Study of Granular Food Material Drying in a Pilot-Scale Rotating Fluidized Bed with Static Geometry Dryer

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Abstract A rotating fluidized bed with static geometry (RFB-SG) drying is a promising technique that is useful for various operations, such as agglomeration, food grain drying, particle coating, separation, and combustion. The advantage of this technique is that a large volume of hot air is circulated across the particles in a very small geometry, which results in higher heat and mass transfer. The higher heat and mass transfer through the RFB-SG dryer makes the drying process faster. Initially, the high-velocity air is injected into the vortex chamber through multi-air inlets, and then the solid particles are inserted into the vortex chamber. The high-velocity air injected into the reactor forces the solid particle to rotate in the form of a solid bed. The air entering into the vortex chamber carries away the moisture of food grains via a centrally located chimney outlet. In the present work, performance of scaled-up RFB-SG dryer has been evaluated considering parameters, such as temperature (55–65 °C), airflow rate (600–800 m^3/h), inventory (400–1000 g), and drying time. The RFB-SG dryer is found to be more efficient than the conventional fluidized bed (CFB) dryers as this dryer works on a higher airflow rate. Drying efficiency is improved by better utilization of the drying air at a temperature of 65 °C.

Keywords RFB-SG · Drying · Fluidization · Inventory

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Nomenclature

A	Cross-sectional area (cm^2)
C_D	Drag coefficient
D	Diameter of the vortex chamber (cm)
d_p	Particle mean diameter (m)
g	Acceleration due to gravity (m/s^2)
H	Height of the vortex chamber (cm)
I	Solid inventory (g)
k	Thermal conductivity (W/m °C)
n	Number of slots
T_a	Temperature of fluidization air (°C)
T_o	Ambient temperature (°C)
v_a	Velocity of the fluidizing air (m/s)
X_{initl}	Initial moisture content (kg water/kg dry paddy)
X_{req}	Required moisture content (kg water/kg dry paddy)

Subscripts

a	Air
i	Inlet
o	Ambient
p	Particle

Greek letters

β	Interphase momentum transfer coefficient (Ns/m^4)
ρ_g	Density of dry gas (kg/m^3)
ρ_s	Density of solid ((kg/m^3)
λ	Force ratio
φ	Angle of initial fraction
θ	Injection angle (°)

1 Introduction

More than half of the world population depends upon staple food source rice, and it is obtained from the post-harvesting process of paddy. An important process of drying is required to preserve nutrients of food grains and reduction of their losses.

Nygaard and Pellett [1] reported that the food grain losses in the post-harvesting process and the drying operation were found 10% and 1–5%, respectively. In order to reduce the food grain losses in improper drying operations, a promising technique of rotating fluidized bed with static geometry dryer is used in the present study. This drying technique is applicable in multiple operations, such as mixing, separation, agglomeration, particle coating, and rapid drying of granular materials. The most important feature of this dryer is its static reactor due to which the cyclic maintenance is almost negligible compared to conventional dryers. Various researches have been carried out on granular drying by using conventional and non-conventional methods. Drying is a process of moisture removal in which the moisture available in food grains is reduced to achieve its safe moisture (MC) level, such that the percentage of MC in paddy is maintained at 13–14% (WB) [2]. Mujumdar [3] stated that by reducing the percentage of moisture content in paddy, the possibilities of fungus, pests, germs, and the growth of biological activities were reduced. Conventional fluidized bed dryers are of two types, such as direct and indirect dryers. In the direct drying methodology, heat is directly exposed to the food grains surfaces, while the indirect drying method involves heat transfer through the heat exchanger wall. Sreekumar et al. [4] developed a solar energy-based forced convection dryer and has successfully conducted drying operations using paddy. Syahrul et al. [5] stated that paddy drying is successfully carried out at a commonly maintained temperature from 55 to 65 °C. They reported that air temperature beyond 65 °C affects the texture of the paddy and its nutritional value. The air is the most commonly used medium in the drying process, but heat can also be supplied by superheated steam, while the commercial application of steam is limited due to high cost and technology complexity [3, 6, 7]. To reduce energy consumption in drying operations, farmers use solar energy, biomass energy, or both types of energy sources [8]. However, conventional fluidized beds (CFBs) have salient features such as excellent heat and mass transfer characteristics [9]. Nevertheless, gas–solid slip velocities bound the process intensification and gas flow at high gas velocities. The width of the solid bed limits the specific gas flow rate per unit mass to its height, which is comparatively low in CFB and RFB, these limitations being due to the Earth's gravitational effect [10]. Quevedo [11] developed a rotating fluidized bed in dynamic geometry and successfully conducted an agglomeration process on it. De Wilde and de Broqueville [12] have given a proof of concept of a rotating fluidized bed with static geometry (RFB-SG) in which all the drawbacks of a rotating fluidized bed with dynamic geometry were eliminated. In this reactor, a rotating solid bed is formed by injecting gas–solids through several gas inlets. The solid particles start moving in the reactor, and the radial outward centrifugal force was experienced due to the effect of the tangent gas–solid drag force. The guidelines for the design of the reactor are given by [13, 14]. Pati et al. [15] have done comparative studies of paddy drying in a bubbling fluidized bed (BFB) and RFB-SG reactor and reported that the RFB-SG dryer was faster than the BFB dryer due to higher process intensity. Singh et al. [16] have developed the RFB-SG dryer for agricultural product drying and reported that both the drying capacity of the reactor and drying efficiency was improved. An experimental study of large cardamom drying has been conducted in traditional Bhatti of the Phu-Joram village farmers in Arunachal Pradesh. Also, they found that the annual cultivation of cardamom can be increased using a scientific approach and technical methods [17]. The thermal study of a natural convection dryer was conducted experimentally, and it was reported that the air heat rating increased and heat loss was reduced using sensible heat storage material in the rectangular chamber of the dryer [18].

In the present work, the performance of a scale-up RFB-SG drying chamber using a staple food paddy has been experimentally evaluated. Experiments were carried out on the developed reactor to investigate the effects of various parameters on drying time, such as air temperature, airflow rate, and inventory. The developed RFB-SG chamber dimensions such as the internal diameter of the chamber, the length of the chamber, the width of the slot, and the number of air inlets are 480, 65, 2.5, and 72 mm, respectively.

2 Experimental Setup and Procedure

2.1 Design of Air Inlet

air inlet slots are designed to meet various airflow rate requirements considering various parameters of the reactor, such as chamber diameter, a width of the slot, and number of slots. Based on an essential factor λ (or force ration) given by Kochetov et al. [13] is employed in the present design. This factor λ (force ratio) varies from 0.025 to 0.038 and can be written as;

$$\text{Force ratio, } \lambda = \frac{\text{Centrifugal force}}{\text{Drag force}} = \frac{n.s}{\pi.D} \tag{1}$$

where n, s, and D are the number of gas slots, slot width, and vortex chamber diameter, respectively.

Figure 1 shows the schematic diagram of the scale-up RFB-SG drying chamber used in paddy drying operation. Various elements of this dryer, such as centrifugal blower, coupling, airflow control valve, air bypass valve, manometer, orifice plate, air heating chamber, rheostat, air distribution unit, air inlet, solid inlet, solid outlet, solid bed region, and freeboard region have been listed systematically. Initially, the air flowing through the centrifugal blower is heated in the air heating chamber, and this conditioned air is injected through the multi-air inlet into the vortex chamber in the tangential direction of the chamber periphery. The inlet air injected into the reactor creates an air vortex and then feeds food grains (paddy) into the reactor using a high-pressure air compressor. High-velocity air causes solid particles to rotate in the form of a rotating solid bed. The moisture available in the food grains is evaporated by hot air and is thrown out with air through a chimney outlet. At the frequency of 5 min, various samples were collected to observe moisture content in the food grain until the percentage of moisture content level reaches 13–14% (Table 1) [2, 14].

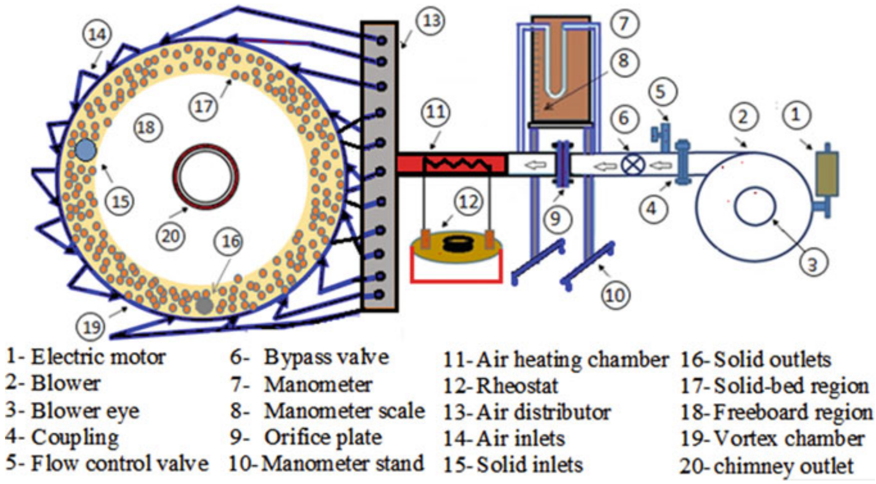

Fig. 1 Schematic of the experimental setup of RFB-SG dryer

Table 1 Input parameters for RFB-SG dryer and environmental conditions [1, 2]

SL-RFBSG chamber	
Dimensions	Vortex chamber diameter (*D*): 480 mm, chamber height (*L*): 65 mm, air inlet port width (*s*): 2.5 mm, and chimney diameter: 120 mm
Characteristics	Particle diameter d_p= 0.0025 mm, initial value of MC (X_{intl}) = 0.33 kg water/kg dry paddy and required value of MC (X_{req}) = 0.13 kg water/kg dry paddy)
Operating conditions	
Inlet air temperature	55, 60 and 65 °C
Inventory	400, 600, 800, and 1000 g
Ambient temperature	27 ± 5 °C
Airflow rate	600, 700, and 800 m^3/h

3 Results and Discussion

Experimentation has been conducted on a scale-up RFB-SG dryer to evaluate its performance, using locally available food grain (paddy). Drying characteristics of paddy in the scale-up RFB-SG chamber are presented and discussed in the following subsections.

3.1 Effect of Air Inlet Temperature on Drying Time

Figure 2 shows the effect of temperature on the drying time for the inventory of

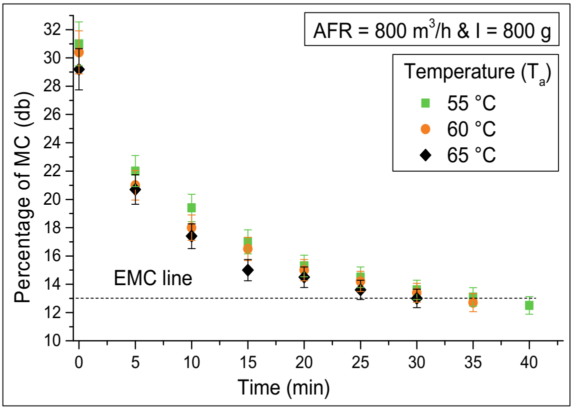

Fig. 2 Variation of MC with time at different air inlet temperature for an inventory of 800 g

800 g and the airflow rate of 800 m^3/h. It is observed that by increasing the air inlet temperature from 55 to 65 °C, the drying time is reduced by 21.62%. Furthermore, an increase in temperature beyond 65 °C reduces the nutritional value of food grain (paddy) [5].

3.2 *Effect of Airflow Rate on Drying Time*

Figure 3 shows the effect of airflow rate on drying time for the inventory of 800 g paddy and inlet air temperatures of 65 °C. The drying time [is] found to be decreased by 21%, with an increase in the airflow rate from 600 to 800 m^3/h. Furthermore, the drying time reduced by increasing airflow rate.

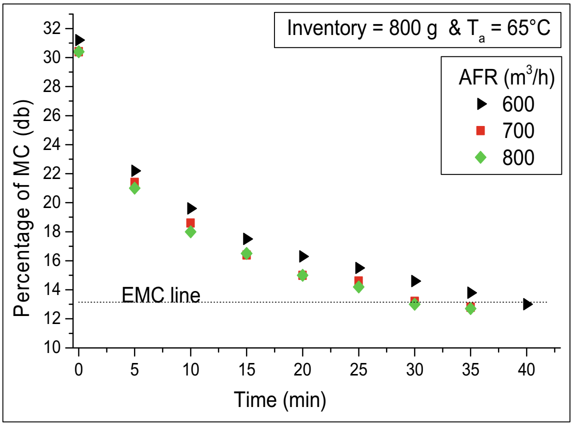

Fig. 3 Effect of airflow rate at an air temperature of 65 °C and inventory of 800 g

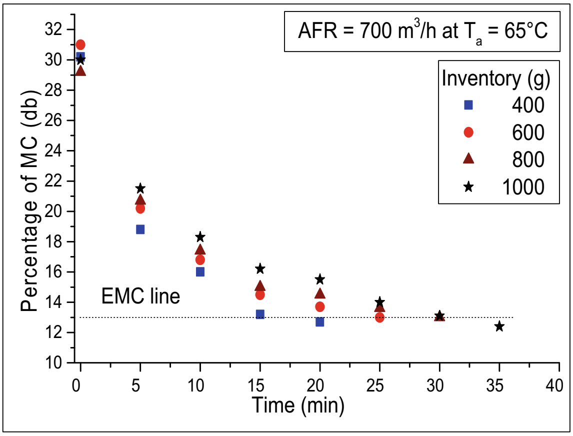

Fig. 4 Effect of inventory on drying time at air temperature 65 °C and inventory of 800 g

3.3 Effect of Inventory on Drying

Figure 4 shows the effect of inventory on the drying time at the airflow rate of 700 m^3/h and air temperature of 65 °C. With an increase in inventory, the time required for drying is observed to be increased. Pati et al. [15] have reported the drying time of 21 min for 400 g of inventory at inlet air temperature 65 °C and the airflow rate of 700 m^3/h, whereas drying time for the same parameters in the current study is 17 min. Hence, drying time is reduced by 19% (4 min).

4 Conclusions

To enhance the drying capacity of the RFB-SG dryer, a pilot-scale setup has been developed and the effects of various parameters on drying time are analyzed throughout the drying process, as the findings of the research are summarized below:

- The drying time is assumed to be significantly reduced by increasing the air inlet temperature as well as the airflow rate, whereas paddy erosion is seen when the air temperature rises above 65 °C.
- Although drying time is increased when paddy inventory is improved, the rate of increase in paddy inventories is comparatively higher than drying time. Hence, the drying capacity and efficiency of paddy are improved.
- A challenging drying process of an unevenly shaped paddy has been conducted successfully.

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