	43.2

3. Results and Discussions
Energy is a major consideration for any drying process, about 10 -12% of total energy is being used only for drying process of any industry. Table 2 shows energy requirement on the basis of initial product, final product and moisture removed are tabulated. The quadratic model for energy requirement was obtained through successive regression analysis. The model F values for ER/FP and ER/MO for drying of *Khoa* were 18.07 and 18.74 respectively. The calculated F values greater than the Table F values at 5 per cent level of confidence has indicated the significance of model terms. Furthermore, the coefficient of determination (R^2) which reflects the proportion of variability in data explained or accounted by the model for ER/FP and ER/MO for drying of *Khoa* were 0.942 and 0.944 respectively.

Table 2: Energy values for drying of *Khoa*

Run Order	ER/FP (kWh/kg)	ER/MO (kWh/kg)
1	1.84	2.86
2	1.58	2.45
3	2.22	3.78
4	3.88	6.36
5	2.15	3.51
6	1.55	2.53
7	1.27	2.16
8	2.26	3.68
9	1.93	3.16
10	1.35	2.22
11	2.08	3.33
12	1.79	2.98
13	3.41	6.19
14	1.31	2.06
15	1.84	2.86
16	1.56	2.47
17	3.52	5.87
18	1.08	1.74
19	1.56	2.5
20	1.79	2.98

Where,
ER/RP: Energy requirement per kg of initial product
ER/FP: Energy requirement per kg of final product
ER/MO: Energy requirement per kg of moisture removed

Lowest value of ER/FP and ER/MO were observed in treatment number 18 (1500 g batch size, 23 m/s air velocity and 70 ºC inlet air temperature). Treatment number 4 had highest values of 2.41 kWh/kg for ER/RP, 3.88 kWh/kg for ER/FP and 6.36 kWh/kg for ER/MO.

Table 3: Coefficients of Selected Models for drying of *Khoa*

Response	Suggested Model	Intercept	Model F Value	Adequate Precision	R2
ER/FP	Quadratic	1.70	18.07	16.29	0.942
ER/MO	Quadratic	2.66	18.74	16.11	0.944

A larger R^2 value approaching to 1.0 suggests a better fit of the quadratic model. The adequate precision value be greater than 4.0. In the present study, the adequate precision value for ER/FP and ER/MO for drying of *Khoa* were 16.29 and 16.11 respectively, which were greater than 4, highlighting the suitability of the model to navigate the design.

3.1. Energy requirement per kg moisture removed
Energy requirement for unit moisture removed for drying of *Khoa* for different treatments are shown in Table 2. Lowest value of ER/MO (kWh/kg) was 1.74 kWh/kg for treatment of 1500 g batch size, 23 m/s air velocity and 70 ºC, whereas 829.55 g batch size, 15 m/s air velocity and 60 ºC had highest value 6.36 ER/MO (kWh/kg).

Table 3: Partial Coefficients of Regression Equations of Suggested Models for drying of *Khoa*

Factors		ER/FP		ER/MO	
		P Value	Partial Coefficient	P Value	Partial Coefficient
Model		< 0.0001**	1.69	< 0.0001**	2.66
Linear Level	A	< 0.0001**	-0.68	< 0.0001**	-1.167
	B	0.8	0.01	0.7835	-0.03
	C	0.46	0.05	0.2857	0.13
Interactive Effect	A x B	0.87	-0.015	0.7791	0.04
	A x C	0.0002	-0.52	0.0001**	-0.92
	B x C	0.656	-0.04	0.4373	-0.13
Quadratic Level	A^2	0.0003	0.37	0.0002	0.67
	B^2	0.9406	-0.005	0.7228	0.04
	C^2	0.2589	0.08	0.1041	0.21

*Significant at 5% level (P<0.05); **Significant at 1% level (P<0.01)
A= Batch size; B=Air velocity; C= Inlet air temperature;

The value of R^2 was 0.944 and adequate precision value was 16.11. Multiple regression equation to predict ER/MO for drying of *Khoa* affected by different factors in terms of coded factors is as follows:

$$\text{ER/MO (kWh/kg)} = 3.5-9.7\times10^{-3}A+0.04B+0.25C +2.24\times10^{-5}AB-3.7\times10^{-4}AC-1.5\times10^{-3}BC +1.1\times10^{-5}A^2+6.6\times10^{-4}B^2+2.1\times10^{-3}C^2$$

Where,
A, B, and C are referred to batch size, air velocity and inlet air temperature respectively.
Fig 2, Fig 3 and Fig 4 show the graphical presentation of effect of factors on ER/MO for drying of *Khoa*.

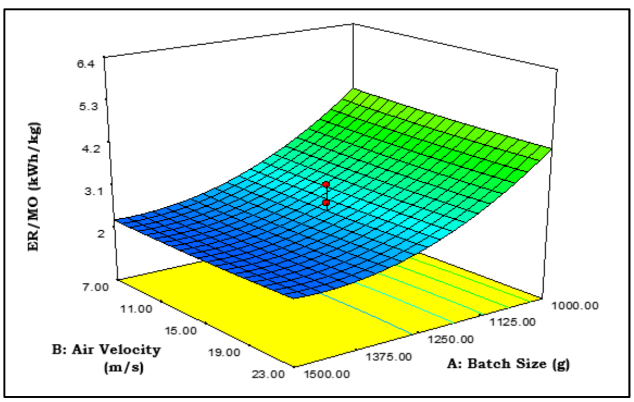

Fig 2: Response surface of ER/MO (kWh/kg) for drying of ***Khoa*** as influenced by air velocity and batch size

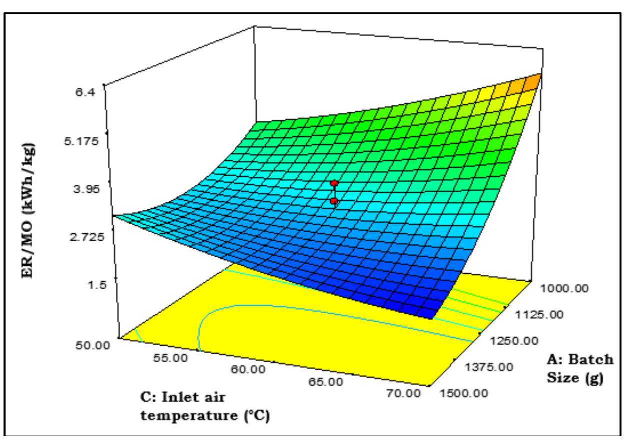

Fig 3: Response surface of ER/MO (kWh/kg) for drying of *Khoa* as influenced by inlet air temperature and batch size

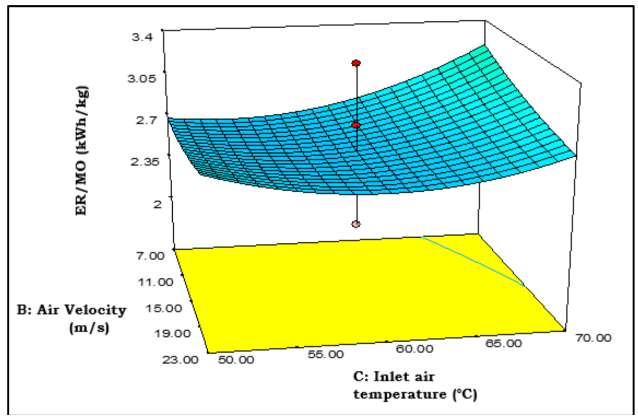

Fig 4: Response surface of ER/MO (kWh/kg) for drying of ***Khoa*** as influenced by air velocity and inlet air temperature.

A significant (P<.01) negative effect on energy requirement per kg of moisture removed (ER/MO (kWh/kg))for drying of *Khoa* was observed with batch size and non-significant positive effect of inlet air temperature and negative effect of air velocity was observed on ER/MO (kWh/kg) for drying of *Khoa*. Batch size and air velocity has effected negatively on ER/MO (kWh/kg) means decrease in both values resulted into higher (increased) ER/MO (Fig 4.2). Fig 4.3 shows the combined negative effect of both factors on ER/MO, decrease in both values has increased ER/MO (kWh/kg). Fig 4 has indicated opposite combined effect of air velocity and inlet air temperature on ER/MO, in other words decrease in air velocity and increase in inlet air temperature resulted in to increased ER/MO (kWh/kg) for drying of *Khoa*. Baker and McKenzie in 2005 found ER/MO (kWh/kg) between 0.8 and 5.5 kWh/kg (3 GJ/t to 20 GJ/t) for spray dryer. Here ER/MO value ranged between 1.7 and 6.36 kWh/kg for energy required to remove 1 kg of moisture.

Optimization

Optimization was done with an objective of determining the best possible combination of inlet air temperature, batch size and air velocity that would lead to the most acceptable product in terms energy efficiency. The goals that were set for obtaining the best combination are shown in Table 4. The data were analysed in Design Expert Package. Considering the constraints and their limits, the RSM has suggested the one most suitable solution.

Table 4: Process optimization criteria for drying of ***Khoa***:

Sr. No	Constraints	Goal	Lower Limit	Upper limit
1	Batch Size (g)	In range	1000	1500
2	Air velocity (m/s)	In range	7	23
3	Inlet air temperature (ºC)	In range	50	70
4	ER/FP (kWh/kg)	Minimize	1.08	3.88
5	ER/MO kWh/kg)	Minimize	1.74	6.36
6	Moisture (%)	Minimize	5.27	7

Table 5: Optimized process solution for drying of ***Khoa:***

Solution No	Solutions			Desirability
	Batch Size	Air Velocity	Inlet Air Temp.	
1	1464.16	12.97	70	0.882

Based on data of energy requirement for drying of *Khoa* with different combinations the lowest possible energy requirement would be a solution from Response Surface Methodology.

Summary and Conclusions

Batch fluidized bed drying is one of the most successfully used methods in food, pharmaceutical and chemical industries due to its higher efficiency. For this reason, many studies in lab and industry-scales are continued on fluidized bed drying concept for improvements of their performance characteristics. Drying of heat desiccated product (*Khoa*) was performed in this experiment. Energy requirement per kg of moisture removed (ER/MO kWh/kg) for drying of *Khoa* in un-optimized treatment was between 1.74 kWh/kg and 6.36 kWh/kg. ER/MO was lower down to the 1.58 kWh/kg for optimized treatment.

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