Inclined Fluidized Bed Dryer Performance in Energy Saving Option

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Abstract-- **Paddy was dried in an inclined bubbling fluidized bed (IBFB) dryer. Fluidization experiments were conducted for batch sizes varying between 0.5 to 2.5 kg with bed inclinations of 0°, 15° and 30°, at superficial air velocities of 1.1, 1.6 and 2.1ms^{-1}and drying air temperatures of 55, 60 and 65°C to evaluate the energy consumption during the drying process. Spirals were used inside the drying chamber for better drying efficiency and reduction in energy consumptions. Experiments were also carried out with the use of spirals. The results obtained are compared without the use of spirals. Best performance with a combination of minimum energy consumption and faster moisture removal rate was obtained with the use of spirals at a bed inclination of 15°, air velocity of 2.1 ms^{-1}, drying air temperature of 65°C and an inventory of 2.5 kg. Better performance was obtained with the inclined bed dryer due to the secondary motion in the bed during the bed inclination.**

Index Terms— **energy consumption, fluidized bed, inclination, spiral**

1. Introduction

Drying of paddy is a very critical process after harvesting and is carried out with the aim of reducing the loss due to pest and fungal attack, long storage life, and easy handling with minimum damage. Delay in drying, incomplete drying or ineffective drying will reduce grain quality and enhance post-harvest losses. Sun drying is the most widely practiced form of drying in the developing countries due its advantages like low cost, easiness and convenience. Even though sun drying requires little capital or expertise, the process is extremely dependent on weather conditions, long drying time, labor intensive, contamination of the product with soil and dust, non uniform drying leading to poor product quality, and large space requirements. By using dryers, paddy with consistent and desirable quality can be obtained which can be preserved for long time periods.

Even though several types of dryers exists, fluidized bed dryers have been found to be very efficient for drying cereal grains such as paddy, rice, wheat, corn, etc. Bizmark (2010) studied the sequential modeling of fluidized bed paddy dryer and reported that the drying time depends on the drying kinetics and hydrodynamic behaviour of the fluidized bed. Wilde (2014) reviewed the gas–solid fluidized beds in vortex chambers. Lim et *al*. (2014) investigated the hydrodynamic characteristics of gas–solid fluidized beds with shroud nozzle distributors. This study revealed that the bed pressure drop fluctuation along the fluidized bed was proportional to the superficial gas velocity. Experimental investigation of the hydrodynamic characteristics of gas–solid pulsed fluidized bed by Bizhaem and Tabrizi (2013) revealed that pulsating airflow decreased the minimum fluidization velocity thereby enhancing the fluidization of fine cohesive particles.

Srinivasakannan and Balasubramanian (2009) investigated the drying characteristics of millet in fluidized beds and reported that the drying rate increased with increase in temperature. Promvonge (2011) reported that increase in air temperature and air velocity in the fluidized bed dryer accelerated the drying rate of peppercorns. Investigation of drying rate in a fluidized bed paddy dryer using superheated steam and hot air by Rordprapat (2005) revealed faster drying was obtained by hot air compared to drying by superheated steam. Ozbey and Soylemez (2005) reported that the moisture extraction rate and efficiency of drying wheat grains by fluidized bed dryer was dependent on air mass flow rate and temperature. They also reported that the temperature has more effect on drying rate that of the mass flow rate. Hematian and Hormozi (2015) investigated the drying behavior of a batch fluidized bed dryer and observed that the moisture ratio decreased continuously with time. Ozahi and Demir (2014) observed that the drying time was reduced by increasing the drying air velocity during the fluidized bed drying of corn and unshelled pistachio nut. Jaiboon et *al.* (2009) reported that higher head rice yield was obtained when the flowing air temperature in a fluidized bed dryer was increased. The dynamics and structure of a fluidized bed in inclined columns was investigated experimentally by Yakubov et al. (2007). Veerachandra et al. (2013) reported that drying method and drying temperature have significant effect on drying time. Srinivasakannan (2012) utilized spirals as internals to reduce the axial mixing of solids in fluidized beds and reported the drying rate in a continuous fluidized bed is lower than the rate of drying in batch fluidized bed. Oluwaleye and Adeyemi (2013) reported achieving fine and uniform drying of products using a batch hot air fluidized bed dryer.

Sarker (2015) studied the energy and exergy analysis of industrial fluidized bed drying of paddy and suggested that exergy can be increased by providing sufficient insulation to the dryer body and recycling the exhaust air. Ozahi and Demir (2013) studied the thermodynamic analysis in a batch type fluidized bed dryer and observed that the effect of air mass flow rate has significant role on exergetic efficiency. Ozahi and Demir (2015) investigated the drying performance of a batch type fluidized bed regarding energetic and exergetic efficiencies and observed that both efficiencies strongly depends on air mass flow rate, particle mass and moisture content of particle to be dried. Golmohammadi et *al*. (2015) reported substantial reduction in energy consumption in intermittent paddy dryer by employing tempering stages in paddy drying. Sarker et *al*. (2015) studied the industrial scale fluidized bed paddy dryer and observed that drying rate is slow with paddy having high initial moisture content.

Literature reveals that crop drying is a high energy-intensive operation due to latent heat of evaporation. One of the key issues to be addressed in drying technology is to reduce the cost of energy sources and increase the efficiency of drying without compromising on the quality of the dried products. This can be achieved by techniques which improve proper gas-solid mixing thereby improving the heat transfer characteristics inside the fluidized with the use of spirals inside the dryer. The drying characteristics and energy consumption in a bubbling fluidized bed paddy dryer for various combinations of bed inclination, air flow rate, air temperature and bed inventory have been investigated. The results obtained are compared with that of the vertical.

2. MATERIALS AND METHOD

The bubbling fluidized bed dryer system consists of a centrifugal blower powered by a 15 HP electric motor, three electric heaters each of 1kW capacity and fitted inside the air blow pipe, orifice plate, distributor plate, dryer column, manometer, thermocouples, and data acquisition system. The desired bed inclination at an interval of 15° from the vertical is achieved using the inclination flange which is connected to the end of the air blow pipe. The dimensions of the dryer are 100 mm x 100 mm cross sectional area and 1625 mm column height. Twenty six pressure taps were used to measure the fluidized bed pressure drops on both sides of the column. The pressure drops were measured from the manometers using water as the manometer fluid. The manometer readings from each pressure tapings during the drying processes were recorded at an interval of 10 minutes from which the pressure drops were determined.

The dryer column was fabricated using Plexiglas for visual observation. The paddy bed of batch sizes 0.5 to 2.5 kg were fluidized at three different dryer positions: vertical bed (0° inclined), 15° and 30° inclined beds with drying air temperatures of 55, 60 and 65°C and air velocities of 1.1, 1.6 and 2.1 ms^{-1}. At the start of the experiment, the blower was switched on and air mass flow rate and velocity were adjusted by means of gate valve installed in the air flow pipe. Air was heated by means of the heater coils and maintained constant at the required temperature. Drying air temperature was measured by the pre-calibrated K-type thermocouples and continuously recorded using the data acquisition system. Paddy of required inventory was loaded into the bubbling fluidized bed dryer. The pressure at different sections along the column of the dryer was recorded to obtain the pressure drop across the bed for fluidized bed behavior. Few grams of paddy samples were taken out at 10 minutes interval for the determination of the moisture content. The moisture content of the paddy was determined using a digital grain moisture meter having an accuracy of ±0.5%. The moisture meter was pre-calibrated using the standard oven method. The experiment was terminated when the moisture content in the paddy dropped to 12 % wet basis. Figs. 1(a) and (b) show the photographs of the fluidized bed dryer at the inclination of 0° and 15° from the vertical.

(a)

(b)

Figs.1 Bubbling fluidized bed dryer with the inclination of (a) $\theta = 0°$ and (b) $\theta = 15°$

2.1 Drying Parameters

System velocity and air mass flow rate are the main parameters for fluidized bed drying system. When a gas passes through a bed of particles, the bed tends to get fluidized. Depending upon the superficial gas velocity, the flow regimes are categorized as fixed bed, bubbling bed, slug bed, turbulent bed, fast bed and pneumatic transports [Davidson and Harrison (1963), Othomer (1956)]. The superficial velocity (*U*) is defined as the volume flow rate of air per unit cross-section of the bed.

i.e., $$U = \frac{\text{Volume flow rate of air through the bed}}{\text{cross} - \text{sectional area of the bed}} \quad (1)$$

where *U* is superficial velocity

For orifice plate, superficial velocity is determined by the relationship of the orifice plate design.

$$U = \frac{\dot{m}_a}{\rho \times A_b} = 1.117\sqrt{\Delta P}\ \text{ms}^{-1} \quad (2)$$

where $\dot{m}_a$ is mass flow rate of air, ρ is density of air, A_b is cross sectional area of the dryer and ΔP is the pressure drop. Mass flow rate of air is determined using the relationship of the orifice plate design.

$$\dot{m}_a = 0.01303 \times \sqrt{\Delta P}\ \text{kgs}^{-1} \quad (3)$$

2.2. Energy consumption

The energy consumed by the dryer is used partly for heating the air and partly for driving the blower fan. The energy calculations presented in this paper is based on the energy input to the dryer and energy consumption by the blower. The energy input for removing the moisture from the wet paddy is

$$Q = V\, i\, t \times P.F. \times 60 \times 10^{-6}\ \text{MJ kg}^{-1} \quad (4)$$

where Q is heat input V is input voltage, i is Ampere, t is drying time (minute) and $P.F$ is power factor.

3. RESULTS AND DISCUSSION

From the experiment, the hydrodynamics behaviour of the vertical and inclined beds, drying characteristics and energy consumption for drying were investigated. The results obtained are presented in the subsequent sub-sections.

3.1 Hydrodynamics behaviour of the system

Variation of pressure along the top side (TS) and bottom side (LS) along the riser height with the use of spirals (SP) and without the use of spirals (XSP) are measured. Fig. 2 presents the pressure drop along the riser height at the different temperature, air velocity of 1.1 ms^{-1} and an inventory of 2 kg for $\theta = 0^{\circ}$.

In the Fig. 2 it is observed that pressure drop along the riser height using spirals is slightly higher than that of without the use of spirals for both temperatures. Pressure drop for 55˚C is higher than that of 65˚C for both cases. Fluidization heights with and without the use of spirals are 44cm for each case. Pressure drop fluctuation decreases significantly when spiral inserts are used.

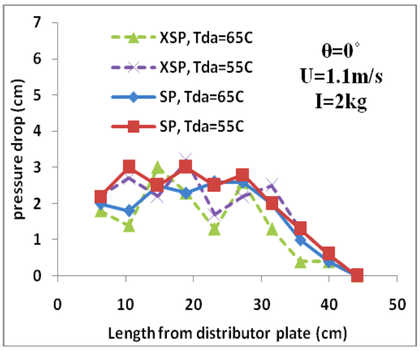
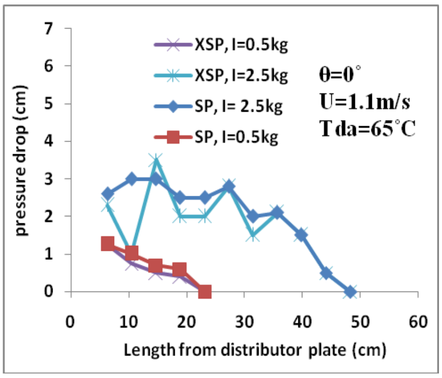
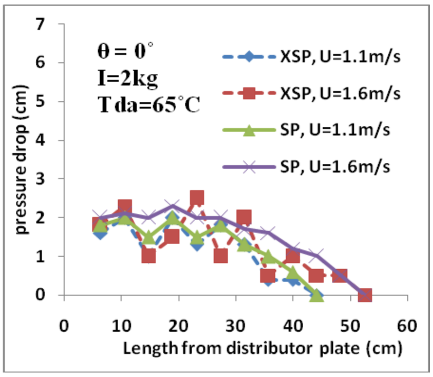


Fig. 2 Pressure drop along the riser height for $\theta = 0^{\circ}$ at different temperature

Figs. 3 (a) and (b) present the pressure drop along the riser height with and without the use of spirals for $\theta = 0^{\circ}$ at different inventory and velocity, respectively. In the Figs. it is observed that pressure drop fluctuation decreases significantly with the use of spirals in compared without the use of spirals. Moreover, pressure drop along the riser height also increases when spirals inserts are used. However, fluidization heights for with and without the use of spirals are same. When the inventory is more, fluidization height is also more. Fluidization height for the inventory of 2.5kg is 48 cm and the inventory of 0.5 kg is 23 cm for both cases in Fig. 3(a). When the velocity is increased, fluidization height also increases. Fluidization heights are 44 cm for air velocity of 1.1m/s and 52 cm for 1.6 m/s, respectively for with and without the use of spirals in Fig. 3(b). For $\theta = 15^{\circ}$, pressure drop along the riser column for lower side and upper is different. Hence, it will be presented lower side and upper side separately.



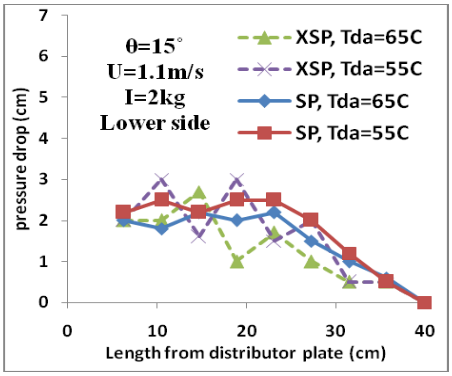
(a)



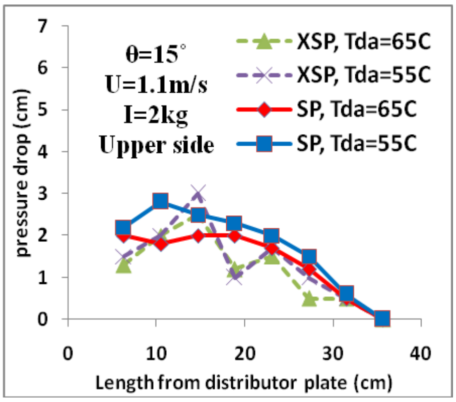
(b)

Figs. 3 Pressure drop along the riser height for $\theta = 0^{\circ}$ with and without the use of spirals at (a) different inventory and (b) different velocity

Figs. 4(a) and (b) present the pressure drop along the riser column for lower side and upper side with and without the use of spirals for $\theta = 15^{\circ}$ at different temperature. It is observed that pressure drop fluctuation becomes smooth when spirals inserts are used in compared without the use of spirals. Moreover, pressure drop with the use of spirals is higher than that of without the use of spirals. However, fluidization heights for with and without the use of spirals are same. Fluidization height for lower side is 40 cm and 36 cm for upper side. Pressure drop at 55˚C is higher than that of 65˚C for both cases.



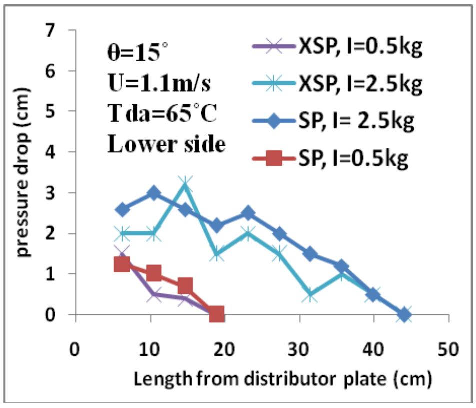
(a)



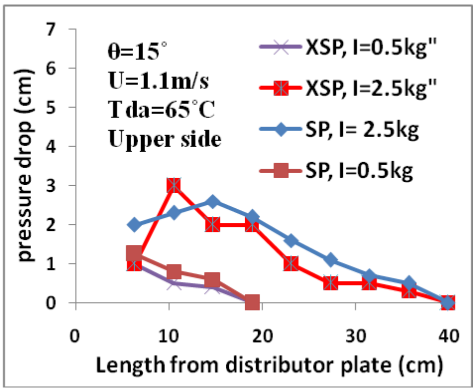
(b)

Figs. 4 Pressure drop verses fluidization height with and without the use of spirals for $\theta = 15^{\circ}$ at different temperature for (a) lower side and (b) upper side of riser column

Figs. 5(a) and (b) show the pressure drop along the riser height for lower side and upper side with and without the use of spirals for $\theta = 15^{\circ}$ at different inventory.



(a)

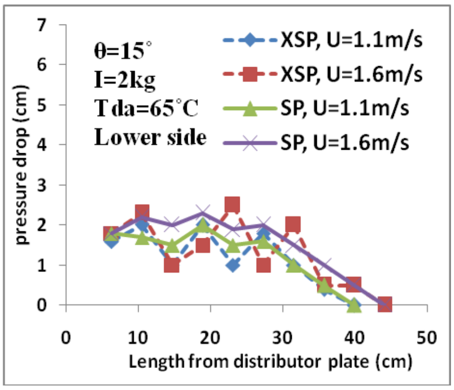


(b)

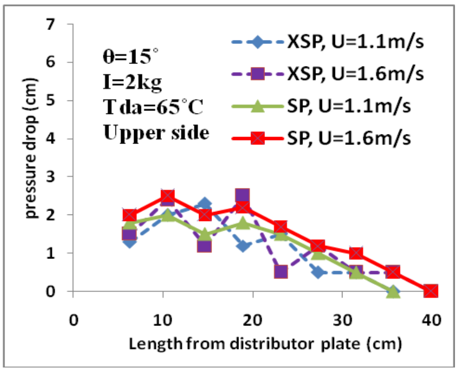
Figs. 5 Pressure drop along the riser height with and without the use of spirals for $\theta = 15^{\circ}$ at different inventory for (a) lower side and (b) upper side of riser column

In the Figs. 5(a) and (b) it is observed that pressure drop and fluidization height are high at an inventory of 2.5 kg whereas it is low at 0.5kg for with and without the use of spirals. Fluidization heights are 20 cm and 44cm for lower side and 20 cm and 40 cm for upper side for both cases. Pressure drop fluctuation decreases significantly when spirals inserts are used.

Figs. 6(a) and (b) show the pressure drop along the riser height with and without the use of spirals for $\theta = 15^{\circ}$ at lower side and upper side of riser column at different velocity. It is found that pressure drop and fluidization height at the velocity of 1.6 m/s is higher than that of 1.1m/s for with and without the use of spirals. Fluidization heights are 44 and 40 cm for lower side and 40 and 32 cm for upper side for the air velocity of 1.6 m/s and 1.1m/s, respectively for with and without the use of spirals. Pressure drop increases when spirals inserts are used. However, fluidization heights are same for with and without the use of spirals.



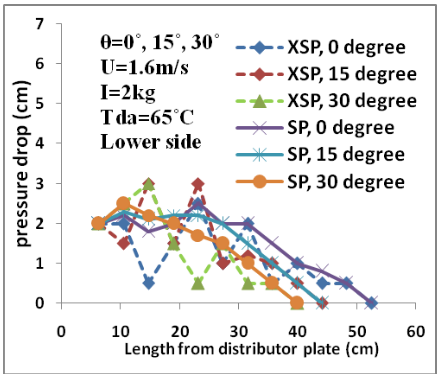
(a)



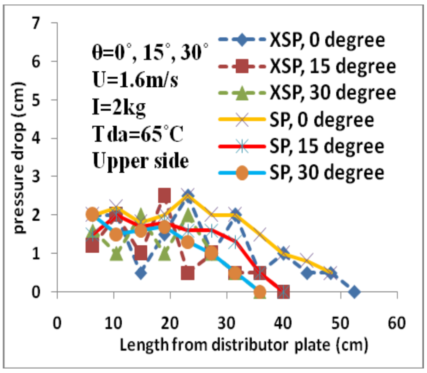
(b)

Figs. 6 Pressure drop verses fluidization height with and without the use of spirals for $\theta = 15^{\circ}$ at different velocity for (a) lower side (b) upper side of riser column

Figs. 7(a) and (b) present the pressure drop along the riser height with and without the use of spirals for $\theta = 0^{\circ}$, 15° and 30° at the drying air temperature of 65˚C, superficial air velocity of 1.6 m/s and the inventory of 2kg.



(a)



(b)

Figs. 7 Pressure drop verses fluidization height with and without the use of spirals for different inclination angles of $\theta = 0^{\circ}$. 15° and 30° (a) lower side and (b) upper side of the riser column

From the Figs. it is observed that pressure drop fluctuation decreases when spirals inserts are used. Pressure drop and fluidization height are higher at $\theta = 0^{\circ}$ than at $\theta = 15^{\circ}$ and 30° for with and without the use of spirals. Fluidization heights are 52, 44 and 40 cm for lower side and 52, 40 and 36 cm for upper side for $\theta = 0^{\circ}$. 15° and 30°, respectively for with and without the use of spirals inserts.

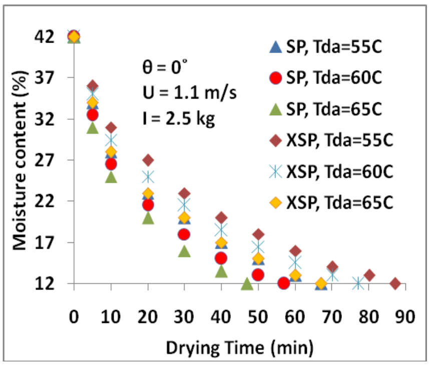
3.2. Drying characteristics

Comparison of moisture content verses drying time of bubbling fluidized bed drying with and without the use of spirals for $\theta = 0^{\circ}$ is presented in Figs. 8 (a) to (c).

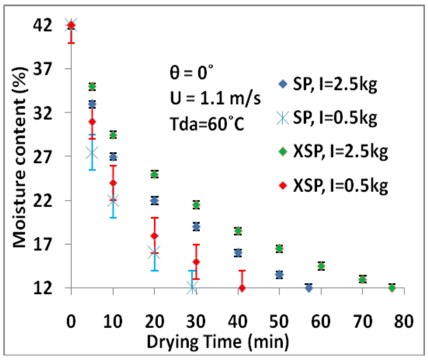
From the Fig. 8 (a) it is evident that use of spirals increased the moisture removal at a faster rate compared to the case without spirals. Providing the spiral in the drying bed promoted better solid gas mixing resulting in higher heat transfer rate from the hot air to particles. In the Fig. 8 (a), the drying times for an inventory of 2.5kg at the air velocity of 1.1m/s are 87, 77, and 67 min for without the use of spirals inserts at the drying air temperature of 55, 60 and 65˚C, respectively to drop the final MC of 12% (w.b), whereas the corresponding drying time are 67, 57 and 47 min for with the use of spiral inserts. It is observed that drying time/kg paddy decreases by 22.9, 25.9 and 29.9%, respectively for air temperature of 55, 60 and 65˚C when spiral inserts are used.

In the Fig. 8 (b), the drying times/kg paddy without the use of spiral inserts at the air velocity of 1.1m/s and air temperature of 60˚C are 82 and 30.8 min, respectively for the inventory of 0.5 to 2.5kg to drop the final MC of 12% (w.b), whereas the corresponding drying time with the use of spiral inserts are 58 and 22.8 min. It is observed that the drying time/kg paddy decreases by 29.3% and 25.9% for the inventory of 0.5kg and 2.5kg, respectively when spiral inserts are used.

In the Fig. 8 (c) the drying times without the use of spiral inserts at the air temperature of 55˚C and an inventory of 2.5 kg are 87 and 77 min for the air velocity of 1.1m/s and 2.1 m/s, respectively to drop the final MC of 12% (w.b). The corresponding drying times with the use of spiral inserts are 67 and 57 min. It is observed that drying time/kg paddy decreases by 22.9% and 25.9% for air velocity of 1.1 m/s to 2.1 m/s, respectively when spiral inserts are used.



(a)



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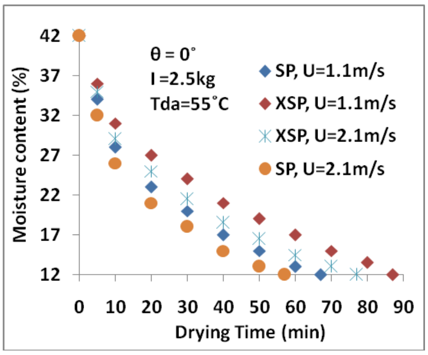
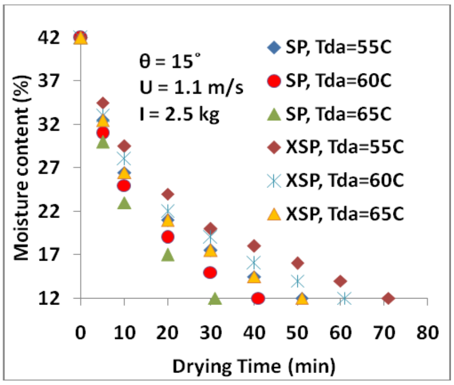


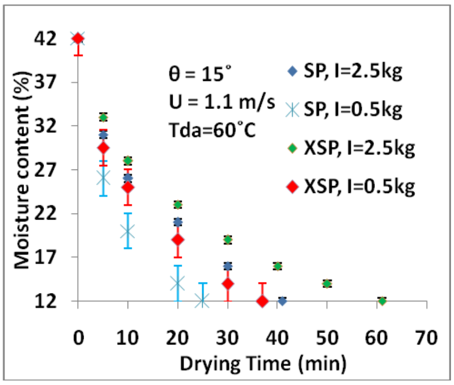
(c)

Figs. 8 Moisture content verses drying time plot for $\theta = 0^{\circ}$ at (a) different temperature (b) different inventory and (c) different velocity

The moisture content verses drying time plots for the fluidized bed dryer with the use of spirals (SP) and without the use of spirals (XSP) for $\theta = 15^{\circ}$ are shown in Figs. 9 (a)-(c).



(a)



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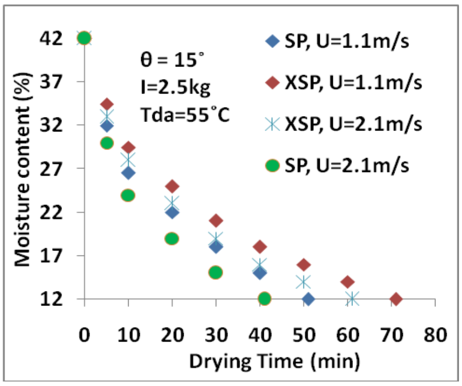
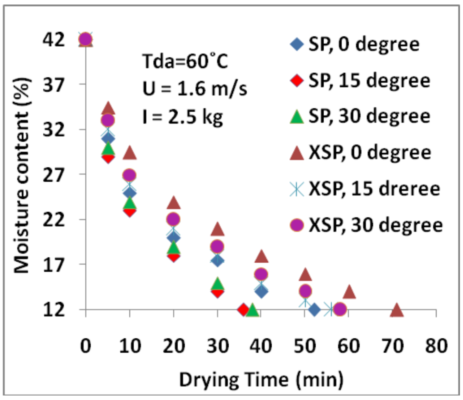


(c)



(d)

Figs. 9 Moisture content verses drying time plot for $\theta = 15^{\circ}$ at (a) different temperature (b) different inventory (c) different velocity and (d) different inclination

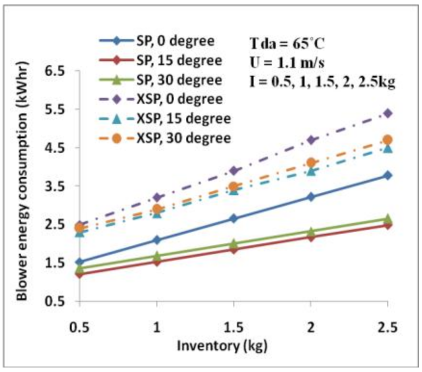
In the Fig. 9 (a) the drying times without the use of spiral inserts for the inventory of 2.5kg at air velocity of 1.1m/s are 71, 61 and 51 min for the drying air temperature of 55˚C, 60˚C and 65˚C, respectively to drop the final MC of 12% (w.b). The corresponding drying times with the use of spiral inserts are 51 min, 41 min and 31 min. It is observed that drying time/kg paddy decreases by 28.2%, 32.8% and 39.2%, respectively for the air temperature of 55˚C, 60˚C and 65˚C when spiral inserts are used.

In the Fig. 9 (b) the drying times/kg paddy without spiral inserts at air velocity of 1.1m/s and air temperature of 60˚C are 74 and 24.4 min, respectively for the inventory 0.5 and 2.5 kg to drop the final MC of 12% (w.b), whereas the corresponding drying time/kg paddy with spiral inserts are 50 and 16.4 min. It is observed that drying time/kg paddy decreases by 32.4% and 32.8% for the inventory of 0.5 and 2.5 kg, respectively when spiral inserts are used. As shown in Figs. 9 (b), uncertainty in measurement of moisture content (%) for the inventories of 0.5 and 2.5kg are calculated to be ±2% and ±0.4%, respectively.

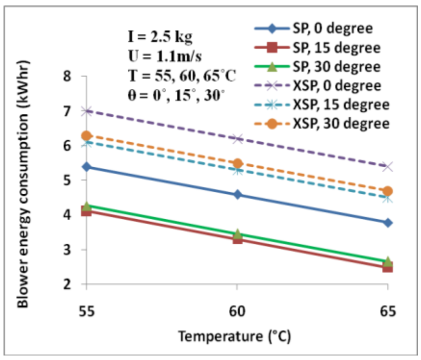
In the Fig. 9 (c) drying times without the use of spiral inserts at the air temperature of 55˚C and an inventory of 2.5 kg are 71 and 61 min, respectively for the air velocity of 1.1 and 2.1 m/s to drop the final MC of 12% (w.b), whereas the corresponding drying time with the use of spiral inserts are 51 and 41 min. It is observed that drying time/kg paddy decreases by 28.2% and 32.8%, respectively for the air velocity of 1.1 and 2.1 m/s when spiral inserts are used. Fig. 10 presents moisture content verses drying time with and without the use of spiral inserts for $\theta = 15^{\circ}$ at different inclination. In the Fig. 9(d), the drying times without the use of spiral inserts for an inventory of 2.5kg, air velocity of 1.6 m/s and air temperature of 60˚C are 72, 56 and 58 min, respectively for $\theta = 0^{\circ}$, 15˚ and 30˚ to drop the final MC of 12% (w.b), whereas the corresponding drying time are 52, 36 and 38 min when spiral inserts are used. It is observed that drying time/kg paddy decreases by 27.8%, 35.7% and 34.5%, respectively for $\theta = 0^{\circ}$, 15˚ and 30˚ when spiral inserts are used.

3.3. Energy consumption

Energy consumptions are measured for different inputs like superficial air velocity, drying air temperature and different amount of paddy inventory. Electrical (blower) energy consumption with and without the use of spiral insert at different inventory, temperature and velocity are shown in Figs. 10 (a)-(c).



(a)



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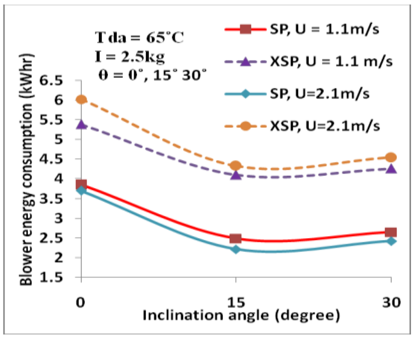


(c)

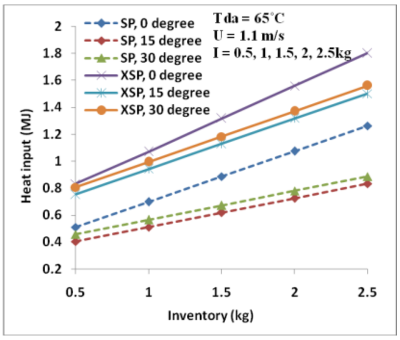
Figs. 10 Electrical energy consumption at (a) different inventory (b) different temperature and (c) different velocity

In the Fig. 10(a), the electrical energy consumption per kg paddy without the use of spirals at the drying air temperature of 65˚C and the air velocity of 1.1m/s are 5, 3.2, 2.6, 2.35 and 2.16 kWhr/kg for $\theta = 0^\circ$, 4.6, 2.8, 2.27, 1.95 and 1.8 kWhr/kg for $\theta = 15^\circ$ and 4.8, 2.9, 2.3, 2.05 and 1.88 kWhr/kg for $\theta = 30^\circ$, respectively for the inventory of 0.5 to 2.5 kg. The corresponding values with the use of spirals are 3.06, 2.1, 1.77, 1.61 and 1.51 kWhr/kg for $\theta = 0^\circ$, 2.42, 1.53, 1.23, 1.08 and 0.99 kWhr/kg for $\theta = 15^\circ$ and 2.74, 1.69, 1.34, 1.16 and 1.06 kWhr/kg for $\theta = 30^\circ$, respectively for the bed inventories of 0.5 to 2.5 kg. It is observed that electrical energy consumption per kg paddy decreases by 38.8%, 47.4% and 42.9% for 0.5 kg and 30.1%, 44.7% and 43.6% for 2.5kg for $\theta = 0^\circ$, 15˚ and 30˚, respectively when spiral inserts are used.

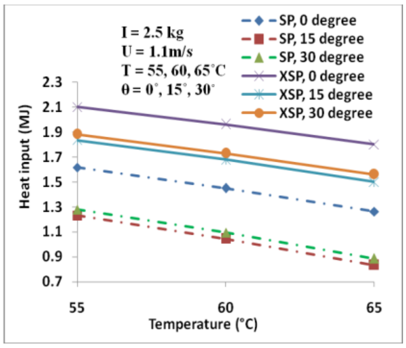
In the Fig. 10(b), electrical energy consumptions without the use of spirals at the air velocity of 1.1m/s and an inventory of 2.5 kg are 7, 6.2 and 5.4 kWhr for $\theta = 0^\circ$, 1, 5.3 and 4.5 kWhr for $\theta = 15^\circ$ and 6.3, 5.5 and 4.7 kWhr for $\theta = 30^\circ$ for the drying air temperatures of 55, 60 and 65˚C. respectively. The corresponding values with the use of spirals are 5.39, 4.59 and 3.78kWhr for $\theta = 0^\circ$, 4.11, 3.3 and 2.49 kWhr for $\theta = 15^\circ$ and 4.27, 3.46 and 2.66 kWhr for $\theta = 30^\circ$, respectively. It is observed that electrical energy consumption per kg paddy decreases by 23%, 32.6% and 32.2% for 55˚C, 25.9%, 37.7% and 37.1% for 60˚C and 30%, 44.7% and 43.4% for 65˚C for $\theta = 0^\circ$, 15˚ and 30˚, respectively when spiral inserts are used.

In the Fig. 10(c), the electrical energy consumptions without the use of spirals at drying air temperature of 60˚C and an inventory of 2.5 kg are 5.39, 4.1 and 4.26 kWhr for air velocity of 1.1 m/s and 6.02, 4.32 and 4.54 kWhr for air velocity of 2.1 m/s, respectively for $\theta = 0^\circ$, 15˚ and 30˚. The corresponding values with the use of spirals are 3.85, 2.49 and 2.65 kWhr for air velocity of 1.1 m/s and 3.7, 2.21 and 2.42 kWhr for air velocity of 2.1 m/s, respectively for $\theta = 0^\circ$, 15˚ and 30˚. It is observed that electrical energy consumption per kg paddy decreases by 28.5%, 39.2% and 37.8% for 1.1m/s and 38.3%, 48.8% and 46.7% for 2.1 m/s for $\theta = 0^\circ$, 15˚ and 30˚, respectively when spiral inserts are used.

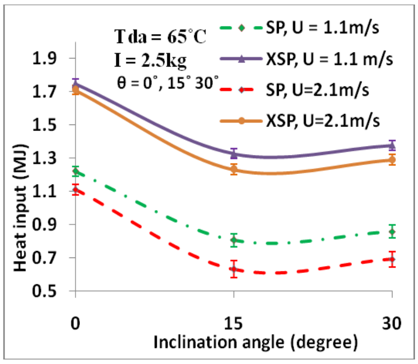
Figs. 11(a)-(c) show the thermal energy consumption using spiral inserts at different inventory, temperature and velocity. In the Fig. 11(a), thermal energy consumption per kg paddy without the use of spirals at drying air temperature of 65˚C and air velocity of 1.1m/s are 1.66, 1.07, 0.87, 0.78 and 0.72MJ/kg for $\theta = 0^\circ$, 1.5, 0.94, 0.75, 0.628 and 0.6 MJ/kg for $\theta = 15^\circ$ and 1.61, 0.99, 0.79, 0.68 and 0.62 MJ/kg for $\theta = 30^\circ$, respectively for the bed inventories of 0.5 to 2.5 kg. The corresponding values with the use of spirals are 1.02, 0.69, 0.59, 0.54 and 0.5MJ/kg for $\theta = 0^\circ$, 0.81, 0.51, 0.41, 0.36 and 0.33 MJ/kg for $\theta = 15^\circ$ and 0.91, 0.56, 0.45, 0.39 and 0.35 MJ/kg for $\theta = 30^\circ$, respectively for the bed inventories of 0.5 to 2.5 kg. It is observed that thermal energy consumption per kg paddy decreases by 38.6%, 46.3% and 43.5% for inventory of 0.5 kg and 30.6%, 45% and 43.5% for inventory of 2.5 kg for $\theta = 0^\circ$, 15˚ and 30˚, respectively when spiral inserts are used.



(a)



(b)



(c)

Figs. 11 Thermal energy consumption at (a) different inventory (b) different temperature and (c) different velocity

In the Fig. 11(b) thermal energy consumption values without the use of spirals at the air velocity of 1.1m/s and an inventory of 2.5 kg, are 2.1, 1.96 and 1.8 MJ for $\theta = 0^\circ$, 1.83, 1.68 and 1.5 MJ for $\theta = 15^\circ$ and 1.88, 1.73 and 1.56 MJ for $\theta = 30^\circ$, respectively for the air temperatures of 55˚C, 60˚C and 65˚C. The corresponding values using spiral inserts are 1.62, 1.45 and 1.26 MJ for $\theta = 0^\circ$, 1.23, 1.04 and 0.83 MJ for $\theta = 15^\circ$ and 1.28, 1.09 and 0.89 MJ for $\theta = 30^\circ$, respectively for the air temperatures of 55˚C, 60˚C and 65˚C. It is observed that thermal energy consumption per kg paddy decreases by 23.3%, 32.9% and 32.1% for 55˚C, 26%, 37.9% and 36.8%

for 60˚C and 29.9%, 44.5% and 43.2% for 65˚C at $\theta = 0˚$, 15˚ and 30˚, respectively when spiral inserts are used.

In the Fig. 11(c) thermal energy consumptions without the use of spirals at the drying air temperature of 65˚C and an inventory of 2.5 kg are 1.75, 1.32 and 1.37 MJ for the air velocity of 1.1 m/s and 1.71, 1.23 and 1.29 MJ for the air velocity of 2.1 m/s, respectively for $\theta = 0˚$, 15˚ and 30˚. The corresponding values with the use of spirals are 1.22, 0.806 and 0.858 MJ for the air velocity of 1.1 m/s and 1.11, 0.63 and 0.69 MJ for the air velocity of 2.1 m/s, respectively for $\theta = 0˚$, 15˚ and 30˚. It is observed that thermal energy consumption per kg paddy decreases by 30.3%, 39% and 37.7% for 1.1m/s and 35.1%, 48.8% and 46.5% for 2.1 m/s for $\theta = 0˚$, 15˚ and 30˚, respectively when spiral inserts are used. It is observed that the inclined bed dryer is having better performance than the vertical one in every condition for this experiment. Moreover, it is found that the best dryer performance with a combination of faster drying rate and minimum energy consumption is achieved at $\theta = 15˚$, air velocity of 2.1ms^{1}, air temperature at 65°C for an inventory of 2.5 kg with the use of spirals.

As shown in Fig. 11(c), uncertainty in measurement of thermal energy consumption for the inventory of 2.5 kg, air temperature of 65˚C, air velocity of 1.1m/s and without the use of spirals are calculated to be ±2.6%, ±2.9%, and ±2.9% and with the use of spirals are ±3%, ±3.9% and ±3.7%, respectively for $\theta = 0˚$, 15˚ and 30˚. Uncertainty in measurement of thermal energy consumption for the inventory of 2.5 kg, air temperature of 65˚C air velocity of 2.1m/s for without the use of spirals are calculated to be ±2.7%, ±3.2% and ±3.1% and with the use of spirals are ±3.4%, ±5.2% and ±4.8%, respectively for $\theta = 0˚$, 15˚ and 30˚. It was found that 95% confidence level for this experiment.

4. CONCLUSION

The drying characteristics of inclined fluidized bed dryer with three bed inclinations, three inlet air temperatures, and three air velocities for different bed sizes was investigated. The hydrodynamic behavior of the system was investigated with and without the use of spirals. When the spirals were used in the dryer, the heat transfer rate and drying efficiency increased due to the proper motion of air flow. The energy consumptions were lower for the inclined bed compared to the vertical bed dryer. The energy consumption per kg paddy decreases with increases in air temperature, air velocity and bed inventory. Electrical as well as thermal energy consumptions per kg paddy decreased by 48.8% at $\theta = 15˚$, air velocity of 2.1 ms^{-1}, air temperature at 65°C for an inventory of 2.5 kg with the use of spirals.

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