Comprehensive study of fluidization characteristics and variations of moisture content in fluidized bed drying of soybean

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Abstract. In this exhaustive study, the investigation has been done on the strength of moisture content, air temperature and air entry speed on the drying kinetics and fluidization height during fluidized bed drying of soybean using electric heater as a heating medium. And it is obvious from the observing values, the height of the fluidized bed increased with the increment in inlet Vs and fluidization height decreased with lower inlet Vs. If the mass flow rate reduced, the corresponding height of the bed increased and vice versa for high mass flow rate. Fluidized bed drying was able to reduce drying time in comparison to the fixed bed and hence it could be used to reduce heterogeneity in the bed during drying. In drying kinetics, with the increase in drying parameters, rate constants and diffusivity have also increased.

Keywords. Fluidized Bed Dryer, Inlet Air Velocity, Fluidization Height, Moisture Content

1. Introduction
Soybean [Glycine max (L.) Merril] has generally utilized as a non-meat, cheap protein fount, used for humans and beast feed. High yield capacity and low harvest cost of soybean make it the most important oil-seed [1]. At the time of harvest, moisture content of soybean ranges from a 25-33% dry basis [2, 3]. To preserve the quality of grain during the storage period, a rapid decrease in moisture content is required [4]. Reduction in moisture content up to 14% dry basis minimizes the microbial spoilage and respiration in the legume, which is a prerequisite for the longer storage period. Additionally, raw soybean cannot be consumed as a human food because of the presence of anti-nutritional substances, i.e. proteases [5]. The presence of these anti-nutritional substances in the legume can also be reduced by rapid heat treatment, provided the heat treatment is maintained at a level that does not significantly reduce the protein level of the legume [6, 7].

Fluidized bed drying (FBD) is a high-temperature short-time treatment method, gaining recognition as a fast-drying technology in the grain processing industry [8, 9]. Due to the large air to product contact area achieved relative to a static bed caused by fluidization of the product, and the high airspeed and high temperature used [10].

The drying characteristics of soybean have investigated throughout combined hot air-microwave drying by Mohsen Ranjbaran and Dariush Zare. The investigation was executed for the combination of five microwave power densities (0.89, 1.6, 3.2, 4.3, 5.3 W/g) and four levels of air temperatures (30, 40, 50 and 60 °C) [11]. M. Ranjbaran and D. Zare recreated and contemplated the outcomes of air temperature at inlet, microwave power density, bed thickness, and Vs on the viability and incapability of the drying cycle [12]. Samira Afraekhteh and Esfandiar Frahmmandfar studied and discussed the results of Seed and Plant Certification and Registration Institute, Iran which involves the effects of independent variables of moving- bed dryers on the quality of soybean seeds [13]. Marcela L.
Martínez, María A. Marín & Pablo D. Ribotta investigated and designed a fluidized bed dryer to improve drying and inactivation of heat-labile inhibitors conditions of soybean. Therefore they reduced treatment time and losses [14]. Suherman Suherman, Slamet Priyanto and Ratnawati studied the simulator fluid bed drying, was utilized to derive one particle drying Kinetics. They performed experiments with different air temperatures in °C as 35, 40, & 45 [15]. H. Darvishi, M. H. Khoshtaghaza, and S. Minaei found that a decrease in energy of activation caused an increase in drying rate. [16].

From the above study, it learned that widely Fluidized bed is used for food and chemical processing industries because of its high heat and mass transfer coefficients and the good quality of dried products obtained. In the event that air made to move through a bed of Soybeans upheld by a perforated plate, frictional drag will cause a compel drop to create over the bed. It will additionally build the drag and weight drop as the air speed, they move separated and the bed grows. Then particles begin to act as a fluid, so it’s called fluidization. When fluidization first happen Vₜ is termed as incipient fluidization velocity and used to obtain optimum results. In this paper it is found that the air temperature of 45°C and air velocity of 7.7 m/s for 60 minutes produced the moisture content reduced from 27db to 13db. Hence it is clear that as we increase the temperature and velocity of hot air, soybean grains dried properly and could be stored for a long time period.

2. Materials and methods

Soybean purchased from nearby market and soaked in water for 24 hrs. Then the sample of 1 kg soybean seeds put in the refrigerator at temperature 6-8 °C for 5-7 days to obtain equilibrium. Sample packed in the sealed plastic bag. Then the sample put in the room temperature for at least 24 hours before experiment.

Soybean samples (1 kg) dried in fluidized bed dryer. Rectangular fluidization chamber of length 0.4m and width 0.08m used. A blower used to blow hot air which passes through the perforated plate or grid on which soybean seeds placed. The grain temperature measured by probe type thermometer and velocity of air measured by digital anemometer. Soybean dried uniformly above the perforated plate and grains behaved like a fluid. Then the dried soybean seeds cooled at room temperature.

2.1. Experimental model

An experimental model has developed and figure 1 shows schematic diagram of a fluidized bed dryer.

![Figure 1. Schematic diagram of a fluidized bed dryer.](image)
The model consists of air heater, air blower, fluidized bed, perforated plate, drying chamber, duct to reuse hot air and five control volumes labeled CV1 to CV5.

2.2. Mathematical Modeling
According to the laws of Heat and Mass Transfer, differential equation of the soybean grain achieved. Hot air coming from the blower assumed uniform. The mass flow rate of the soybean grain considered as uniform throughout the bed length. The soybean seeds assumed as spherical in shape.

2.2.1. Modeling of the Moisture Ratio. Calculation of Moisture content is done by the following formula:

\[
X(t) = X_0 - \frac{M_g}{M_{s,\text{dry}}} \int_{t=0}^{t} (Y_{\text{out}}(t) - Y_{\text{in}}(t))dt
\]

(1)

where, \(X_0\) = Initial content of Moisture, \(M_g\) = mass flow-rate of Air, \(M_{s,\text{dry}}\) = Dry mass particle & \(Y\) = humidity [15].

Drying rate is:

\[
\dot{m} = \frac{M_g}{M_{s,\text{dry}}} \frac{\rho_p d_p}{6} (Y_{\text{out}}(t) - Y_{\text{in}})
\]

(2)

where, \(\rho_p\) = Particle density, \(d_p\) = Particle diameter [15]

To describe the moisture ratio as a function of drying time, an empirical drying model is considered. The moisture ratio was calculated as follow:

\[
MR = \frac{M(t) - M_e}{M_0 - M_e}
\]

(3)

where, MR, \(M_0\), \(M(t)\) and \(M_e\) are the moisture ratio.

In the present study the equilibrium moisture content was estimated using Henderson and Perry relationship for soybeans:

\[
1 - RH = \exp \{ -0.000032 \ (492 + 1.8T) M_e^{1.52} \}
\]

(4)

It has been reported by several researchers that this simplification does not have a great influence on the accuracy of prediction [17].

3. Results & discussion

3.1. Analysis of fluidization characteristics
The investigation has done to determine fluidization characteristics of soybean with the help of experimental set up. Taking mass flow rate of soybean as 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2 kg/min in the bed, measurements of initial bed height (\(h_i\)) has taken respectively. At a fixed inlet air velocity as 5.9 m/s blower has run, fluidization taken place and final bed height has measured. Five values of final bed height has taken by repeating the experiment five times for each mass flow rate and average of these values has considered as final bed height (\(h_f\)). Then fluidization height has obtained for each mass flow rate of soybean by subtracting initial bed height from final bed height.
The above process repeated for two other inlet air velocities as 6.7 and 7.7 m/s for the aforesaid mass flow rates of soybean and fluidization heights calculated. Some observations tabulated in Table 2 and summary of bed characteristics and experimental conditions of bed shown in Table 1.

Table 1. Experimental conditions of bed.

| S No | Parameter                        | Value          |
|------|----------------------------------|----------------|
| 1    | Soybeans diameter, $d_p$ (mm)   | 6 to 11        |
| 2    | Bed length (m)                  | 0.4            |
| 3    | Bed width (m)                   | 0.08           |
| 4    | Bed mass of soybeans (kg)       | 0.5, 0.75, 0.1, 1.25, 1.5, 1.75, 2 |
| 5    | Superficial air velocity, $u_{air}$ (m/sec) | 4.5, 5.9, 6.7, 7.7 |
| 6    | No. of holes in perforated sheet | 1830           |
| 7    | Radius of a hole (mm)           | 1              |
| 8    | Thickness of perforated sheet (mm) | 0.5            |
| 9    | Area of perforated sheet ($m^2$) | 0.032          |

Table 2. Summary of bed characteristics for 5.9 m/s inlet air velocity.

| Soybean on the bed (m) in kg | 0.5 | 0.75 | 1 | 1.25 | 1.5 | 1.75 | 2 |
|-----------------------------|-----|------|---|------|-----|------|---|
| Initial bed height ($h_i$) in cm | 1.7 | 2.8  | 3.8 | 4.9  | 6   | 7    | 8.1 |
| Final bed height ($h_f$) in cm | 4.4 | 5.4  | 6.2 | 7.2  | 8.1 | 9    | 10 |
| Fluidization height ($h_f-h_i$) in cm | 2.7 | 2.6  | 2.4 | 2.3  | 2.1 | 2    | 1.9 |

Figure 2. Fluidization height versus mass flow rate of soybean with respect to inlet air velocity.

Figure 3. Fluidization height versus inlet air velocity with respect to mass flow rate of soybean.

Figure 2 shows the behavior of curves drawn between fluidization height and mass flow rates of soybean with respect to three different inlet air velocities. Blue colored curve has drawn for fluidization at 5.9 m/s inlet air velocity. Red and green curves have drawn for 6.7 and 7.7 m/s inlet air velocities respectively. All three curves show that as we increase the mass flow rate of soybean in the bed, fluidization height decreases. We can also observe that when we increase mass flow rate of soybean by 0.25 kg, fluidization height decreases very less that is 1 to 2 mm and for 1.5 kg increment in mass flow rate of soybean, fluidization height decreases 8 to 10 mm.

Taking the mass flow rate of soybean in the bed above 2 kg, an abrupt behavior of fluidization has seen throughout the bed. The fluidization of soybeans was good in the middle of the bed but in both corners, it was very less so the fluidization obtained was not considered as uniform fluidization.
We can see the behavior of curve between fluidization height and inlet air velocity with respect to two mass flow rates of soybean as 0.5 and 0.75 kg/min can in figure 3. Blue and red curve represent 0.5 kg/min and 0.75 kg/min mass flow rates respectively. With the decrease in inlet air velocity, there is a significant reduction in fluidization height of soybean in both curves. We can observe that at 7.7 m/s inlet air velocity, the fluidization heights are very good as 4.3 and 4.2 cm for blue and red curve respectively but reaching to 4.5 m/s inlet air velocity, the value of fluidization height found is very less as 1.5 and 1.4 cm. Considerable fluidization height and uniform fluidization has not achieved in the bed at the inlet air velocity less than 4.5 m/s.

![Figure 4. Curve between moisture content & time period of drying Soybean w.r.t. Various temperature of air.](image)

Figure 4 shows the graph between moisture content versus time period with respect to different temperatures represented with the unique signs. As the time exceeds the moisture content of the grains decreases gradually. At 35°C temperature, reduction in moisture was less than other two temperatures. Highest reduction in moisture was found at 45°C temperature. It shows that reduction in moisture is more with increasing temperature of inlet air.

**4. Conclusions**

From the study it can observe that at the lower values of mass flow rate of soybean, one can get higher values of fluidization height and for the mass flow rate of soybean above 2 kg, uniform fluidization is not observed. We can also observe that for the experimental set up, the inlet air velocity should not less than 4.5 m/s to achieve uniform fluidization. It can be done experimentally with the air velocities 5.9, 6.7 and 7.7 m/s and observed that the uniform fluidization occurred. It is also observed that as we increased the air velocity, the fluidization height also increased and when we increase mass flow rate, the fluidization height reduced. The implemented mathematical modeling with the fluidization model was able to predict the accurate values of reduction in moisture content as well as drying rates according to the different air velocities, different mass flow rate and inlet air temperatures. The soybean meal drying behavior in fluidized bed may provide important data for control, optimization and design of this kind of dryer. We can conclude that the values of fluidization heights with the different inlet air speeds ranged from 2 to 4.3 cm observed decreasing with increasing mass flow rate. And at different mass flow rates, the fluidization height decreases with the decreasing inlet air speed.
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