An experimental investigation of soybean fluidization height in a fluidized bed dryer

Sandip K[1], Paliwal H K [2] and Sharma A K[3]

Mechanical Engineering Department, REC Atarra, Banda, UP, India[1]
Mechanical Engineering Department, IET Lucknow, UP, India[2,3]
E-mail: kunwarsandip@gmail.com

Abstract

Manufacturers have been compelled to improve soybean meal, a vital protein source for global human and animal nutrition, due to continuous advancements in product quality and cost reduction. The utilization of fluidized bed dryers (FBD) has gained significant popularity in the drying of diverse products, primarily due to their numerous benefits. These advantages encompass efficient gas-solid contact resulting in a high drying rate, exceptional thermal efficiency, and relatively economical operational costs, among others. The primary focus of our investigation was to experimentally investigate the drying of soybean meal using a fluidized bed dryer. The height of fluidization during fluidized bed drying of soybean was thoroughly examined in this comprehensive study, focusing on the influence of mass flow rate, number of holes in the perforated sheet, and air entry speed. An electric heater was employed as the heating medium. The results clearly indicate that the fluidized bed height exhibited an upward trend as the inlet Us (air entry speed) increased, while the height of fluidization decreased at lower inlet Us values. When the mass flow rate was decreased, the corresponding bed height increased, whereas a higher mass flow rate led to a decrease in bed height. Furthermore, an increase in the quantity of holes present in the perforated plate leads to a reduction in the height of fluidization.

Keywords Fluidized Bed Dryer, Soybean, Hot Air Inlet Velocity, Height of Fluidization, Mass Flow Rate, Perforated Sheet.

Introduction

Soybean (Glycine max (L.) Merril) has been widely recognized as an affordable protein source, suitable for both human and animal consumption, particularly due to its high yield capacity and low harvest cost.[1] At the time of harvest, soybean typically contains a moisture content ranging from 25 % to 33 % on a db.[2] To ensure the grain's quality during storage, it is crucial to rapidly reduce its moisture content. Lowering the moisture content to around 14 % on a dry basis is essential to prevent microbial spoilage and respiratory activity in the legume, facilitating an extended storage period.[3] Furthermore, raw soybean is unsuitable for direct human consumption due to the presence of adverse nutritional elements such as proteases.[4] However, the application of rapid heat treatment can reduce the levels of these anti-nutritional substances while preserving the protein content of the legume, provided the heat treatment is carefully controlled.[5]

Fluidized bed drying (FBD) is an increasingly acknowledged rapid drying technique in the grain processing sector.[6] It is characterized by high temperatures and short treatment durations, allowing for efficient moisture removal. This method capitalizes on the fluidization of the product, which enhances the contact area between the air and the product, and utilizes high airspeeds and elevated temperatures.[7] The utilization of a fluidized bed dryer (FBD) leads to a notable increase in the contact area between the air and the product being dried, surpassing what can be achieved in static bed drying methods. This enhanced air-to-product contact area is a distinctive advantage offered by the fluidized bed drying technique.[8]

In their research, R. Martín Torrez Irigoyen and Sergio A. Giner investigated the pressure drop of air passing through fixed and fluidized beds of soybeans, with a focus on the superficial air velocity.[9] Their objective was to determine the coefficients of the Ergun equation and identify the minimum fluidization velocity (U_{mf}) for each sample. The authors emphasized the crucial need for automatic control of the fluidization velocity in this process. They highlighted that an uncontrolled process, coupled with the reduction in pressure drop caused by bed drying, could lead to the fan increasing the airflow. This scenario could result in excessive energy consumption to maintain a constant air temperature and the risk of undesired pneumatic transport leading to solids losses.[10,11]

In a comprehensive investigation carried out by Fernanda Ribeiro Gaspar Branco da Silva, both experimental and computational approaches were employed to study the drying of soybean meal within a fluidized bed dryer. The primary objective was to determine the drying kinetics of soybean and evaluate how temperature, drying agent speed, and bed height affect the fluidized bed drying process. Remarkably, the numerical simulations conducted by the researcher exhibited an exceptional level of agreement when compared to the experimental data. This striking outcome serves as strong evidence that the mathematical model utilized by the researcher effectively captures the intricate fluid dynamics and drying behavior of soybean within a fluidized bed. The successful application of Computational Fluid Dynamics in this study not only emphasizes its potential in the field of fluidized bed drying but also underscores its capability to enhance our understanding of complex drying processes.[12]

Mohsen Ranjbaran and Dariush Zare conducted a comprehensive study on the drying characteristics of soybean using a combined hot air-microwave drying method. The investigation involved five different microwave power densities (0.89, 1.6, 3.2, 4.3, and 5.3 W/g) and four levels of air temperatures (30, 40, 50, and 60 °C).[13] The researchers meticulously analyzed and interpreted the results, specifically focusing on the impact of inlet air temperature, microwave power density, bed thickness, and air velocity (Us) on the effectiveness and limitations of the drying process.[14]

With the objective of gaining a deeper understanding of the microwave-assisted fluidized bed drying process and generating practical insights for enhancement, M. Ranjbaran and D. Zare conducted a comprehensive investigation. They employed a previously validated mathematical model to simulate and analyze the performance of microwave-assisted fluidized bed drying of soybeans. The study encompassed an energy and exergy analysis under various drying conditions. By simulating and examining the effects of inlet air temperature, microwave power density, bed thickness, and inlet air velocity, they assessed the efficiency and inefficiency of the drying process.[15]

Samira Afrakhteh and Esfandiar Frahmandfar conducted a study analyzing the effects of various independent variables in moving-bed dryers on the quality of soybean seeds, utilizing data from the Seed and Plant Certification and Registration Institute in Iran.[16] Marcela L. Martínez, María A. Marín, and Pablo D. Ribotta conducted research focused on improving the drying process and inactivating heat-labile inhibitors in soybean, leading to reduced treatment time and losses. They also designed a fluidized bed dryer for this purpose.[17] Suherman Suherman, Slamet Priyanto, and Ratnawati utilized a simulator fluid bed drying method to investigate the drying kinetics of individual soybean particles. Through experiments involving different air temperatures, bed masses, and superficial air velocities, they designed a simulated continuous fluidized bed dryer for soybean, capable of handling 500 kgh^{-1} of seeds using the scale-up method.[18]

The impact of air temperature and velocity on the drying kinetics and specific energy consumption in the fluidized bed drying of soybean was examined by H. Darvishi, M. H.

Khoshtaghaza, and S. Minaei.[19] The study encompassed different temperatures and airflow rates, and six mathematical models were explored to characterize the behavior of fluidized bed drying. The findings revealed that a decrease in the energy of activation corresponded to an increase in the drying rate. Additionally, the researchers identified the minimum and maximum specific energy requirements for the soybean drying process.[20]

H. Darvishi, Md. H. Khoshtaghaza, and S. Minaei conducted a study to examine the impact of air temperature and air velocity on the drying characteristics of soybean kernels using a fluidized bed drying method. The study focused on evaluating the drying qualities, including cracking, bulk density, shrinkage, and rehydration. The researchers successfully established regression equations that could be utilized to estimate the quality parameters based on the drying variables.[21,22]

Based on the aforementioned study, it was discovered that fluidized bed drying is widely employed in the food and chemical processing industries due to its ability to achieve high heat and mass transfer coefficients, resulting in high-quality dried products. When air passes through a bed of Soybeans supported by a perforated plate, the frictional drag generated leads to a pressure drop across the bed. As the air velocity and bed size increase, the drag and pressure drop also increase. This causes the particles to behave like a fluid, a phenomenon known as fluidization. The incipient fluidization velocity (Us) marks the point at which fluidization first occurs and is utilized to attain optimal outcomes.

Experimental Setup

For experimental purposes, a fluidized bed dryer has been designed, incorporating various components. It includes a single-phase electric motor rated at 1 kW and operating at 900 rpm, a centrifugal fan with four heating coils, each rated at 1 kW. A schematic sketch of the fluidized bed dryer is shown in the Figure 2.1. Additionally, the setup consists of a fluidized bed and a perforated sheet. The fluidization chamber is equipped with both an inlet and an outlet specifically designed for soybean. Furthermore, a duct has been installed connecting the top of the fluidization chamber to the centrifugal fan, enabling the expulsion of hot air from the chamber. Detailed specifications of the fluidized bed and the perforated plate can be found in Table 2.1.

Table 2.1 Specifications of Fluidization Bed

Sr. Nos.	Specifications	Values
1	L_b (m)	0.41
2	W_b (m)	0.084
3	H_b (m)	0.27
4	n_h	1096, 1824, 3348
5	Th_{pp} (mm)	0.55
6	d_h (mm)	2
7	A_{pp} (mm)^2	0.03

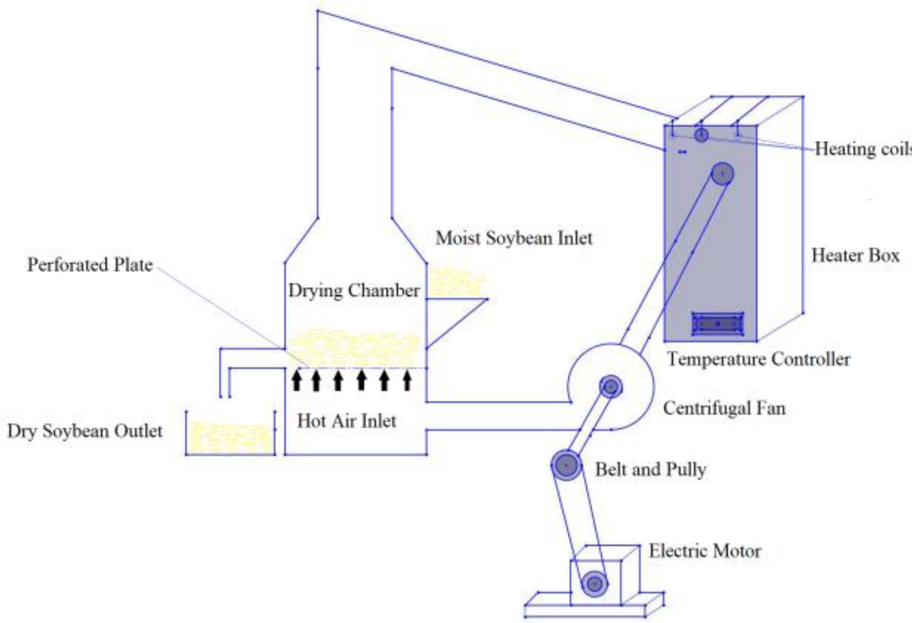

Figure 2.1 Schematic sketch of a fluidized bed dryer

Materials and methods

The soybean seeds were acquired from a local market and subsequently soaked in water for a duration of 24 hours. Afterward, a 1 kg sample of the soybean seeds was placed inside a refrigerator set at a temperature range of 6-7 °C. This step was carried out for a period of 5-7 days to allow the seeds to reach equilibrium. Once the equilibrium was achieved, the sample was carefully packed inside a sealed plastic bag. Subsequently, the sample was left at room temperature for a minimum of 24 hours prior to conducting the experiment.

A 1 kg batch of soybean samples was subjected to the drying process in a fluidized bed dryer. The drying operation took place within a rectangular fluidization chamber, measuring 0.41 m in length and 0.084 m in width. To facilitate the drying, a blower was utilized to deliver hot air, which passed through a perforated plate or grid where the soybean seeds were positioned. The grain temperature was monitored using a probe-type thermometer, while the velocity of the air was measured using a digital anemometer. During the drying process, the soybean seeds dried uniformly above the perforated plate, and their behavior resembled that of a fluid. Following the drying process, the dried soybean seeds were allowed to cool down to room temperature. Properties and conditions of soybean as well as hot air are mentioned in the Table 3.1.

Table 3.1 Soybean and hot air properties and conditions[12]

S. No.	Parameter	Value
1	ρ_s (kgm^{-3})	1106
2	ρ_a (kgm^{-3})	1.234
3	d_s (mm)	5 to 8
4	U_{mf} (ms^{-1})	1.5 to 3.0
5	m_s (kg)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0
6	U_a (ms^{-1})	4.5, 5.9, 6.7, 7.7

Results & discussion

The aim of this investigation was to determine the fluidization characteristics of soybean using an experimental setup. Different mass flow rates of soybean, ranging from 0.5 to 2 $kgmin^{-1}$, were introduced into the bed. For each mass flow rate, the initial bed height (h_1) was measured. With a fixed inlet air velocity of 4.5 ms^{-1}, the blower was activated, leading to fluidization within the bed. The final bed height was measured after the fluidization process. To ensure accuracy, the experiment was repeated five times for each mass flow rate, resulting in five values of the final bed height. The average of these values was considered as the final bed height (h_2). By subtracting the initial bed height from the final bed height, the height of fluidization (h_F) for each mass flow rate of soybean was determined.

The aforementioned process was repeated for three additional inlet air velocities: 5.9, 6.7 and 7.7 ms^{-1}, using the same mass flow rates of soybean. The heights of fluidizations were calculated for each combination of mass flow rate and inlet air velocity. Notable observations from the experiments were compiled and organized in Table 4.1.

Table 4.1 Experimental observations of bed characteristics for various inlet air velocities

For U_a = 4.5 ms^{-1}							
m_s (kg)	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**
h_1 (cm)	1.6	2.7	3.7	4.8	5.9	6.9	8
h_2 (cm)	3.3	4.3	5.1	6.1	7	7.9	8.9
$h_F = h_2 - h_1$ (cm)	1.7	1.6	1.4	1.3	1.1	1	0.9
For U_a = 5.9 ms^{-1}							
m_s (kg)	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**
h_1 (cm)	1.6	2.7	3.7	4.8	5.9	6.9	8
h_2 (cm)	4.4	5.4	6.2	7.2	8.1	9	10
$h_F = h_2 - h_1$ (cm)	2.8	2.7	2.5	2.4	2.2	2.1	2
For U_a = 6.7 ms^{-1}							
m_s (kg)	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**
h_1 (cm)	1.6	2.7	3.7	4.8	5.9	6.9	8
h_2 (cm)	5.3	6.2	7.1	8.1	8.9	9.8	10.7
$h_F = h_2 - h_1$ (cm)	3.7	3.5	3.4	3.3	3	2.9	2.7
For U_a = 7.7 ms^{-1}							
m_s (kg)	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**
h_1 (cm)	1.6	2.7	3.7	4.8	5.9	6.9	8
h_2 (cm)	6	7	7.8	8.8	9.8	10.6	11.6
$h_F = h_2 - h_1$ (cm)	4.4	4.3	4.1	4	3.9	3.7	3.6

The relationship between height of fluidization and mass flow rates of soybean for four different inlet air velocities is illustrated in Figure 4.1. The curves plotted in the figure represent this behavior, with the black curve depicting fluidization at an inlet air velocity of 4.5 ms^{-1}, while the red, blue and green curves represent 5.9, 6.7 and 7.7 ms^{-1} inlet air velocities, respectively. It can be observed from all four curves that an increase in the mass flow rate of soybean in the bed leads to a decrease in height of fluidization. Additionally, a closer examination reveals that a small increase of 0.25 kg in the mass flow rate of soybean results in a minimal reduction of height of fluidization, typically in the range of 1 to 2 mm. On the other hand, a larger increment of 1.5 kg in the mass flow rate of soybean leads to a more significant decrease in height of fluidization, typically ranging from 8 to 10 mm.

When the mass flow rate of soybean in the bed exceeded 2 kg, a distinct behavior of fluidization was observed. While fluidization of soybeans was effective in the central region of the bed, it was significantly lower in both corners. As a result, the fluidization achieved was not deemed uniform throughout the bed.

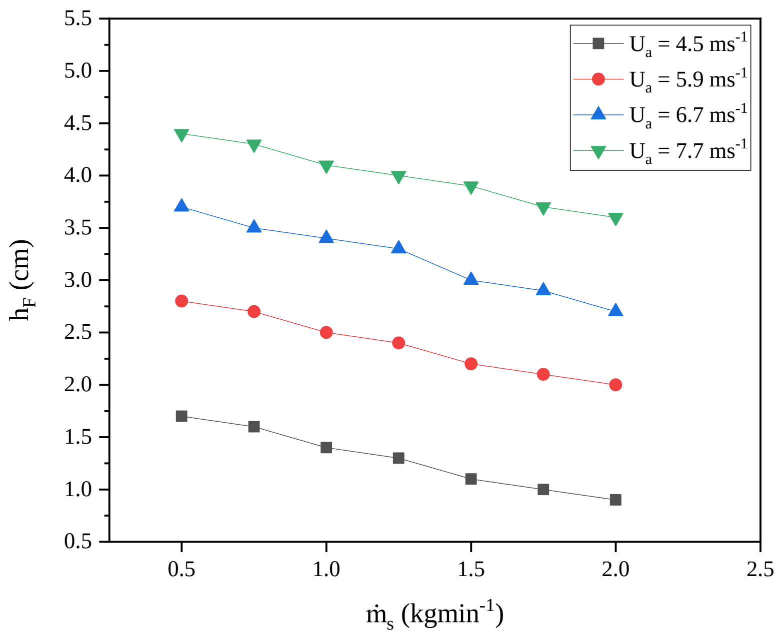

Figure 4.1 Variation of height of fluidization Vs mass flow rate with respect to four different hot air inlet velocities

Figure 4.2 illustrates the relationship between height of fluidization and inlet air velocity for seven different mass flow rates of soybean: 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2 kgmin^{-1}. The black curve represents the 0.5 kgmin^{-1} mass flow rate, while the red, blue, green, purple, brown and sky blue curves represent the 0.75, 1, 1.25, 1.5, 1.75 and 2 kgmin^{-1} mass flow rates. All the curves demonstrate a noticeable decrease in height of fluidization as the inlet air velocity decreases.

At an inlet air velocity of 7.7 m/s, the heights of fluidizations are relatively high, measuring 4.4 and 4.3 cm for the black and red curves, respectively. However, as the inlet air velocity decreases to 4.5 ms^{-1}, the heights of fluidizations substantially decrease to 1.7 and 1.6 cm for the respective curves. It is evident that achieving a significant and uniform height of fluidization in the bed is challenging at inlet air velocities below 4.5 m/s.

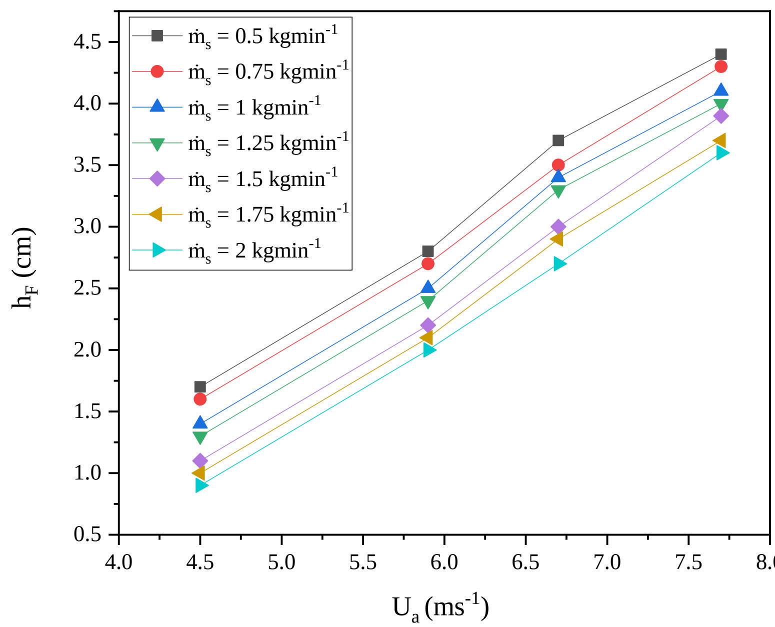

Figure 4.2 Variation of height of fluidization Vs hot air inlet velocity with respect to seven different mass flow rates

Figures 4.3 and 4.4 depict the relationship between height of fluidization and hot air inlet velocity for soybean at mass flow rates of 0.5 and 0.75 kgmin^{-1} respectively. The graphs indicate that an increase in hot air inlet velocity leads to a corresponding increase in height of fluidization. Figure also displays three distinct curves, each representing a different number of holes in the perforated sheets. As the number of holes in the perforated sheet increases, the height of fluidization decreases. Increasing the number of holes in the perforated plate leads to a reduction in hole diameter and open area. Consequently, the resulting heights of fluidizations decrease. Conversely, decreasing the number of holes in the perforated plate causes an increase in hole diameter while decreasing the open area. As a result, the attained heights of fluidizations increase. It is not advisable to use a perforated plate with hole diameters below 1 mm since it does not provide significant fluidization. On the other hand, hole diameters above 3 mm result in the expulsion of soybean seeds by the airflow, without achieving any substantial fluidization.

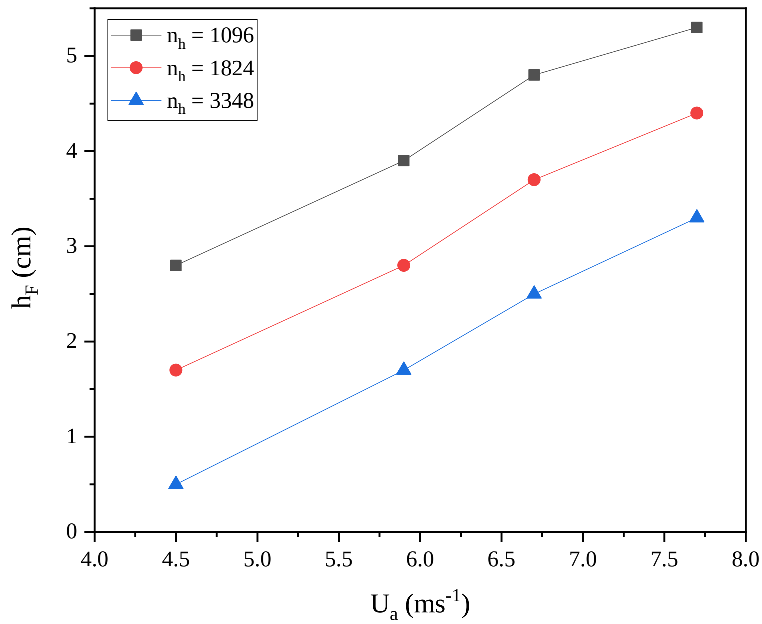

Figure 4.3 Variation of height of fluidization Vs hot air inlet velocity with respect to number of holes in perforated plate at a fixed mass flow rate of 0.5 kgmin^{-1}

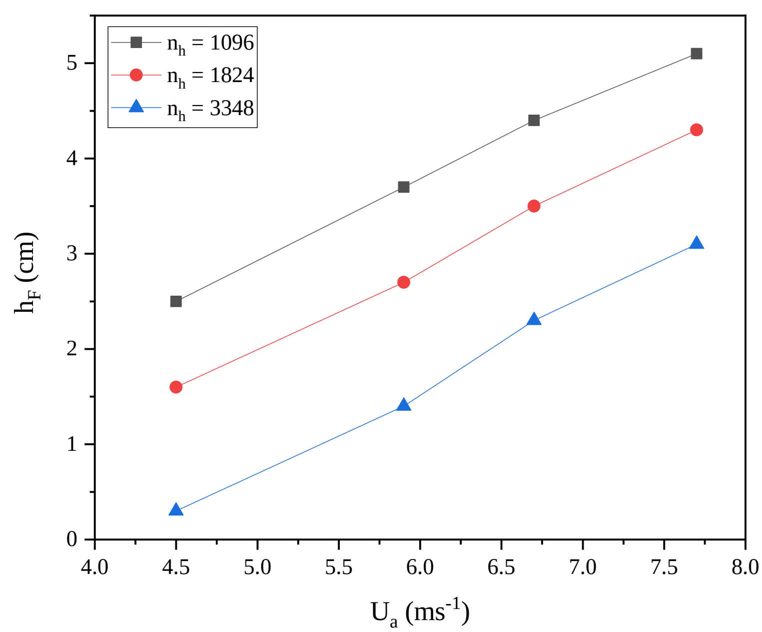

Figure 4.4 Variation of height of fluidization Vs hot air inlet velocity with respect to number of holes in perforated plate at a fixed mass flow rate of 0.75 kgmin^{-1}

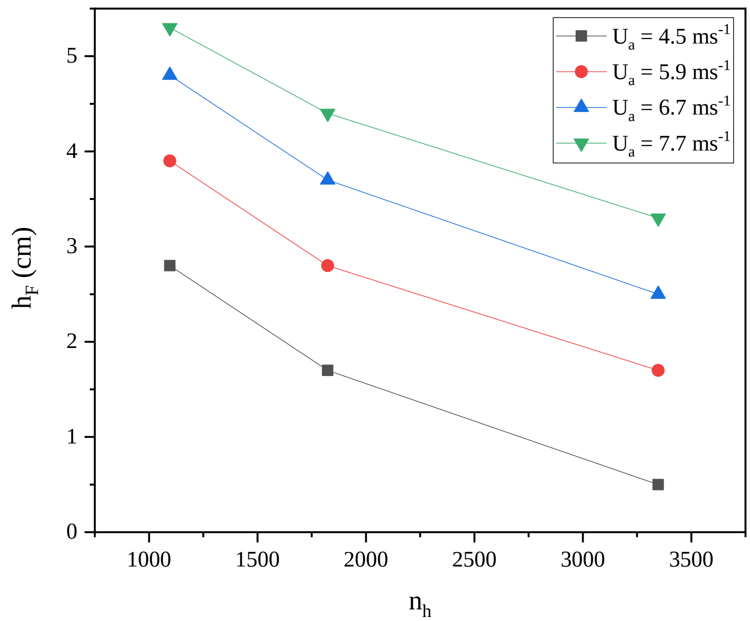

Figure 4.5 Variation of height of fluidization Vs number of holes in perforated plate with respect to hot air inlet velocities at a fixed mass flow rate of 0.5 kgmin^{-1}

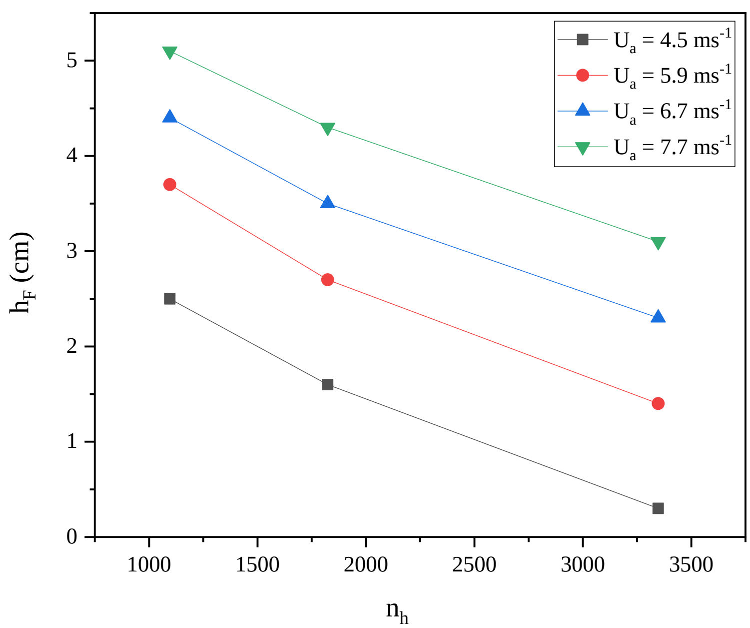

Figure 4.6 Variation of height of fluidization Vs number of holes in perforated plate with respect to hot air inlet velocities at a fixed mass flow rate of 0.75 kgmin^{-1}

Figures 4.5 and 4.6 illustrate the correlation between height of fluidization and the number of holes in the perforated plate for soybean at mass flow rates of 0.5 and 0.75 $kgmin^{-1}$, respectively. It is evident from the figures that as the number of holes increases, the height of fluidization decreases. Additionally, the figures feature four curves representing different hot air inlet velocities and they also demonstrate that an increase in hot air inlet velocity corresponds to an increase in height of fluidization.

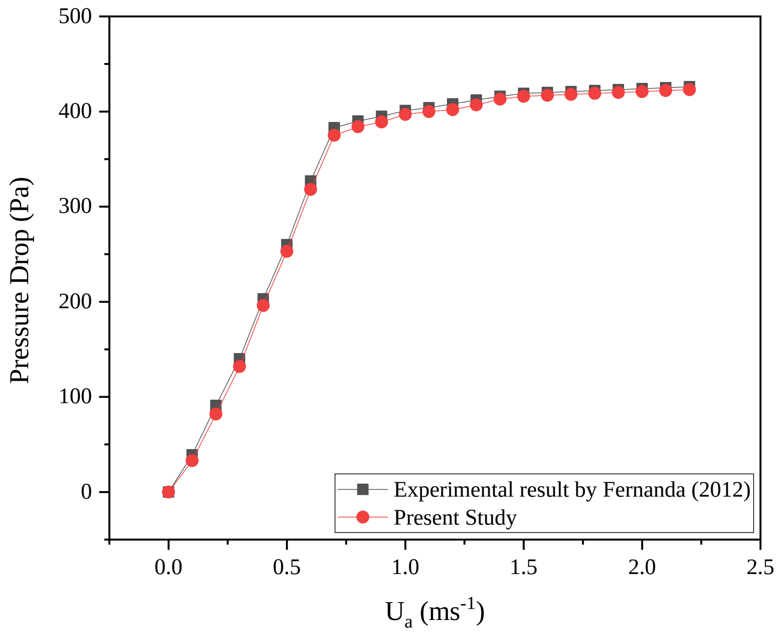

Figure 4.7 Variation of pressure drop Vs hot air inlet velocity

Figure 4.7 represents the relationship between pressure drop and hot air inlet velocity, with two distinct curves: one in black representing Fernanda's experimental results, and another in red representing the findings of the present study. The curves clearly demonstrate that as the hot air inlet velocity rises, the pressure drop experiences a sharp increase for certain initial values of hot air inlet velocities. However, it reaches a point where the pressure drop becomes nearly constant for higher velocities.

Based on the aforementioned data, it is evident that an increase in the velocity of the hot air inlet leads to a corresponding increase in the height of fluidization. Conversely, when the mass flow rate rises, the height of fluidization decreases. Furthermore, a decrease in the height of fluidization occurs with an increase in the number of holes present in the perforated plate.

Conclusions

The study reveals several important findings. Firstly, it is observed that lower mass flow rates of soybean result in higher height of fluidizations. Conversely, for mass flow rates exceeding 2 kg, uniform fluidization is not achieved. Secondly, it is evident that a minimum inlet air velocity of 4.5 ms^{-1} is necessary for achieving uniform fluidization in the experimental setup. This was confirmed through experiments conducted at air velocities of 4.5, 5.9, 6.7, and 7.7 ms^{-1}, which demonstrated uniform fluidization.

Furthermore, the study indicates that increasing the air velocity leads to higher height of fluidizations, while increasing the mass flow rate of soybean results in a reduction in height of fluidization.

The investigation of soybean meal drying within a fluidized bed offers crucial knowledge that can be applied to effectively manage, optimize, and design such drying systems. Notably, the experimental results revealed variations in height of fluidizations ranging from 2 cm to 4.3 cm, depending on the specific inlet air velocities employed. Interestingly, it was observed that as the mass flow rate increased, the height of fluidization showed a corresponding decrease. Moreover, when examining different mass flow rates, a decrease in height of fluidization was observed with decreasing inlet air velocity. This finding suggests a clear relationship between mass flow rates, inlet air speeds, and the resulting height of fluidizations, providing valuable insights for the control and optimization of fluidized bed dryers.

Nomenclature

d_s	Soybean diameter (mm)
U_{mf}	Minimum fluidization velocity of hot air (ms^{-1})
U_a	Superficial air velocity (ms^{-1})
m_s	Mass of soybean (kg)
$\dot{m}_s$	Mass flow rate of soybean ($kgmin^{-1}$)
RH	Relative humidity (dimensionless quantity)
db	Dry basis

L_b	Bed length (m)
W_b	Bed width (m)
H_b	Bed height (m)
n_h	Number of holes in perforated plate
d_h	Diameter of hole
Th_{pp}	Thickness of perforated plate
A_{pp}	Area of perforated plate
h_1	Initial height of soybean bed
h_2	Final height of soybean bed
h_F	Height of fluidization

Greek symbols

ρ_s	Density of soybean (kgm^{-3})
ρ_a	Density of air (kgm^{-3})

Subscripts

$_1$	Initial
$_2$	Final
s	Soybean
a	Air
mf	Minimum fluidization

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