DRYING KINETICS, ENERGY AND EXERGY ANALYSES OF SINGLE AND MULTISTAGE FLUIDIZED BED DRYERS

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by

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CERTIFICATE

This is to certify that the thesis entitled **“Drying kinetics, Energy and Exergy Analyses of Single and Multistage Fluidized Bed Dryers”** being submitted by Mr. **D. Yogendrasasidhar** for the award of the degree of Doctor of Philosophy (Ph.D) in Chemical Engineering to the National Institute of Technology, Warangal, India is a record of the bonafide research work carried out by him under my supervision. The thesis has fulfilled the requirements according to the regulations of this Institute and in my opinion has reached the standards for submission. The results embodied in the thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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DECLARATION

This is to certify that the work presented in the thesis entitled "Drying kinetics, Energy and Exergy Analyses of Single and Multistage Fluidized Bed Dryers" is a bonafide work done by me under the supervision of Prof. Y. Pydi Setty and was not submitted elsewhere for award of any degree.

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original source. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission.

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CONTENTS

ABSTRACT

Generally drying operation is a process that is used for reducing the moisture content in the wet product. The fluidized bed dryers are prominent moisture removal devices in particulate industries. Various studies have been conducted by previous researchers to improve the product quality and efficiency of dryers with various modified designs. In the present scenario, the main goal of researchers is to obtain maximum energy from the process equipment and several modifications and designs have been suggested by many earlier investigators in this line. The energy assessment is one of the important studies of process equipment. The energy utilization, exergy losses and exergy efficiency vary with material properties and dryer conditions.

In the present study, experiments were carried out in batch wall heated fluidized bed dryer with Kodo millet, Fenugreek seeds and in continuous wall heated multistage fluidized bed dryer with Pearl millet and Barnyard millet grains as bed materials. The exergy and energy of drying was analyzed by changing wall temperature (313 to 333 K), air velocity (1.01 to 1.7 m/s), bed height (3 to 5 cm) and initial moisture content (10 to 20%) in batch dryer and the continuous multistage dryer was operated by varying wall temperature (313-328 K), velocity of air (1.01-1.3 m/s), downcomer height (50-70 mm) and solid flow rate (5 - 10 kg/h). The drying characteristics of Kodo millet and Fenugreek seeds were reported using the batch process. In continuous multistage drying, drying characteristics of Pearl millet and Barnyard millet were reported. Experimental data of pearl millet grains were validated with various models and the model constants of multistage fluidized bed drying at various conditions and stage-wise were reported at minimum RMSE error. Moisture diffusivity and activation energies were estimated at various conditions and were reported. The energy utilization ratio, exergy loss and exergy efficiency of the batch dryer and continuous multistage dryer were analyzed and reported.

In fluidized bed drying, the proper distribution of gas is very important in industrial practice. Improper distribution of gas may lead to non-idealities like channeling, short-circuiting and accumulation which gives rise to non-uniform quality of the dried product. Gas distribution depends on the distributor plate used. Gas distribution mainly depends on orifice diameter, number of orifices and the opening area of the distributor plate. Small orifice diameter leads to clogging, and a large orifice diameter gives an uneven distribution of gas. The present work

involves experimental studies using different distributor plates and simulation studies using Aspen Plus steady state simulator. The effect of various parameters such as orifice diameter, number of orifices and the opening area of the distributor plate on the performance of fluidized bed dryer have been studied through simulation and experimentation. Simulations were carried out (i) with increasing air inlet temperature to study the characteristics of solid temperature and moisture in the outlet (ii) with increasing orifice diameter and (iii) with the increase in number orifices to study the solid outlet temperature profiles. It can be observed from the simulation that, an increase in orifice diameter and number orifices increases solid outlet temperature upto certain condition and then after there is no effect with further increases. Experiments were carried out with increasing opening area (3.4 to 42%) in the form of increasing orifice diameter keeping the number of orifices constant and increasing number of orifices of the distributor plate keeping the orifice diameter constant. It can be seen that the drying rate and solid outlet temperature increase up to certain condition and then after with further increase in the orifice diameter and the number of orifices, the change in the drying rate and solid outlet temperature observed is little.

To study the energy aspects of multistage dryer, simulations were carried with continuous hot air multistage fluidized bed dryer using Aspen Plus Simulator by changing the values of air temperature from 313 to 353 K, flow rate of air from 40 to 80 kg/h, flow rate of solids from 6.7 to 12.5 kg/h and feed moisture percentage from 7.5 to 12.5%. The exergy loss and exergy efficiency of multistage fluidized dryer model were analyzed. Comparison was made with single stage dryer and reported. The simulation results have shown similar trends with experimental results.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Drying is one of the traditional unit operations in pharmaceutical, food and fertilizer industries. It describes the reduction of moisture concentration from the material. Generally, dryers can be classified based on the mode of heat transport to the wet solids. Drying involves both heat and mass transfer operations, where heat is needed to provide necessary latent heat of vaporization and liberated vapor is removed by air stream. There are many dryers commercially available. The quality is key parameter for many products. The product quality and energy usage are affected by choice (Mujumdar, 2014).

1.1 Fluidized bed drying

Particulate drying methods are increasing due to an increase in human needs mostly for food and pharmaceutical products. In particulate drying, one of the most suitable and more prominent dryers is fluidized bed dryer. Fluidized bed dryers have shown good applicability in particle drying and also have shown high efficiency in product drying. FBDs have different applications to process the product in various industries like pharmaceutical, food, granules, and fertilizer etc. Advantages of FBDs are high moisture removal rate, facilitating easy material transport, ease of control, good gas-solid mixing and uniform temperature distribution in the bed. In a fluidized bed, hot gas stream flows through the bed resulting in high heat and mass transfer rates due to more gas-particle mixing. This leads to high moisture removal rate and the moisture gets carried away with the gas stream.

1.1.1 Batch fluidized drying

Batch fluidized bed dryer is operated with small quantity of solids for drying. This type of drying method is used when the production capacity is low or for drying of several products in parallel.

1.1.2 Continuous fluidized bed drying

In industrial usage, continuous fluidized bed dryers are preferred as they can handle large throughputs for drying. In this dryer, the feed material is admitted into the dryer continuously and the dried solid particles are discharged out of the dryer continuously. As the residence time for particles may vary from particle to particle in a continuous dryer, several developments have taken place to reduce the spread of residence times, thus resulting in improved designs of the dryer to obtain uniform moisture content product.

1.1.3 Multistage fluidized bed drying

Fluidized beds offer many distinct features and advantages for processing of particulate materials. To decrease the drying time than single stage dryers, continuous multistage fluidized bed dryer is introduced and they also have an advantage with better particle gas mixing and good heat and mass transfer The multistage dryer is designed by connecting two or more fluidized beds internally or externally, where each bed is termed as a stage. Advantages of the multistage dryer are the improvement in gas-solid axial mixing, which results in good quality of product. Due to stage-wise contact of solids with gas, dried product can be obtained uniform moisture content.

1.1.4 Hot air fluidized bed drying

Generally, in a fluidized bed, the bed of solids is suspended in a gas stream that gives good mixing between gas and solids. In hot air fluidized bed dryer, the dryer is operated with the hot gas stream to dry the wet solids. Hence the necessary heat input for drying of wet particles is through hot air. This requires a pre-heater for supplying hot air at the required temperature.

1.1.5 Wall heated fluidized bed drying

Wall heating is a method used in a fluidized bed dryer to intensify the drying process. In a hot air fluidized bed dryer, one has to preheat air in a pre-heater to the desired temperature which requires energy for heating and also the heating process of air requires more energy as the thermal conductivity of air is less. But in wall heating method, the temperature of wall reaches required temperature in a very short interval of time and heat transport can be done by different modes like wall to gas, gas to solid and wall to solids. Thus wall heated fluidized bed dryer improves the drying efficiency in a fluidized bed dryer.

1.1.6 Air flow distribution

Proper gas distribution is very important in fluidized bed drying to provide good fluidization behavior in industrial practice for uniform quality of the product. Improper distribution of gas may lead to non-idealities like channeling, short-circuiting and accumulation which gives rise to the non-uniform quality of the dried product. Gas distribution depends on the distributor plate used. Gas distribution mainly depends on orifice diameter, number of orifices and the opening area of the distributor plate. The distributor plate gives support for material in the bed and also gives the desired distribution of fluidizing gas. Generally, fluidized bed requires uniformity of gas distribution in the bed as gas distribution plays a vital role on particle drying. It can influence gas-solid contact, mixing, solid circulation, heat and mass transfer rates in a fluidized bed dryer. Further, few investigators have studied on (i) hydrodynamics, changing distributor plates in a conical fluidized bed (Son et al., 2005), (ii) drying behavior of porous material and gas-solid mixing and mass transfer of biomass in pulsed fluidized bed dryer (Jia et al., 2016; Nitz and Taranto, 2009) (iii) simulation studies of transient gas to particle heat transfer in fluidized bed dryer (Fattahi et al., 2016) and (iv) development of mathematical model for emulsion phase in a continuous fluidized bed dryer (Garnavi et al., 2006). The distributor plate design has a significant role in the performance of a fluidized bed dryer (Hilal et al., 2001; Nienow et al., 1987; Wormsbecker and Pugsley, 2009, 2007).

1.2 Bed materials

The drying rate in the fluidized bed is strongly influenced by the material characteristics and the fluidization condition. Based on the particle size and the nature of solids, different types of fluidization behavior can be observed. Based on fluidization velocity, one can observe bubbling fluidization, fast fluidization, spout fluidization and slug type fluidization. Fluidized bed dryer can be implemented for a wide range of particle sizes. According to Geldart classification, the solid particles are classified into four types such as C, A, B and D based on their fluidization behavior. Group B and D solid particles are mostly used in different types of industries like Food, Pharmaceutical and Cement. Type B particles are easily fluidized with good growth rate of bubbles and Type D solid particles are dense particles and in deep beds they are difficult to fluidize and it may result in severe channeling and spouting at higher velocities (Kunii and Levenspiel 1991).

Bio-originated solids are difficult to dry due to the presence of inherent moisture. The fluidized bed dryers are suitable to perform drying operations and removing the moisture from agro-based solids like grains and seeds. Now a days, rapid climatic changes are resulting in an unpredictable manner around the globe. Maintaining the grains and seeds with good quality in the rainy season and winter season is becoming difficult. Moisture content present in grains or seeds during storage, causes fungal attack which leads to changes in the natural properties of grains and seeds. Hence, proper drying is necessary to avoid this. Fluidized bed dryers are most commonly used for drying grains, seeds and other agro-based products either for storage or for further processing.

Grains are one of the important crops in many countries like India, Sri Lanka, Africa, etc. Generally, grains contain a large amount of nutrients, fiber and protein. In ancient civilization, grains were used for eating purposes and as wages for workers. Drying behavior of materials varies with the material characteristics like structure, porosity, diameter, etc. Determination of drying characteristics and moisture diffusion is also important to maintain proper quality of the product. Seeds and grains play a vital role in the food products. Millets are one of the oldest grains, containing higher protein, fat, and minerals than rice, corn, or sorghum. Many countries like India, China and Srilanka, etc., produce various types of millets such as Finger millet, Pearl millet, Kodo millet and Barnyard millet etc. Each type of millet grain has its own importance and applications.

Many researchers have conducted drying studies on grains like wheat, finger millet and pearl millet, etc (Srinivasakannan and Balasubramanian, 2006; Srinivasakannan and Balasubramanian, 2009a). Also, some other researchers have worked on similar drying studies on different food materials like pepper seeds, rambutan seeds, hazelnuts, and maize, etc (Kaensup et al., 1998; Prachayawarakorn et al., 2004).

1.2.1 Fenugreek seeds

Fenugreek seeds are native to South-Eastern Europe, but now it is also being produced in India and is largely used as a spice ingredient in food. These seeds are also rich in carbohydrates and vitamins.

1.2.2 Pearl millet

Pearl millet is an important species, which is fifty percent of the total millet production. India and Africa are the main producer countries. These are grown in hot and dry conditions. The pearl millet has higher fat and protein content, and better quality protein than most other cereal grains.

1.2.3 Kodo millet

Kodo millet grains are grown once a year mostly, in India, also in some other countries like Indonesia, Philippines, Thailand, and Vietnam, etc. These grains are rich in fibers and carbohydrates.

1.2.4 Barnyard millet

Barnyard millet is rich in iron and calcium and it contains high carbohydrate, protein, fat and fiber nutrients. The unique quality of Barnyard millet grains is the presence of phosphorous and it helps in fat metabolism, repair of body tissue and conversion of food into energy (Singh et al., 2010). Barnyard millet (Echinochloa frumentacea L.) is grown in the arid and semiarid regions in countries like Nepal, Pakistan, and India, etc. In India, it is widely grown in Andhra Pradesh, Telangana, Tamil Nadu, Uttaranchal, Chhattisgarh and Karnataka states.

1.3 Drying kinetics

1.3.1 Thin layer drying models

The thin layer drying models are useful tools for the prediction of the drying kinetics of heat-sensitive bed materials. The drying curves can be used by fitting the drying rates for a suitable model for the drying process under respective operating conditions. Thin layer modeling is based on having a set of mathematical equations that are detailed and simplified enough that they can approximately describe the drying system.

1.3.2 Effective moisture diffusivity

Moisture diffusion is a complex process during porous particle drying. It can be by molecular diffusion, surface diffusion, Knudsen flow, or capillary flow and if one combines all these phenomena into one, the transport property is termed as effective moisture diffusivity. The moisture diffusivity depends on material moisture, material characteristics and drying temperature (Khanali et al., 2016).

1.3.3 Activation energy in drying

During drying, the bonding potential between moisture and wet material is the main parameter for detaching the moisture from wet solids. The bonding potential of moisture can be quantified with the activation energy, which is the energy needed for detaching one mol moisture from the wet material with constant compositions and given moisture content (Miraei Ashtiani et al., 2017).

1.4 Energy and Exergy analyses

Now days, the demand for energy is increasing around the globe because of economical development and industrialization and population growth (Reddy, 2013). Energy is an important parameter of study for any process equipment and thermo-dynamical approach can be used to analyze the energy assessment of any process. To maintain proper quality of the product, the quantity of energy consumption as well as heat and mass transfer studies are important for any drying process. The thermodynamic analysis is the key study of the system design for energy analysis and optimization. The second law of thermodynamics facilitates the assessment of the maximum amount of work achieved in a given system with different energy sources.

1.4.1 Energy utilization ratio

The ratio of the amount of energy required to convert moisture present in the material into the steam of the dryer to the energy input to the dryer. The values of EUR show the effectiveness of the input energy into the dryer used for removing the moisture from the product (Karthikeyan and Murugavelh, 2018).

1.4.2 Exergy

The energy examination of any system by considering the first law of thermodynamics does not describe the process system irreversibility. In this context, based on the second law of thermodynamics, the exergy analysis will be able to describe the work potential of the system.

Exergy is the useful work of a system or stream as it proceeds to an equilibrium state with respect to a reference environment (Mehmood et al., 2015; Regulagadda et al., 2010).

1.4.3 Exergy efficiency

Exergy efficiency is defined as the ratio of the exergy outflow to exergy inflow for the dryer. It can tell the performance of the dryer with a true measure which can be found thermodynamically. (Karthikeyan and Murugavelh, 2018).

Table 1.1 Comparison and contrast between energy and exergy: (Dincer and Rosen, 2013)

Energy	**Exergy**
Depends on only energy flow, and independent of properties of the environment	Depends on energy flow and the environment
Can be neither destroyed nor produced	Can be neither destroyed nor produced in a reversible process, but is always destroyed (consumed) in an irreversible process
Appears in various forms (e.g., potential energy, kinetic energy, heat and work) and is measured in that form	Appears in various forms (e.g., potential energy, kinetic energy, heat and work), and is measured on the basis of work or ability to produce work
A measure of quantity only	A measure of both quantity and quality

1.5 Modeling and simulation

In general, the successful design of any research equipment takes more process time and cost. Before designing any process equipment, work on modeling and simulation of the process helps in achieving better design. Various simulators which are based on the computer-aided design are available for simulating the process.

Modeling is defined as the process of translating physical laws to mathematical equations used to design or analyze the process. A simulator is computer software which consists of mathematical models and graphical interface for predicting the performance of the system or process. Drying characteristics of particles in dryers are time-variant, complex and nonlinear. Modeling of a drying process is important for simulating and optimizing the process and to control the moisture. Presently, modeling and simulation studies have increased in drying fields with various methods and different bed materials. Various researchers have investigated on modeling of the drying process and conducted simulation studies using different mathematical equations and modeling and simulation software (like MATLAB, ANSYS, ASPEN, DryDSim etc). A process simulator is a software like Aspen Plus that allows modeling and simulation for different industrial processes and it suits better for studying the performance of any process.

1.6 Motivation for the study

Industries are very energy consuming organizations. In industry, the drying operation is one of the energy-intensive processes (Karthikeyan and Murugavelh, 2018). It is an important thermal unit operation of the commercial industries of agriculture, food, pharmaceutical, and mineral. Hence it is necessary to design the dryers with minimal energy consumption for particulate handling industries.

Drying behavior of materials varies with the material characteristics like structure, porosity, diameter, etc. Determination of drying characteristics and moisture diffusion is also important to maintain proper quality of the product. Maintaining the grains and seeds with good quality in the rainy season and winter season is becoming difficult. Moisture content present in grains or seeds during storage causes fungal attack which leads to changes in the natural properties of grains and seeds. To maintain proper quality of the product, the quantity of energy consumption as well as heat and mass transfer studies are important for any drying process. The most exergy demanding process is the popular convective dryer either batch or continuous (Dincer and Rosen, 2013).

Many researchers have conducted drying studies on grains like wheat, finger millet and pearl millet, etc (Srinivasakannan and Balasubramanian, 2006; Srinivasakannan and Balasubramanian, 2009a). Also, some other researchers have worked on similar drying studies on different food materials like pepper seeds, rambutan seeds, hazelnuts, and maize, etc (Kaensup et al., 1998; Prachayawarakorn et al., 2004). Several authors have analyzed energy and exergy for Fluidized bed dryers with different materials like wheat grains, paddy and poppy seeds (Syahrul et al., 2002; Skoneczna Luczkow and Ciesielczyk, 2015).

In the present scenario, the main goal of researchers is on energy assessment of process equipment and making studies for product quality improvement. Various drying methods have been suggested by many earlier investigators in this line. These reasons have motivated to start studies on fluidized bed drying with various bed materials. Different fluidized bed dryers were used to study on drying, energy and exergy analyses.

1.7 Present Work

In this work, studies were made using single and multistage fluidized bed dryers using various bed materials.

The thesis has been framed into mainly five chapters. In Chapter 1, the introduction to the present work has been presented. Chapter 2 presents a detailed literature review with reference to various aspects such as drying studies on various fluidized bed drying methods, drying studies using various bed materials, airflow distribution, studies on drying kinetics, energy and exergy analyses, modeling and simulation studies on fluidized bed drying. In Chapter 3 (Materials and Methods) experimental details of the work and equations used for calculations have been presented. Analyses of results obtained from the studies are included in Chapter 4, (Results and Discussion). In Chapter 5, conclusions drawn from the studies and scope for future work have been presented.

CHAPTER 2: LITERATURE REVIEW

This chapter framed with a detailed overview of literature survey to identify the gaps from earlier findings. The chapter has been divided into the following sections.

1. Fluidized bed drying: (i) batch fluidized bed drying (ii) continuous fluidized bed drying, (iii) air flow distribution
2. Different bed materials and various drying methods: (i) drying of various bed materials (ii) Studies on moisture diffusivity and activation energy in fluidized bed drying (iii) Studies on various fluidized bed drying methods.
3. Energy and exergy analyses of fluidized bed drying
4. Modeling and simulation studies in fluidized bed drying.

2.1 Fluidized bed drying

2.1.1 Batch fluidized bed drying

Thomas and Varma (1992) have studied the drying characteristics of black pepper, green pepper and mustard using batch fluidized bed dryer. Air velocity was varied from 2.1 to 2.4 m/s, temperature from 328 to 378 K with different solids holdup 0.5, 0.8 and 1.6 kg. They have reported that fluidized bed drying technique has shown substantial reduction in drying time compared to tray and solar drying methods.

Kaensup et al. (1998) have conducted studies on combined microwave fluidized bed dryers using pepper seeds as the bed material for drying. The operating conditions of the dryer are power input of 500 Watts, air temperature with a range of 313 - 363 K and air velocities of 5 and 8 m/s. From the reports, it was noticed that drying rate is effected by temperature at low air temperatures and the effect has reduced after 20 minutes of drying. Higher drying rates have been reported at higher temperatures and air velocities.

Poomsa-ad et al. (2002) have conducted studies on drying and tempering models using a fluidized bed dryer and developed a tempering model to predict the moisture movement of single paddy kernel. The parameter of this equation has been evaluated in the temperature range 383 to 443 K with regression analysis using 189 experimental data. They have reported that the drying rate during the second stage drying in the fluidized bed dryer has improved when the tempering treatment between drying stages is included.

Kaensup and Wongwises (2004) have conducted studies on fluidized bed dryer and combined microwave fluidized bed dryers with fresh ripe peppercorns as bed material. The operating conditions of the dryer are power input 2.3 and 1.5 kW, air temperature 313 - 363 K and air velocities 3.5 – 6 m/s. They have reported drying characteristics in the form of average moisture contents and drying rates. They have reported that the microwave field from the combined microwave fluidized bed dryers has increased the potential of the conventional fluidized bed drying. From results, it has been seen that the drying rate of peppercorn increased with an increase in air temperature and the air velocity of both dryers.

Bauman et al. (2005) have studied on drying behavior of grape, apricot, peace fruits using fluidized bed dryer. Initial moisture content in grape berries as 81.5%, peach as 87.7% and apricot as 86.9% were observed. The study was conducted changing air temperature from 343 to 373 K and air velocity from 0·98 m/s to 5·2 m/s. Based on studies it was mentioned in their reports that the drying time of fluidized bed is minimum even at lower temperatures (it is important for fruit quality after rehydration), than conventional drying methods.

Kulshreshtha et al. (2009) have investigated the effect of fluidized bed drying condition on mushroom quality. Drying was carried at air temperatures of 323, 343, and 363 K and air velocities of 1.71 and 2.13 m/s, and two batch sizes 0.5 kg and 1 kg of sliced milky mushrooms. It was noticed that the drying rate of mushroom increased with an increase in air temperature and air velocity. They have concluded from their results that the drying rate constant is maximum (k = 0.064) for the batch size of 0.5 kg at air temperature of 363 K and the air velocity of 2.13 m/s. The best efficiency has been reported at a batch size of 1 kg, air velocity of 1.7 m/s and air temperature of 323 K.

Ozahi and Demir (2014) have investigated the drying characteristics of corn and unshelled pistachio nut using a batch fluidized bed dryer at different particle mass loading of 0.1 to 0.3 kg at different air temperatures of 323 to 348 K at different gas stream velocities ranging from 6.87 to 10.86 m/s. It has been reported that the increase of amount of particle mass caused the increase of drying time and an increase in air temperature and air velocity resulted in a decrease of the drying time.

Chen et al. (2017) have investigated the drying performance of two differently sized batch fluidized bed dryers (Miniglatt and GPCG-1) at different parameters such as initial moisture content, material loading, temperature of air and air flow rate using dibasic calcium phosphate powders. Operating conditions of two dryers are different 1.Miniglatt dryer operated at initial moisture content (10 and 20%), material loading (0.5 and 0.8 kg), temperature of air (333K and 353K) and air flow rate (10 and 15 m^3/h) 2. GPCG-1 dryer operated at initial moisture content (6, 10 and 20%), material loading (3 and 4 kg), temperature of air (333K, 353K and 373K) and air flow rate (40 and 54 m^3/h). From the results, it has been reported that for large scale fluidized bed dryer the four parameters have significant influence, whereas for a small scale fluidized bed dryer only initial moisture content and air flow rate have the significant influence on the drying behavior. From the study, they reported in conclusions that the drying operation can be carried out at low temperatures and at high airflow rate for both small and large scale fluidized bed dryers.

2.1.2 Continuous fluidized bed drying

Chandran et al. (1990) have investigated drying kinetics in a continuous fluidized bed dryer using ion exchange resin and sand as bed materials varying parameters such as air flow rate (0.092 to 0.152 m^3/s), temperature (300 to 350 K) and solids flow rate (55 to 80 $kg/m^2.s$). They have developed mathematical models to predict average moisture content and residence time of solids in the continuous fluidized bed dryer and comparison was made with the experimental results. The authors found that the model predicted results were in good agreement.

Srinivasakannan et al. (1995) have studied the drying kinetics in continuous single stage and multistage fluidized bed dryers using different materials such as sand, ragi, mustard and poppy seeds varying parameters like air flow rate (0.06 to 0.098 m^3/s), air temperature (313 to 353 K), and solids feed rate (0.03 to 1.5 $kg/m^2.s$). They have developed correlations to predict the average moisture content in the fluidized bed and residence time in a continuous fluidized bed dryer provided with a single stage and incorporating all the variables. They compared the experimental results with predicted results and found that the predicted results were satisfactorily matching the experimental results.

Hoehne et al. (2010) have studied drying kinetics in a pressurized steam continuous fluidized bed dryer using wet lignite particles of size ranging from 0 to 10 mm at different pressures ranging from 1.1 to 7 bar with different initial moisture contents ranging from 55 to 65% and different temperatures ranging from 373 to 433 K using saturated steam as heating medium. They have experimentally investigated the optimum conditions for the drying of lignite from different countries for large scale operations of 10 T/h in a continuous fluidized bed dryer.

Akbari et al. (2012) have studied the drying behavior in a continuous fluidized bed dryer for drying of baker's yeast at different velocities, temperatures and bed loadings. They have operated with four zones (Areas from 28 to 4.4 m^2) for continuous drying of baker's yeast for large scale operations. The authors have reported that the operating conditions such as temperature, loading rate of compressed yeast granules, and hot air humidity had direct effects on both yeast activity and viability. They have reported observations, that the most influencing parameters that affected the drying quality of the product were loading rate and the operational temperature in each zone of the bed.

Srinivasakannan et al. (2012) have examined the drying kinetics of solids using a continuous fluidized bed dryer with and without internals. Bed material was taken as finger millets (Ragi grains) of size 1.48 mm diameter at different bed loadings of 1.3 and 2.6 kg at different temperatures ranging from 333 to 353 K using an air velocity of 1.2 m/s. The experimental results of continuous fluidized bed dryer have been compared with batch fluidized bed dryer and reported that the continuous dryer without internal gives lower drying rates in comparison with batch fluidized bed dryer and continuous fluidized bed dryer with internal. Continuous fluidized bed dryer with internal gives drying rates nearer to batch drying rates.

Khanali et al. (2018) have investigated the drying characteristics of shelled corn using continuous plug flow fluidized bed dryer. Differential equation model was developed for the drying process. The validation of the model has been done with experimental results at three inlet dry solid mass flow rates (245, 420 and 565 g/min), air temperatures (from 323 to 373 K) and two weir heights (0.025 and 0.05 m). It has been seen from the results that the solid moisture content decreased by increasing both the inlet gas temperature and weir height, and increasing the inlet dry solid mass flow rate led to the increased solid moisture content.

Table 2.1. Experimental investigations of fluidized bed dryer by various researchers

Author	Type of dryer	Study	Bed material	Operating conditions	Reports
Soponronnarit (1999)	Batch and Continuous fluidized bed dryer	He has conducted the basic study on drying kinetics, factors affecting paddy quality, moisture reduction rate and energy consumption	Paddy	Air velocity: 1.7 - 2.3 m/s, Solid flow rate: 0.025 - 0.058 kg/s	Concluded that fluidized-bed paddy dryer could be competitive at high moisture level with conventional hot air dryers especially at lower energy consumption. The cost is less and gives a product of acceptable paddy quality
Tirawanichakul et al. (2004)	Batch fluidized bed dryer	Studied the effect of temperature on various quality attributes of Paddy in a fluidized bed dryer	Paddy	Constant air velocity: 2.5 m/s, bed height of rice: 9.5 cm , Air temperature: 313 to 353 K, 373 to 423 K	Reported average grain temperature and final moisture content of paddy using batch fluidized bed dryer
Niamnuy and Devahastin (2005)	Industry scale Batch fluidized bed dryer	Studied on drying kinetics and quality of coconut dried in a Batch industrial scale fluidized dryer	Finely chopped coconut pieces	Conducted different sets of experiments varying air temperature and air velocity	Reported the drying kinetics and quantity of oil on the surface of the dried product at the fixed stepwise change of air

					temperature and air velocity
Tatemoto et al. (2015)	Batch fluidized bed dryer	Studied the drying characteristics of food materials injected with organic solvents in a fluidized bed of inert particles under reduced pressure	Rice and soybean protein powders were mixed (mass ratio, 3:2)	With the injection of different organic solvents to material	Reported the drying behavior and effective diffusivity with the injection of various organic solvents
Cardenas-Bailo et al. (2016)	Batch spout fluidized bed dryer	Studies on quality parameters of dried carrot cubes in a spout fluidized bed dryer with and without the draft tube	carrot cubes	At various temperatures (333 to 353 K) and different volumes of cubes	Reported the drying kinetics, effective diffusivity and rehydration ratio of carrot cubes varying temperature and volume of cubes
Idakiev et al. (2017)	Fluidized bed dryer with inductive heating	Investigated the drying of particulate solids (porous and non-porous solids) using a cylindrical fluidized bed dryer by inductive and convective heating	Porous gamma aluminum oxide spheres and non-porous alpha aluminum oxide spheres	Conducted experiments for different bed materials of different diameter varying initial moisture content (22.90 to 34.40%), air inlet temperature (293 to 336	Reported the drying behavior of bed material and gas outlet temperature at different temperatures, initial moistures and air velocities using inductive heating balls in cylindrical

				K) and air velocity (3.24 to 4.34 m/s)	fluidized bed dryer
Taghavivand et al. (2017)	Batch conical Fluidized bed dryer	Experimental investigation of drying of pharmaceutical granules and tribocharging behavior in a fluidized bed dryer	Lactose Monohydrate, Microcrystalline Cellulose, Hydroxypropyl Methylcellulose and Croscarmellose Sodium	Air velocity: 1 to 1.8 m/s, Air temperature: 311 to 348 K	Reported drying kinetics and activation energy of pharmaceutical granules and reported tribocharging behavior varying different parameters
Zhang et al. (2018)	Batch fluidized bed dryer	Studies conducted on the measurement of moisture content in a fluidized bed dryer using an electrostatic sensor array	Corn particles with 1 to 1.8 mm particle size	Air velocity: 0.43 to 0.67 m/s, Air temperature: 318 to 348 K	Studied the drying behavior of material varying air temperature and air velocity and reported the relation of electrostatic fluctuation

2.1.3 Effect of air flow distribution

Saxena et al. (1979) have studied the distributor influence on gas-solid fluidization using the fluidized bed. Experimentations were conducted using a porous plate, two bubble cap distributors having different geometries and Johnson screen distributor having different opening areas in the fluidized bed. From reports, it was noticed that the distributor pressure drop was found to be increasing with increase in fluidizing velocity and decreasing with increase in the opening area of the distributor plate.

Ouyang and Levenspiel (1986) have studied using spiral distributor to know the effect of opening area of the distributor in a fluidized bed. The fluidization quality, hydrodynamic characteristics and heat transfer coefficients were determined. From their results, it has been found that the heat transfer coefficient increases with increasing opening area percentage from 1.43 to 4.1% of the spiral distributor.

Nienow et al. (1987) have conducted studies on mixing/ segregation of particles in the fluidized bed with porous, perforated and standpipe distributor. The mixing index was presented with changing orifice diameter, pitch and number of orifices. They have reported that at same air velocity the perforated plate and standpipe distributors gave improved mixing behavior than porous plate.

Srinivasakannan et al. (1994) developed a model with heat and mass transfer rates for batch fluidized bed drying of solids with assumptions of the gas phase, solids phase, and a bubble phase. They reported that the model is valid with consideration of the bubble rise velocity, bubble size and the bubble volume fraction covering two drying rate periods, constant and falling rates. They have reported the comparison with experimental conditions and literature data.

Depypere et al. (2004) have performed CFD simulations of fluidized bed coater, and stainless steel woven wire mesh distributors were used as the standard distributor plates. Two types of boundary conditions were chosen to model a distributor, and comparison was made. Simulation results were verified with lab-scale fluidized bed unit varying air mass flow rate, pressure drop and inner wall temperatures.

Son et al. (2005) have studied on fluidization characteristics with the effect of air distributor in the conical fluidized bed. They have conducted experiments with distributor opening fraction from 0.009 to 0.37 with different orifices and pitches, taking 1mm glass beads as bed material with the conical gas fluidized bed having a diameter of 0.1 m and height of 0.6 m. From the study, they have reported the variation of bed pressure drop profiles and axial bubble frequency with changing distributor opening area.

Amer (2006) has studied on air distributor influence on heat transfer in the fluidized bed. The bubble cap and perforated plate distributor were used with an open area percentages (21.6%, 6.36%, 3.97%). From their reports, it was understood that the heat transfer coefficient of bed increased with increasing opening area of the distributor plate in the fluidized bed.

Wormsbecker and Pugsley (2007) have investigated the influence of distributor in the fluidized bed dryer. They have conducted studies with three types of distributors punched, perforate and Dutch weave mesh at different bed loadings and air velocity from 1.0 to 1.5 m/s. In reports, it was mentioned that the punched plate has given good performance with shorter drying time than other perforated plate and Dutch weave mesh distributor designs in batch fluidized bed dryer based on the bed temperatures.

Wormsbecker and Pugsley (2009) have conducted studies with different distributors in the conical fluidized bed dryer. To determine the hydrodynamics characteristics, they used three types of distributors namely punched, perforated, and mesh (Dutch weave) using dry pharmaceutical granule as bed material at inlet superficial gas velocities ranging from 0.5 to 3.5 m/s. They have reported that the punched plate design showed improved hydrodynamics based on limited segregation and reduced bubble frequencies for gas velocities up to 2.0 m/s.

Sutar and Sahoo (2011) have analyzed the drying characteristics of tea-particles in a fluidized bed dryer with different orifice sizes, orifice size ranging from 1.5 to 3.5 mm while keeping the number of orifices constant at 66. The bed material used was tea-particles with the moisture content of 13.38%. Experimentation was conducted with the temperature of air from 313 to 333 K, with constant bed height and air velocity. Moisture profiles were reported with different distributors. The experimental results showed that the drying rate increased with the orifice size up to a certain limit.

Chuwattanakul and Eiamsa-Ard (2019) have investigated the drying behavior of pepper in fluidized bed dryer with swirling air flow (designed with multiple twisted tape swirl generators). For drying of pepper, the dryer was operated with a range of air velocities from 1.0 to 1.2 m/s. Moisture profiles were presented with time and the comparison was reported with fluidized bed dryer results without swirling flow. From the comparison, it was observed that the drying rates are high with swirling flow. The results have fitted with existing drying models, and the logarithmic model reported the good fit with R^2 value of 0.996.

2.2 Different bed materials and various fluidized bed drying methods

2.2.1 Studies on various bed materials

Srinivasakannan et al**.** (1995) have studied the drying rates with respect to the moisture content of the materials like sand, ragi, mustard and poppy. They have reported that drying rates of sand showed constant drying rate and linear falling drying rate periods but drying rates of other materials showed curves with two falling rate periods. The comparison of results from continuous and batch fluidized bed dryers were reported along with batch drying kinetics, and the contact efficiency and residence time distribution were predicted and reported.

Soponronnarit et al. (1997) have studied the drying of corn in a fluidized bed dryer with batch process. They have studied at operating conditions like, air inlet temperature range of 393 – 473 K, velocity of air ranging from 2.2- 4 m/s, depth of bed with a range of 4 - 12 cm, recycle fraction for air as 0.5-0.9 and feed moisture was taken as 43% (dry basis). From their experiments, they have reported that recycle fraction of air and air temperature showed affect on drying rate of corn in fluidized bed dryer. They have validated the results with various models and from that, it was shown that Wang and Singh equation described the results with sufficient accuracy.

Calban and Ersahan (2003) have studied the drying kinetics of Turkish lignite in a batch fluidized bed. In their experiments, the temperature was varied from 333 to 353 K and velocity of drying air from 6.92 $x10^{-3}$ to 8.89 $x10^{-3}$ m/s and different particle sizes of the lignite samples were chosen. From their results, it was observed that the drying rate increased with increasing air temperature and air flow rate and with decreasing particle size.

Senadeera et al. (2003) have conducted drying studies of three different shapes, sphere, cylinder and parallelepiped using peas, potatoes and green beans. They have conducted experiments at temperatures of 303, 313 and 323 K. They have validated the exponential results with page mode and it was reported that the page model showed better fit with experimental data showing less than 10% error. In results, it was reported that the diffusivity coefficient values are in the range of 10^{-12}–10^{-8} m^2/s and activation energy values, in the range of 12.32 to 42.35 kJ/mol.

Srinivasakannan and Balasubramanian (2006) have examined the drying behavior of ragi (Eleusine corocana) in a fluidized bed by varying the operating parameters like temperature, solids holdup, and flow rate. It was reported that the drying rate increased with an increase in flow rate of the heating medium and its temperature and decreased with an increase in solids holdup. The experimental results were compared with various drying models and the model parameters were evaluated. The Page model was reported as the best fit model with RMSE of 2.5. The effective diffusion coefficient reported is in the range of 5.7 to 14 x 10^{-11} m^2/s with RMSE value of 5%.

Srinivasakannan and Balasubramanian (2009a) have studied the drying behavior of green pepper in a fluidized bed dryer by changing temperature from 338 to 378 K. The experimental drying kinetics was validated with existing drying models and kinetic parameters have been reported. The Henderson Pabis model and Page Model were shown as better fit with less error. They have reported that the kinetic parameter (k) of all drying models increased with the temperature. The activation energy (E) was reported as 30.3 kJ/mol and the effective diffusivity coefficient was reported to be ranging from $1.95x10^{-11}$ to $7x10^{-11}$ m^2/s.

Srinivasakannan and Balasubramanian (2009b) have conducted experiments to estimate the drying kinetics of pearl millet using a batch fluidized bed. Experiments were conducted by maintaining air temperatures from 313 to 338 K, air velocity as1.69 and 2.25 m/s and solids holdup as 0.155 and 0.270 kg in the dryer. From results, it was observed that the drying rate increased with an increase in flow rate and temperature of air, showed decreased manner with increasing solids holdup. They have compared results with various drying models and reported Page model matched with the experimental data with less error of 1.4% (RMSE) and the effective diffusivity coefficients were reported in the range of 2 $x10^{-11}$ to 3 x 10^{-11} m^2/s.

Cil and Topuz (2010) have studied the drying performance of beans, chickpeas and corn with the change of air temperature and air velocity in fluidized bed dryer. They have reported that the drying rate was enhanced by an increase in temperature. They have explained the difference between drying curves of bean and corn and reason reported is due to capillary forces in the bean are larger than corn. The experimental results were validated with Henderson and Pabis model. They have reported the activation energy values.

Zielinska and Markowski (2010) have investigated drying kinetics of carrot cubes at different air temperatures from 333 to 363 K in a spout-fluidized bed dryer. They reported the effective diffusion coefficients and experimental data were fitted with four mathematical models and reported constants. The two-term model was reported as satisfactory for drying of carrot cubes. They have reported that, at the initial phase of drying the effective moisture diffusivity in carrots is underestimated and at the final drying phase it is overestimated.

Syahrul et al. (2019) have done experimental studies on fluidized bed drying of unhulled rice at different air intake temperatures. The drying operation was conducted with intake air temperature from 313 to 323 K, initial moisture content as 22% and reduction of moisture content was reported as 13.1% by drying. In reports they have mentioned that the moisture content of rice reduced with drying time, the drying rate was higher at lower bed loading of 1 kg than 2 kgs, and fast drying occurrence was reported at 323 K air temperature.

Zhu et al. (2019) have studied the drying characteristics of lignite in the fluidized bed dryer. The experiments were carried out with a range of lignite diameters from 13 to 25 mm, the surface water content of 0.4 to 2%, temperature from 313 to 358 K and air velocity of 0.035 to 0.066 m/s. The water removal efficiency of the dryer was reported with drying time. The removal efficiency decreased with increasing surface moisture, increased with increase in temperature and velocity of the dryer. Highest removal efficiency was reported as 91% under experimental conditions.

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2.2.2 Effective diffusivity and activation energy studies

Table 2.2. Studies on effective diffusivity and activation energy in fluidized bed drying

Author	**Study**	**Material**	**Operating conditions**	**Reported D_{eff} and E_a**	**Reports**
Mohammadpour et al. (2008)	Investigation on the determination of effective diffusivity in fluidized bed dryer with shelled pistachio	shelled pistachio	Air temperature- 298 to 333 K, air velocity- 6 to 10 m/s.	D_{eff}- 7.02 x10^{-10}- 3.34 x10^{-9} m^2/s	They have reported moisture ratio profile with temperature, air velocity and drying time. The two-term and Henderson-Pabis models are shown as better fit models.
Madhiyanon et al. (2009)	Studies on thin layer modeling of chopped coconut using fluidized bed dryer	chopped coconut	Air temperature- 333 to 393 K, air velocity- 2.5 m/s	D_{eff}- 5.99 x10^{-8} -2.6 x10^{-7} m^2/s and E_a is 25.94 kJ/mol	Reported that the drying rate increased with air temperature and presented Modified Henderson and Pabis model as the most predictive model, with R^2 = 0.99524
Arumuganathan et	Studies on drying	milky	Air temperature- 323 to	D_{eff}-	Showed that the Wang

al. (2009)	of milky mushroom with mathematical modeling in fluidized bed dryer	mushroom	333 K, air velocity- 1.5 m/s, solids holdup-0.5 kg	1.55 x10^{-9} -16.5 x10^{-9} m^2/s and E_a are found in the range of 73.23–79.43 kJ/mol	and Singh drying model was a better model to predict the drying results and reported 333 K air temperature for minimum activation energy for the drying process
Gazor. and Mohsenimanesh (2010)	Studies on the Thin layer modeling of Canola in batch fluidized bed dryer	Canola (new oil seeds in Iran)	Initial moisture content- 20%, Air temperature- 303 to 373 K, air velocity- 1 m/s and solids holdup-2.2 kg	D_{eff}- 3.76 x10^{-11} -8.46 x10^{-11} m^2/s and E_a is 11.03 kJ/mol	Reported that drying rate increased with air temperature and Diffusion and logarithmic models showed the better fit with RMSE less than 0.02.
Meziane (2011)	Studies conducted on drying kinetics of olive pomace in a batch fluidized bed dryer	Olive pomace (biomass)	Air temperature- 323 to 353 K, air velocity- 1 m/s and bed heights-41, 52 and 63 mm	D_{eff}- 0.68 x10^{-7} -2.15 x10^{-7} m^2/s and E_a – 34.05, 36.84 and 38.10 kJ/mol (at different bed heights)	Reported that drying rate increased with air temperature and Midilli et al model was reported the best suitable model.

Chayjan et al. (2013)	Studies on activation energy, energy consumption and thin layer modeling, moisture diffusivity using semi fluidized and fluidized bed drying with squash seeds	Squash Seeds	Air temperature- 323 to 353 K, air velocity- 2.51 to 5.32 m/s, solids holdup-0.040 kg	D_{eff}- 0.551 x10^{-10} -0.160 x10^{-9} m^2/s and E_a are found in the range of 31.94–34.49 kJ/mol	Reported squash seeds drying in a semi-fluidized and fluidized dryer and Two-term model showed good agreement with experimental results.
Parlak (2015)	Studies on fluidized bed drying characteristics and modeling of ginger (zingiber officinale) slices	ginger (zingiber officinale) slices	Air temperature- 313 to 343 K, air velocity- 3 to 5 m/s m/s, solids holdup- 1 kg and initial moisture content- 0.88 to 0.9 (kg/kg) on wet basis	D_{eff}- 1.1 x10^{-7} -2.2 x10^{-7} m^2/s	It was reported that the drying rate increased with increase in temperature and velocity. The Two term model presented as a better fit model with RMSE value 0.005344
Khanali et al.(2016)	Studies on activation energy,	Rough rice	Air temperature- 323 to 343 K, air velocity- 2.3 to	D_{eff}- 4.78 x10^{-11} -1.364 x10^{-10}	Presented moisture profiles with air

	energy consumption and moisture diffusivity in fluidized bed drying with rough rice		2.8 m/s, solids holdup- 1.32 kg and initial moisture content- 25%	m^2/s and E_a are found in the range of 36.59–44.31 kJ/mol	velocities, temperatures and specific energy consumption of dryer was analyzed at various operating conditions

2.2.3 Various fluidized bed drying methods

Reyes et al. (2002) have studied the drying kinetics of carrot slices in a mechanically agitated fluidized bed. They have carried out experiments at the temperature between 343 and 433 K, velocity of drying air between 1.1 and 2.2 m/s, stirring speed between 30 to 60 rpm and have taken 3 kg of carrot slices in bed. They have reported that the loss of moisture from carrots was observed with increase in temperature and air velocity during the drying process. They have determined diffusivities and developed a correlation to calculate the values of effective diffusivity as a function of air velocity, particle size and temperature.

Ceylan and Gurel (2016) have developed a new mixed-mode drying technique using solar energy system for fluidized bed dryer. The dryer system contains a collector (parabolic), solar air collector and heat pump system. Drying kinetics of mint leaves was determined at air temperatures of the solar system of 318 K and heat pump system of 323 K using solar assisted fluidized bed dryer. They have presented the variation of moisture content, moisture rate and drying air temperature with drying time and reported final moisture content as 17% of mint leaves.

Moreno et al. (2016) have conducted studies on biomass particles using a mechanically agitated fluidized bed dryer. They have studied on heat transfer between the gas and surface of particles by changing the particle diameters and air velocity. The heat transfer coefficient of gas and biomass particles was reported to be in the range of 13 to 25.7 W/m^2K from experimental study. The moisture profile with time and variation of Nusselt number with Reynolds number was presented in their reports. They have developed a correlation to the calculated heat transfer of fluidizing biomass particles.

Zhao et al. (2016) have conducted studies to determine the Shengli lignite drying kinetics using various drying methods of fluidized bed (FB), medium fluidized bed (MFB), vibrated fluidized bed (VFB) and vibrated medium fluidized bed (VMFB). Drying kinetics were determined using seven existing drying models by changing air temperature from 353 to 433 K. The VMFB showed short drying time and highest drying rates and reported as the best drying method. From experimental results, Midilli– Kucuk model has shown to be the best fit than among all drying models with lower RMSE values. The effective diffusivity coefficients reported are in the range of 7.11 x 10^{-9} to 5.73 x 10^{-8} m^2/s and activation energies are in the range of 27.92 to 30.21 kJ/mol.

Hu et al. (2017) have investigated the drying kinetics of carrot cubes using microwave assisted fluidized bed dryer. They have operated with a varying power density at air temperatures of 313, 323 and 333 K to dry the carrot cubes. From results, it has been noticed that the drying rate of carrot cubes increased with an increase in air temperature and power density. The shortest drying time was obtained as 25.97 min at 333k air temperature and 1.21 W/g of power density. The page model was reported as the best fit for their results and they reported effective diffusivity in the range of 0.7 x 10^{-8} to 2.009 x 10^{-8} m^2/s.

Jafari and Zare (2017) have examined the drying behavior of paddy in ultrasonic assisted fluidized bed dryer. The initial moisture content of paddy was taken as 26.5% approximately and operated dryer varying power density with the frequency level (20 - 30 kHz), and three levels of temperatures (303, 313 and 323 K). Moisture content profiles of paddy were reported with drying time and it has shown increment in drying rate with increasing the drying air temperature from 303 to 323 K at different power densities. They reported that the drying rate declined with power density and no significant difference has been reported in drying curves with different frequencies.

Si et al. (2019) have done simulation and experimental study on microwave-assisted fluidized bed dryer for lignite drying. They have conducted modeling study using CFD software by approaching the Euler- Euler method. The moisture percentage in reports showed the decreasing trend with increase in microwave power from 1500 to 2700 W, air velocity from 1.6 to 2.2 m/s and air temperature from 313 to 363 K. The authors discussed about the heat transfer distribution in the dryer. They have reported that the modeling results have a good consistency with experiment results.

There are very few investigations on continuous multistage fluidized bed dryer, internally staged which are reviewed as given below:

Hasatani et al. (1985) have studied on multistage inclined fluidized dryer experimentally and developed a mathematical model. Drying was conducted with brick particles using the three-stage inclined fluidized dryer. The results from the model have shown good agreement with the experimental results at air temperatures from 313 to 333 K. They reported that the overall drying rate of the particles enhanced due to the assistance of vertical mechanical vibration to the dryer and its effect was considered as same as the increase in the air velocity.

Srinivasakannan et al. (1994) have investigated on pressure drop and solids holdup of internally staged multistage fluidized bed, sectioned using horizontal perforated plates with and without downcomers internally. They have conducted experiments in the multistage fluidized dryer with and without downcomers and reported the increase in pressure drop at the transition indicates the existence of lean and dense phase fluidization. From their study, they have reported that the pressure drop is adequately correlated to the characteristics of particles, a geometry of plate and the flow rates of phases in multistage fluidized bed dryer.

Srinivasakannan and Balasubramanian (1998) have investigated on drying kinetics of internally staged multistage fluidized bed with and without downcomers. They have carried out experiments at various experimental conditions like material flow rate, air temperature, air flow rate and the number of stages. From their results, it has been observed that the drying behavior in the multistage dryer was found to be better than batch dryer.

Choi et al. (2002) have studied the drying characteristics of millet using multistage fluidized bed dryer, staged internally. They have examined the drying efficiency by varying gas velocity, solids feed rate and gas temperatures and reported the bed temperatures and outlet moisture content in multistage fluidized bed dryer. From their findings, it was noticed that the final solid moisture content showed increment with an increase in solids feed rate from 0.0021 to 0.0054 kg/s and drying efficiency increased when there is an increase in gas temperatures from 310 to 338 K.

2.3 Energy and exergy analyses of fluidized bed drying

Nazghelichi et al. (2010) have conducted drying experiments in batch fluidized bed dryer by varying temperature of air from 323 to 343 K, depths of bed at 3, 6, and 9 cm with different squared and cubed dimensions of carrot as 4, 7, and 10 mm. They have reported that energy utilization ratio varied between 0.074 to 0.486, exergy loss and exergy efficiency in the range of 0.206 to 1.612 kJ/s and 0.103 to 0.707. Nazghelichi et al. (2011) have conducted the artificial neural network modeling with different hidden neurons for batch fluidized bed dryer results. The energy and exergy of carrot cubes were predicted based on the model and R^2 value was reported to be in the range of 0.95 and 0.97.

Karagüzel et al. (2012) have conducted energy and exergy analyses of fluidized bed dryer using chickpea and beans. From the study, It has been observed that the exergy loss is proportional to the air temperature and velocity and reported that EUR percentage increased (presented approximately 30 to 50%) with increasing air temperature from 308.6 to 343.1 K. From results it was seen that the exergy efficiency at air temperature 320.1 K is in the range of 56 to 65% for bean and 45 to 62% for chickpea.

Sarker et al. (2015) have conducted the thermodynamical analysis of industrial fluidized bed paddy drying to find the energy and exergy rates, which has the maximum capacity of 22 T/hour. They developed a model applying thermodynamic first and second laws for energy and exergy rate calculations of the fluidized bed dryer. They have found that the energy usage and the energy utilization ratios were in the range 5.24 to 13.92% whereas the exergy efficiency varies from 46.99 to 58.14% and also reported that the fluidized bed can be insulated thoroughly and also that the recycling of the outlet air stream can reduce the energy and exergy losses.

Ceylan and Gürel (2016) have studied the performance of solar-assisted fluidized bed dryer integrated with a heat pump using mint leaves. The performance has been analyzed using energy and exergy analyses. The drying kinetics for mint leaves has been determined in the Solar-assisted fluidized bed dryer. The authors found that the 50% as energy efficiency and 26% exergy efficiencies of the solar drying system and a heating coefficient of performance (HCOP) of the dryer was found to be 10.

Azadbakht et al. (2017) have studied the drying behavior of potato cubes at various inlet temperatures from 318 to 328 K, air velocity of 3.2, 6.8, and 9.1 m/s, and bed depth of 1.5, 2.2, and 3 cm in batch fluidized bed dryer. Utilization of energy, utilization ratio, exergy loss and efficiency were reported at different parameters and artificial neural network modeling was carried out using experimental data to predict the energy and exergy values.

Ergun et al. (2017) have conducted energy and exergy analyses for solar assisted fluidized bed dryer. The plant species like cranberry, cherry laurel and medlar, endemic obtained from Turkey, were used as bed materials, the tests were conducted at a solar radiation level range from 500 to

900 W/m^2 and at an air flow of 3 to 5 m/s, at drying air temperature of 313 K. The thermodynamic analysis was examined at different solar radiations, air temperatures, flow rates to determine the produced energy. The artificial neural network modeling was used to determine the outlet air temperature from collectors was predicted based on the solar radiation, ambient air temperature and air flow rate. The authors developed correlations to fit the experimental values.

Hideo et al. (2007) have studied energy and exergy rates of fluidized bed dryer based on the first and second law of thermodynamics. Experimentations were carried out with two different materials wheat and corn. The model study was done to find the effects of heat and mass transfer parameters on the efficiency of the dryer. They have proposed non-dimensional experimental correlations for predicting the efficiency of fluidized bed dryer. The energy and exergy efficiencies were reported with Fourier and Reynolds numbers. A good agreement has been reported between the non-dimensional correlations, model predictions and experimental results.

Motevali and Amiri Chayjan (2017) have conducted thermodynamics analysis of two plant dill and mint using three different beds for drying like fixed bed, semi-fixed bed and fluidized bed at four different temperatures (303, 313, 323 and 333 K). From the analysis, they have reported that dill leaves have shown high energy consumption (16.41 MJ) at 313 K in the fluidized bed (at air velocity 2.37 m/s), and minimum (2.77 MJ) was obtained at 303 K in the fixed bed (at air velocity 0.7 m/s). The highest efficiency of thermal energy for both mint and dill were reported at 333 K in the fixed bed and the lowest efficiency was observed at 313 K in the fluidized bed.

Yahya et al. (2017) have designed continuous fluidized bed drying system with hybrid solar assisted system having biomass furnace and studies were conducted on that system. The system consisted of a fluidized bed, a biomass furnace and solar collector. Drying kinetics of biomass was determined with experiments and energy and exergy analyses was examined. From results, they have reported that average temperature of the drying air were 334 and 351 K. The paddy mass flow rate was maintained 0.125 kg/s and moisture content of paddy reduced to 14% (wet basis) with drying. The average exergy efficiency of the dryer was obtained as 47.6% and 49.5% at drying air temperatures of 334 and 351 K.

2.4 Modeling and simulation studies of fluidized bed drying

Chandran et al. (1990) have developed a kinetic model for the drying of solids in fluidized beds with assumptions of constant and falling rate periods. The results were reported in fluidized bed drying with batch and continuous, and also of spiral fluidized drying. The results were reported with good agreement of assumed drying kinetics. They have concluded that the residence time distribution of solids is appropriate for the type of dryers.

Milan and Tijana (2011) have conducted experimental and numerical simulation study on vibrated fluidized bed dryer. Model validation has been done with the basis of the experimental data reported with poppy seeds having a particle diameter (0.75 mm), initial moisture content (0.54) for all experiments. From the results, it was reported that the influence of deeper beds is higher than other parameters, and uniform bed temperatures were observed in vibrated fluidized bed values than packed bed values.

Ranjbaran and Zare (2012) have studied the energetic and exergetic performance of microwave-assisted fluidized bed drying of soybeans and simulation was executed using CFD software. They have simulated the effects of operating conditions like microwave power densities, the initial gas temperature for prediction of solids moisture content, gas absolute humidity and gas temperature. The model predictions were reported with a lesser deviation of below 10% for solids moisture content, gas temperature, and gas absolute humidity.

Askari et al. (2013) have worked on fluidized bed drying of apple cubes with microwave assistance. The model was reported to describe the heat and mass transfer coefficients of apple cubes in the dryer. The model was developed with data on moisture and temperature distribution in samples during drying and a numerical solution based on the finite difference method was used for model development. The model was reported with good consistency with experimental average moisture content, center and surface temperature at microwave power densities and various air temperatures.

Özahi and Demir (2013) have proposed a model to predict the exergetic efficiency for batch fluidized bed dryer considering two separate systems comprised of drying air medium as a control volume and particles to be dried as a control mass. The authors have examined energy and exergy for a batch fluidized bed dryer with the proposed model. They have made a comparison of energetic efficiencies given in literature with the proposed model and found good agreement between them with an error of ±9%. They have developed a new correlation to evaluate energetic efficiency with a mean deviation of ±10% for different particles.

Khanali et al. (2014) have investigated the drying behavior in continuous plug flow fluidized bed dryer using rough rice under dynamic conditions. They also developed a model for prediction of the plug flow fluidized bed drying process under dynamic conditions. They have reported the dynamic response for a change in solid moisture content. They further reported the variation of particle temperature and gas temperature with bed length and solids flow rate. The authors also compared the model predicted results with experimental values and found that there was good agreement between the experimental and model predicted results.

Mohseni et al. (2019) have done DEM-CFD simulations for drying of biomass in the continuous vibratory fluidized bed dryer. They have conducted the simulation study with the Lagrangian-Euler approach. The studies were conducted with different cases by changing gas temperature range from 473 to 503 K, gas velocity range from 1.45 to 1.85 m/s with initial moisture content range from 51.8 to 60% (wet basis). Their reports have shown that the particle mean temperatures increased with the drying time and higher temperatures were reported with the lower size of diameters. The results from simulations have shown good agreement with experimental results in reports, the particle temperature was observed to be high with lower initial moisture content and drying rates of biomass were reported to be increasing with increase in temperature and air velocity.

Table 2.3. Various modeling and simulation studies in fluidized bed dryers

Authors	Dryer	Study	Material	Modeling approach	Reports
Ranjbaran and Zare (2013)	FBD	Simulation study of fluidized bed drying of soybeans with microwave assistance and determined the energetic and exergetic performance of dryer.	Soybeans	Mathematical modeling	The energy and exergy analyses of soybeans with the effect of power density, inlet air temperature, and inlet air velocity and bed height have been simulated and discussed.
Poos and Szab (2017)	FBD	The modeling study of fluidized bed dryer to investigate the drying time and volumetric heat transfer coefficient.	Granules	Mathematical modeling	Developed a mathematical model to determine the drying time and also reported temperature, humidity of gas, temperature and moisture content of material from the model.
Pires Thayse Naianne et al. (2017)	Spouted bed	Worked on modeling and mathematical simulations for drying of pulp fruit in the spouted bed.	Pulp fruit	Mathematical modeling	Described the heat and mass transfer of the fruit pulp during the spouted bed drying process and validated the model with experimental results.
Gili et al. (2018)	FBD	Modeling studies were conducted on thermal treatment to wheat germ in fluidized bed dryer and developed a mathematical model to	Wheat germ particles	Mathematical modeling	Thin layer mathematical model was developed to describe heat and mass transfer for thermal treatment of wheat germ for 363 to

		determine heat and mass transfer in the dryer.			423 K and validated with experimental values.
Azmir et al. (2018)	FBD	Simulation study of food grain drying in a fluidized bed with a discrete particle method	Food grain particles	CFD-DEM	A CFD-DEM model was developed for the fluidized bed drying of food grains. Examined and reported the influences of air inlet velocity and air inlet temperature.
Khanali et al. (2018)	Plug flow FBD	A modeling study was conducted for plug flow fluidized bed dryer with shelled corn	Shelled corn	Mathematical modeling	Differential model was developed for plug flow fluidized bed dryer and experimental results of drying shelled corn were validated

2.5 Gaps identified from the literature

- The millets and seeds gives health benefits but quality of drying analysis is required for long term storage. But from the literature, there is no information on any drying analysis or exergy analysis for few important millets and seeds like Kodo, Barnyard and Pearl millets and Fenugreek seeds. There is more potential for research on drying kinetics and exergy analysis of these materials.
- Knowledge of drying kinetics, effective diffusivity coefficient and activation energies can describe the drying system and moisture diffusion in material. Such studies were not reported on above quoted materials for batch wall heated dryer or multistage fluidized bed dryer and hence there is need for research in this area.
- The exergy analysis determines the performance and potential for the energy utilization of drying system. The energy analysis tells the wastage of energy in a drying system. Hence it is necessary to have energy and exergy analyses for any drying system. But there is no reported literature work on energy and exergy analyses of batch wall heated fluidized bed dryer and Continuous multistage fluidized bed dryer. Hence it is necessary to take up work in this area.
- Proper air distribution is needed for uniform quality of drying. In fluidization phenomena the quality of drying mainly depends on hot stream flow. Hence air distribution studies are needed to find the effect of flow distribution on wet particles. There are no studies observed on the effect of distributor plate and orifice configuration in continuous fluidized bed drying.
- Simulation studies help to increase the practical application feasibilities. The air flow distribution and multistage drying studies have not been reported in literature. But such type of simulation work on drying helps to improve the drying efficiency.

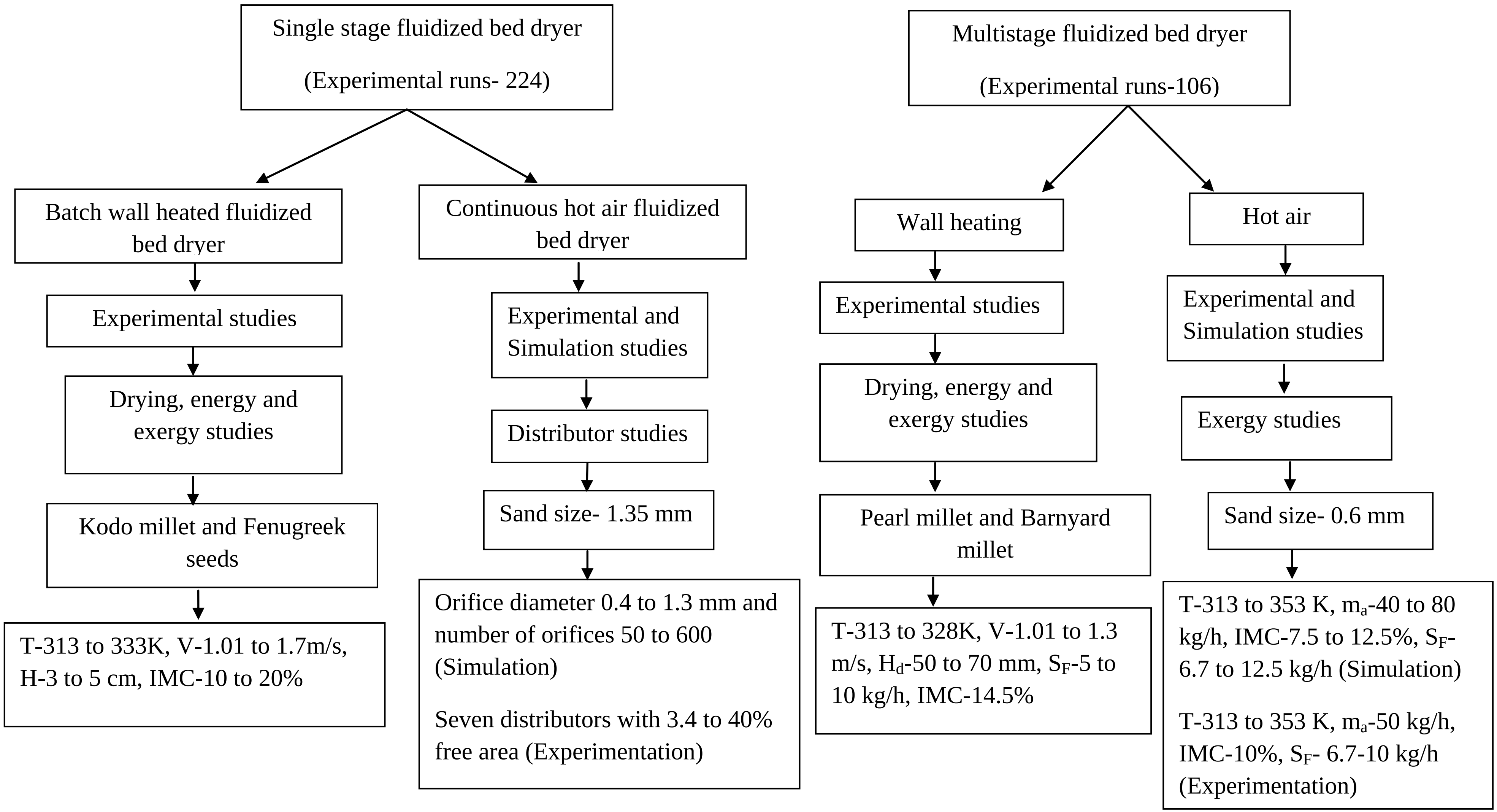
2.6 Objectives of the present study

- The Challenge is conducting drying experiments with any heat sensitive material and finding appropriate system to obtain the data. The present study aims to determine the drying characteristics of selected bed materials like Kodo millet, Barnyard millet, Pearl millet grains and Fenugreek seeds using wall heated batch fluidized bed dryer and continuous multistage fluidized bed dryer, staged externally.

- To determine the drying kinetics- effective diffusivity coefficient, activation energies, and to validate with the existing drying models and to report constants, errors and fits, using the experimental data of multistage drying.
- To conduct energy and exergy analyses of the batch wall heated fluidized bed dryer and multistage fluidized bed dryer, and to study the effect of parameters on results.
- To identify the influence of air distributor in continuous single stage hot air fluidized bed dryer from experimental and simulation studies.
- To study the exergy aspects of multistage fluidized bed drying using Aspen Plus simulator.

2.7 Work Plan of the Thesis

<u>Drying kinetics, energy and exergy analyses of single and multistage fluidized bed dryers</u>



CHAPTER 3: MATERIALS AND METHODS

This chapter deals with:

I. Experimental description of a) Batch wall heated fluidized bed dryer b) Continuous wall heated multistage fluidized bed dryer c) Continuous hot air single stage fluidized bed dryer, d) Continuous hot air multistage fluidized bed dryer.

II. Aspen simulation studies using a) Continuous hot air single stage fluidized bed dryer b) Continuous hot air multistage fluidized bed dryer,

III. Drying kinetics

IV. Energy and Exergy analyses.

3.1 Batch wall heated fluidized bed dryer

3.1.1 Equipment description

Batch wall heated fluidized bed dryer:

The experimental setup is designed with columns for fluidized bed drying section and the calming section having a height of 1 m and diameter of 0.083 m. The columns and pipe are entirely made up of stainless steel material and are connected tightly with threading and coating to avoid the air leakages. The glass wool insulations were used as insulation to avoid the thermal losses. Operating velocity was based on material minimum fluidization and terminal velocity. For distribution of air, rubber gaskets were used with tight fit at the junction of calming section and fluidization section. One temperature sensor was arranged in the bed to detect the bed temperature and another one arranged on wall surface with insulation to detect the wall temperature. One humidity and temperature sensor was arranged at inlet of air and one kept at outside of dryer to detect exhaust humidity and temperature of air. One temperature data logger was used for recording the temperature with continuous intervals. The humidity and temperature data logger were used for continuous recording of humidity and temperature data. For the stable flow of air bypass valve was used at the outlet of the compressor. Rotameter having a range of 0 to 120 kg/h was used to indicate air flow rate. Distributor plate with 40% opening area has been used for proper distribution of air into the column. The wall heater of fluidized bed dryer has been made by winding the nichrome wire to the column wall. The heat to the system is controlled with the rheostat. The power given to the wall heater is measured with the help of ammeter and voltmeter.

3.1.2 Experimental procedure

Kodo millets and Fenugreek seeds were used as bed materials. The known amount of water was added to know the initial moisture content of the bed material. After attaining the desired experimental conditions, the bed material was introduced from the top of the fluidized bed column. Air is introduced to the fluidized bed drying zone from the bottom of the column. The samples were collected and humidity and temperatures were found simultaneously at regular time intervals. The collected samples were analyzed. The exergy and energy analyses were carried using the experimental data for the wall heated batch fluidized bed dryer. The properties of materials and experimental conditions are tabulated in Tables 3.1 and 3.2.

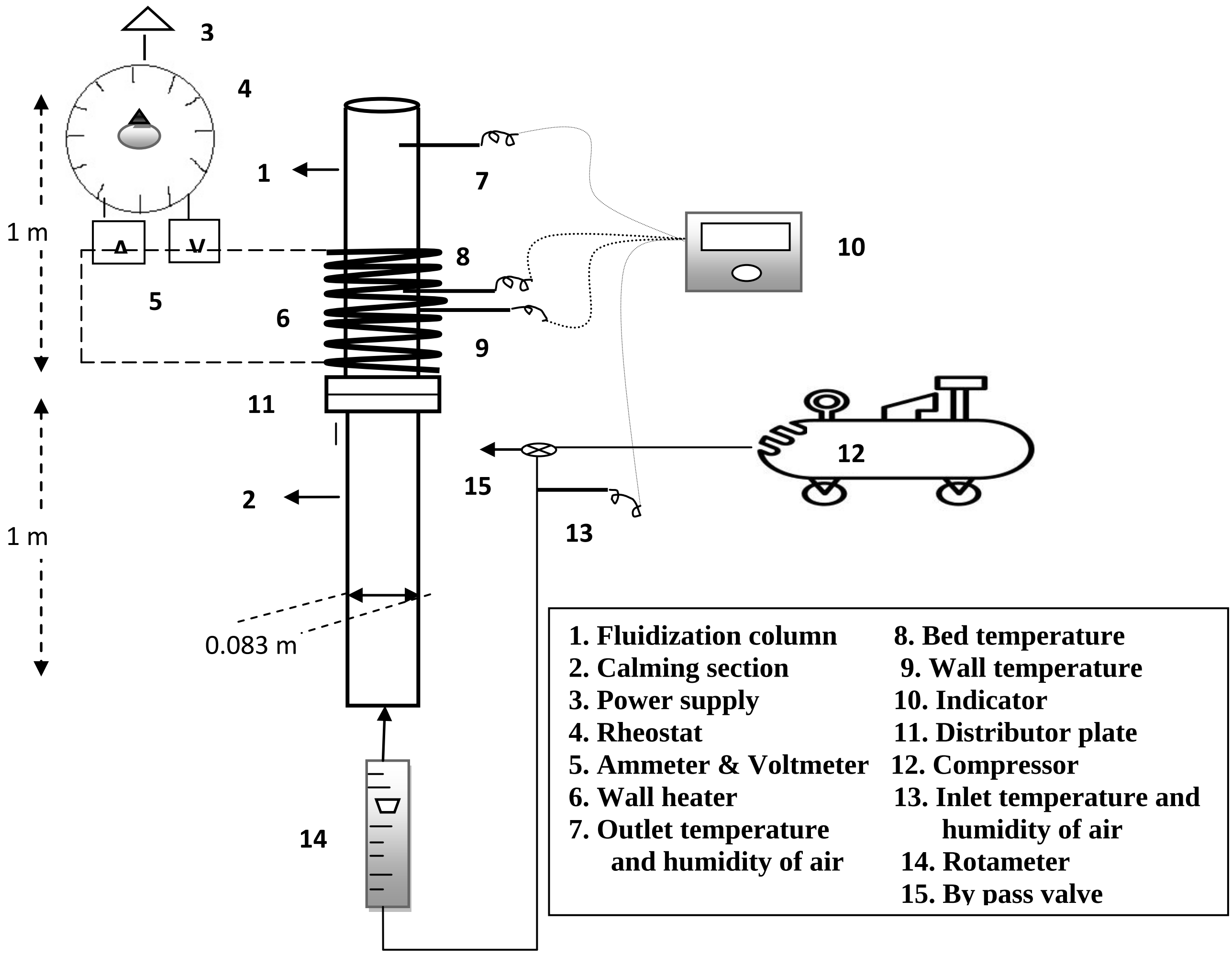


Figure 3. 1 Batch wall heated fluidized bed dryer

Table 3. 1 Properties of the Kodo millet and Fenugreek seeds

Name of the material	Kodo millet	Fenugreek seeds
Shape of the material	Spherical	Angular
Mean diameter, mm	2.2	2.35
True density, kg/m^3	1360	1296
Minimum fluidization velocity, m/s	0.91	0.93

Table 3. 2 Operating conditions of the batch dryer

Parameter	**Range**
Initial moisture content	10%, 15% and 20% (on dry basis)
Air velocity	1.01 m/s, 1.35 m/s and 1.7 m/s
Bed height	3 cm, 4 cm and 5 cm
Wall temperature	313, 323 and 333 K

3.2 Continuous hot air single stage fluidized bed dryer

3.2.1 Experimental setup and procedure

The experimental setup (Figure 3.2) consists of a fluidization column of 0.083 m internal diameter, 1 m in length and the calming section of 1m length and same diameter, which are separated by a distributor (Table 3.3) plate for distribution of gas. The distributor plate is fitted with rubber gaskets to avoid air leakage. The gas is drawn from the compressor. The gas was passed through the air heater and temperature of the air was controlled using rheostat and then passed through the rotameter with a range of 0-120 kg/h. To avoid heat losses, proper insulation was made with glass wool. Temperature indicator and two thermocouples were used to determine the outlet solid and gas temperatures.

The solid stream enters from the top of the fluidized bed through a vibratory feeder and a downflow pipe. The solids are introduced from the top of fluidized bed dryer using vibratory feeder DR 100 (Retsch India) and the flow was controlled by setting the vibration frequency. The solids were collected with respect to time from the downcomer of the fluidized bed dryer. After collecting the samples, the moisture content was analyzed. In the present study solids (sand) with a density of 2600 kg/m^3 of the average particle diameter 1.3 mm were used.

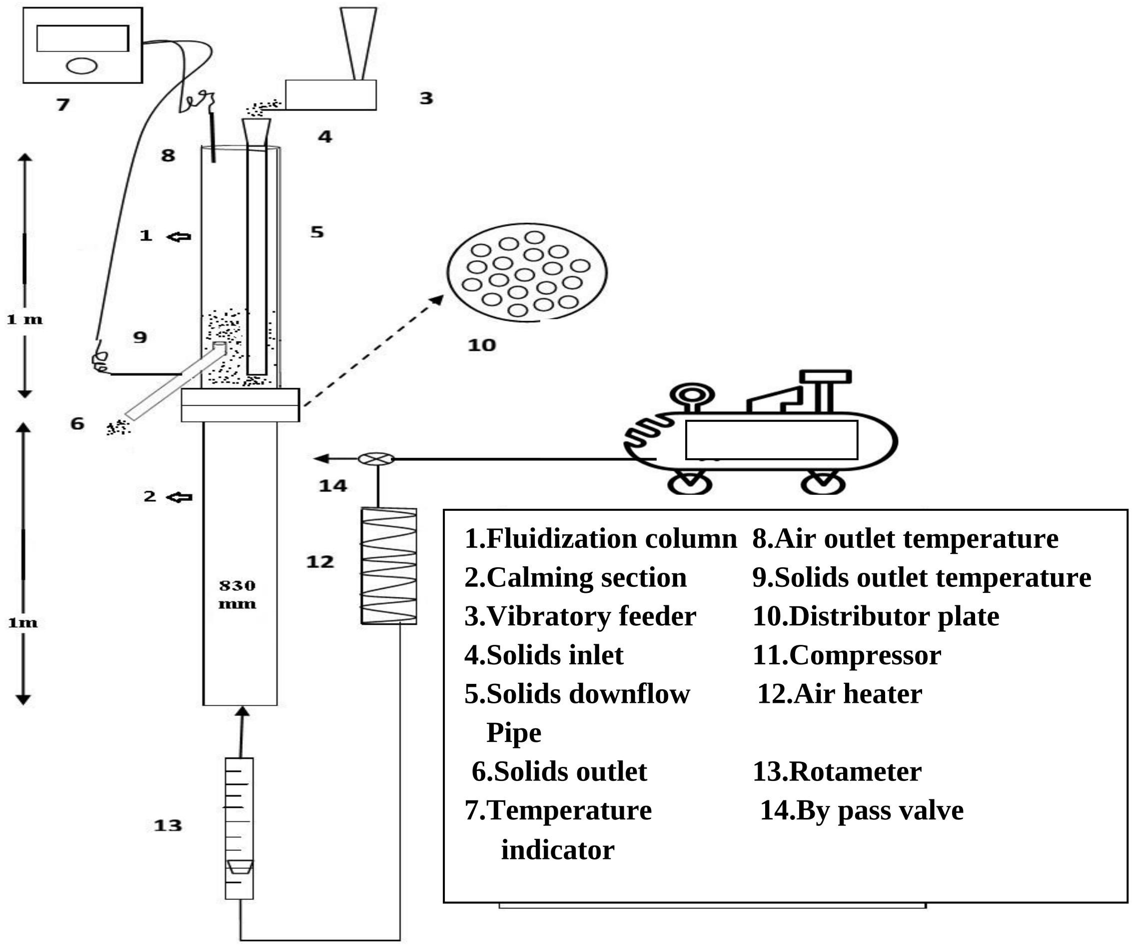


Figure 3. 2 Continuous hot air single stage fluidized bed dryer

Table 3. 3 Distributor plate configurations

Orifice diameter (mm)	**No of orifices**	**Opening area (%)**
2	60	3.4
3	60	7.8
5	40	14
5	60	22
5	110	40

7	60	42

3.2 Continuous wall heated multistage fluidized bed dryer

3.2.1 Experimental description

A continuous wall heated multistage fluidized bed dryer was designed and fabricated to determine the drying performance of barnyard millet grains. The equipment consists of four stainless steel chambers (with 100 cm diameter and 400 cm height) externally connected. The air flow pipes used are silicone rubber pipes for proper heat resistance and easy dismantling. The equipment and pipes were tightly fitted with Teflon material and thread lining to avoid air leakages. The wall heaters of stages are made up with nichrome wire and the complete equipment was sealed with glass wool to avoid the heat losses. The distributor plates were arranged for each section and completely fitted with gaskets. The advantages of this drying system are continuous fluidization phenomena at each stage, continuous solids outlets at each stage and a separate air passage at each stage. The presence of separate outlets for solids at each stage helps for easy handling of solids. As the unit is externally staged, assembling and dismantling the equipment during the change over from experiment to experiment is easier compared conventional dryers. The process of solids feeding in the first stage and discharge of solids from stage to stage for the remaining stages is simpler. Sample collection is also made easier due to the provision of solids outlet at each stage.

A schematic diagram of continuous multistage fluidized bed dryer was presented in Figure 3.3. Air compressor was used for supplying air flow for each stage in the dryer, wall heating system with a temperature controller was used for each stage. The solids discharge rate was maintained with known moisture of 14.5% (dry basis) using vibratory solids feeder (DR 100 Retsch India). After reaching the required experimental conditions, the air flow was maintained with the help of the bypass valve and rotameter. The temperature of the wall was controlled by four different controller Temperature controllers and to maintenance of constant wall temperature. The temperature sensors (PT-100) were arranged at bed, and solids outlet for each column. For uniform distribution of gas in each stage, gas distributors with 2 mm holes of 40% opening area were used. The samples of solids were collected at each section at equal time intervals, and collected samples were analyzed for moisture using dry basis method. The inlet, outlet humidities and temperatures at each stage were recorded by the use of data scanner (8 Channel universal scanner logger-CT708U) and sensors.

The drying kinetics, exergy and energy analyses were conducted using continuous wall heated multistage fluidized dryer by changing air flow, wall temperature of stages, downcomer height at each stage and solids discharge rate. The properties of millets were tabulated in Table 3.3. The lab scale equipment of multistage fluidized bed dryer was shown in Figure 3.4.

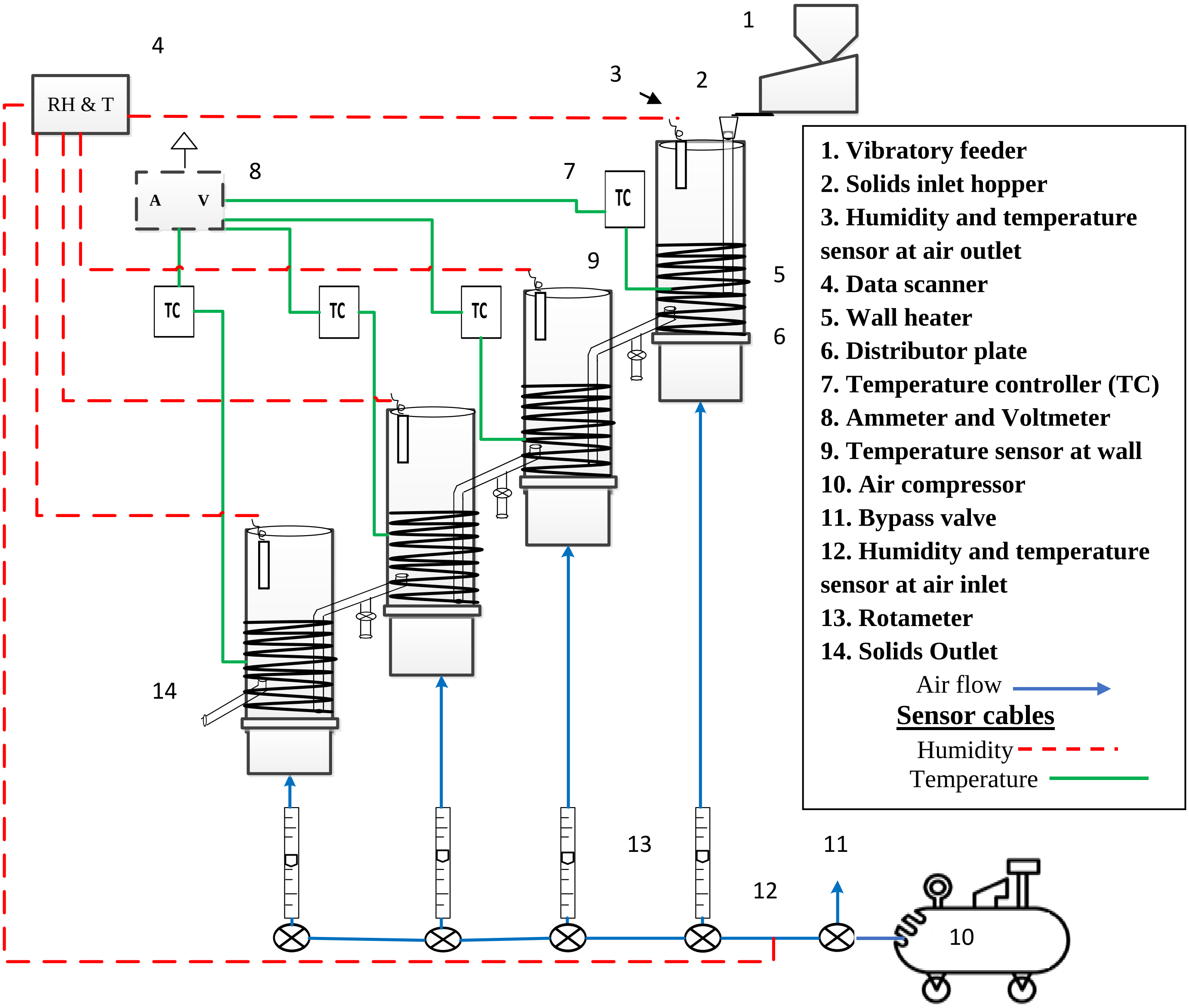


Figure 3. 3 Continuous wall heated multistage fluidized bed dryer

Table 3. 4 Properties of Pearl millet and Barnyard millet

Name of the material	Pearl millet	Barnyard millet
Shape of the material	Spherical	Spherical
Mean diameter, mm	2.2	2
True density, kg/m^3	1290	1355
Minimum fluidization velocity, m/s	0.88	0.86

Figure 3. 4 Lab scale equipment of continuous multistage fluidized dryer

3.4 Continuous hot air multistage fluidized bed dryer

3.4.1 Experimental equipment and procedure

In the experimental approach, continuous multistage fluidized dryer (Figure 3.5) used consists of four stages with 0.4 m height and 0.1 m diameter for each column. The distributor plates having 40% opening area with 2 mm orifice size were used in each stage. The air temperature was maintained through temperature controllers and air heater. The hot air was passed through rotameter and the flow rate was maintained by operating bypass valve. Air leakages and temperature losses were avoided by using gaskets and glass wool sealing.

Temperature and humidity sensors were placed at inlet and outlets of each stage and data was recorded using USB interface data scanner (8 Channel universal scanner logger-CT708U). Solids outlet temperatures were measured using temperature sensors and data logger. In the present study, sand particles were used as bed solids having a density of 2600 kg/m^3 with 0.6 mm uniform particle size. The solids were discharged through the solid hopper into stage 1 and then passed through remaining stages. Experimentation was done to determine the moisture, exergy loss and exergy efficiency of continuous multistage fluidized bed dryer.

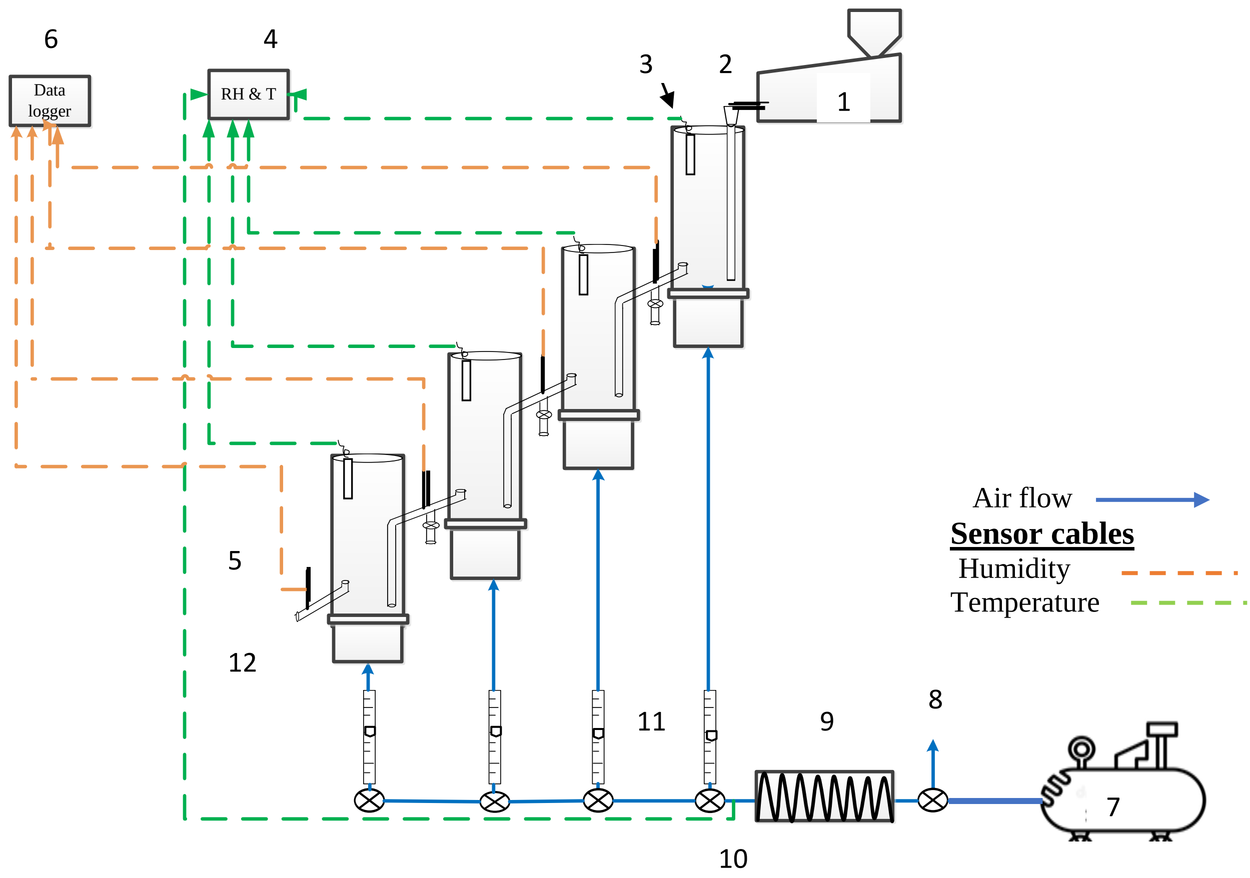


Figure 3. 5 Continuous hot air multistage fluidized bed dryer

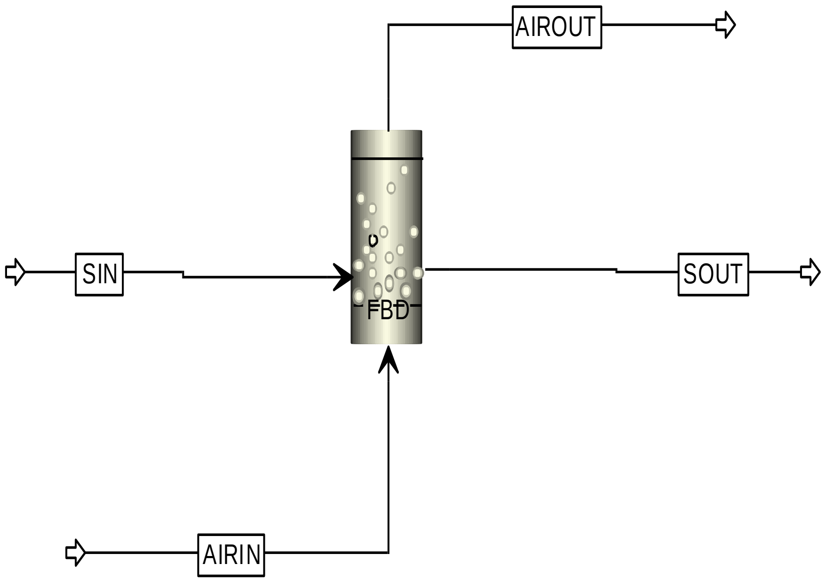
(1. Vibratory solids feeder, 2. Inlet hopper for solids, 3. Humidity and temperature sensors at air outlet, 4. Data scanner (for air), 5. Solids outlet temperature measurement, 6. Data logger (for solids), 7. Air compressor, 8. By pass valve, 9. Air heater, 10. Humidity and temperature sensor at air inlet, 11. Rotameter and 12. Solids outlet)

3.5 Simulation Studies

3.5.1 Continuous hot air single stage fluidized bed dryer

Simulation studies have been carried out using the continuous fluidized bed model available in the Aspen Plus steady-state simulation software (Aspen Corp V 8.4). In Aspen Plus, before entering into the simulation environment the components have to be specified in the property estimation. The Aspen Plus simulator has inbuilt database sources and from that, the different components like water and air have been selected as conventional fluids and sand (SiO_2 silica) as a solid component. The common SOLIDS method has been chosen for property estimation to the selected components.

In a simulation environment of the fluidized bed dryer, a model is selected which is located in the Solids model. The dimensions of the fluidized bed dryer model were given as the height of 2 m and cross-sectional area of 0.0051 m^2. Two input streams were selected for solid and air. The solid input stream is attached from the left side to model and gas stream attached from the bottom. Two output streams were attached to the model from the top for the air and right side for the solids. An inlet solid condition like particle size was given as 1.3 mm under particle size distribution. Remaining conditions were given at room temperature, 1 atm pressure and solids flow rate. The input stream of solids is sent through the mixed inlet with water for the purpose of the initial moisture content of solids. The air inlet conditions like temperature and flow rate were changed during the simulation study. Fluidized bed model has features like gas distribution configuration parameters with orifice diameter and number of orifices. After completely giving the basic input conditions of the dryer, the equilibrium moisture content is given as 0.3%. Through sensitivity parameter analysis, the simulations were carried out changing inlet air temperature, orifice diameter and the number of orifices as input parameters to study the change in output parameters like moisture content and solid outlet temperature. Iterations for each simulation run were given as 100 and minimum error as 0.0001.



Flow streams: AIRIN ➔ AIRINLET ; AIROUT ➔ AIROULET
SIN➔ SOLIDS INLET; SOUT ➔ SOLIDS OUTLET

Figure 3. 6 Continuous single stage fluidized bed dryer in Aspen Plus

In simulation and experimentation, various parameters have been changed such as the opening area of distributor plate, number of orifices and orifice diameter. The Fluidized Bed Dryer simulation model is shown in Figure 3.6 and the parameters and their range have been reported in Table 3.5.

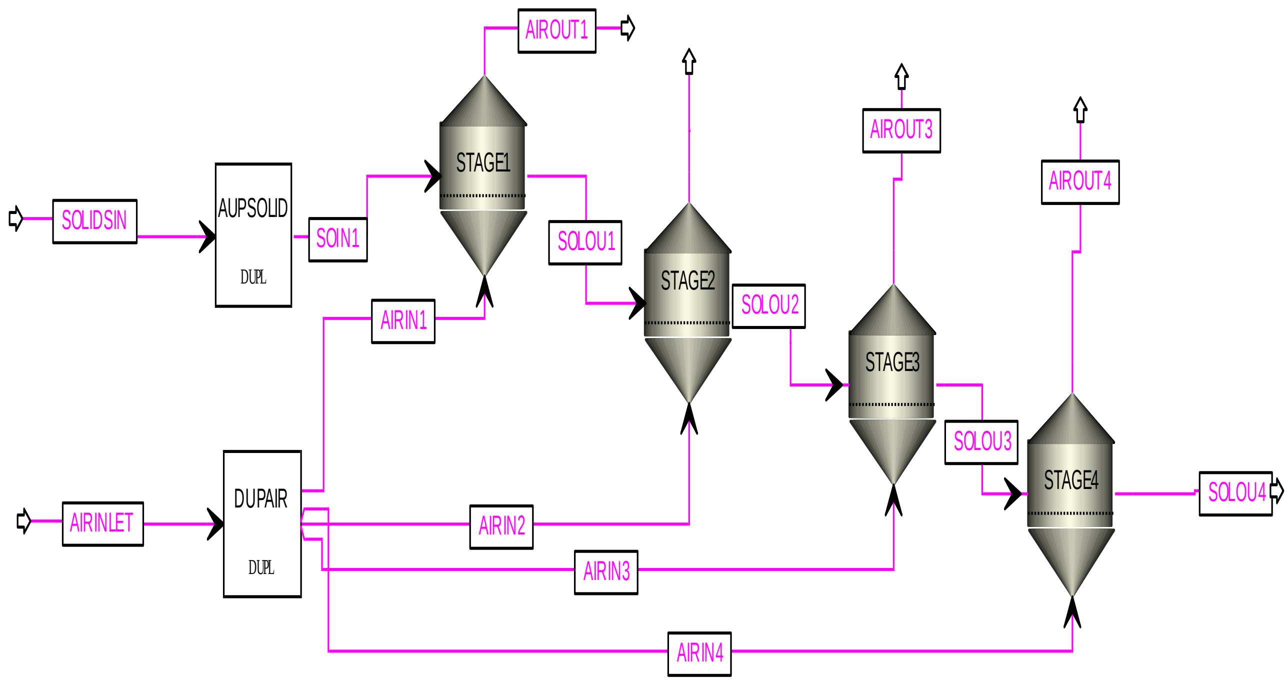
Table 3. 5 Specifications for the single stage fluidized bed drying simulation

Parameter	**Range**
inlet temperature	303-353K
inlet air flow rate	30-80 kg/h
solid flow rate	5 to 10 kg/h
inlet moisture content	10%
diameter of particle	1.3 mm
Geldart powder type	Geldart D
minimum fluidization velocity	0.53757 m/s
bed voidage	0.5
number of orifices	50-600

orifice diameter	0.4-1.3 mm

3.5.2 Continuous hot air multistage fluidized bed dryer

A model for continuous multistage fluidized bed dryer is designed using Aspen Plus simulator (Aspen Corp V 8.4). The model consists of four stages of fluidized bed dryers (Figure 3.7). Simulations have been carried out by stepwise process, (i) the components were specified as water, air and sand (silica) from Aspen database (ii) the dimensions of continuous multistage fluidized bed dryer model were given with height as 0.4 m and area as 0.0078 m^2 for each stage. Here in this study, solids and air were used as two major streams. Size of particles was given as 0.6 mm in particle size distribution section. The solid and water were given in mixed inlet stream to obtain the moisture content of solids. The simulation was carried out with 100 iterations for each run with a minimum error of 0.0001. Simulations were executed with changing condition of air flow rates, air temperatures, solids flow rates and initial moisture contents. Inlet parameters were varied using sensitivity analysis and outputs of the dryers were examined. The simulation of multistage fluidized bed drying is done for steady-state operation and exergy loss and exergy efficiency were analyzed. The input parameters were specified in Table 3.6.



SOIN ⟶ : Solids inlet stream, AIRIN ⟶: Air inlet stream, SOLOU ⟶ : Solids outlet stream, AIROUT ⟶ : Air outlet stream

Figure 3. 7 Continuous hot air multistage fluidized bed dryer in Aspen Plus

Table 3. 6 Operating parameters of multistage fluidized bed dryer model

Parameter	Range
inlet temperature	313 - 353 K
inlet air flow rate	40-80 kg/h
inlet moisture content	7.5 to 12.5 %
solid flow rate	6.7 to 12.5 kg/h
diameter of particle	0.6 mm

3.6 Drying calculation

After the experimentation, results were analyzed. The moisture content of samples was measured on the basis of weight as a function of time. The moisture content was calculated based on the equation (3.6.1).

$$\mathrm{MC} = (w_t - w_d)/w_d \tag{3.6.1}$$

3.6.1 Effective diffusivity based on drying kinetics

Diffusion model is used in general for describing the drying behavior of materials. Many authors have estimated effective diffusion coefficient for different materials using diffusion model given by Equation 3.6.2 (Mohammadpour et al., 2008; Mirzaee et al., 2009; Gazor and Mohsenimanesh, 2010; Askari et al., 2013; Parlak, 2015).

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}exp\left(-{n^2\pi^2 D_{eff}t}/{r^2}\right) \tag{3.6.2}$$

where the moisture ratio of material was calculated based on the equation presented below

$$MR = {(M_t - M_e)}/{(M_i - M_e)} \tag{3.6.3}$$

Table 3. 7 Models of drying kinetics

Name of Model	**Equation of Model**	**Reference**
Newton	MR = exp(-kt)	(Onwude et al., 2016)
Page	MR = exp(-kt^n)	(Kaleta et al., 2013)
Modified Page	MR = exp[-(kt)^n]	(Ojediran and Raji, 2010)
Henderson and Pabis	MR = a exp(-kt)	(Altay et al., 2019)
Logarithmic	MR = a exp(-kt)+ c	(Miraei Ashtiani et al., 2017)
Two term	MR = a exp(-k$_0$t)+ b exp(-k$_1$t)	(Meziane, 2011)
Diffusion approach	MR = a exp(-kt)+(1 -a) exp(-kbt)	(Mohammadpour et al., 2008)
Modified Henderson and Pabis	MR = a exp(-kt)+ b exp(-gt)+ c exp(-ht)	(Madhiyanon et al., 2009)
Midilli et al.	MR = a exp(-kt^n)+ bt	(Midilli et al., 2002)

Different empirical and semi-empirical models like Newton, Page, and logarithmic models (Table 3.7) have been developed by earlier investigators for describing the drying kinetics. Many authors have used these models and estimated model parameters using their experimental results (Mohammadpour et al., 2008;Chayjan et al., 2013; Parlak, 2015). In the present study also, parameters of the models have been estimated using the present experimental data and the models with the best fit have been reported.

3.7 Energy analysis

3.7.1 Batch wall heated fluidized bed dryer

A thermodynamic analysis is important for any system like a fluidized bed dryer. The thermal energy analysis of drying process of wall heated fluidized bed dryer was performed. Energy aspects, as well as drying behavior of the material, have been determined. The energy equations were developed for wall heated fluidized bed dryer with the help of literature (Dincer and Rosen, 2013; Ge et al., 2014; Sarker et al., 2015).

In the present study, experiments were performed in the wall heated fluidized bed dryer. In this dryer, heat transfer effect will be of different forms. They are i) wall to air heat transfer ii) air to particle heat transfer and iii) particle to particle heat transfer (Yang, 2003; Srinivas et al., 2015) The inlet and outlet humidity ratios were calculated using Psychometric chart from experimental data. W_o and W_i indicates inlet and outlet humidity ratios. The evaporation rate m_s were calculated from the following relation (Equation 3.7.1). Energy utilization rate was calculated from equation 3.7.2.

$$m_w = m_a (W_o - W_i) \quad (3.7.1)$$

Where m_a (kg dry air/s) is the mass flow rate of air. Accordingly, the energy required for converting water into steam was obtained from equation 3.7.2.

$$\text{Energy utilization rate} = E_{out} = m_s . L_g \quad (3.7.2)$$

Here L_g (kJ/kg water) is the latent heat of vaporization of moisture

$$\text{Input energy to dryer } (E_{in}) = \text{Energy supplied for wall heating} \quad (3.7.3)$$

Energy utilization ratio was calculated from equation 3.7.4.

$$EUR = E_{out}/E_{in} \quad (3.7.4)$$

3.7.2 Continuous wall heated multistage fluidized bed dryer

The energy analysis of barnyard millet grains drying was performed to examine the energy efficiency of continuous multistage fluidized bed drying process as per the first law of thermodynamics. As per literature, the equations were developed for continuous multistage fluidized bed drying process (Karthikeyan and Murugavelh, 2018). In experimentation, dryer inlet and outlet humidity of air at different stages have been measured and the moisture evaporation rates of each of the stages in the dryer are calculated from the humidity values. In the dryer, the carryover moisture in the air from the wet material can change the air humidity at the outlet. Wo_1, Wo_2, Wo_3, Wo_4 are the outlet specific humidity ratios of the respective stage and W_i is the inlet air specific humidity ratio of the multistage fluidized bed dryer. From the psychometric chart and mass balance, the heat used in multistage fluidized bed drying process was determined. The moisture evaporation rates of the stages m_{w1}, m_{w2}, m_{w3} and m_{w4} were determined from the equations.

The mass balance provides the following relation for the evaporation rate of water, stage-wise in the multistage fluidized bed dryer (from equations 3.7.5 to 3.7.8).

$$m_{w1} = m_a (Wo_1 - W_i) \quad (3.7.5)$$

$$m_{w2} = m_a (Wo_2 - W_i) \quad (3.7.6)$$

$$m_{w3} = m_a (Wo_3 - W_i) \quad (3.7.7)$$

$$m_{w4} = m_a (Wo_4 - W_i) \quad (3.7.8)$$

Here m_w moisture evaporation rate, m_a (kg/s) flow rate of air, the specific humidity ratio is W (kg/kg) at temperature T, the latent heat of vaporization is L_g (kJ/Kg).

The energy utilization of dryer, stage-wise was calculated using the equations 3.7.9 to 3.7.12.

$$E_{out1} = m_{w1} \cdot L_g \quad (3.7.9)$$

$$E_{out2} = m_{w2} \cdot L_g \quad (3.7.10)$$

$$E_{out3} = m_{w3} \cdot L_g \quad (3.7.11)$$

$$E_{out4} = m_{w4} \cdot L_g \quad (3.7.12)$$

The total energy flow from the outlet of multistage fluidized bed dryer was calculated from equation 3.7.13.

$$E_{mfout}= E_{out1}+ E_{out2}+ E_{out3}+ E_{out4} \quad (3.7.13)$$

Energy supplied through the wall heating of each stage E_{in1}, $E_{in2,}$ E_{in3} and E_{in4} of the multistage dryer, E_{mfin} is calculated from the equation 3.7.14.

$$E_{mfin}= E_{n1}+ E_{in2}+ E_{in3}+ E_{in4} \quad (3.7.14)$$

Energy utilization ratio of multistage fluidized bed dryer is calculated from equation 3.7. 15.

$$EUR= E_{mfout}/ E_{mfin} \quad (3.7.15)$$

3.8 Exergy Analysis

According to the second law of thermodynamics, the exergy can explain the quality and quantity of energy flow of system (Sarker et al., 2015; Karthikeyan and Murugavelh, 2018). At steady state flow condition, the general form of exergy equation for drying reported as equation 3.8.1 in literature and specific heat of air determined using equation 3.8.3a (Nazghelichi et al., 2010).

$$Ex = m_a\, c_{pa} [(T- T_\infty) - T_\infty \ln(T/ T_\infty)] \quad (3.8.1)$$

$$Cp_a = 1.004+1.88W \quad (3.8.1a)$$

3.8.1 Batch wall heated fluidized bed dryer

Exergy in (Ex_{ain}) and Exergy out (Ex_{aout}) of air in the batch wall heated fluidized bed dryer were calculated from equations 3.8.2 and 3.8.3 as given below

$$Ex_{ain} = m_a .c_{pa} .[(T_{ain}-T_\infty)-T_\infty. \ln(T_{ain} / T_\infty)] \quad (3.8.2)$$

$$Ex_{aout} = m_a .c_{pa} .[(T_{aout}- _\infty)-T_\infty. \ln(T_{aout} / T_\infty)] \quad (3.8.3)$$

In the present study exergy rate of wall hater (Ex_w) of fluidized bed dryer was calculated as follows (Ge et al., 2014)

$$Ex_w = Q_w. A. (1-(T_\infty/T_w)) \quad (3.8.4)$$

Here Q_w is the wall heat flux for wall heated fluidized bed dryer, T_w is the Temperature of wall

Total Exergy rate into the dryer (Ex_{din}) was calculated as follows:

$$Ex_{din} = Ex_w + Ex_{ain} \quad (3.8.5)$$

Here Ex_{ain} = 0 because in these experiments, inlet air at ambient temperature was passed as inlet to dryer.

Exergy loss (Ex_L) and Exergy efficiency (η_{Ex}) were calculated using equations 3.8.6 and 3.8.7.

$$Ex_L = Ex_{din} - Ex_{aout} \quad (3.8.6)$$

$$\eta_{Ex} = (Ex_{din} - Ex_{loss})/ Ex_{din} \quad (3.8.7)$$

3.8.2 Continuous wall heated multistage fluidized bed dryer

According to the thermodynamics second law, the inflow and outflow exergy rates and exergy losses of the multistage fluidized bed dryer were analyzed.

Exergy inflow for stage 1 (air) = $m_a \cdot c_p \cdot [(T_{in1} - T_\infty) - T_\infty . \ln(T_{in1}/ T_\infty)]$ (3.8.8)

Exergy inflow through wall (for stage 1) = $Q_{wall} \cdot A. (1-(T_\infty/T_w))$ (3.8.9)

Exergy in (stage 1) (Ex_{in1}) = Exergy inflow (air) + Exergy inflow (wall) (3.8.10)

Here exergy inflow (air) = 0 inlet air at ambient temperature was passed to dryer due to this exergy air inflow is equal to zero.

Similarly, for remaining stages Ex_{in2}, Ex_{in3} and Ex_{in4}, the exergy inflows of dryer, stage wise were calculated based on equation 3.8.8 to 3.8.10. Total exergy inflow for multistage fluidized bed dryer was calculated from equation 3.8.11.

$$Ex_{mwin} = Ex_{in1} + Ex_{in2} + Ex_{in3} + Ex_{in4} \quad (3.8.11)$$

Exergy outflow, stage wise was calculated based on equations 3.8.12 to 3.8.15.

$$Ex_{out1} = m_a \cdot c_p \cdot [(To_1 - T_\infty) - T_\infty . \ln(To_1/ T_\infty)] \quad (3.8.12)$$

$$Ex_{out2} = m_a \cdot c_p \cdot [(To_2 - T_\infty) - T_\infty . \ln(To_2/T_\infty)] \quad (3.8.13)$$

$$Ex_{out3} = m_a \cdot c_p \cdot [(To_3 - T_\infty) - T_\infty . \ln(To_3/T_\infty)] \quad (3.8.14)$$

$$Ex_{out4} = m_a \cdot c_p \cdot [(To_4 - T_\infty) - T_\infty . \ln(To_4/T_\infty)] \tag{3.8.15}$$

Total exergy outflow for MFBD was calculated from equation 3.8.16.

$$Ex_{mwout} = Ex_{out1} + Ex_{out2} + Ex_{out3} + Ex_{out4} \tag{3.8.16}$$

Exergy Efficiency for MFBD was calculated from equation 3.8.17.

$$\eta_{Exmw} = Ex_{mfout} / Ex_{mfin} \tag{3.8.17}$$

Exergy loss of MFBD was calculated from equation 3.8.18.

$$Ex_{mwLoss} = (Ex_{mfin} - Ex_{mfout}) / Ex_{mfin} \tag{3.8.18}$$

3.8.3 Continuous hot air multistage fluidized bed dryer

Equation 3.8.1 is used to find the exergy inlet or outlet for each individual stage in dryer.

From the above relation, the exergy inflow and outflow for multistage fluidized bed dryer can be written as equations 3.8.19 and 3.8.20.

$$Ex_{mhi} = Ex_{i1} + Ex_{i2} + Ex_{i3} + Ex_{i4} \tag{3.8.19}$$

$$Ex_{mho} = Ex_{o1} + Ex_{o2} + Ex_{o3} + Ex_{o4} \tag{3.8.20}$$

Exergy loss for multistage fluidized bed dryer was obtained from equation (3.8.21)

$$Ex_{mhL} = Ex_{msi} - Ex_{mso} \tag{3.8.21}$$

Exergy efficiency can be determined using the equation (3.8.22) for multistage fluidized bed dryer

$$\eta_{mhEx} = (Ex_{msi} - Ex_{msL}) / Ex_{msi} \tag{3.8.22}$$

Typical experimental data are shown in Appendix I in Tables A-E and Table I. Simulation results for typical runs are given in Tables F-H.

3.9 Uncertainty analysis

The uncertainties analysis was conducted for dryers using equations 3.9.1, 3.9.2 and 3.9.3 (Chauhan and Kumar, 2016; Elsayed et al., 2011). The uncertainties of the instruments used for the present study was tabulated in Table. 3.8.

$$O_m = \sum_{i=1}^{n} O_i \big/ n \tag{3.9.1}$$

$$S_d = \left[1 \big/ (n-1) \right] \sum_{i=1}^{n} (O_i - O_m)^2 \tag{3.9.2}$$

$$U_n = \sqrt{S_d} \tag{3.9.3}$$

Where O= Observations, n=Number of readings, O_m= Mean for the observations, i=integer, S_d= standard deviation and U_n = Uncertainty

Table 3. 8 Accuracy of instruments used for experimentation

Parameter	Uncertainty	Manufacture defined accuracy (%)
Sample moisture measurement	±0.0002(g)	±0.0001
Humidity sensors	±0.15(%RH)	±0.1
Rotameter	±0.5(kg/h)	±0.5
Batch wall heated Fluidized bed dryer		
Vibratory feeder	±0.1(kg/h)	±0.1
Tin	±0.4(°C)	±0.2
Tout	±0.4(°C)	±0.2
T_∞	±0.5(°C)	±0.2
Continuous wall heated multistage Fluidized bed dryer		
T_{out1}	±0.4(°C)	±0.2
T_{out2}	±0.4(°C)	±0.2
T_{out3}	±0.4(°C)	±0.2
T_{out4}	±0.4(°C)	±0.2

From the Mumtaz et al., (2016), the error range associated with results were calculated for the dryers.

- The exergy values of batch wall heated fluidized bed dryer uncertainties were observed in the range of ±0.61%
- The exergy values of Continuous wall heated multistage fluidized bed dryer uncertainties were observed in the range of ±1.56%

CHAPTER 4: RESULTS AND DISCUSSION

The Kodo millet and Fenugreek seeds are heat sensitive materials which, when exposed in the experiment to hot stream temperature, may change the material properties. That's why wall heated fluidized bed drying was chosen for these experiments. Wall heating is by indirect heat operation and hence it does not change material properties much than direct drying operation like hot air or steam heated drying. In continuous hot air fluidized bed dryer direct contact takes place and hence sand which is not heat sensitive was used. Hence study on millets was done using wall heated dryer whereas study on hot air dryer was done using sand.

4.1 Batch wall heated fluidized bed dryer

In the present study, experiments were performed to study the drying characteristics of Kodo millet and Fenugreek seeds changing various parameters like air velocity, wall temperature, bed height and initial moisture content (Appendix- Data A and B).

4.1.1 Drying characteristics of Kodo millet and Fenugreek seeds

4.1.1.1 Effect of wall temperature on drying characteristics

Experiments have been performed to determine the influence of wall temperature on drying characteristics in the fluidized bed dryer varying wall temperature from 313 to 333K and keeping operating parameters like air velocity, initial moisture content and bed height as constant.

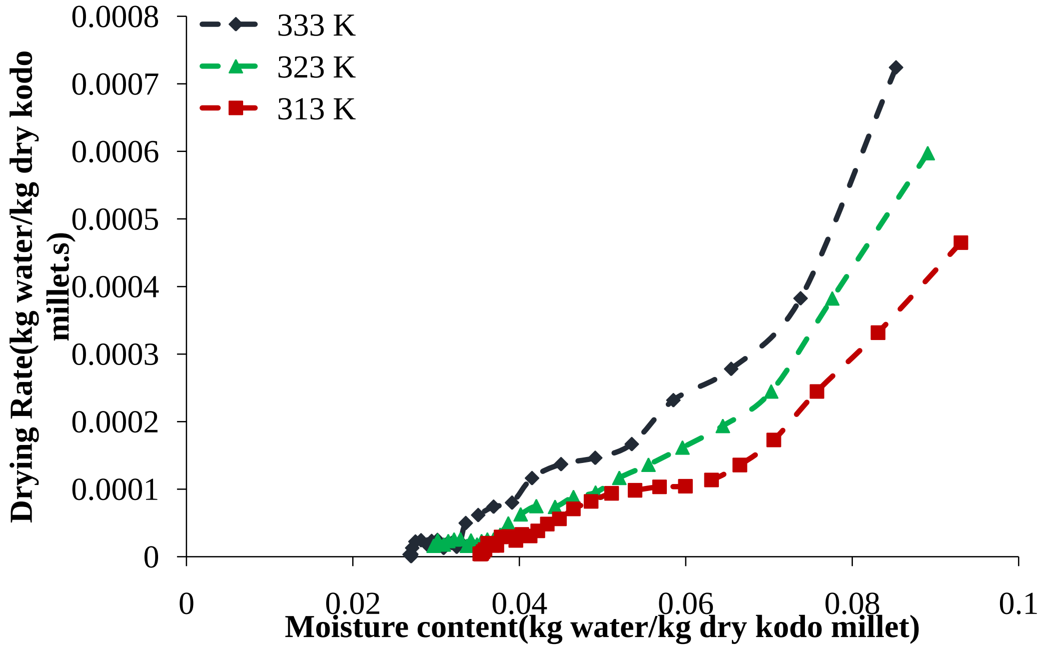


Figure 4. 1 Effect of wall temperature on drying characteristics of Kodo millet (Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

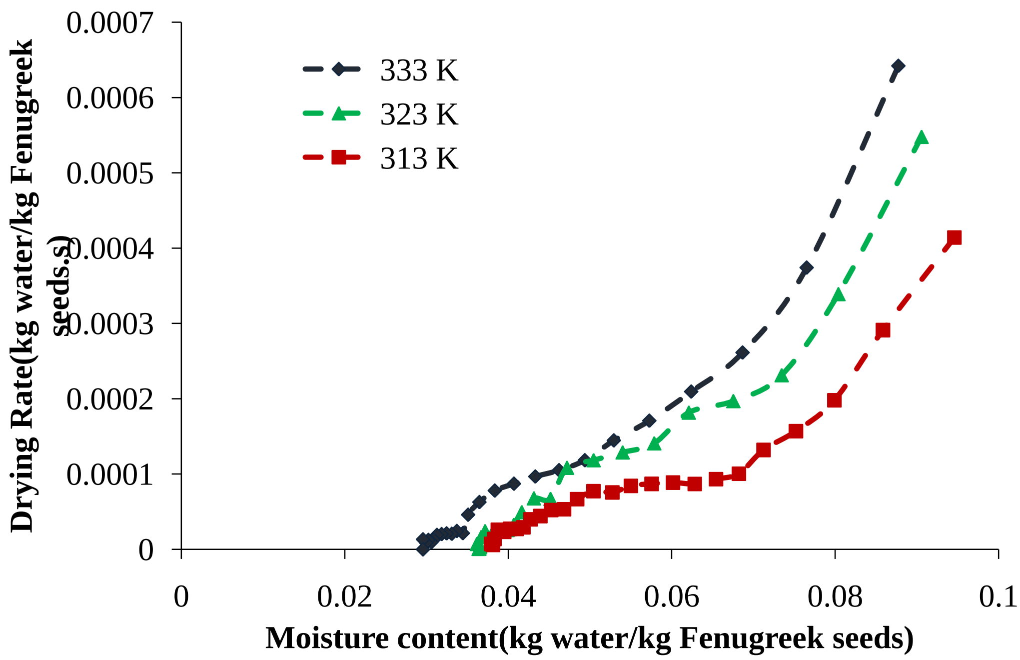


Figure 4. 2 Effect of wall temperature on drying characteristics of Fenugreek seeds (Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

From Figs 4.1 and 4.2 it can be observed that the drying rate of Kodo millet and Fenugreek seeds increased with increasing wall temperature. This is due to the fact that increasing wall temperature enhances wall to gas heat transfer, gas to particle heat transfer and particle to particle heat transfer. From Fig 4.3, it can be observed that bed temperature increased with increasing wall temperature of dryer due to the increase in heat transfer between the wall to gas and wall to particles.

Meziane (2011) has studied the drying behavior of olive pomace using batch hot air fluidized dryer. He has reported that the drying rate of olive pomace increased with increasing air temperature from 323 to 353 K at an air velocity of 1.0 m/s. Parlak (2015) has studied the dying characteristics of ginger slices using batch hot air fluidized bed dryer. From his results, it was observed that the bed temperature of ginger slices increased with time. Similar trends were observed in the present study also. The drying rate of bed material increased with increasing wall temperature (from 313 to 333 K) and bed temperature increased with increase in time and wall temperature of the dryer.

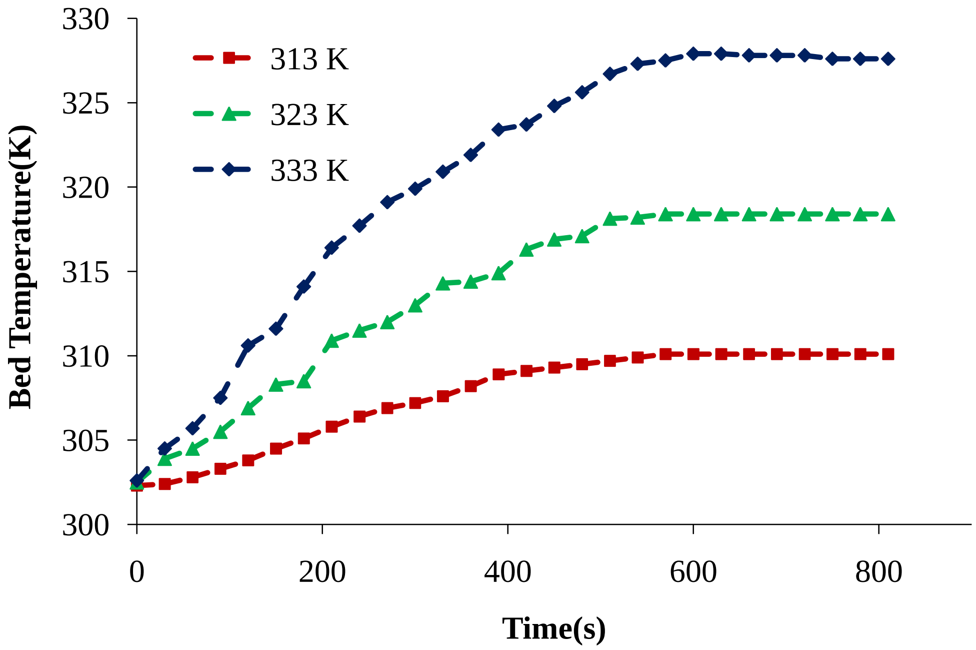


Figure 4. 3 Bed temperature profiles of Kodo millet at different wall temperatures (Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

4.1.1.2 Effect of air velocity on drying characteristics

Experiments were performed with Kodo millet and Fenugreek seeds based on physical properties and minimum fluidization velocity. Experiments were carried out varying the air velocity from 1.01 to 1.7 m/s and remaining parameters like wall temperature, initial moisture content, and initial bed height being kept in constant.

From Figs 4.4 and 4.5, it can be observed that the drying rate of Kodo millet and Fenugreek seeds increased with increasing air velocity and equilibrium moisture decreased with increasing air velocity. Increasing air velocity increases gas solid contact which results in increased moisture removal. With the increase in air velocity, the rate of diffusion of moisture is increased which results in increased drying rate. Also at higher velocities, rapid heat transfer occurs between solid and air.

Srinivasakannan and Balasubramanian (2009b) have conducted an experimental study on pearl millet using a batch hot air fluidized bed dryer. From their results, it has been noticed that the moisture content of pearl millet decreased with increasing air velocity from 1.69 to 2.25 m/s with air temperature kept at 313 K. Kaymak (2002) has conducted studies on green pepper and red pepper using hot air fluidized bed dryer. He has presented that the drying rate increased with increasing air velocity from 0.5 to 4.5 m/s at an air temperature of 333 K. The influence of air velocity in the present study also showed a similar effect. The drying rate of Kodo millet and Fenugreek seeds increased with increasing air velocity from 1.01 to 1.7 m/s.

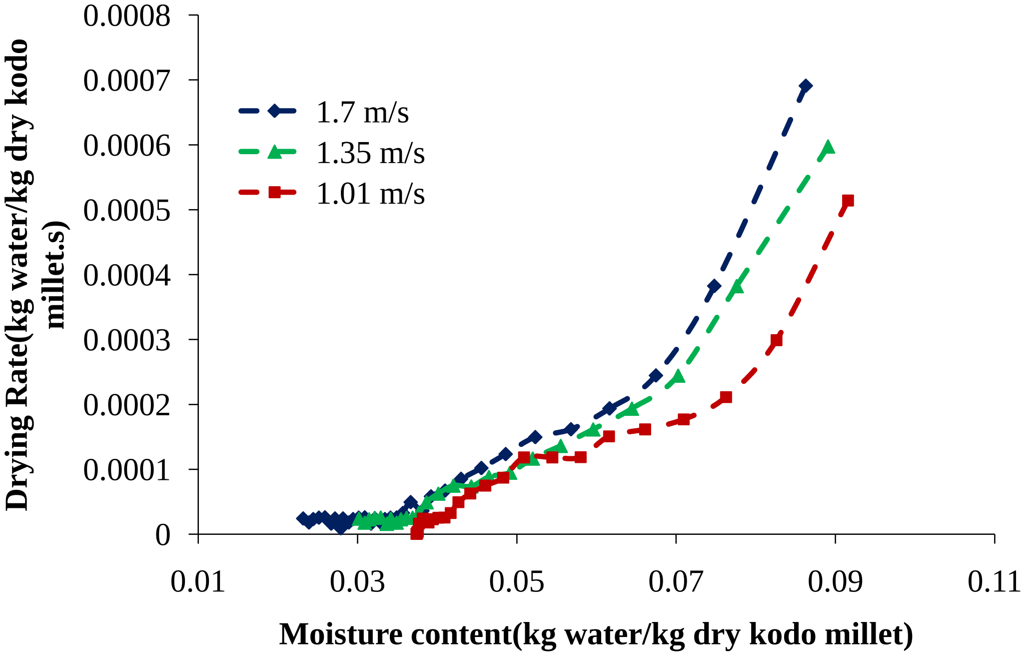


Figure 4. 4 Effect of air velocity on drying behavior of Kodo millet

(Wall temperature-323 K, bed height-4 cm and initial moisture content-10%)

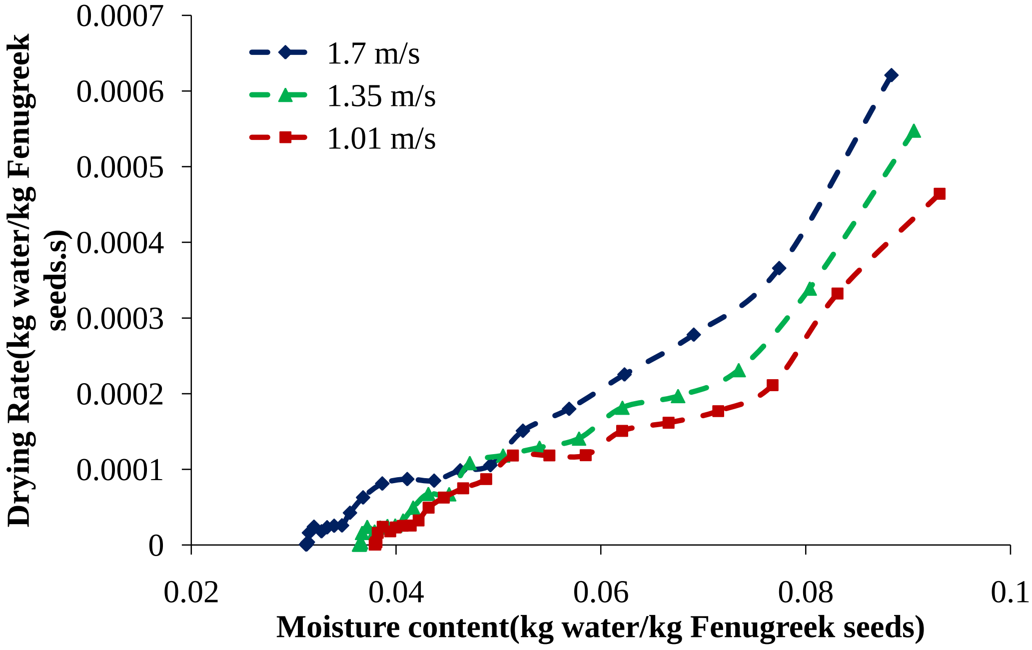


Figure 4. 5 Effect of air velocity on drying behavior of Fenugreek seeds
(Wall temperature-323 K, bed height-4 cm and initial moisture content-10%)

4.1.1.3 Effect of bed height on drying characteristics

Experiments were performed with constant operating conditions like air velocity, wall temperature and initial moisture content varying bed height from 3 to 5 cm to know the effect of bed height on drying behavior of Kodo millet and Fenugreek seeds.

From the results shown in Figs 4.6 and 4.7, it can be observed that the drying rate of Kodo millet and Fenugreek seeds decreased with increasing bed height. This is because there will be higher loading at higher bed heights, which results in decrease of gas to solid contact. Higher bed height also increases the amount of water content to be removed in comparison with lower initial bed heights.

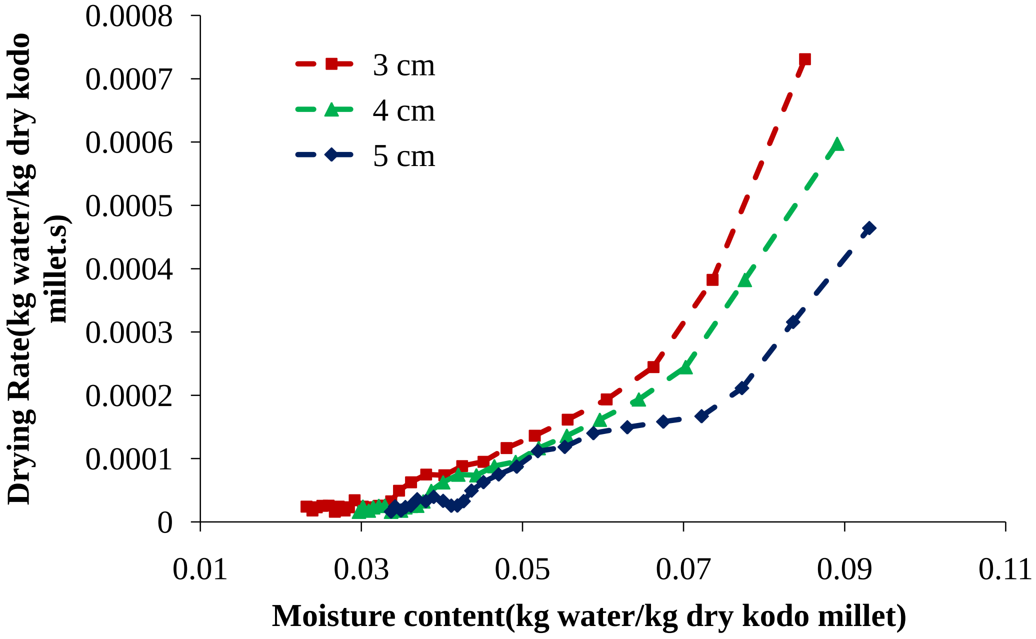


Figure 4. 6 Effect of bed height on drying behavior of Kodo millet

(Air velocity-1.35 m/s, Wall temperature-323 K and initial moisture content-10%)

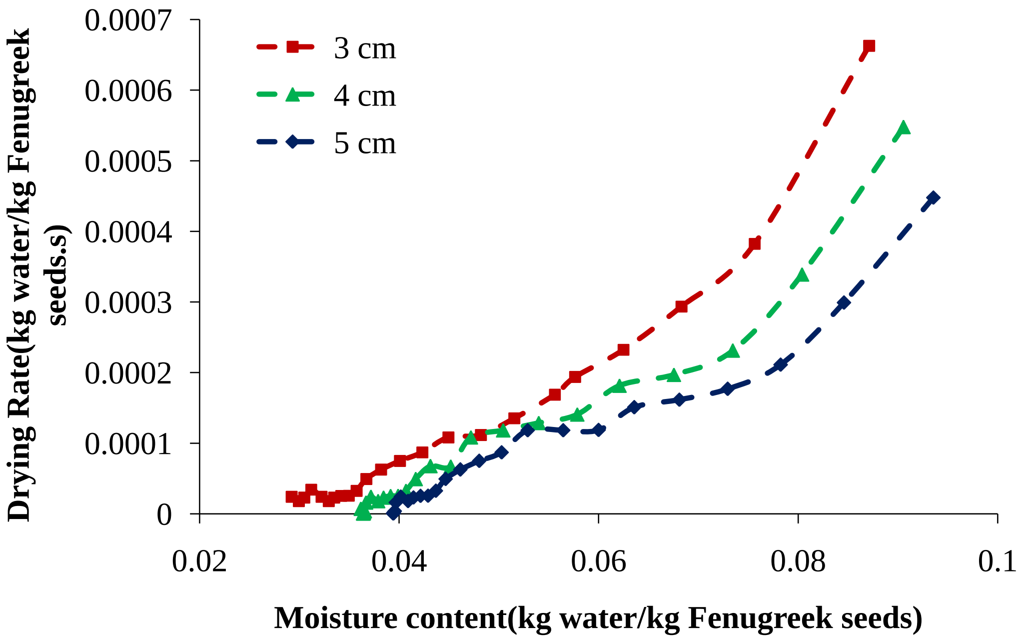


Figure 4. 7 . Effect of bed height on drying behavior of Fenugreek seeds

(Air velocity-1.35 m/s, Wall temperature-323 K and initial moisture content-10%)

Thomas and Varma (1992) have investigated experimentally on various granular products using batch and continuous hot air fluidized bed dryer. The investigators have observed the similar trend as seen in the present study. The drying rate decreased with increasing bed height in the dryer.

4.1.1.4 Effect of initial moisture content on drying characteristics

Experiments were performed to determine the effect of initial moisture content on drying characteristics of Kodo millet and Fenugreek seeds. The drying characteristics were carried out varying initial moisture content from 10 to 20% and keeping remaining parameters constant.

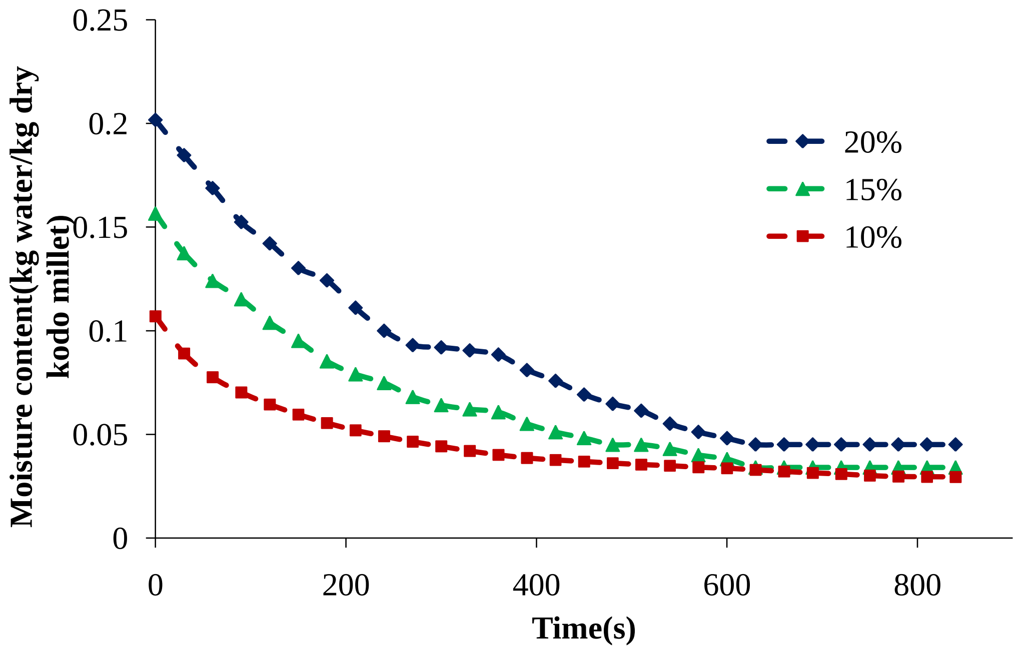


Figure 4. 8 Effect of initial moisture content on drying behavior of Kodo millet (Air velocity-1.35 m/s, Wall temperature-323 K and bed height-4 cm)

It can be observed from Figs 4.8 and 4.9 that, at any given time, the moisture content of solids in the dryer will be higher for particles of higher initial moisture content. Moisture content decreases with time due to drying. Syahrul et al. (2002) study worked on drying of wheat grains in a batch hot air fluidized bed dryer, similar reports were noticed from his study.

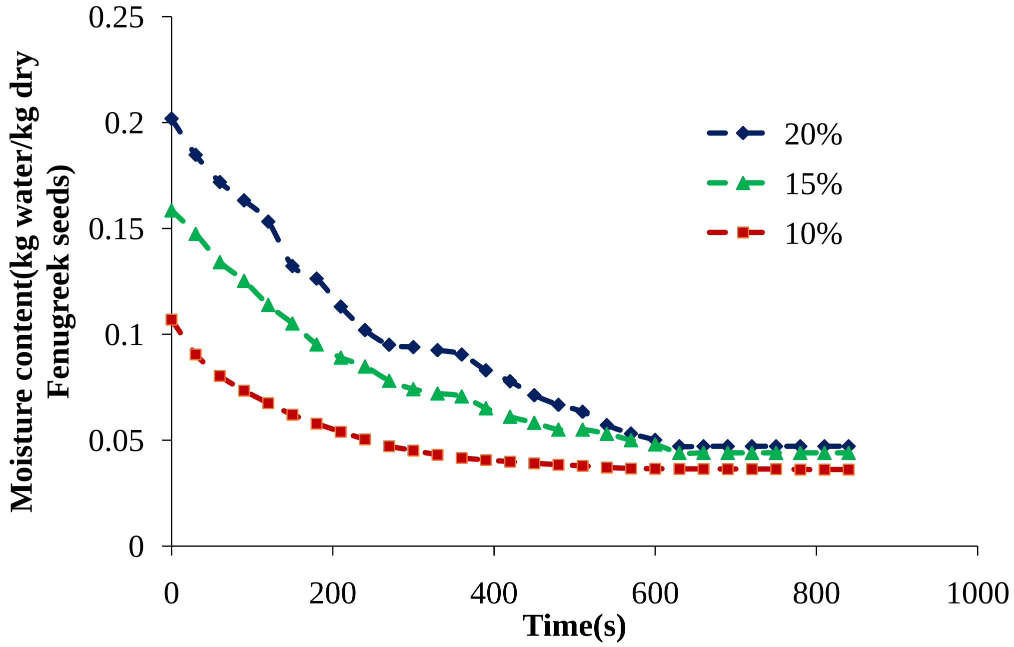


Figure 4. 9 Effect of initial moisture content on drying behavior of Fenugreek seeds (Air velocity-1.35 m/s, Wall temperature-323 K and bed height-4 cm)

4.1.2 Energy utilization ratio

Experiments were conducted varying wall temperature, air velocity, initial moisture content and bed height with two different bed materials Kodo millet and Fenugreeks seeds and the energy utilization ratio obtained from experimental results is presented for all the parameters.

4.1.2.1 Effect of wall temperature on energy utilization ratio

Experiments were carried out varying wall temperature from 313 to 333 K and keeping remaining parameters constant. From the results, EUR is presented in Figs 4.10 and 4.11. It can be observed that the energy utilization ratio increased by increasing wall temperature from 313 to 333 K. The highest energy utilization ratio is observed at starting of the drying time, then its value decreased with time. From the results, the energy utilization ratio is increased with increasing wall temperature in the batch fluidized bed dryer. Increasing wall temperature enhances the heat transfer between the wall to gas and gas to solid, thus resulting in increased moisture evaporation rate.

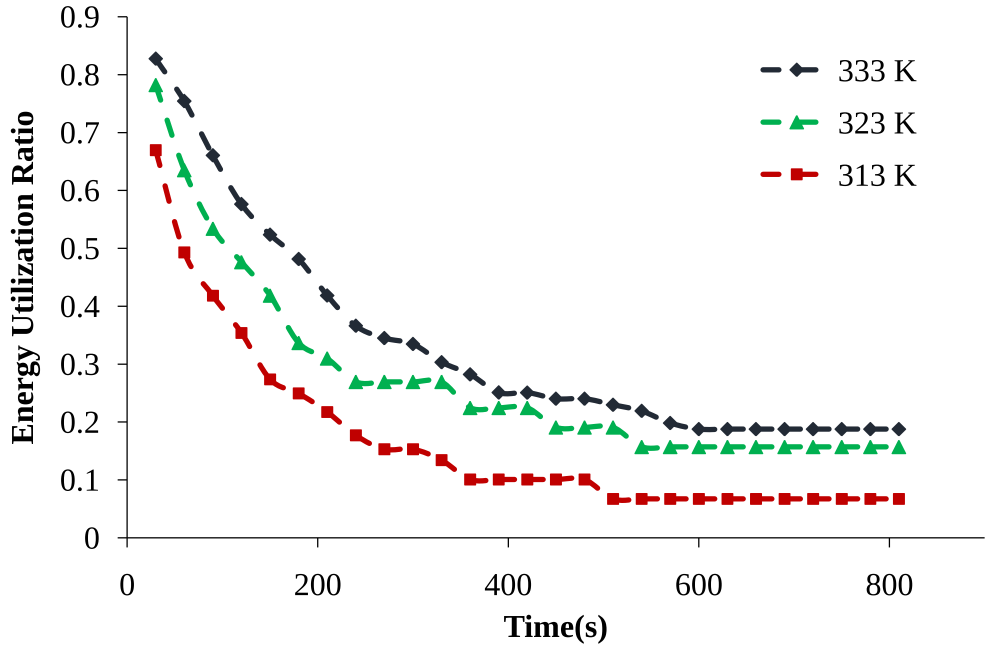


Figure 4. 10 EUR profiles of Kodo millet at different wall temperatures
(Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

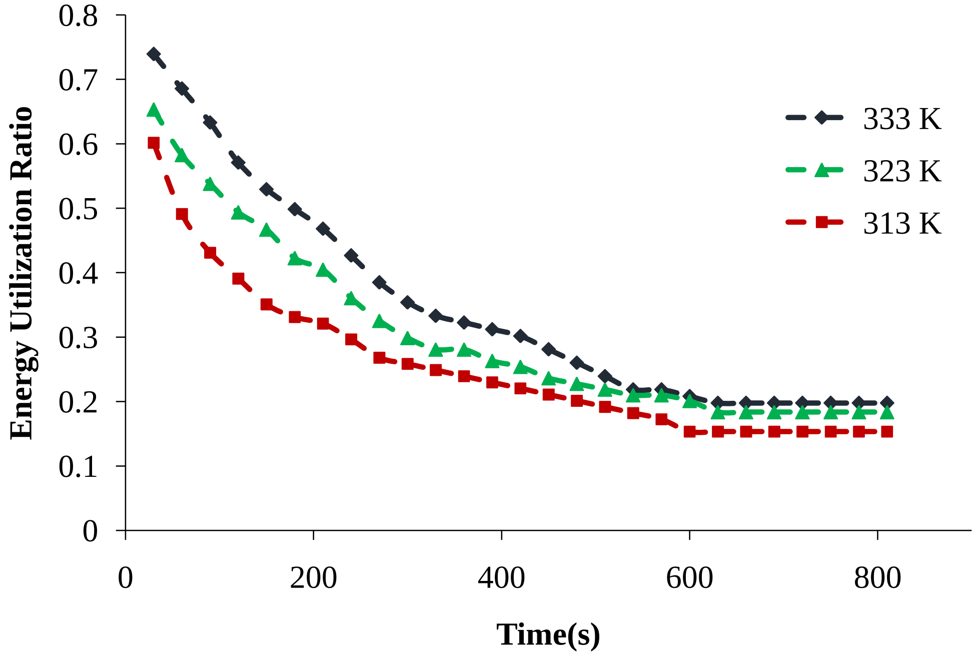


Figure 4. 11 EUR profiles of Fenugreek seeds at different wall temperatures
(Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

4.1.2.2 Effect of air velocity on energy utilization ratio

Experiments were conducted varying air velocity from 1.01 to 1.7 m/s and with remaining parameters kept constant. From Figs 4.12 and 4.13, it can be observed that the energy utilization ratio increased with increasing air velocity and decreased with drying time. In fluidized bed dryer, the gas-solid contact plays an important role. Increasing air velocity results in increased gas solid contact. Also increasing air velocity increases the moisture removal rate from solids, which results in increased energy utilization ratio in wall heated fluidized bed dryer.

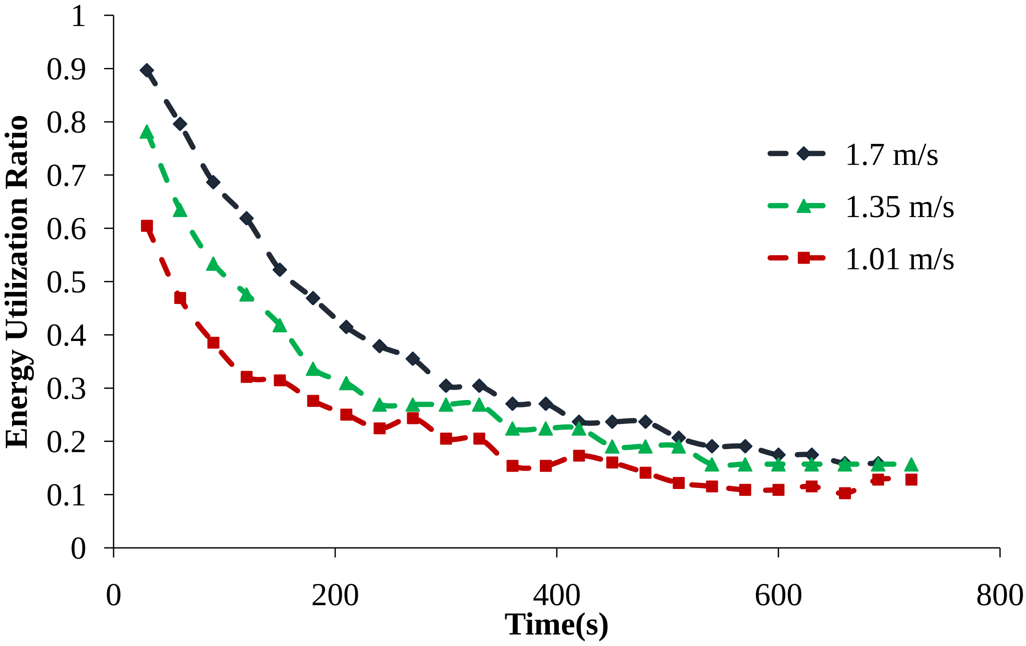


Figure 4. 12 EUR profiles of Kodo millets at different air velocities

(Wall temperature-323 K, bed height-4 cm and initial moisture content-10%)

Karagüzel et al. (2012) have studied the energy and exergy analyses of chickpea and beans in hot air fluidized bed dryer and reported that EUR percentage increased (presented approximately 30 to 50%) with increasing air temperature from 308.6 to 343.1 K.. Motevali and Minaei (2012) have studied on energy and exergy analyses of pomegranate arils in microwave oven at different air temperatures and air velocities and it has been noticed that EUR and exergy efficiency increased (EUR presented approximately 0.001 to 0.006) with increasing air velocity from 0.5 to 1.5 m/s and air temperature from 323 to 343 K. The present study also shows similar trends ie. EUR (approximately 0.6 to 0.9) increases with increasing air velocity and wall temperature for Kodo millet and Fenugreek seeds.

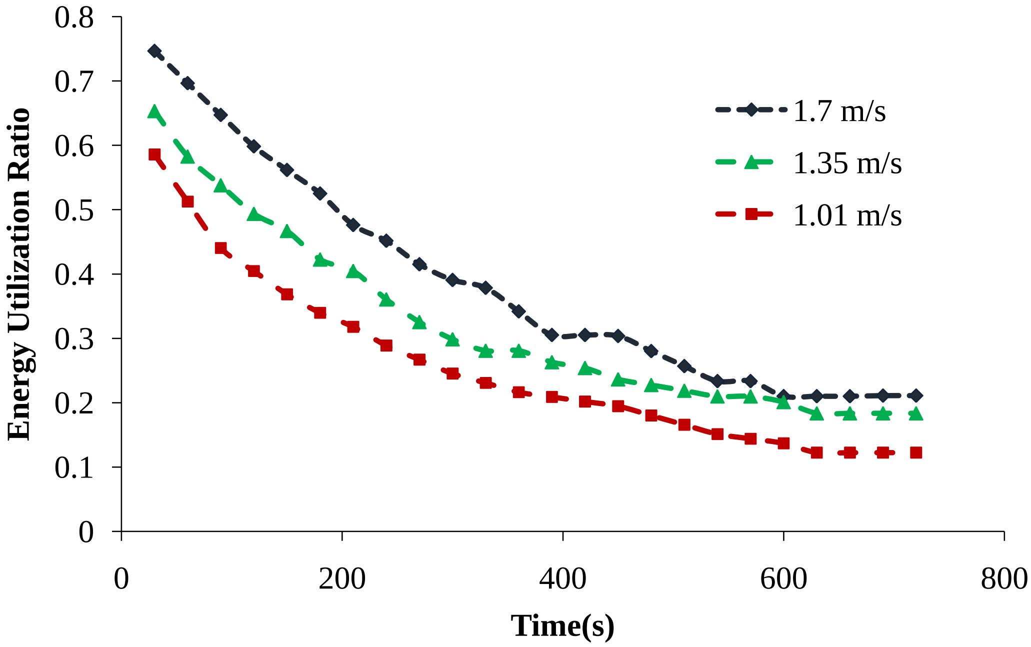


Figure 4. 13 EUR profiles of Fenugreek seeds at different air velocities
(Wall temperature-323 K, bed height-4 cm and initial moisture content-10%)

4.1.2.3 Effect of bed height on energy utilization ratio

Experiments were performed varying bed height from 3 to 5 cm in batch wall heated fluidized bed dryer and keeping remaining parameters constant. From the results shown in Figs 4.14 and 4.15, it can be observed that the energy utilization ratio increased with increasing bed height and decreased with drying time in the wall heated fluidized bed dryer. The height of the bed also affects the efficiency of fluidized bed dryer. Increasing the bed height increases the amount of bed material in fluidized bed dryer. Energy utilization ratio increases with an increase in bed height as more moisture is available in the bed and hence more moisture removal rate takes place which increases the humidity ratio in exit air. Similar EUR profiles were seen in Nazghelichi et al. (2010). They have conducted experiments for thermodynamic analysis of hot air fluidized bed dryer of carrot cubes. From their studies, it was noticed that EUR increased (0.2 to 0.5) with increasing bed height (3 to 9 cm). In the present study also, it has been observed that EUR increased (0.78 to 0.94 for Kodo millet and 0.65 to 0.8 for Fenugreek seeds).

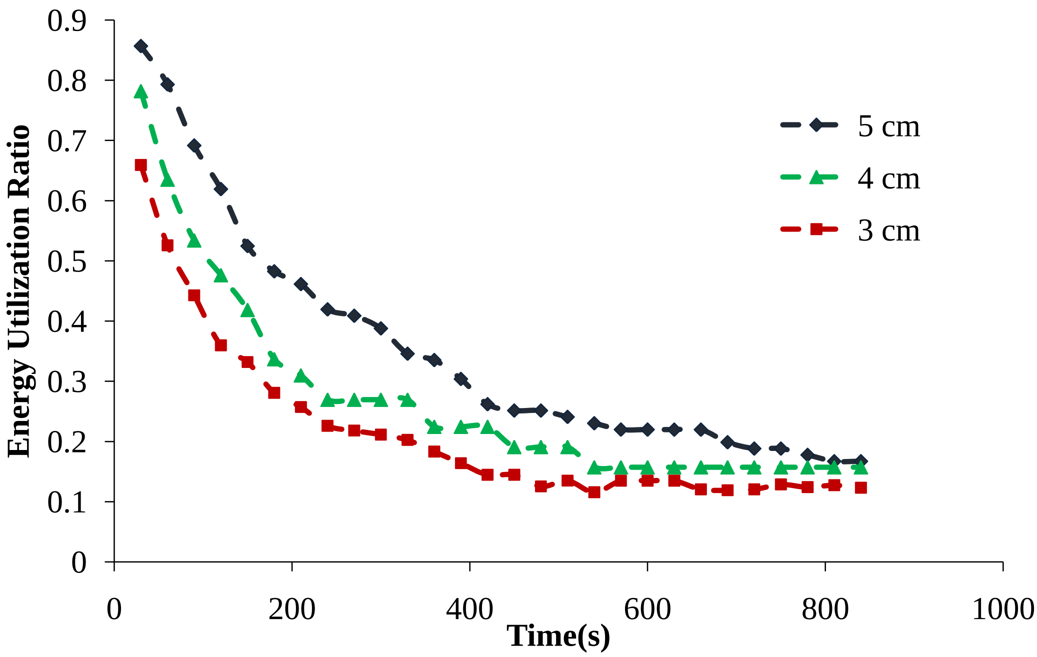


Figure 4. 14 EUR profiles of Kodo millet at different bed heights
(Air velocity-1.35 m/s, Wall temperature-323 K and initial moisture content-10%)

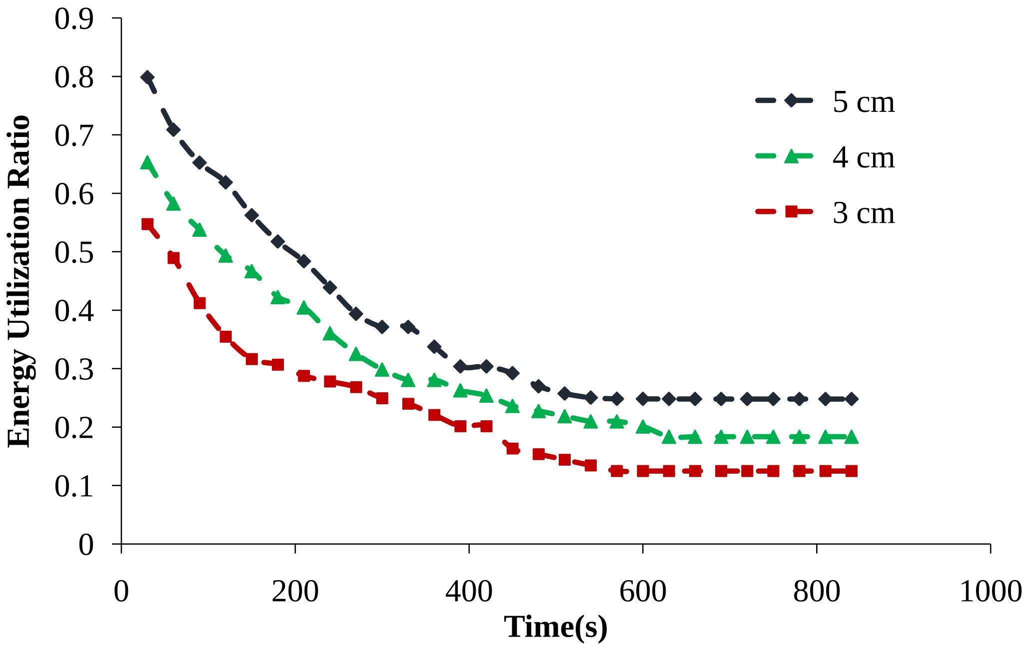


Figure 4. 15 EUR profiles of Fenugreek seeds at different bed heights
(Air velocity-1.35 m/s, Wall temperature-323 K and initial moisture content-10%)

4.1.2.4 Effect of initial moisture content on energy utilization ratio

Experiments were carried out varying initial moisture content from 10 to 20% and with remaining parameters kept constant. From Figs 4.16 and 4.17, it can be observed that energy utilization ratio increased by increasing initial moisture content of solids and decreased with drying time in wall heated fluidized bed dryer. More moisture in the bed results in increase in humidity ratio in exit air. Thus energy utilization ratio increases with increase in initial moisture content of solids.

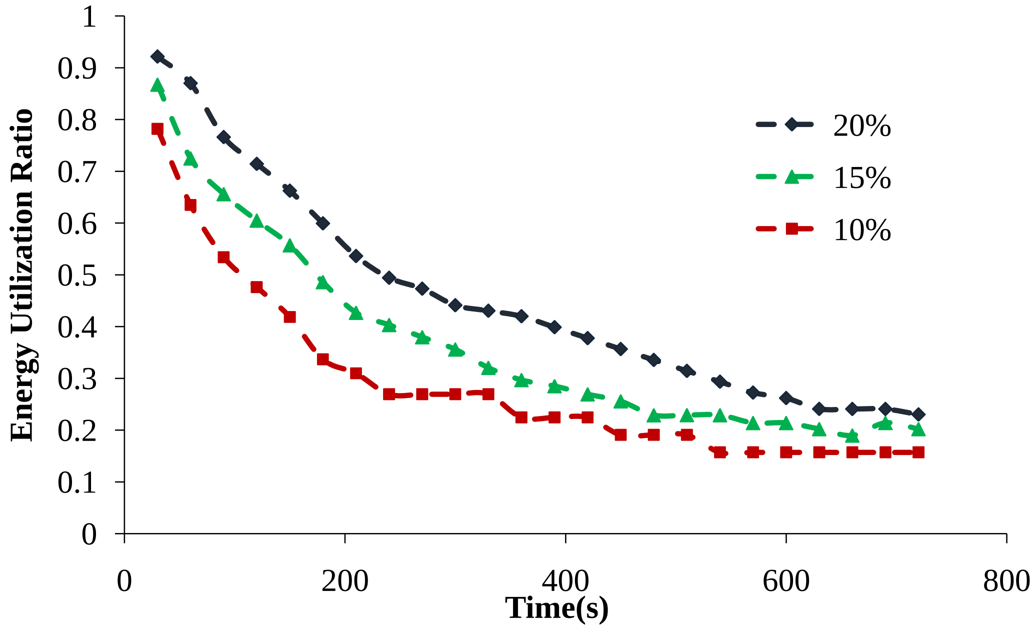


Figure 4. 16 EUR profiles of Kodo millets at different initial moisture contents (Air velocity-1.35 m/s, Wall temperature-323 K and bed height-4 cm)

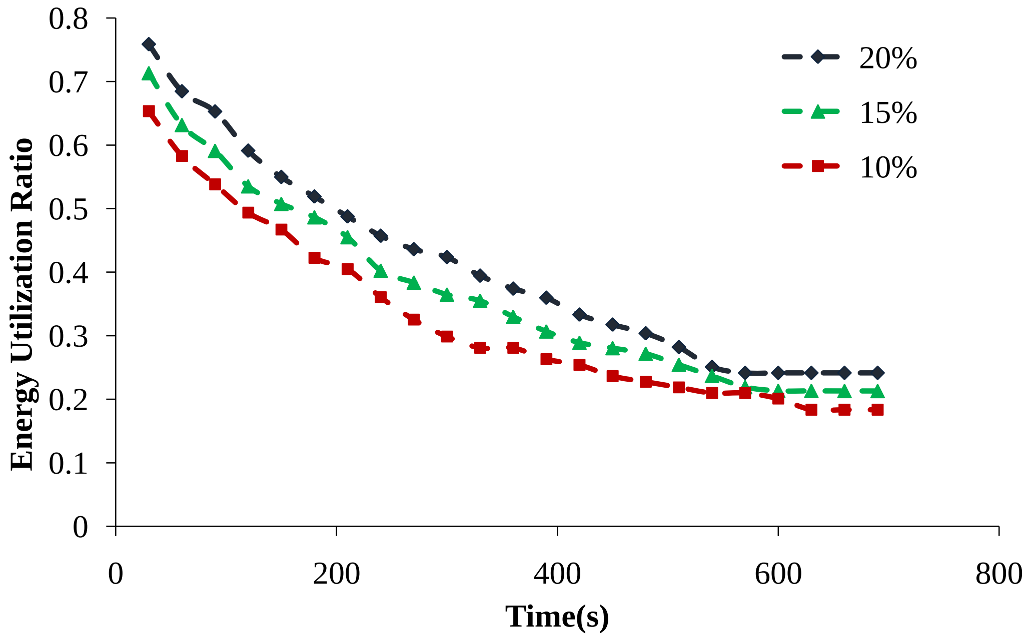


Figure 4. 17 EUR profiles of Fenugreek seeds at different initial moisture contents

(Air velocity-1.35 m/s, Wall temperature-323 K and bed height-4 cm)

4.1.3 Exergy loss

4.1.3.1 Effect of wall temperature on exergy loss

The exergy loss is the difference between input exergy and output exergy of the dryer. Here input exergy is based on wall temperature (Equation 3.8.4) and output exergy is based on outlet air temperatures (Equation 3.8.3). Experiments were performed to analyze the exergy loss varying wall temperature from 313 to 333 K of fluidized bed dryer and with remaining parameters kept constant. Exergy loss obtained from experimental results is presented in Figs 4.18 and 4.19. From the figures, it can be observed that the exergy loss increased with increasing wall temperature. The exergy loss is found to be higher at the initial stage of drying and later decreased with drying time. At the initial stage due to evaporation of more water from the product, exergy losses are found to be high. Corzo et al. (2008) have worked on exergy, energy studies of corobo slices in the micro oven. From their study, it has been observed that the exergy loss increased with increasing air temperature and reported values of maximum exergy loss as 0.11 kJ/s at 363 K and minimum exergy loss as 0.005 kJ/s at 344 K. Also Karagüzel et al. (2012)have reported that exergy loss increased approximately from 0.002 to 0.013 kJ/s with increasing air temperature from 309 to 333 K of chickpea and beans in hot air fluidized bed dryer. In the present study also, where heat input is given through wall, exergy loss increased (0.004 to 0.0121 kJ/s for Kodo millet and 0.0046 to 0.0124 kJ/s for Fenugreek seeds) with increasing wall temperature from 313 to 333 K.

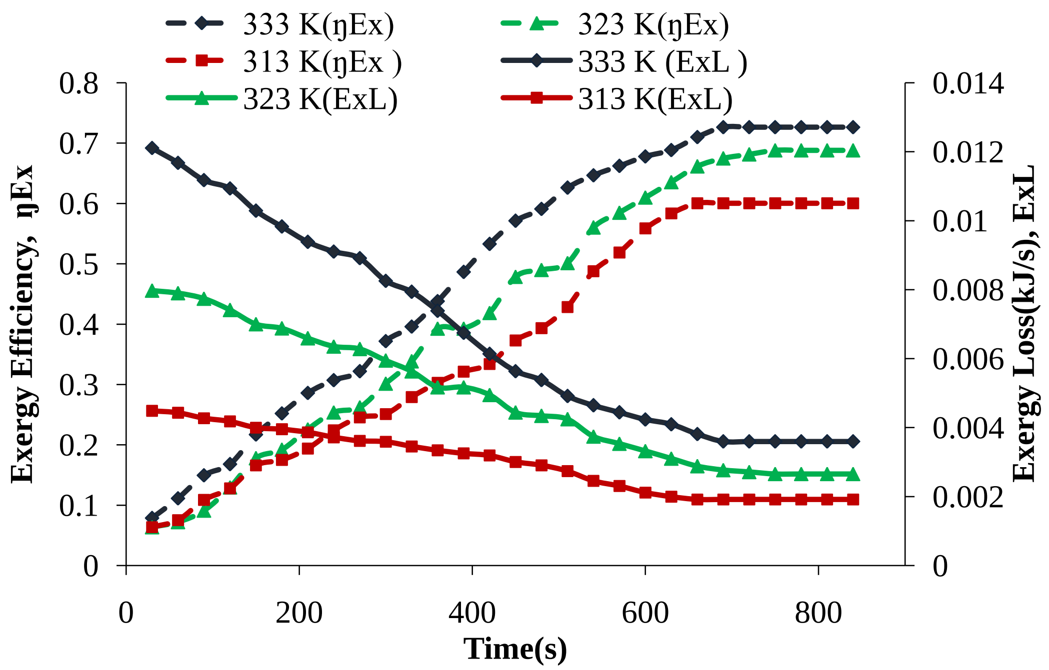


Figure 4. 18 Exergy loss and Exergy Efficiency profiles of Kodo millet at different wall temperatures (Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

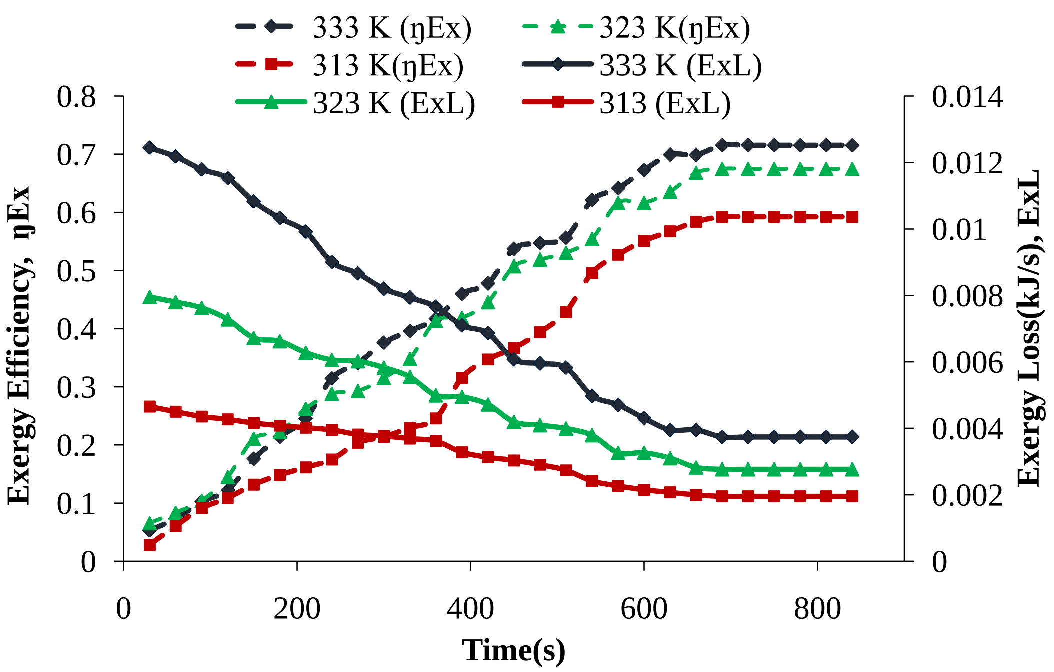


Figure 4. 19 Exergy loss and Exergy Efficiency profiles of Fenugreek seeds at different wall temperatures (Air velocity-1.35 m/s, bed height-4 cm and initial moisture content-10%)

4.1.3.2 Effect of air velocity on exergy loss

To determine the influence of air velocity on exergy loss, experiments were performed varying air velocity from 1.01 to 1.75 m/s and keeping remaining parameters in a constant mode in fluidized bed dryer. From the results shown in Figs 4.20 and 4.21, it can be observed that the exergy loss of dryer decreased with increasing air velocity and decreased with drying time. Exergy loss is the difference of exergy in and exergy out. Exergy in is not affected with increase in air velocity as heat flux and wall temperature are constant. Exergy out increased with increasing air velocity due to increase in gas solid heat transfer leading to higher evaporation of moisture. This increases the available energy at the outlet, thus increasing the exergy outlet. Hence exergy loss decreases with increase in air velocity. Akbulut and Durmus (2010) have conducted a study on exergy, energy analyses of mulberry in a forced solar dryer and reported that exergy loss decreased from 10.82 to 2.6 W (0.01082 to 0.002 kJ/s) with increasing mass flow rate of air from 0.014 to 0.036 kg/s which is in agreement with the present study where exergy loss decreased (for Kodo millet 0.0082 to 0.0072 kJ/s and for Fenugreek seeds 0.0083 to 0.0074 kJ/s) with increase in air velocity (mass flow rate from 0.0069 to 0.0112 kg/s).

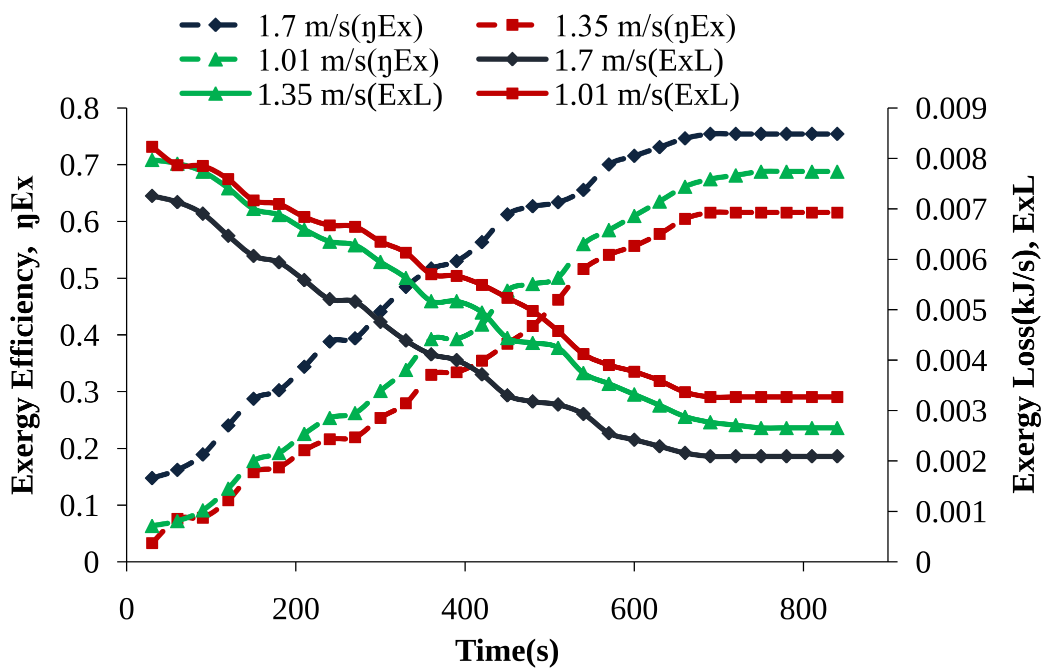


Figure 4. 20 Exergy loss and Exergy Efficiency profiles of Kodo millet at different air velocities

(Wall temperature-323 K, bed height-4 cm and initial moisture content-10%)

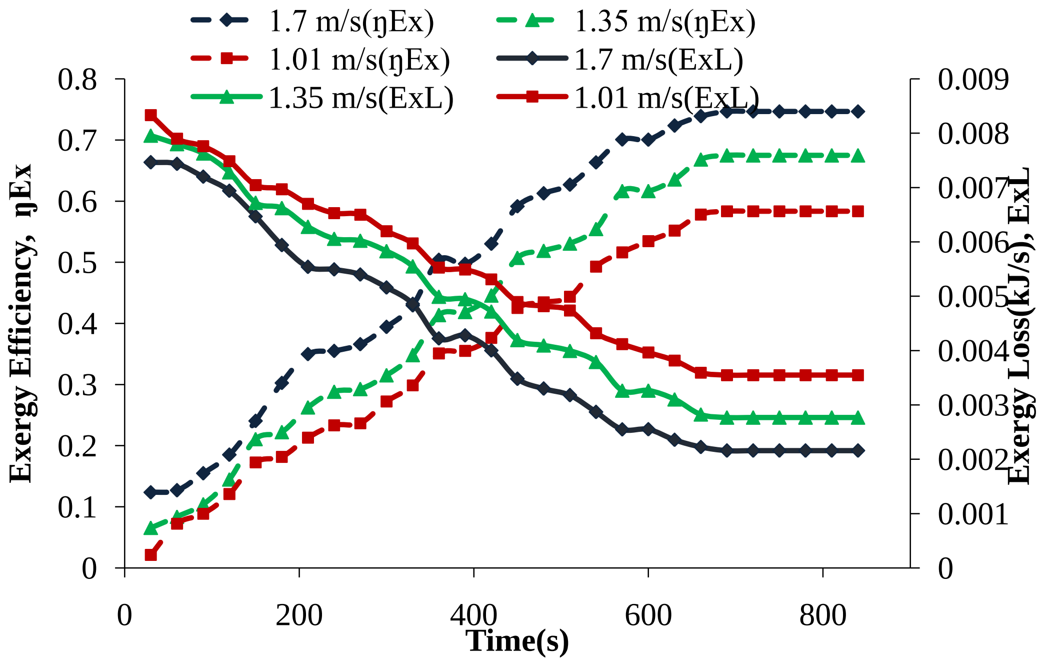


Figure 4. 21 Exergy loss and Exergy Efficiency profiles of Fenugreek seeds at different air velocities (Wall temperature-323 K, bed height-4 cm and initial moisture content-10%)

4.1.3.3 Effect of bed height on exergy loss

Experiments were carried varying bed height from 3 to 5 cm in wall heated fluidized bed dryer and with remaining parameters kept constant. Exergy loss was calculated from experimental results to determine the influence of bed height on exergy loss. From the results presented in Figs 4.22 and 4.23, it can be observed that exergy loss increased with increasing bed height and decreased with drying time. Increasing bed height of dryer increases the amount of material and moisture. Due to the decrease in outlet air temperature, exergy out of dryer decreases and hence exergy loss increases. Similar trends were noticed with Nazghelichi et al. (2010) and Azadbakht et al. (2017). Nazghelichi et al. (2010) have reported that the exergy loss (from 0.5 to 1.6 kJ/s) increased with increase in bed height in hot air fluidized bed dryer.

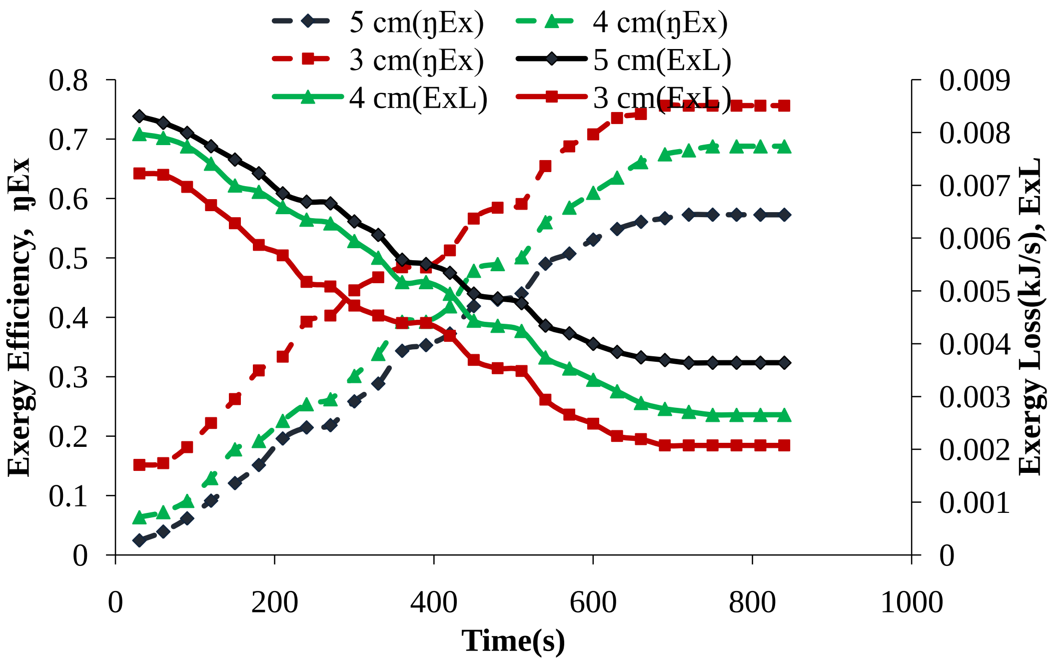


Figure 4. 22 Exergy loss and Exergy Efficiency profiles of Kodo millet at different bed heights

(Air velocity-1.35 m/s, Wall temperature-323 K and initial moisture content-10%)

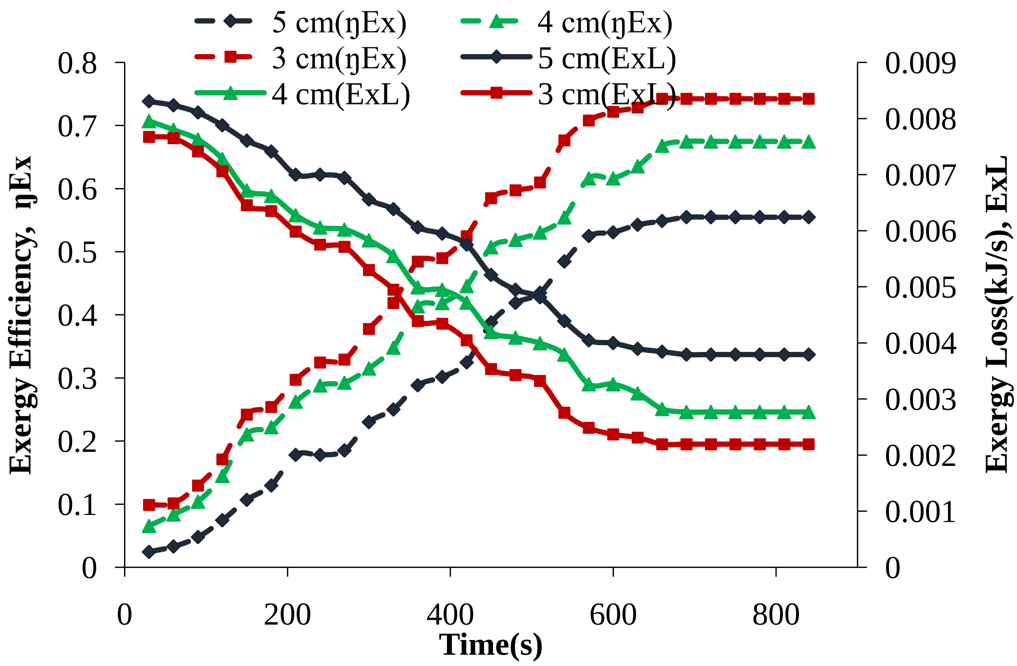


Figure 4. 23 Exergy loss and Exergy Efficiency profiles of Fenugreek seeds at different bed heights (Air velocity-1.35 m/s, Wall temperature-323 K and initial moisture content-10%)

4.1.3.4 Effect of initial moisture content on exergy loss

Experiments were performed varying initial moisture content of bed material from 10 to 20% and with remaining parameters kept constant to determine the influence of initial moisture content on exergy loss. From Figs 4.24 and 4.25, it can be observed that the exergy loss increased with increasing initial moisture content of solids and decreased with drying time in the dryer. Increase in initial moisture content of solids decreases outlet exergy of air, thus increasing exergy loss.

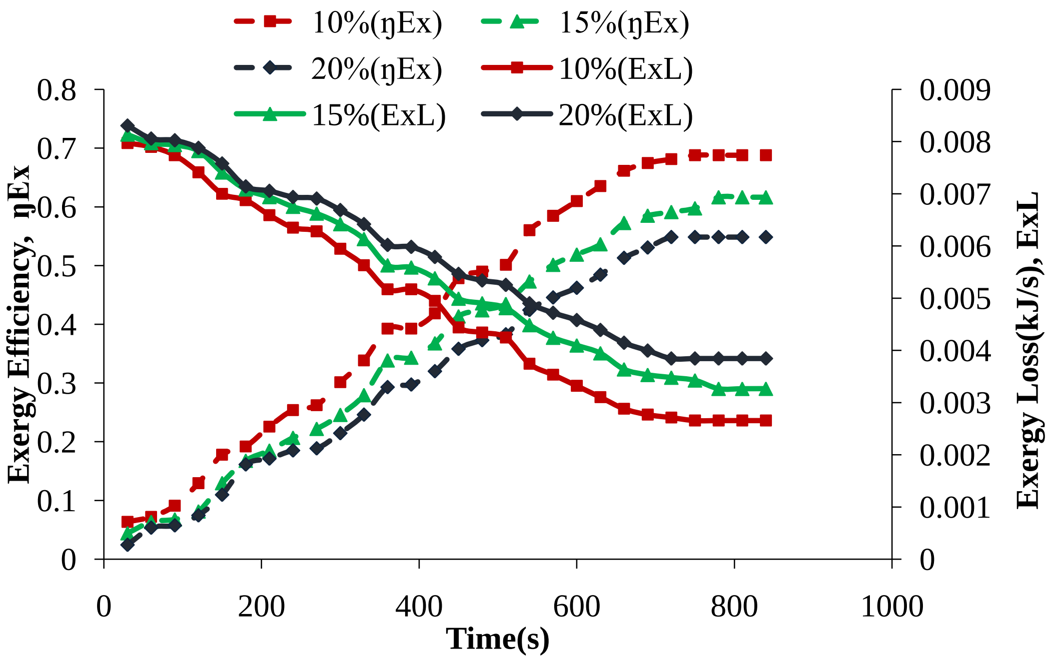


Figure 4. 24 Exergy loss and Exergy Efficiency profiles of Kodo millet at different initial moisture contents (Air velocity-1.35 m/s, Wall temperature-323 K and bed height-4 cm)

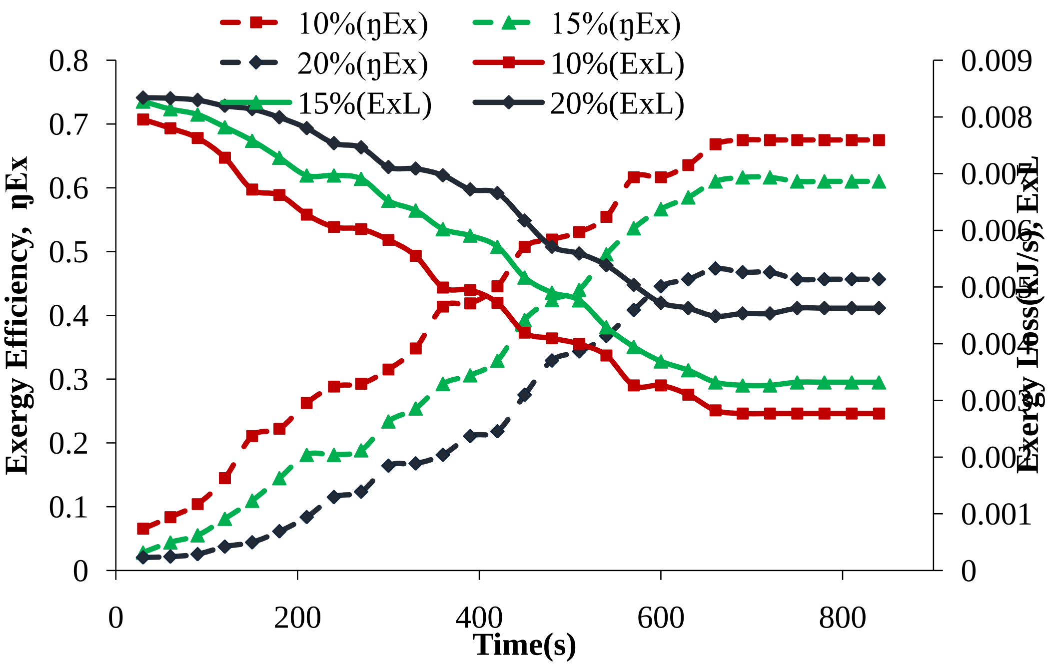


Figure 4. 25 . Exergy loss and Exergy Efficiency profiles of Fenugreek seeds at different initial moisture contents (Air velocity-1.35 m/s, Wall temperature-323 K and bed height-4 cm)

4.1.4 Exergy efficiency

4.1.4.1 Effect of temperature on exergy efficiency

The exergy efficiency of wall heated fluidized bed dryer is presented varying wall temperature from 313 to 333 K. From Figs 4.18 and 4.19, it can be observed that the exergy efficiency increased with increasing wall temperature and increased with drying time. The exergy efficiency is directly proportional to energy utilization of dryer. Here the moisture evaporation rate and heat transfer between solid and gas are increased with increasing wall temperature. This leads to an increase in exergy efficiency of the fluidized bed dryer.

4.1.4.2 Effect of air velocity on exergy efficiency

Experiments were conducted varying air velocities from 1.01 to 1.7 m/s and remaining parameters were kept constant. The exergy efficiency of batch wall heated fluidized bed dryer with Kodo millet and Fenugreek seeds is presented at different air velocities from 1.01 to 1.7 m/s. From Figs 4.20 and 4.21, it can be observed that the exergy efficiency increased with increasing air velocity and increased with drying time.

The results have shown the similarity with Karaguzel et al. (2012) and Motevali and Minaie (2012). Karagüzel et al. (2012) have reported that the exergy efficiency increased (presented approximately 30 to 50%) with increase in air temperature. Motevali and Minaie (2012) have reported that the exergy efficiency increased (approximately from 62.54 to 84.75%) with increasing air velocity from 0.5 to 1.5 m/s and air temperature from 323 to 343 K. In this study, the exergy efficiency of batch wall heated fluidized bed was found to be increasing from 0.60 to 0.75 for Kodo millet drying and from 0.58 to 0.74 for Fenugreek seeds drying with increase in wall temperatures from 313 to 333K and air velocity from 1.01 to 1.7 m/s.

4.1.4.3 Effect of bed height on exergy efficiency

To analyze the influence bed height on exergy efficiency of batch wall heated fluidized dryer, exergy efficiency has been presented in Figs 4.22 and 4.23 at different bed heights ranging from 3 to 5 cm. From Figs 4.22 and 4.23, it can be seen that the exergy efficiency increased with decreasing bed height and increased with drying time. From the results it can be noticed that the exergy loss due to increase in bed height is inversely proportional to exergy efficiency. In this study results have shown consistency with the results of Nazghelichi et al. (2010) and Azadbakht et al. (2017). From Nazghelichi et al. (2010) results, it was seen that the exergy efficiency is found to be decreasing (0.75 to 0.5) with increasing bed height (3 to 9 cm). Also from Azadbakht et al. (2017) results, it was observed that the exergy efficiency decreased with increase in bed loading (from 1.5 to 3 cm) in hot air fluidized bed dryer.

4.1.4.4 Effect of initial moisture content on exergy efficiency

To analyze the influence of initial moisture content on exergy efficiency of batch wall heated fluidized bed dryer, exergy efficiency at different initial moisture contents ranging from 10 to 20% has been presented in Figs. 4.24 and 4.25. From the figures, it can be noticed that exergy efficiency increased with decreasing initial moisture content and increased with drying time. From the results, it can be observed that exergy loss due to the increase in initial moisture content is inversely proportional to exergy efficiency. Akpinar (2007) has studied thermodynamic analysis using strawberry in cyclone type dryer and reported that the exergy loss increased with increasing initial moisture content.

Kodo millet showed better drying, exergy and energy rates than Fenugreek seeds due to its spherical shape. The spherical particle gives good fluidization behavior and smooth mixing with gas than other shapes.

4. 2. Continuous hot air single stage fluidized bed dryer

4.2.1 Effect of distributor configuration

Experimental studies on continuous fluidized bed dryer have been made and the performance of the fluidized bed dryer varying the orifice diameter, number of orifices and the opening area of the distributor plate has been studied (Appendix-Data C). Various distributor plates used in experimentation have been reported in Table 3.3.

4.2.1.1 Effect of orifice diameter

Experiments have been carried out with four different orifice diameters such as 2, 3, 5 and 7 mm in distributor plate and remaining parameters like particle diameter, air velocity, air temperature, initial moisture content and solids flow rate have been kept constant. For a very small orifice diameter, clogging may occur and when varied to a large orifice diameter of distributor plate non-uniform gas distribution may occur in the fluidized bed (Kunii and Levenspiel, 1991). The performance of the continuous fluidized bed dryer is proportional to the drying rate in the fluidized bed. The experimental results of drying rate varying the orifice diameter of the distributor plate have been presented in Figs. 4.26. From the results, it can be observed that with increase in orifice diameter the drying rate increases for 2 to 5 mm perforations and with further increase in the orifice diameter, the drying rate varies little for 7 mm perforations in comparison with the results of 5 mm orifice distributor plate. From the experimental results, it can be observed that the drying rate increases with an increase in orifice diameter up to a certain range and there after it changes little. From Fig 4.26, it is noticed that the equilibrium moisture content also varies with orifice diameter of the distributor plate. With increase in orifice diameter, the equilibrium moisture content has been found to be decreased little. It can be observed from Fig 4.27 that the solid outlet temperature increases with increasing orifice diameter up to 5 mm and the afterwards little effect is shown on solid outlet temperature. Increasing orifice diameter enhances heat transfer between gas-solid and contact ratio till it attains certain orifice diameter after which change is little. At higher orifice diameters there will be change in the fluidization quality due to large bubble formation in the emulsion phase. Increasing orifice diameter increases gas holdup and hence increases the heat transport to solids which increases solids outlet temperature. But after certain diameter, the increase in orifice diameter does affect much which may be due to increased bubble size which reduces the area of contact for heat transfer. Because of the two opposing factors namely increased heat input and decreased contact area, the solids outlet temperature does not vary much when considered for higher orifice diameters.

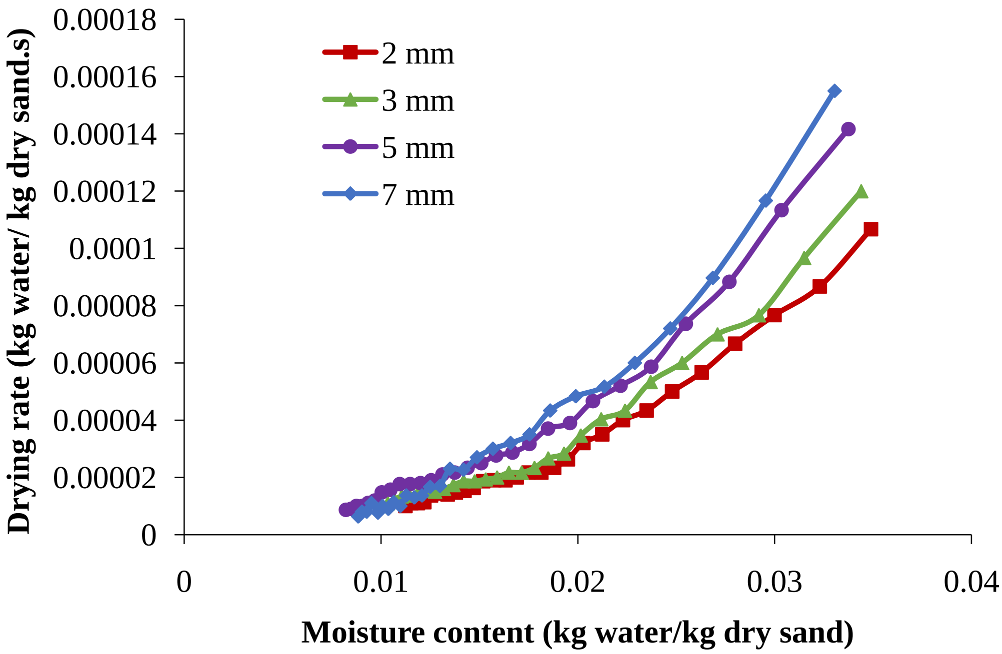


Figure 4. 26 Effect of orifice diameter on drying behavior of solids
(Initial moisture content-4%, solid flow rate -10 kg/h, air flow rate-40 kg/h, inlet air temperature- 323 K)

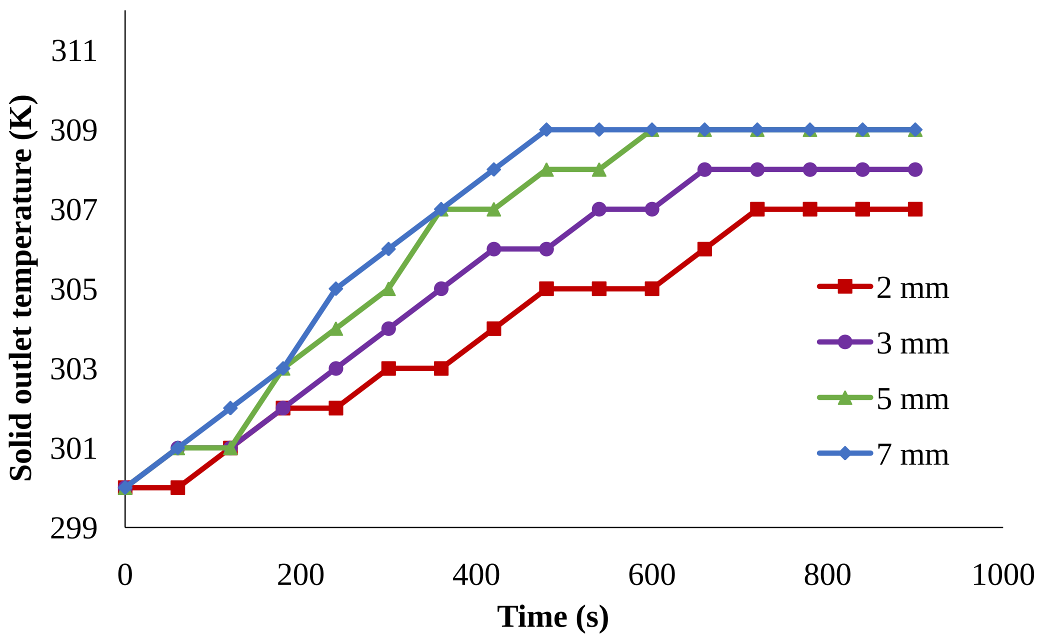


Figure 4. 27 Effect of orifice diameter on solid temperature profile

(Initial moisture content-4%, solid flow rate -10 kg/h, air flow rate-40 kg/h, inlet air temperature- 323 K)

4. 2.1.2 Effect of number of orifices

Experiments have been carried out varying the number of orifices of distributor plate and keeping the remaining parameters such as orifice diameter, air velocity, initial moisture content, particle diameter, air temperature and solids flow rate as constant. An increase in the number of orifices increases the opening area of the distributor plate. In the present study, the numbers of orifices studied are 40, 60 and 110 of 5 mm orifice diameter and the solids outlet temperature varying with time are presented in Fig 4.28. With the increase in the number of orifices in the distributor plate the gas to solid contact increases. By varying the number of orifices, distributor plate pressure drop varies. At a lower value of the number of orifices, due to less gas to solid contact, the drying rate is found to be less and with increase in the number of orifices the drying rate increases to a certain extent and with further increase in the number of orifices the drying rate, does not get affected. With increase in the number of orifices, the number of bubbles will be more and there can be agglomeration of bubbles taking place thus increasing the bubble size and decreasing the contact area for heat transfer between gas and solid. On the other side, there is the increase in gas hold up due to increase in free area. Thus the drying rate and solids outlet temperature do not get affected after a certain value of the number of orifices.

The effect of orifice diameter and number of orifices can be also interpreted in terms of effect of opening area which varies from 3.4 to 40%. Results of variation of drying rate with moisture content for different opening areas were presented in Fig 4.29. From the figure, it can be observed that with increase in opening area the drying rate increases and after some time the drying rate and the equilibrium moisture contents are not changing much. It is important to obtain the optimum opening area to keep good gas to solid contact in the fluidized bed. The opening area of distributor plate is mainly dependent on the orifice diameter and number of orifices. From Fig 4.29 it can be observed that the with increasing the opening area from 3.4 to 22% increase in the drying rate can be identified significantly and further increase in opening area from 22 to 40% only little change in the drying rate can be noticed. The studies indicate that the solids temperature and drying rate increase with increase in free opening area to a certain value as the gas solid contact increases and vary little afterwards. In the experimental study, this is found to be 22%. Above this value, two more distributors one with 40% and the other one with 42% (7 mm orifice with 60) were used. In the distributor with 40% free area, the number openings are more (110 with 5 mm orifice) and hence the number of bubbles also will be more and there can be agglomeration of bubbles taking place thus increasing the bubble size and decreasing the contact area for heat transfer between gas and solid. But on the other side, there is increase in gas hold up due to the increase in free area. Due to these two opposing factors increase in the opening area from 22% to 40% is effect is little. Similarly with the other plate with 42% area, the orifice diameter is large. This gives bubbles of larger size thus decreasing the heat transfer area. Hence it is not much effective.

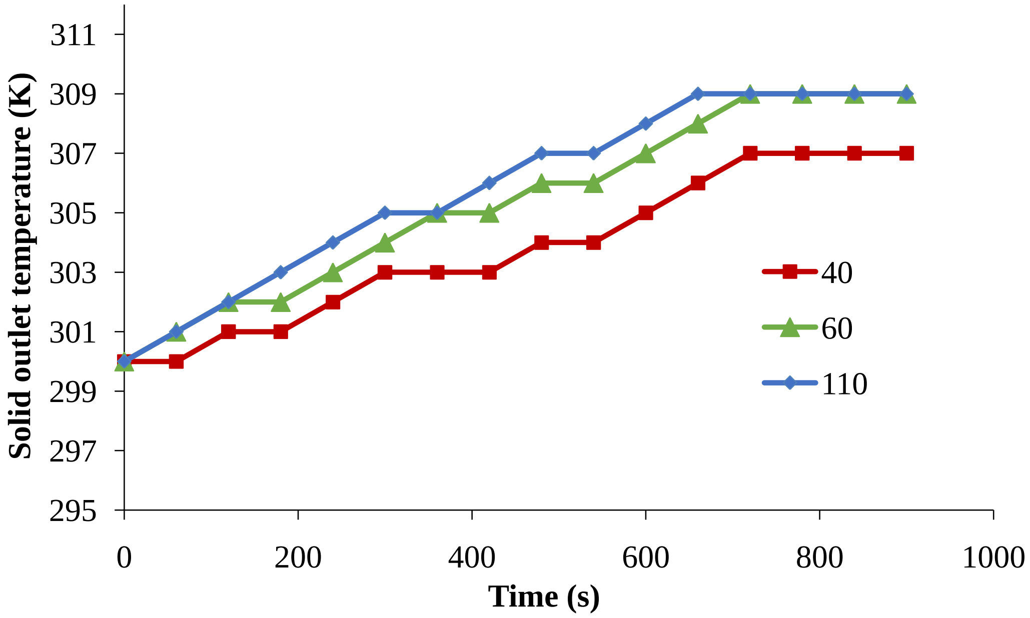


Figure 4. 28 Effect of number of orifices on solid temperature profile
(Initial moisture content-4%, solid flow rate -10 kg/h, air flow rate-40 kg/h, inlet air temperature- 323 K)

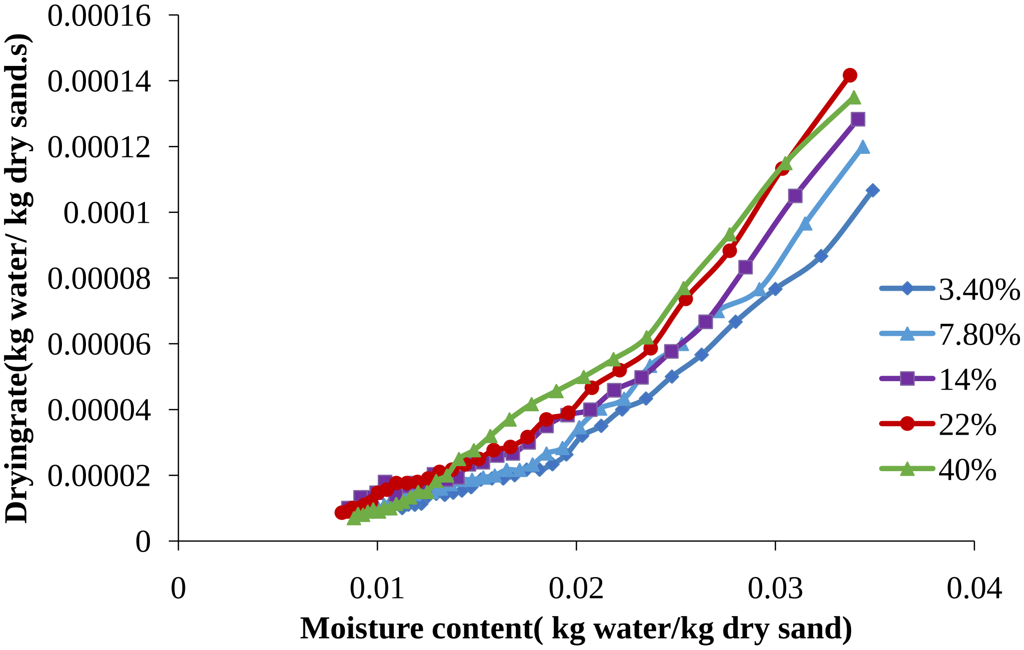


Figure 4. 29 Drying rate of solids at different opening areas of distributor plate (Initial moisture content-4%, solid flow rate -10 kg/h, air flow rate-40 kg/h, inlet air temperature- 323 K)

4.3 Continuous wall heated multistage fluidized bed dryer

Experiments were performed to study continuous multistage fluidized bed dryer performance varying parameters such as wall temperature, velocity of air, bed height and solids flow rate (Appendix- Data D). As discussed above, wall heated dryer involves indirect drying and hence is used for wallheated multistage fluidized bed drying of Pearl millet and Barnyard millet which are heat sensitive, whereas for drying of sand which is not heat sensitive, hot air fluidized bed dryer was used. Also in multistage dryer the the exposure of heat to the material is much more and hence wall heated dryer is used for millets.

4.3.1 Multistage drying characteristics of pearl millet

4.3.1.1 Effect of wall temperature on multistage drying

To determine the wall temperature influence on drying characteristics of solids, experimentation was performed in the multistage fluidized bed dryer changing wall temperature of stages from 313 to 328 K and keeping remaining operating conditions such as air velocity, initial moisture content, bed height and solids flow rate, constant.

It can be observed from Fig 4.30 that the solids drying rate increased by increasing wall temperature and equilibrium moisture content decreased by increasing wall temperature. In multistage fluidized bed dryer, higher drying rates are noticed in multistage dryer compared to a single stage dryer as the heat transfer area is higher in a multistage dryer.

4.3.1.2 Air velocity influence

To study the air velocity influence on drying characteristics of solids, experiments have been conducted in the multistage fluidized bed dryer at air velocities varying from 1.01 to 1.35 m/s and keeping remaining operating parameters such as wall temperature of multistage, initial moisture content of solids, bed height and flow rate of solids, constant.

It can be seen from Fig 4.31 that the moisture ratio of solids decreased by the rising velocity of air and drying time decreased for a multistage fluidized bed dryer. Solid moisture carryover increases by increasing air velocity and hence it shows better drying behavior at higher velocities. From the results, it is noticed that the solids drying rate in three stage dryer (Stage-3) is higher than that for two stage dryer (Stage-2).

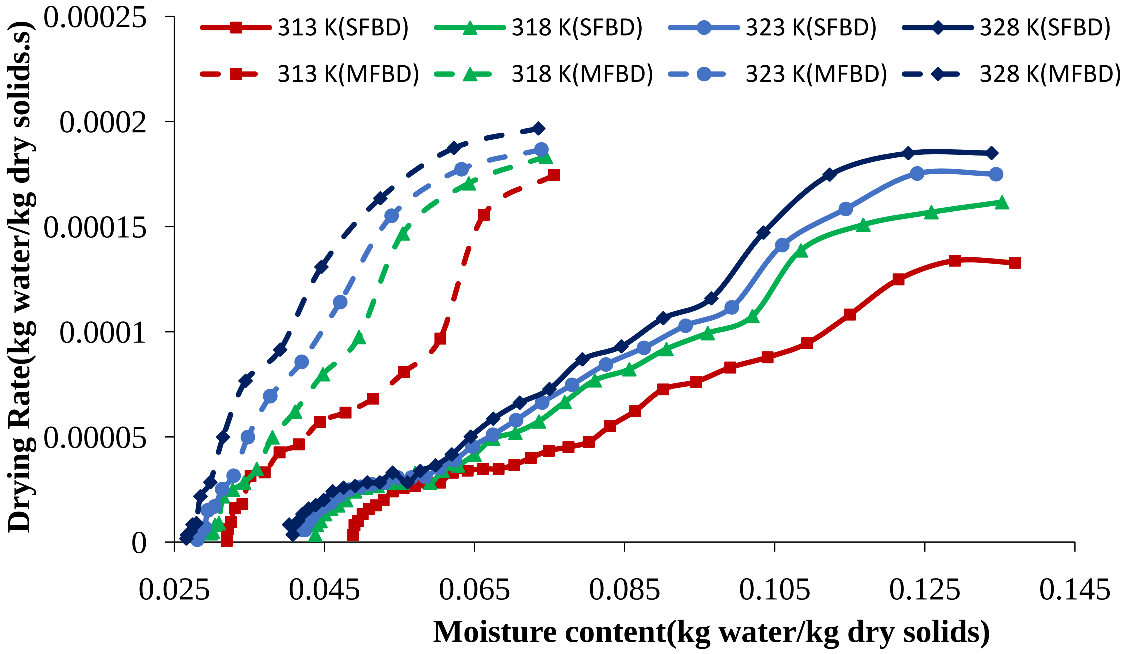


Figure 4. 30 Drying characteristics of solids in multistage fluidized bed dryer at various wall temperatures

(V- 1.01 m/s, H_d-50 mm, S_F-6.7 kg/hr and MFBD-Stage 4)

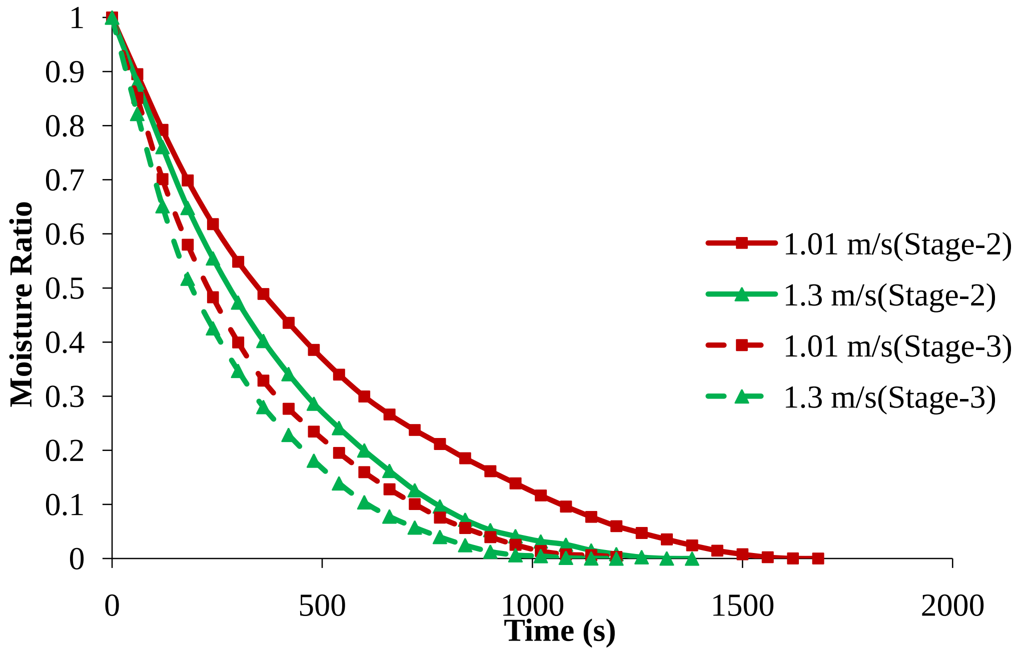


Figure 4. 31 Moisture ratio profiles of solids in multistage fluidized bed dryer at various air velocities (T_w-313 K, H_d -50 mm and S_F-6.7 kg/h)

Taghavivand et al. (2017) have studied the drying kinetics of pharmaceutical granules using the batch fluidized bed dryer. It has been seen that the solids moisture ratio decreased with increasing air temperature from 311 to 348 K and air velocity from 1 to 1.8 m/s from their results. Calban and Ershan (2003) have conducted studies on Turkish lignite using fluidized bed dryer with the batch process. It has been noticed that the solids drying behavior shows increment by increasing temperature of air from 333 to 353 K and also it was noticed from their results that the drying rate is more at the initial stage and later it decreased with moisture content. It has been observed from the study of Srinivasakannan and Balasubramanian (2006) that the relative moisture ratio of ragi (finger millet) decreased with increasing air temperature 333 to 373 K and air velocity 1.2 to 1.6 m/s in a batch fluidized dryer. Also in the present study, similar behavior was observed in results. The solids moisture ratio decreased by rising wall temperature of stages and air velocity for a multistage fluidized bed dryer.

4.3.1.3 Downcomer height influence

It is important to study the influence of solids holdup in any dryer. The solids holdup is an important parameter for the design of any dryer. The solids flow rate and bed height are key variables which cause increasing or decreasing solids holdup in a fluidized bed dryer for continuous process. To vary the bed height in a fluidized bed dryer in continuous process, we need to change the height of downcomer in the dryer. In this study, to know the bed height influence in a multistage fluidized bed dryer, downcomer height of each stage in the dryer was varied. Experiments have been carried out for downcomer height ranging from 50 mm to 70 mm and keeping remaining operating conditions such as wall temperature of stages, initial moisture content of solids, velocity of air and solids flow rate as constant in the multistage fluidized bed dryer. It can be seen from Fig 4.32 that the solids drying rate decreased with increasing downcomer height of multistage fluidized bed dryer. The increase in downcomer height increases fluidized bed height of solids in the dryer and also increases the solids holdup. With increasing solids holdup in the bed, the gas holdup decreases.

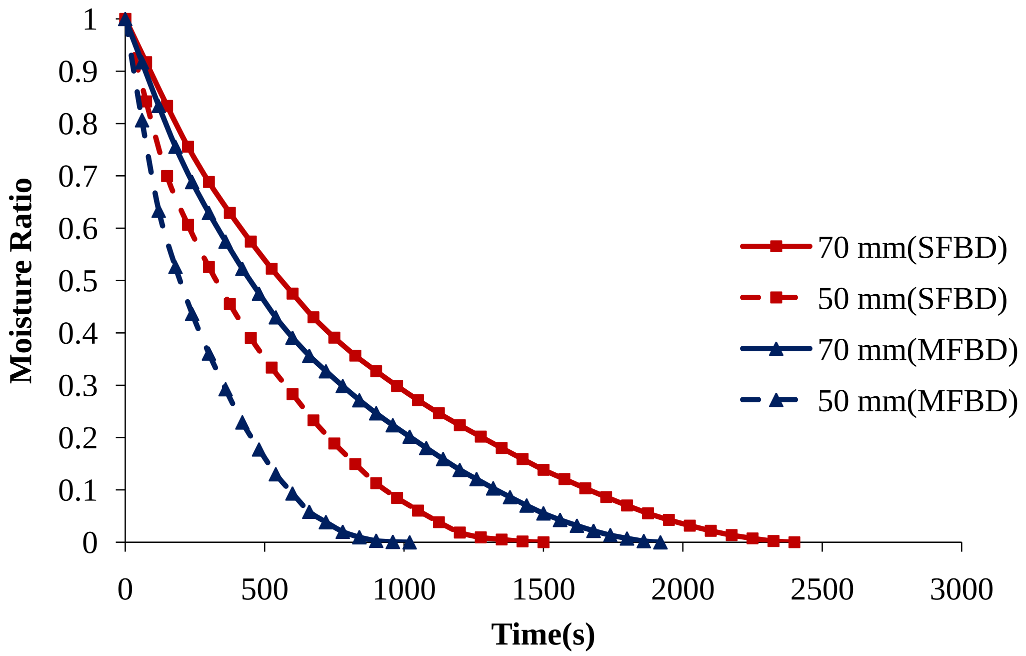


Figure 4. 32 Moisture ratio profiles of solids in multistage fluidized bed dryer at various bed heights (V- 1.01 m/s, T_w -313 K, S_F-6.7 kg/h and MFBD-Stage 4)

4.3.1.4 Effect of solids flow rate

Experiments have been carried out to study the influence of solids flow rate on drying behavior of solids using multistage fluidized bed dryer at flow rate ranging from 5 to 10 kg/h and keeping remaining operating parameters such as wall temperature of stages, velocity of air, initial moisture content of solids and bed height as constant.

It can be observed from Fig 4.33, that the solids drying rate is decreased by increasing solids flow rate and equilibrium moisture content increased with increasing solids flow rate of multistage fluidized bed dryer. Higher solids flow rate increases the bed loading and it contains higher water content than that at lower solids flow rates. Hence drying rate decreases. It can be noticed from the results that solids drying rate is more at the initial time and later decreases with moisture content in both single and multistage fluidized bed dryer.

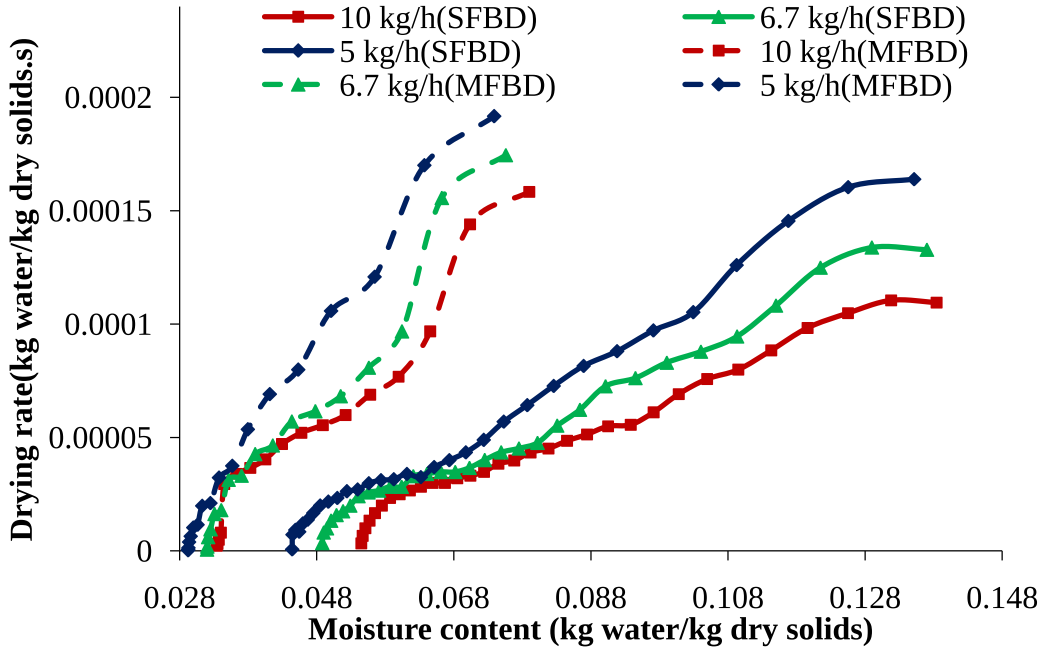


Figure 4. 33 Drying characteristics of solids in multistage fluidized bed dryer at various solid flow rates (V- 1.01 m/s, T-313 K, H_d -50 mm and MFBD-Stage 4)

Tasirin et al. (2007) have investigated drying studies on bird's chilies using the fluidized bed dryer in a batch process. It has been noticed that the solids drying rate decreased with increasing bed depth from 2 to 4 cm from their study. It has been noticed that the solids drying rate reduced with increasing downcomer height of continuous fluidized bed dryer from the study of Srinivasakannan et al. (2012). Same profiles are seen from the present study that the drying rate is high at lower bed heights than those for higher bed heights of multistage fluidized bed dryer. It has been observed from the results of Srinivasakannan and Balsubramanian (2008) that the relative moisture decrement is higher at low solid holdup comparatively than that for higher solid holdup and also relative moisture decreased with time. Chen et al. (2017) have studied the particle drying behavior in continuous horizontal fluidized bed dryer. It has been noticed from their results that the mean solid moisture is higher at higher solids mass flow rate and decreased with decreasing solids mass flow rate. In the present study, similar trends have been observed in results, that the solids drying rate decreased with increasing solids flow rate of multistage fluidized bed dryer.

4.3.1.5 Number of stages influence

To study the effect of the number of stages on drying characteristics of solids, experiments have been conducted in the multistage fluidized bed dryer at various wall temperatures, air velocity, initial moisture content and solids flow rate. It can be observed from Fig 4.34, that the solids moisture ratio and drying time in the dryer decreased with increasing number of stages. In the form of drying rate vs moisture content by stagewise multistage fluidized bed dryer was presented in Fig 4.34. It can be observed that the drying rate of solids increased with increase in stages and equilibrium moisture content of solids decreased with increasing stages. It can be noticed that the increase in number of stages shows drying behavior similar to that of a fluidized bed dryer in a batch mode as seen from Figs 4.34 and 4.35. This indicates that the increase in number of stages improves the quality of the dried product. From Fig 4.36, it can be noticed that the bed temperature increases with increasing number of stages in a multistage fluidized bed dryer.

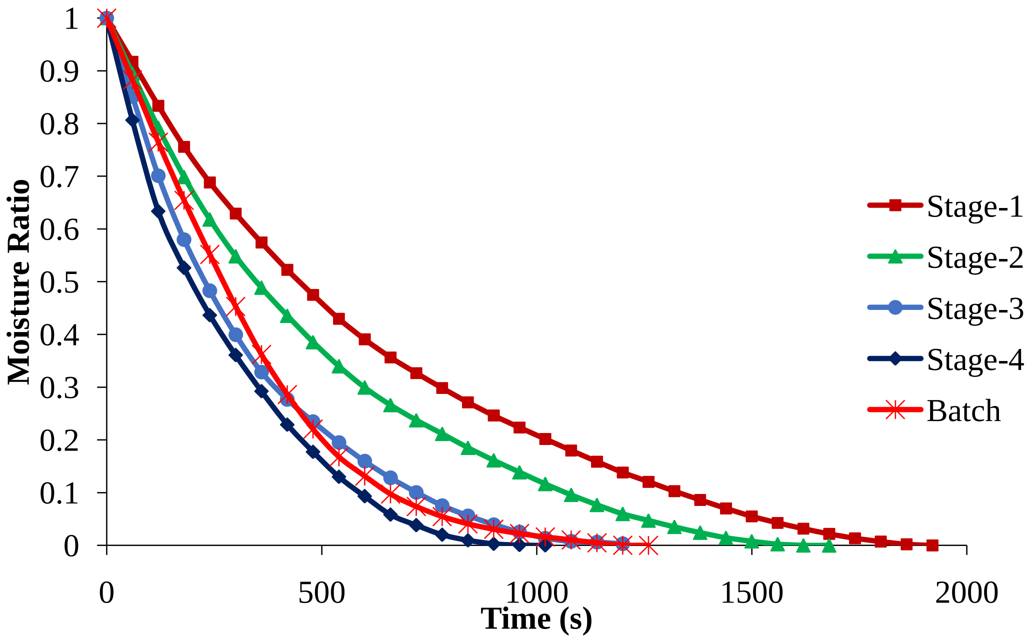


Figure 4. 34 Moisture ratio profiles of solids in multistage bed dryer at various stages (V- 1.01 m/s, T-313 K, H_d -50, S_F-6.7 kg/h)

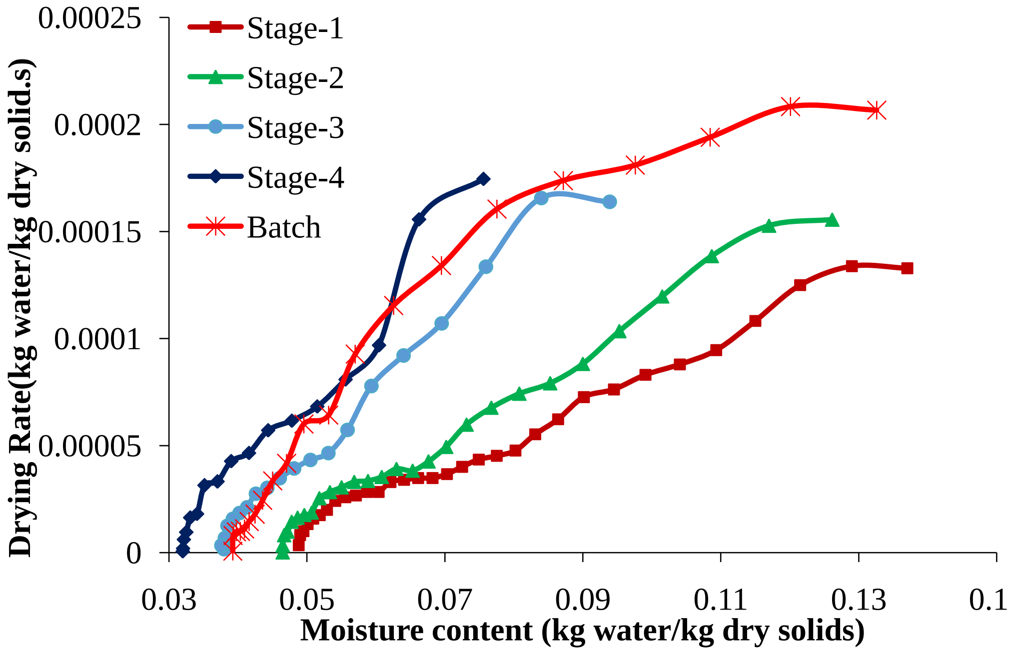


Figure 4. 35 Drying characteristics of solids in multistage fluidized bed dryer at various stages

(V- 1.01 m/s, T-313 K, H_d -50 mm and S_F-6.7 kg/h)

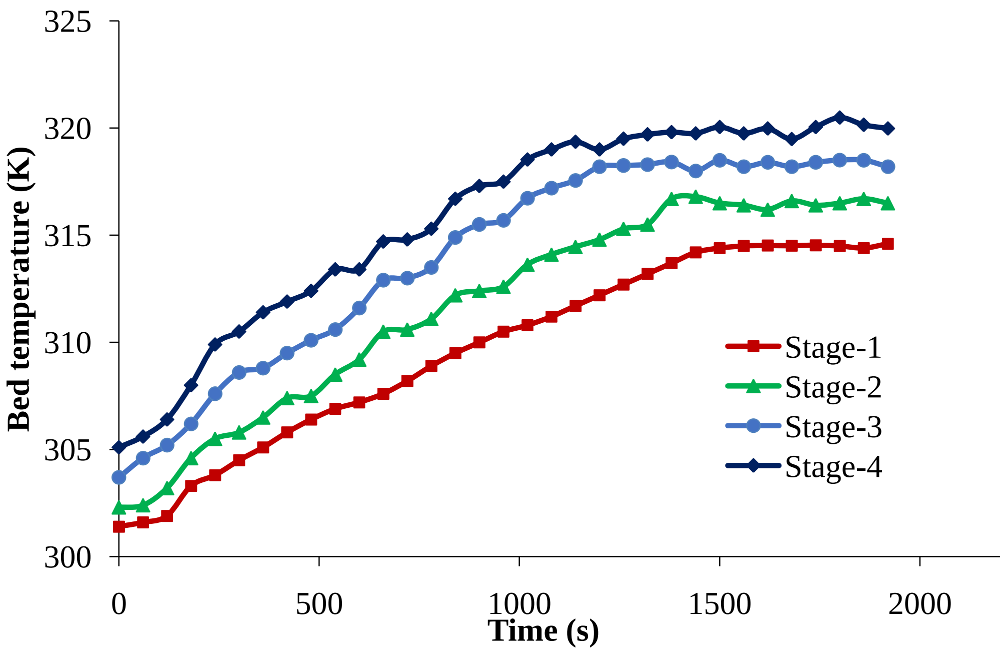


Figure 4. 36 Bed temperature profiles in multistage fluidized bed dryer

(V- 1.01 m/s, T-328 K, H_d -50 mm and S_F-6.7 kg/h)

Bareschino et al. (2017) have investigated the effect of operating conditions of fluidized bed dryer in a batch process using various granular solids. The bed temperature rises at different air velocities and air temperatures of the dryer as noticed from their study.

The drying studies reported using multistage fluidized bed dryers is very less. It has been reported in Srinivasakannan et al. (1995) studies that the solids outlet moisture of ragi grains and poppy seeds decreased with increasing number of stages in concurrent internal multistage fluidized bed dryer. From the study of Srinivasakannan and Balasubramanian (1998) in countercurrent operation with one, two and three stages of continuous multistage fluidized bed dryer staged internally, it has been observed that the drying rate shows increment with increasing number of stages (two to three) of the dryer. Also from Choi et al. (2002) investigation, it was noticed that the bed temperature raised with increasing number of stages from one to five of continuous multistage fluidized bed dryer. In this study, similar curves of moisture ratio of millet grains were obtained with increasing number of stages from one to four in multistage fluidized bed dryer and also similar trends are seen, that the bed temperatures increase with number stages of the dryer.

4.3.1.6 Drying time

The time taken for total drying can be decided by the performance of the dryer. The drying time can vary with operating conditions and material characteristics. From the results of Khanali et al. (2016), it has been observed that the drying time of rough rice (bed weight has 1.32 kg) decreased from 2500 to 1000 seconds with increase in air velocity from 2.3 to 2.8 m/s in batch fluidized bed dryer . From Chayjan et al. (2013) study, it has been observed that the drying time of squash seeds has decreased from 8500 to 2500 seconds with increase in air velocity from 2.51 to 5.32 m/s and increase in temperature from 323 to 353 K in a batch fluidized bed dryer. There are few studies conducted in continuous dryers. Chandran et al. (1990) have studied drying behavior of resin and sand with the particle size range of 0.5- 1 mm using single stage continuous fluidized bed dryer (diameter of 310 to 390 mm). From their results, it has been shown that the drying time is in the range of 1440 to 1940 seconds for continuous drying and the drying time is higher for continuous drying than batch dryer because of time taken to reach equilibrium moisture content. Thomas and Varma (1992) have studied the drying behavior of food materials in continuous fluidized bed dryer. From their results, it has been observed that the drying time of mustard increased from 3600 to

4800 seconds by the decrease in temperature from 378 to 358 K to dry the material. Similarly, in this study of externally staged continuous multistage fluidized bed drying, the drying time of pearl millet decreased from 1020 to 900 seconds by increasing wall temperature from 313 to 328 K, decreased 1020 to 840 seconds with increasing solids flow rate from 5 to 10 kg/h, increased from 1020 to 1920 seconds by increase in bed height 50 to 70 mm.

4.3.2 Multistage drying characteristics of Barnyard millet

To determine the parametric influences on drying characteristics of Barnyard millets, experiments were carried out in the multistage dryer by changing conditions, i.e., wall temperatures of stages from 313 to 328 K, downcomer height from 50 to 70 mm, velocity of air from1.0 to 1.3 m/s, and solids flow rate, from 5 to 10 kg/h.

From the results, the increment in drying rate of barnyard millet was observed with increase in wall temperatures of MFBD. In virtue of an increase in wall temperature, heat transfer between gas and wall, gas and solid is increased thus influencing on moisture removal rise. Fig 4.37 showed the increment in drying rate of barnyard millet with increase in velocity of air in the MFBD. Increase in air velocity increases moisture carryover of wet barnyard millet from each stage, and the moisture carryover rate increased at each stage and thus influences towards higher drying rates. The solids holdup of the dryer is also an important considerable parameter. It is mainly influenced by either solids flow rate or bed height. The increase/decrease in the bed height in continuous fluidized bed drying process can be obtained by varying downcomer height. From the study, the drying rate of barnyard millet showed decrement with the increase in downcomer height in the dryer, because an increment in downcomer height increases the fluidized bed height of barnyard millet which results in increment in the solids holdup. Then gas holdup is decreased in the bed due to increasing solids holdup of the dryer. The flow rate of solids is also one of the key parameters for the dryer performance. The decrement in the drying rate of barnyard millet was observed in results when solids flow rate increases in MFBD. Due to increase in flow rate of solids, the bed loading increases and the moisture of bed also increases at higher flow rates than at lower flow rates. The stage wise moisture removal profiles are different in the MFBD and were shown in Fig 4.38. From Fig 4.38, the increment in drying rate of barnyard millet can be observed with increase in the number of stages in MFBD.

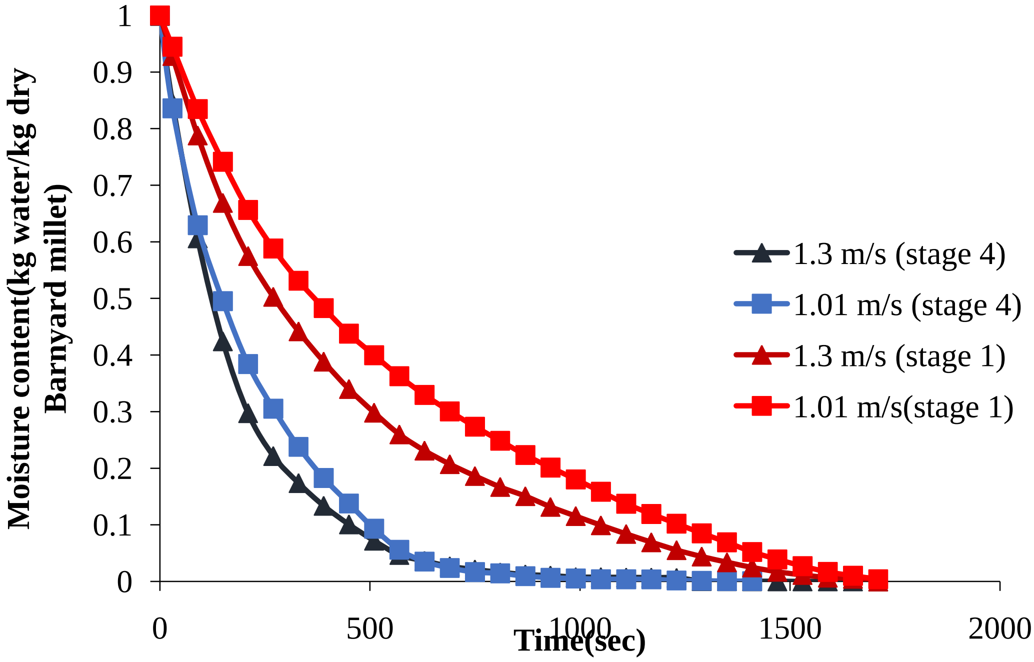


Figure 4. 37 Moisture ratio profiles of Barnyard millet in MFBD with change of air velocity (T_w-313 K, S_F-6.7 kg/hr, H_d -50 mm)

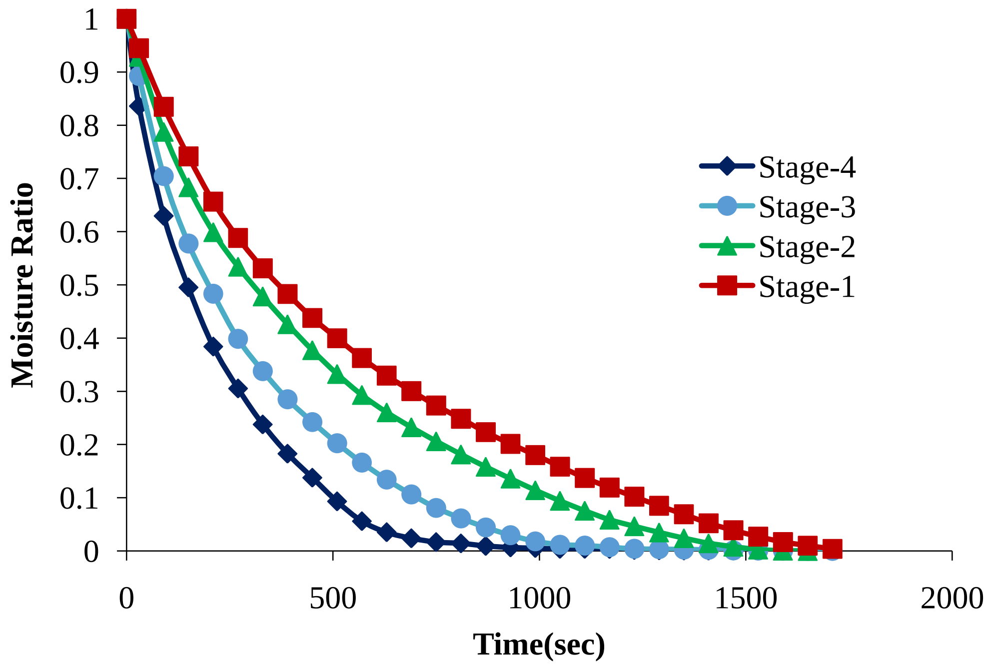


Figure 4. 38 Stage wise moisture ratio profiles in MFBD

(T_w-313 K, V- 1.01 m/s, S_F-6.7 kg/hr, H_d -50 mm)

Studies on drying were conducted by several authors using different varieties of millets like Finger millet by Srinivasakannan and Balasubramanian (2006), Pearl millet by Srinivasakannan and Balasubramanian (2009b), etc., varying operating conditions in the fluidized bed dryer. The drying rates of materials have shown increment with increase of temperature and air velocity in literature reports. In this study, similar drying characteristics were observed with Barnyard millet with increase in air velocities and wall temperatures in the multistage dryer. The height of downcomer or flow rate of air can influence the drying characteristics and the solids holdup of the multistage fluidized bed dryer. The decrement in drying rate of bird chilies was observed in Tasirin et al. (2007) reports when bed height is increased from 2 to 4 cm in batch fluidized bed dryer. Srinivasakannan et al. (2012) have reported that there is decrease in drying rate of solids with increase in height of downcomer in continuous fluidized bed. In the present study also similar drying behavior of Barnyard millet was noticed which shows the influence of the solids holdup in the multistage fluidized bed dryer. Srinivasakannan et al. (1995) have examined the multistage fluidized bed drying of ragi and mustard using dryer which is internally staged and reports have shown increment in drying rates when there is the increase in stages of the dryer. Relevant reports are observed from the Choi et al (2002) studies that the increment in drying rate of solids was noticed with increasing stages in multistage fluidized bed dryer, staged internally. Similar curves were observed in Barnyard millet grains drying with increase in external stages of MFBD.

4.3.4 Model comparison

The experimental results of pearl millet drying data of multistage fluidized bed dryer were converted into dimensionless moisture ratio (MR) for model comparison. The list of various models used for comparison is presented in Table 3.7. The user-defined MATLAB program was written to determine the constants of various models. The experimental data are fitted with model equations. Root Mean Square Error (RMSE) (Equation 4.3.1) was used for error calculation and coefficient of determination (Equation 4.3.2) was also determined.

$$RMSE = \sqrt{\left(\tfrac{1}{N}\right)\sum_{i=1}^{n}(MR_{pre,i} - MR_{\exp,i})^2} \qquad (4.3.1)$$

$$R^2 = 1 - \left(\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp,i}\right)^2 \Big/ \sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp\,mean}\right)^2 \right) \qquad (4.3.2)$$

Here MR refers to moisture ratio, N is the number of data points and i= 1, 2, 3……n

The estimated RMSE and R^2 values and model constants of experimental data at different temperatures, bed heights, solids flow rates, number of stages and air velocities of multistage fluidized bed dryer are reported in Tables 4.1 and 4.2.

Table 4.1. Model constants, RMSE and R^2 at different wall temperatures, bed heights and solids flow rates

Parameters	**Wall temperature, T (K)**				**Downcomer height, H (mm)**		**Solids Flow rate, S_F (kg/h)**		
	313	**318**	**323**	**328**	**50**	**70**	**5**	**6.7**	**10**
Newton									
k	0.003684	0.00496	0.004661	0.00496	0.003684	0.0023	0.004303	0.0037	0.003285
RMSE	0.009981	0.015883	0.008555	0.015883	0.009981	0.0163	0.005139	0.0099	0.017895
R^2	0.995	0.994	0.997	0.994	0.995	0.993	0.998	0.995	0.992
Page									
k	0.002282	0.002359	0.001757	0.001195	0.002282	0.0011	0.002306	0.0023	0.001636
n	1.081842	1.109074	1.174693	1.257902	1.081842	1.1543	1.109669	1.0819	1.117107
RMSE	0.007337	0.000577	7.22E-05	0.000277	0.007337	0.0099	0.001137	0.0074	0.012294
R^2	0.995	0.999	0.999	0.999	0.995	0.995	0.999	0.995	0.993
Modified Page									
k	0.003615	0.004277	0.004513	0.004749	0.003615	0.0023	0.004203	0.0037	0.003205
n	1.081791	1.108866	1.174682	1.257766	1.081791	1.0966	1.109499	1.0818	1.117048
RMSE	0.007337	0.000577	7.22E-05	0.000277	0.007337	0.0119	0.001137	0.0074	0.012294
R^2	0.995	0.999	0.999	0.999	0.995	0.994	0.999	0.995	0.993
Henderson and Pabis									
k	0.003725	0.004481	0.004824	0.0052	0.003725	0.0024	0.004396	0.0038	0.003343
a	1.011962	1.026448	1.038453	1.054615	1.011962	1.0137	1.023104	1.0120	1.018721
RMSE	0.009732	0.003345	0.006313	0.011526	0.009732	0.0160	0.004293	0.0098	0.017239
R^2	0.9952	0.9985	0.9937	0.9968	0.9952	0.993	0.9982	0.9952	0.9914
Logarithmic									
k	0.003173	0.004171	0.00449	0.004824	0.003173	0.0018	0.004053	0.0031	0.002619
a	1.046409	1.039604	1.052357	1.070325	1.046409	1.0667	1.037682	1.0464	1.081797
c	-0.057	-0.02361	-0.02403	-0.02584	-0.057	-0.0842	-0.02648	-0.057	-0.09545
RMSE	0.002187	0.00106	0.003511	0.007763	0.002187	0.0026	0.001049	0.0022	0.003378
R^2	0.998	0.999	0.994	0.993	0.998	0.998	0.999	0.998	0.997
Two-term									
k_0	0.002062	0.002941	0.003113	0.003251	0.002062	0.0035	0.002808	0.0021	0.001601
a	-6.98666	-6.97152	-6.96564	-6.95792	-6.98666	-6.9928	-6.95768	-6.9867	-6.97104
k_1	0.002205	0.003089	0.003278	0.003439	0.002205	0.0033	0.002957	0.0023	0.001742
b	7.967348	7.982493	7.988374	7.996096	7.967348	7.9707	7.961637	7.9674	7.947814
RMSE	0.002255	0.000645	0.002206	0.005204	0.002255	0.0096	0.000357	0.0023	0.003426
R^2	**0.998**	**0.999**	**0.996**	**0.997**	**0.998**	**0.997**	**0.999**	**0.998**	**0.997**
Diffusion approach									

k	0.002335	0.003062	0.003169	0.003262	0.002335	0.0014	0.002954	0.0024	0.001877
a	6.935121	6.945112	6.945043	6.944966	6.935121	6.9464	6.974818	6.9352	6.974848
b	0.929427	0.944781	0.940263	0.934993	0.929427	0.9189	0.942193	0.9295	0.912796
RMSE	0.00257	0.000821	0.00297	0.007338	0.00257	0.0037	0.000401	0.0026	0.003943
R^2	**0.998**	**0.996**	**0.998**	**0.998**	**0.998**	**0.998**	**0.999**	**0.998**	**0.998**
Modified Henderson and Pabis									
k	0.005927	0.006392	0.007703	0.009511	0.005927	0.0038	0.002838	0.0060	0.001393
a	-6.91678	-6.85833	-6.86369	-6.89584	-6.91678	-6.929	-6.83507	-6.917	-6.8684
b	0.005474	0.006069	0.007154	0.008533	0.005474	0.0035	0.002992	0.0055	0.001537
g	7.826101	7.880972	7.876017	7.844502	7.826101	7.8306	7.851436	7.8262	7.81623
h	0.499974	0.499974	0.499974	0.499974	0.499974	0.4999	0.499974	0.4999	0.499974
c	0.090827	-0.02318	-0.01212	0.057854	0.090827	0.0968	-0.0149	0.0909	0.045285
RMSE	0.004782	0.000558	7.87E-05	0.000114	0.004782	0.0073	0.000287	0.0048	0.00302
R^2	**0.997**	**0.999**	**0.9985**	**0.9996**	**0.997**	**0.9943**	**0.9998**	**0.997**	**0.9971**
Midilli et al.									
k	0.003677	0.002682	0.001807	0.001237	0.003677	0.0025	0.002611	0.0037	0.003335
n	0.984933	1.083989	1.168841	1.251877	0.984933	0.9655	1.083601	0.9850	0.973653
a	0.995419	1.00185	0.999617	1.002698	0.995419	0.9932	0.996709	0.9955	0.994922
b	-5.3E-05	-1E-05	-2.9E-06	-8.9E-07	-5.3E-05	-5.3E-5	-1.3E-05	-5.3E-5	-8.34E-5
RMSE	0.002354	0.000272	4.08E-05	0.000266	0.002354	0.0027	0.00043	0.0024	0.003507
R^2	**0.998**	**0.999**	**0.999**	**0.998**	**0.998**	**0.999**	**0.999**	**0.998**	**0.997**

Table 4.2. Model constants, RMSE and R^2 at different stages and air velocities

Parameters	**Stages**				**Velocity(m/s)**	
	One	**Two**	**Three**	**Four**	**1.01**	**1.3**
Newton						
k	0.001623	0.002066	0.003113	0.003684	0.003113	0.003654
RMSE	0.019102	0.012074	0.005126	0.009981	0.005126	0.00448
R^2	0.995	0.993	0.996	0.995	0.996	0.998
Page						
k	0.000842	0.001205	0.002016	0.002282	0.002016	0.002492
n	1.098965	1.084263	1.072472	1.081842	1.072472	1.065309
RMSE	0.011374	0.007284	0.002667	0.007337	0.002667	0.002689
R^2	0.998	0.997	0.998	0.995	0.998	0.998
Modified Page						
k	0.001588	0.002031	0.0035	0.003615	0.0035	0.0036

n	1.074253	1.083677	1.065146	1.081791	1.065146	1.065146
RMSE	0.006301	0.007284	0.025687	0.007337	0.025687	0.002689
R^2	0.998	0.997	0.993	0.995	0.993	0.998
Henderson and Pabis						
k	0.001601	0.002082	0.003171	0.003725	0.003171	0.003171
a	1.011274	1.016352	1.019323	1.011962	1.019323	1.019323
RMSE	0.002841	0.006252	0.004411	0.009732	0.004411	0.037097
R^2	0.998	0.997	0.998	0.9952	0.998	0.998
Logarithmic						
k	0.001347	0.001789	0.002853	0.003173	0.002853	0.003403
a	1.072587	1.053595	1.039282	1.046409	1.039282	1.029102
c	-0.08074	-0.05884	-0.03614	-0.057	-0.03614	-0.02742
RMSE	0.001325	0.000989	0.000677	0.002187	0.000677	0.000854
R^2	0.999	0.997	0.997	0.998	0.999	0.999
Two-term						
k_0	0.00092	0.00125	0.001926	0.002062	0.001926	0.002352
a	-6.95613	-6.95618	-6.9496	-6.98666	-6.9496	-6.95019
k_1	0.000986	0.001321	0.002039	0.002205	0.002039	0.002476
b	7.9432	7.943153	7.943398	7.967348	7.943398	7.94289
RMSE	0.001932	3.20E-03	0.001071	0.002255	0.001071	0.000925
R^2	**0.999**	**0.998**	**0.999**	**0.998**	**0.999**	**0.999**
Diffusion approach						
k	0.001103	0.001319	0.002139	0.002335	0.002139	0.002568
a	6.965258	6.969214	6.967328	6.935121	6.967328	6.970832
b	0.941195	0.930385	0.941863	0.929427	0.941863	0.945716
RMSE	0.000998	0.001777	0.000943	0.00257	0.000943	0.000889
R^2	**0.999**	**0.999**	**0.999**	**0.998**	**0.999**	**0.999**
Modified Henderson and Pabis						
k	0.000711	0.001135	0.001872	0.005927	0.001872	0.002339
a	-6.79811	-6.79855	-6.7793	-6.91678	-6.7793	-6.78295
b	0.000786	0.001214	0.001989	0.005474	0.001989	0.002462
g	7.768417	7.768106	7.77001	7.826101	7.77001	7.766375
h	0.499974	0.499974	0.499974	0.499974	0.499974	0.499974
c	0.002763	0.031724	0.012334	0.090827	0.012334	0.014714
RMSE	0.005484	0.002224	0.001201	0.004782	0.001201	0.000931
R^2	**0.995**	**0.998**	**0.988**	**0.985**	**0.995**	**0.996**
Midilli et al.						
k	0.001977	0.002214	0.002922	0.003677	0.002922	0.003229
n	0.950732	0.975408	1.002546	0.984933	1.002546	1.014878

a	1.005963	1.003578	1.00453	0.995419	1.00453	1.00065
b	-4.4E-05	-3.4E-05	-2.8E-05	-5.3E-05	-2.8E-05	-2.1E-05
RMSE	0.000689	7.18E-04	0.000641	0.002354	0.000641	0.000967
R^2	**0.999**	**0.999**	**0.999**	**0.998**	**0.999**	**0.999**

From R^2 and RMSE values, it has been observed that the experimental data of multistage fluidized bed dryer shows better fit with two time constant models.

4.3.5 Effective diffusivity

Effective diffusivity can describe the moisture transport rate of solids in dryers. In this study, effective diffusivity has been evaluated using Equation 3.6.3 respectively in MATLAB user-defined program at different temperatures and air velocities by minimizing RMSE. The error between the experimental and predicted moisture ratio is analyzed using Equation 4.2.1 and at minimum RMSE the moisture ratio and the effective diffusivity are evaluated.

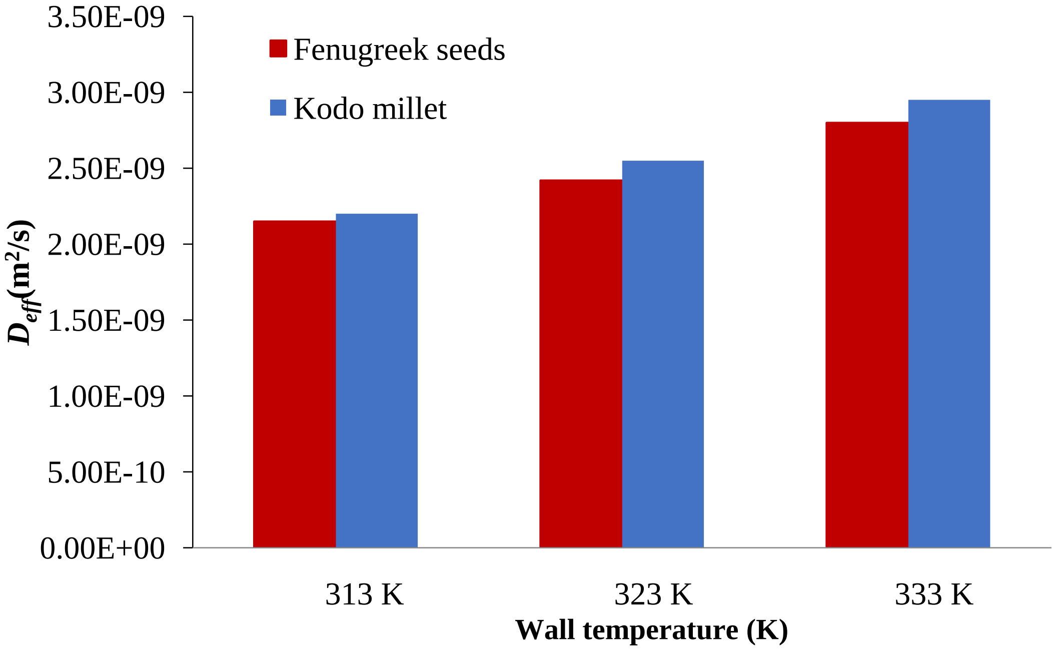


Figure 4. 39 Effective diffusivity of kodo millet and Fenugreek seeds (V-1.35 m/s, H-4 cm and IMC-10%)

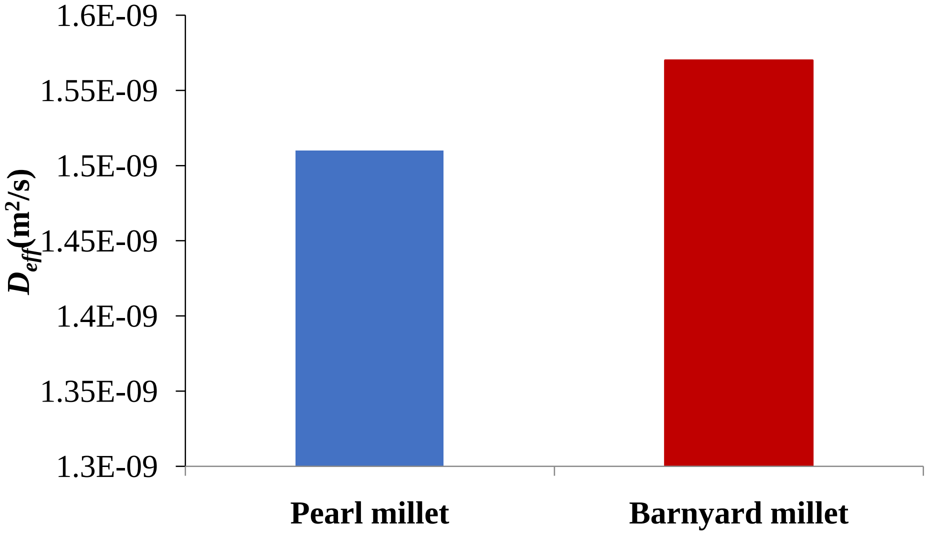


Figure 4. 40 Effective diffusivity of Pearl millet and Barnyard millet

(V- 1.01 m/s, T-313 K, H_d -50 mm and S_F-6.7 kg/hr)

From the experimental data of batch fluidized bed drying, the effective diffusivity is calculated for kodo millet and Fenugreek seeds. From Fig 4.39, it can be observed that the effective diffusivity of Kodo millet is higher than Fenugreek seeds. It can be seen from the multistage drying results shown in Fig 4.40 that the effective diffusivity of Barnyard millet is higher than Pearl millet.

From multistage drying, it can be observed from Fig 4.41 that the diffusivities of bed material increased with increasing stages of the dryer. From the results, the effective diffusivity of solids increased from 6.40×10^{-10} to 8.90×10^{-10} m^2/s in stage 1 and from 1.5×10^{-9} to 2.4×10^{-9} m^2/s in stage 4 with increasing wall temperature of dryer from 313 to 328 K. The effective diffusivity increased from 0.830×10^{-9} to 1.90×10^{-9} m^2/s in stage 2 and from 1.26×10^{-9} to 1.5×10^{-9} m^2/s in stage 3 with increasing air velocity from 1.01 to 1.3 m/s. The effective diffusivity was obtained from 7.3×10^{-10} to 5.80×10^{-10} m^2/s in stage 1 and from 1.78×10^{-9} to 1.30×10^{-9} m^2/s in stage 4 with changing inlet solids flow rate from 5 to 10 kg/h of the dryer. The effective diffusivity was obtained between 6.4×10^{-10} and 5.10×10^{-10} m^2/s in stage 1 and from 1.51×10^{-9} and 0.920×10^{-9} m^2/s in stage 4 at different down comer heights of dryer 50 and 70 mm.

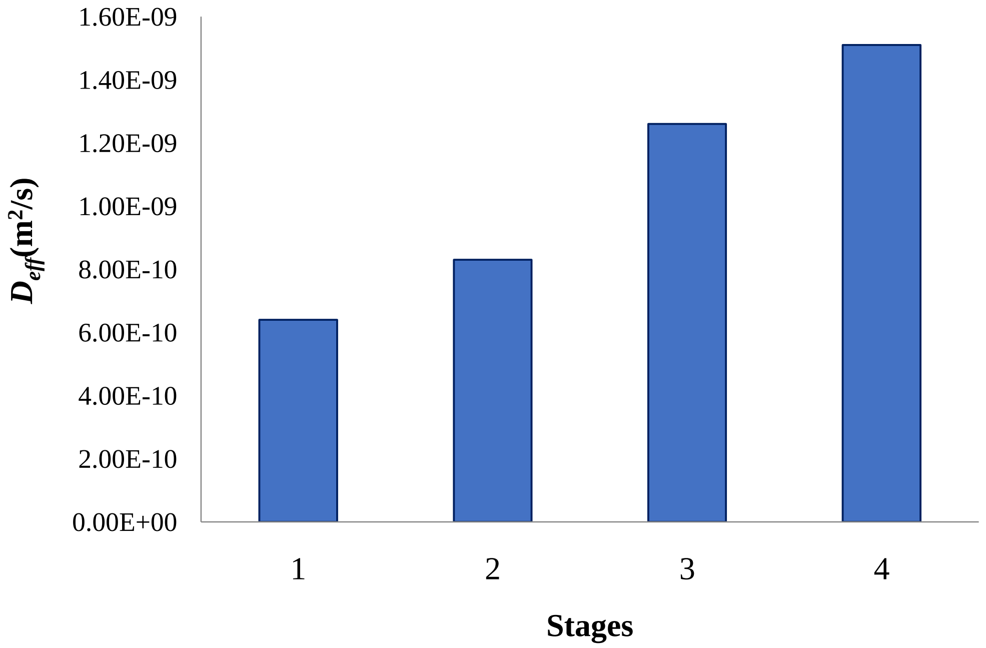


Figure 4. 41 Effect of number of stages on Effective diffusivity in multistage fluidized bed dryer

(V- 1.01 m/s, T-313 K, H_d -50 mm and S_F-6.7 kg/hr)

4.3.5 Activation energy

To emphasize the drying kinetics of multistage fluidized bed dryer, the activation energies can be derived using the Arrhenius equation (Equation 4.3.3)

$$D_{eff} = D_0 . \exp\left(-E_a/RT\right) \tag{4.3.3}$$

Equation 4.3.4 with logarithmic form

$$\ln D_{eff} = \ln D_0 - \left(E_a/RT\right) \tag{4.3.4}$$

In the drying process, activation energy E_a is the minimum amount of energy that is required to make the process realizable. Based on the experimental diffusivities, from equation 4.3.4 a graph was plotted between ln(D_{eff}) vs 1/T. From Fig 4.42, activation energies of single and multistage fluidized bed dryers have been evaluated by slopes from temperatures ranging from 313 to 328 K. The activation energies were obtained as 17.56 kJ/mol for single stage fluidized bed dryer and 24.34 kJ/mol for multistage fluidized bed dryer. From the results, it was noticed that the activation energy raised with increasing stages of fluidized bed dryer.

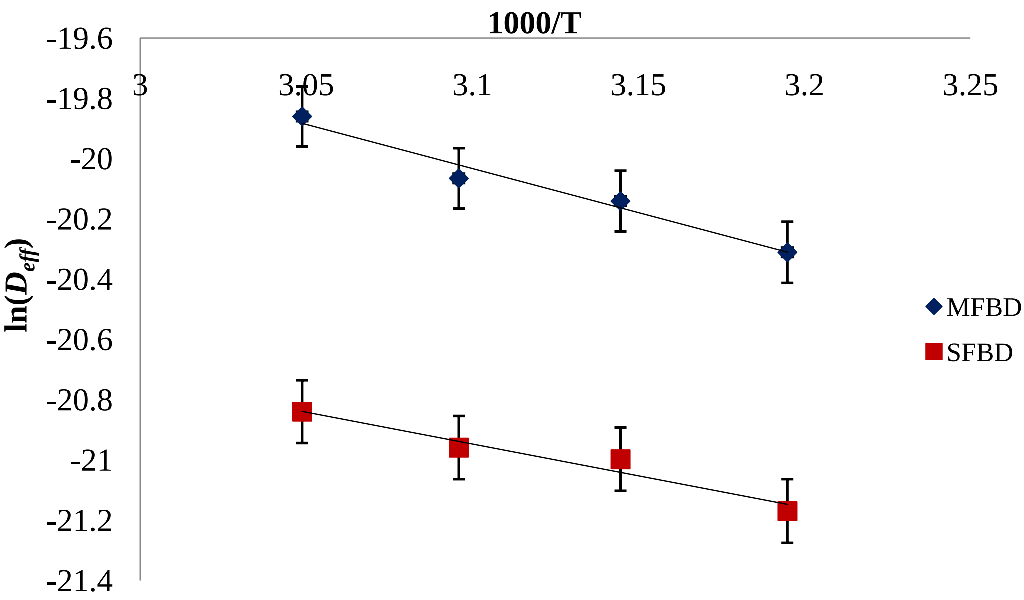


Figure 4. 42 ln(D_{eff}) vs 1/T plot for single stage and multistage dryer (V- 1.01 m/s, H_d -50 mm, S_F-6.7 kg/hr and MFBD-Stage 4)

A similar influence on effective diffusivity and the activation energy was seen in previous studies. Senadeera et al. (2003) have reported using batch fluidized bed dryer that the effective diffusivity increased with increase in temperature from 303 to 323 K and reported values within the range of 10^{-12}–10^{-8} m^2/s. Khanali et al. (2016) have reported that the effective diffusivity increased from 4.78×10^{-11} to 13.64×10^{-11} m^2/s with increase in temperature from 323 to 343 K and air velocity from 2.3 to 2.8 m/s of batch fluidized bed dryer using rough rice and reported activation energies between 36.59 to 44.31 kJ/mol. It has been seen that the effective diffusivity and activation energies in fluidized bed dryer increased from 0.582×10^{-10} to 1.58×10^{-10} m^2/s and 31.94 to 34.48 kJ/s by increasing temperature from 323 to 353 K and air velocity 2.51 to 5.32 m/s from the results of Chayjan et al. (2013). Zhao et al. (2016) have studied drying characteristics of Shengli lignite using several batch fluidized beds (Fluidized bed, Vibratory fluidized bed, Medium fluidized bed and vibrated medium fluidized bed). From their results, it has been noticed that effective diffusivity and activation energies increased from 7.11×10^{-9} to $5.37\times10^{-8}$$m^2$/s and 27.92 to

30.21 kJ/mol with increasing temperature from 353 to 433 K. In this study, also seen a similar rise in effective diffusivity and activation energies is seen in multistage fluidized bed dryer.

4.4 Energy and exergy analyses for multistage fluidized bed dryer

4.4.1 Energy analysis

Experimentation was made for Barnyard millet drying at different wall temperatures, air velocity, downcomer height using MFBD (Appendix- Data E). From experimental results, the obtained energy utilization ratio of Barnyard millet is presented with change of all parameters. From results, the highest EUR was found to be as 0.82 at initial time later it reached steady state at 0.46 of dryer with wall temperatures of 328 K, air velocity at 1.01 m/s, solids flow rate of 6.7 kg/h and lowest value found as 0.73 at initial time later at steady state as 0.25 for dryer at wall temperature of 313 K, air velocity at 1.01 m/s, solids flow rate of 5 kg/h.

4.4.1.1 EUR at different wall temperatures

Experiments were performed with the change of wall temperatures in multistage dryer in the range 313-328 K and other parameters keeping aside in constant mode. Fig 4.43 shows that the increment in energy utilization ratio with increase in temperature of walls of stages in the multistage dryer. The higher energy utilization ratio of the dryer is observed in the initial period of the drying time and later it was found to decrease with the drying time of the dryer. Due to high moisture content present in the bed initially and high moisture in the outlet air owing to high moisture removal rate, Energy Utilization Ratio is high initially. With the increase in wall temperature of stages, the heat transfer rate across the bed of particles with gas, between wall and particles, wall and gas are enhanced and it leads to higher moisture evaporation rate in the dryer. Higher temperature utilizes higher energy input obviously due to increase in heat input and moisture carryover increased, due to which higher EUR was obtained at high wall temperatures. The EUR in each stage was reported in Fig 4.44, from that it has noticed that the energy utilization ratio with increase in stages in dryer.

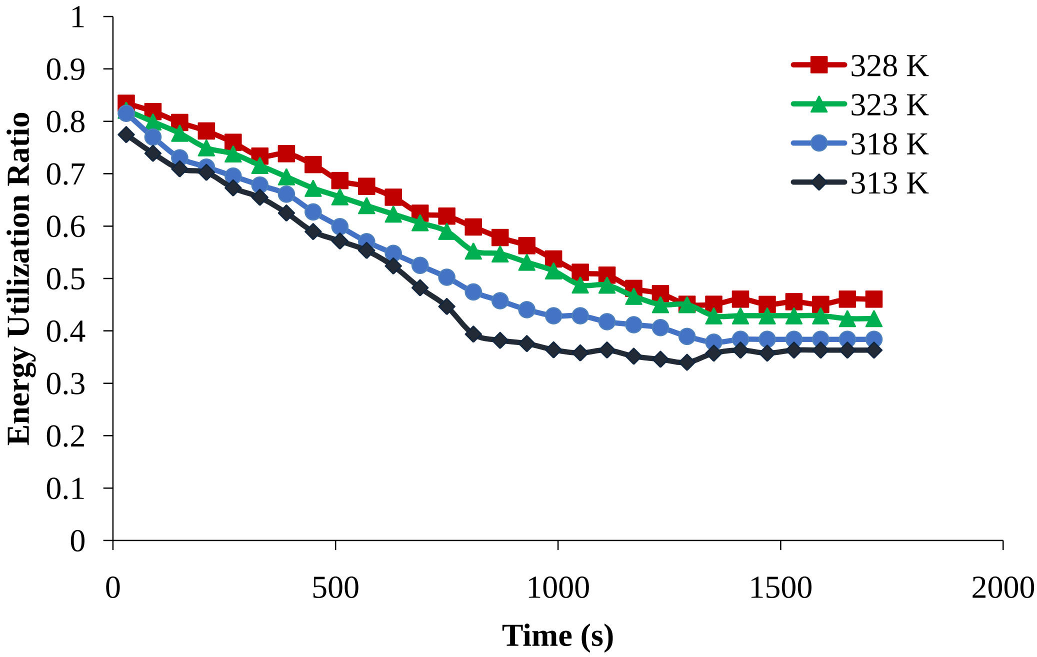


Figure 4. 43 EUR with the variation of wall temperatures in MFBD

(V- 1.01 m/s, S_F-6.7 kg/h, H_d -50 mm)

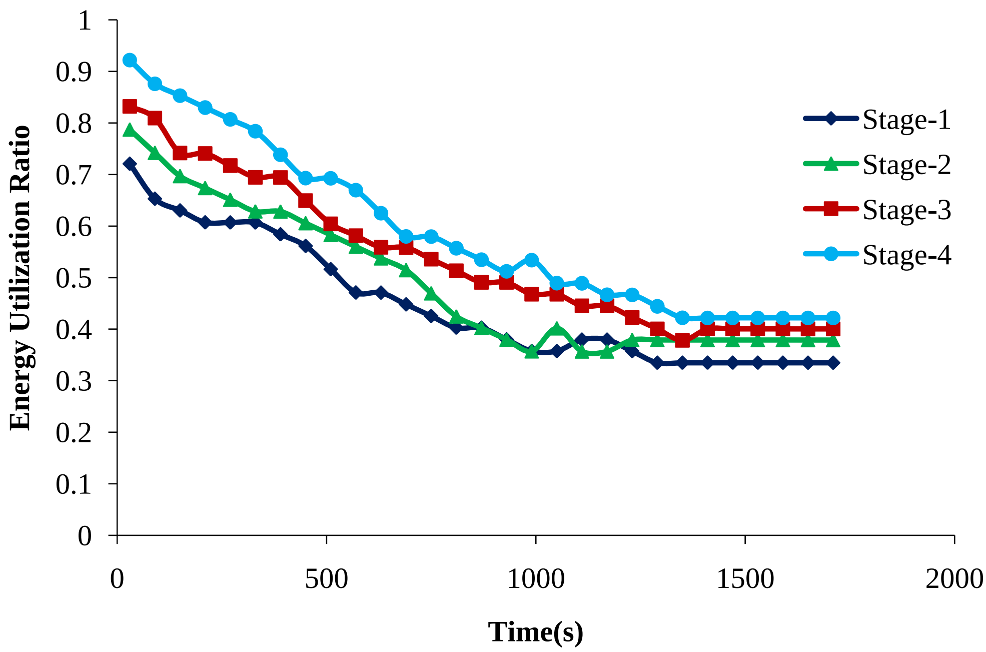


Figure 4. 44 Stage wise energy utilization ratio of MFBD

(T_w-313 K, V- 1.01 m/s, S_F-6.7 kg/h, H_d -50 mm)

4.4.1.2 EUR at different air velocities

The air velocity influence was checked in MFBD by changing air velocity in the range of 1.01- 1.3 m/s and other parameters keeping aside in constant mode. Fig 4.45 shows that there is the increment in energy utilization ratio when air velocity is increased and decrement with the drying time of multistage dryer. Convection heat transfer increases with increasing air velocity of the dryer, and then moisture carryover rate from Barnyard millet increases in each stage, which results in higher energy utilization ratios in continuous wall heated multistage fluidized bed dryer.

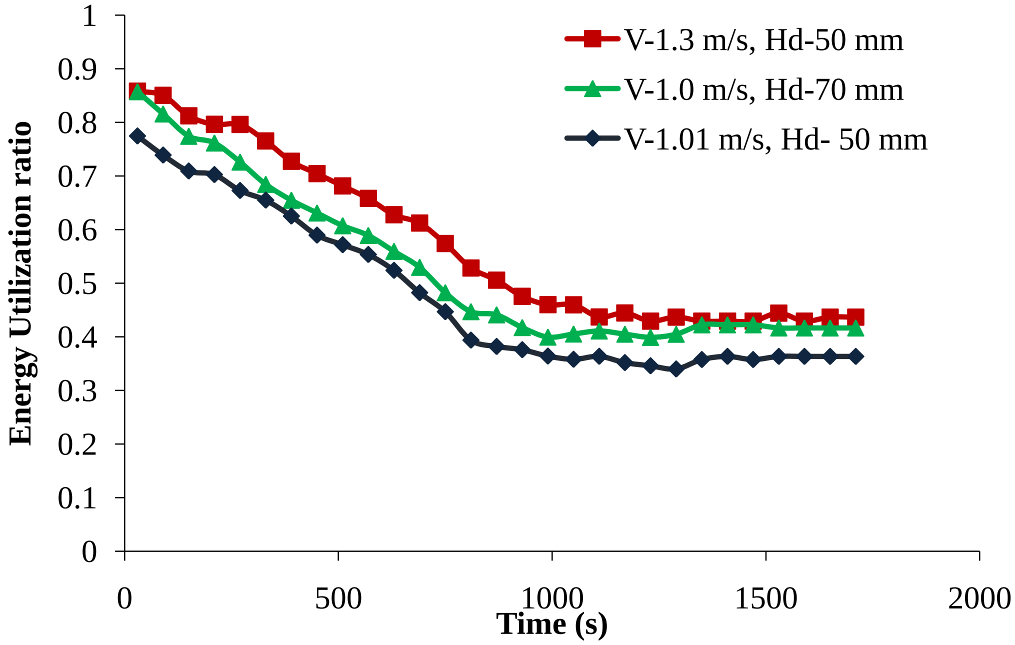


Figure 4. 45 EUR with the variation of air velocities and downcomer height in MFBD (T_w-313 K, S_F-6.7 kg/h)

4.4.1.3 EUR at different solids flow rates

Experiments were conducted by changing the solids flow rate of the MFBD to examine the flow rate of solids influence on energy utilization ratio of the dryer and keeping remaining parameters as constant. It can be observed from Fig 4.46, that there is increment in energy utilization ratio with increase in the solids flow rate of Barnyard millet in the dryer. The increase in solids flow rates increase the moisture input and bed loadings with moisture in dryer and then the requirement of energy for drying also increased. Due to that, the energy consumption is high when solids flow rates increased in the multistage dryer

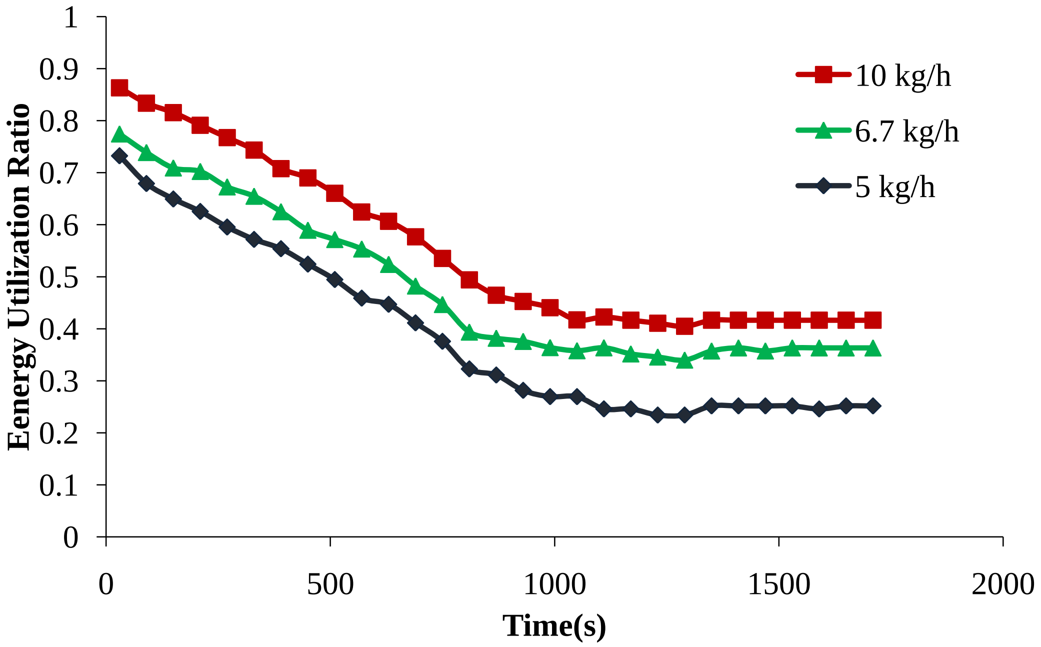


Figure 4. 46 EUR with the variation of solids flow rates in MFBD

(T_w-313 K, V- 1.01 m/s, H_d -50 mm)

4.4.1.4 EUR at different downcomer heights

Experiments were performed to determine the downcomer effect in MFBD with Barnyard millet varying downcomer height from 50 to 70 mm and other parameters being kept in constant mode. Fig 4.45 represents an increment in energy utilization ratio with drying of Barnyard millet when downcomer height of MFBD was increased. Increasing bed height results in presence of more moisture in the bed which leads to more energy utilization to evaporate that moisture thus resulting in higher energy utilization ratio of the multistage dryer at higher downcomer heights.

Azadbakht et al. (2017) have analyzed the batch fluidized bed dryer energy and exergy with potato cubes. It was seen that the energy utilization ratio of dryer showed increment (nearly from 30 to 70%) with increasing air temperature (318 - 328 K), velocity of air (3.2 - 9.1 m/s) and depth of bed (1.5 - 3 cm). Similar reports were seen in Karaguzel et al. (2012) study, that the energy utilization ratio of fluidized bed dryer increased (nearly 0. 3 to 0.5) when an increasing temperature of air in the dryer. In this study continuous MFBD also showed similar trends with the change in the parameters. The EUR values at steady state are increased from 0.36 to 0.46 with an increment of wall temperature (313 to 328 K), from 0.36 to 0.43 with increasing air velocity (1.01 to 1.3 m/s), from 0.36 to 0.41 with an influence of downcomer height (from 50 to 70) and showed increment from 0.25 to 0.41 by increment of solids flow rate (5 to 10 kg/h) for Barnyard millet grains in continuous multistage fluidized bed dryer.

4.4.2 Exergy losses in multistage fluidized bed dryer

Exergy loss for multistage drying of Barnyard millet was determined by changing wall temperature of stages, velocity of air, height of downcomer and flow rate of solids. From this study, the maximum exergy loss at steady state was found to be as 0.014 kJ/s of dryer with temperature -328 K, air velocity-1.01 m/s, solids flowrate-6.7 kg/h and lowest value found as 0.009 kJ/s for dryer at wall temperature -313 K, air velocity-1.3 m/s, solids flowrate-6.7 kg/h.

4.4.2.1 Exergy losses of MFBD at different wall temperatures

The difference in exergy of inflow and outflow of the dryer is defined as exergy loss. In this study, input exergy was purely based on wall temperatures of stages in the multistage dryer and output exergy was evaluated based on outlet air temperatures of the dryer. The exergy loss of MFBD was evaluated from experimentation by varying wall temperatures of stages in the range 313- 328 K and other parameters being kept in constant mode. Wall temperature influence on exergy loss of dryer was presented in Fig 4.47. The figure shows increment in exergy loss of dryer with increase in wall temperatures of stages. The exergy loss of dryer is more at the initial time of drying and later it reduced with the drying time because at initial time, supplied heat was utilized for moisture removal (drying). Then moisture content in material decreases during drying and hence exergy utilization also decreased with drying time. Due to the reason, exergy outflow values increase from dryer outlet. After certain drying time, material will be at equilibrium condition and does not allow enough heat to dry the material. The exergy inflow increases due to increasing wall temperature and on the other side due to increase in temperature effect, fast drying takes place, The supplied exergy increment at higher temperature leads to increment of heat utilization to evaporate the moisture thus results in exergy loss increment.

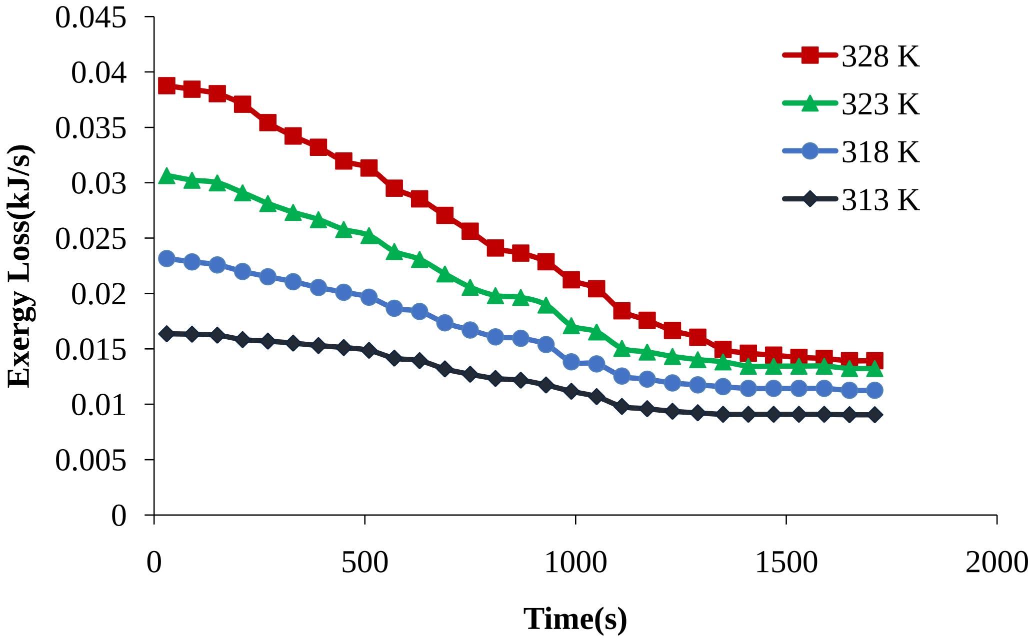


Figure 4. 47 Effect of wall temperatures in MFBD on exergy losses

(V- 1.01 m/s, S_F-6.7 kg/hr, H_d -50 mm)

4.4.2.2 Exergy loss of MFBD at different air velocities

The influence air velocity on exergy loss of MFBD was experimentally evaluated by operating velocity of air in the range, 1.01 - 1.3 m/s and maintaining other parameters constant. As seen from the results presented in Fig 4.48, the exergy loss of MFBD showed decrement with increase in air velocity of the dryer and showed decrement with drying time. The exergy loss is nothing but the difference between exergy input and exergy output. In this study, exergy inlet in the MFBD is not affected when the increase in the velocity of air. Exergy outflow of the dryer showed increment when the velocity of air is increased, due to convective heat transfer in the dryer. Hence there is a decrement in exergy loss of MFBD with the increase in velocity of air.

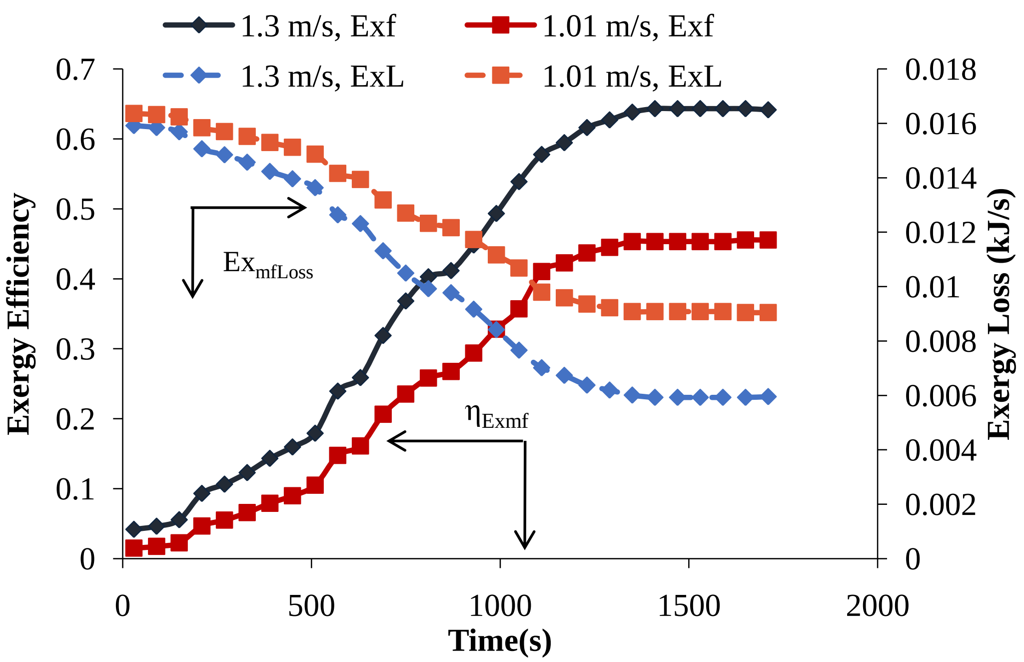


Figure 4. 48 Effect of air velocity in MFBD on exergy efficiency and exergy losses (T_w-313 K, S_F-6.7 kg/hr, H_d -50 mm)

4.4.2.3 Exergy loss of MFBD at different solids flow rates

To determine the influence of flow rate of solids on exergy loss of the dryer, experiments were performed by operating solids flow rate with a range of 5-10 kg/h and keeping other parameters in constant mode. Results presented in Fig 4.49 showed an increment of exergy loss of MFBD when there was an increase in the flow rate of solids in the dryer and decreasing trend was observed with increasing drying time. An increment in solids flow rate in dryer increases bed loading, thus increasing the bed mass which is subjected to dry and consumes more available energy from the inlet. Hence it showed increment in exergy loss of the dryer.

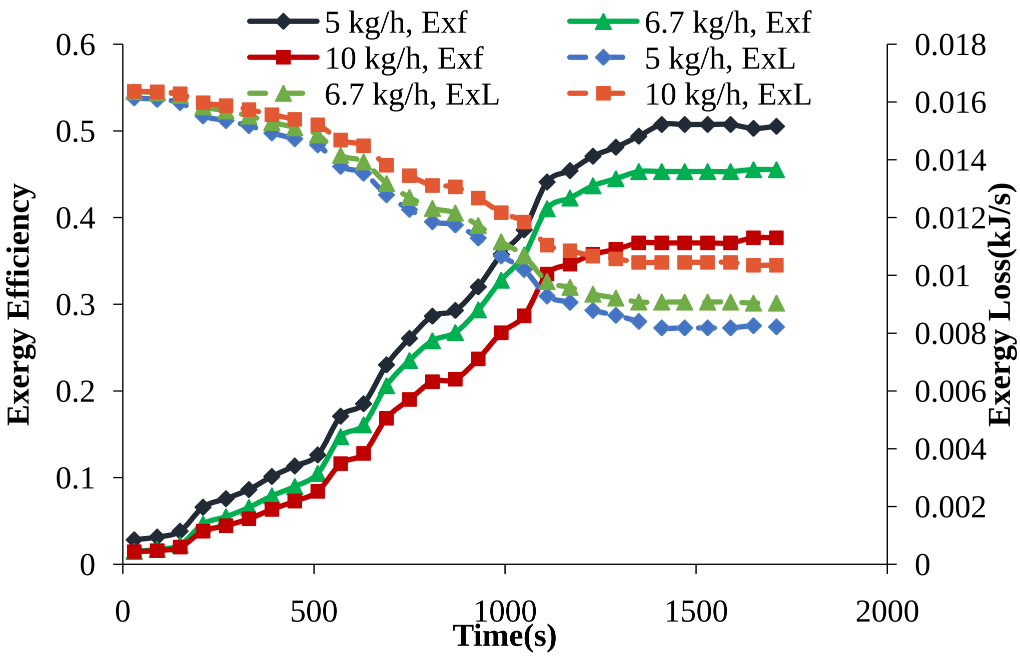


Figure 4. 49 Effect of solids flow rate in MFBD on exergy efficiency and exergy losses (V- 1.01 m/s, T_w-313 K, H_d -50 mm)

4.4.2.4 Exergy loss of MFBD at different downcomer heights

To determine the influence height of downcomer on exergy loss of the dryer, experiments were performed by operating downcomer height with a range of 50-70 mm and keeping other parameters in constant mode. From Fig 4.50, it can be observed that the exergy loss of multistage fluidized bed dryer increased with increase in downcomer height in the dryer and decreases with an increase in drying time. Increasing downcomer height increases the bed height which increases bed loading of MFBD. This increases the amount of material in the bed which increases the moisture. Thus consumption of exergy inflow increases to remove this moisture resulting in lower values of exergy outflow and increasing exergy loss.

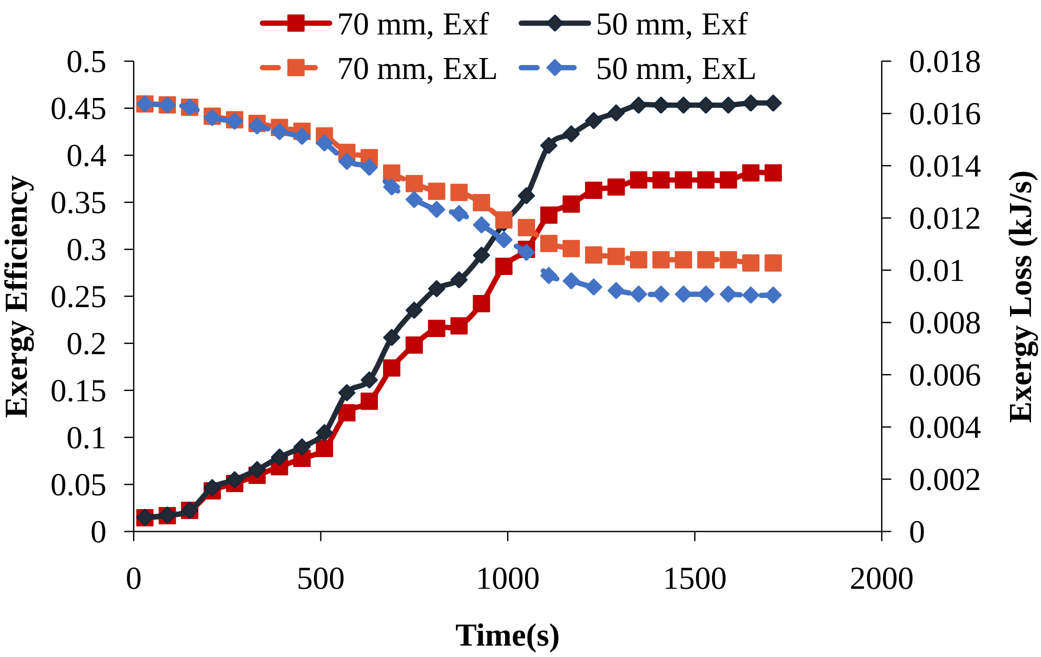


Figure 4. 50 Effect of downcomer height in MFBD on exergy efficiency and exergy losses (V- 1.01 m/s, T_w-313 K, S_F-6.7 kg/hr)

The exergy analysis of microwave oven using coroba slices by Corzo et al. (2008) study showed exergy loss increment (range of 0.005 – 0.11 kJ/s) with the increment of air temperature (range of 344 -366 K). Akbulut and Durmus (2010) have reported exergy loss decrement from 10.82 to 2.6 W with the increase in air flow rate in the range of 0.014- 0.036 kg/s for forced solar dryer. The trends in the current study also showed similar behavior, ie. Exergy loss of Barnyard millet increased from 0.016 to 0.038 kJ/s with an increment of wall temperatures, and exergy loss showed decrement with an air velocity increment in the multistage dryer. From Nazghelichi et al. (2010) study, the increase in solids holdup resulting from increment in bed depth of batch fluidized bed dryer, the increment in exergy loss (range 0.5 – 1.6 kJ/s) was observed when operated bed heights of carrot cubes with a range of 3 – 9 cm. Azadbakht et al. (2017) also reported similar reports with increase in bed depths of cubes in batch fluidized bed dryer. Similar trends were also observed in the present study, The exergy loss of multistage dryer at steady state increased from 0.009 to 0.014 kJ/s with an increment of wall temperatures (313 to 328 K), increased from 0.009 to 0.010 kJ/s with increase in downcomer height (from 50 to 70), increased from 0.0082 to 0.0103 kJ/s with an increment of solids flow rate (5 to 10 kg/h), showed decrement from 0.0090 to 0.0059 kJ/s with increasing air velocity (1.01 to 1.3 m/s) for Barnyard millet grains drying.

4.4.3 Exergy efficiency for multistage fluidized bed dryer

From the experimentation of multistage drying of Barnyard millet grains, profiles of exergy efficiency were reported by changing operating conditions like the temperature of stages, velocity of air, height of downcomer and solids flow rate. From the study, the maximum exergy efficiency for multistage fluidized bed dryer was found to be as 0.64 of dryer with wall temperatures -328 K, air velocity-1.01 m/s, solids flowrate-6.7 kg/h and lowest efficiency was 0.371 for dryer at wall temperatures -313 K, air velocity-1.3 m/s, solids flowrate-10 kg/h.

4.4.3.1 Exergy efficiency of MFBD at different wall temperatures

The exergy efficiency of MFBD is presented with change of wall temperature of stages from 313 to 328 K. Fig 4.51 shows increment in exergy efficiency of MFBD when there is an increase in wall temperatures of the dryer. The input exergy or heat is correlated with wall temperature than supplying more helps to more moisture removal at higher temperatures. During drying, fast drying occurs at higher temperatures, with time more moisture evaporation helps to exergy utilization decrement and due to that losses decreased and efficiency increased with time. Fig 4.52 shows that the exergy efficiency increases with increased stages in MFBD. In multistage fluidized bed drying, due to stage by stage operation, moisture removal efficiency increased stage by stage. Then exergy from outlet of stage increased with increase in stages and it helps in exergy efficiency increment with increase in stages of dryer. At the end of drying period, the enough exergy is unable to be utilized for the drying of material. As the material is at equilibrium moisture content, exergy is not utilized and the remaining supplied exergy comes from the outlet air of the dryer.

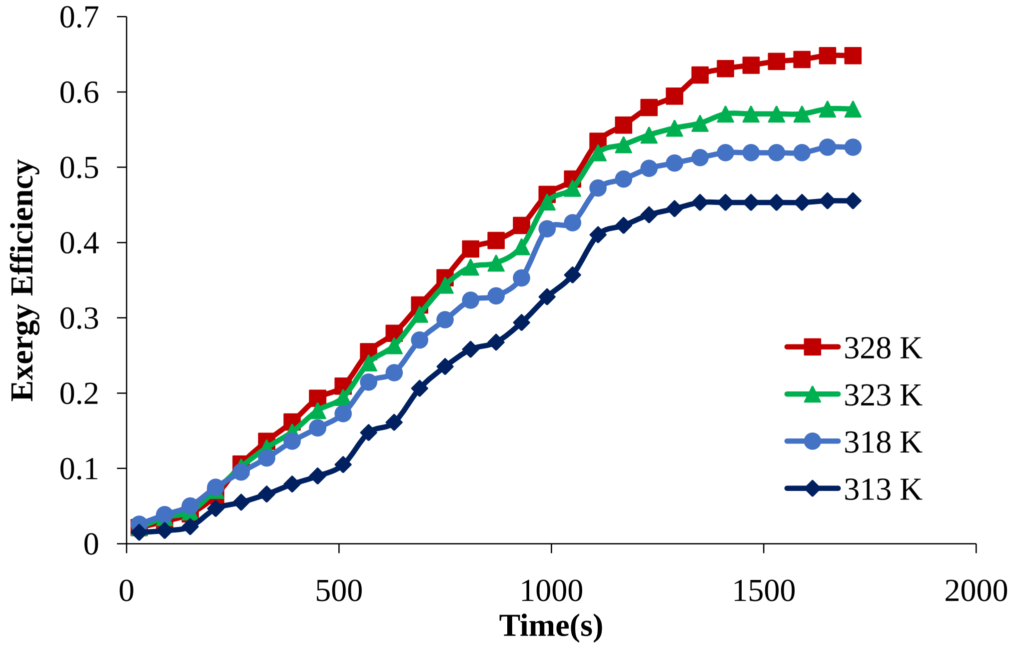


Figure 4. 51 Effect of wall temperatures in MFBD on exergy efficiency

(V- 1.01 m/s, S_F-6.7 kg/hr, H_d -50 mm)

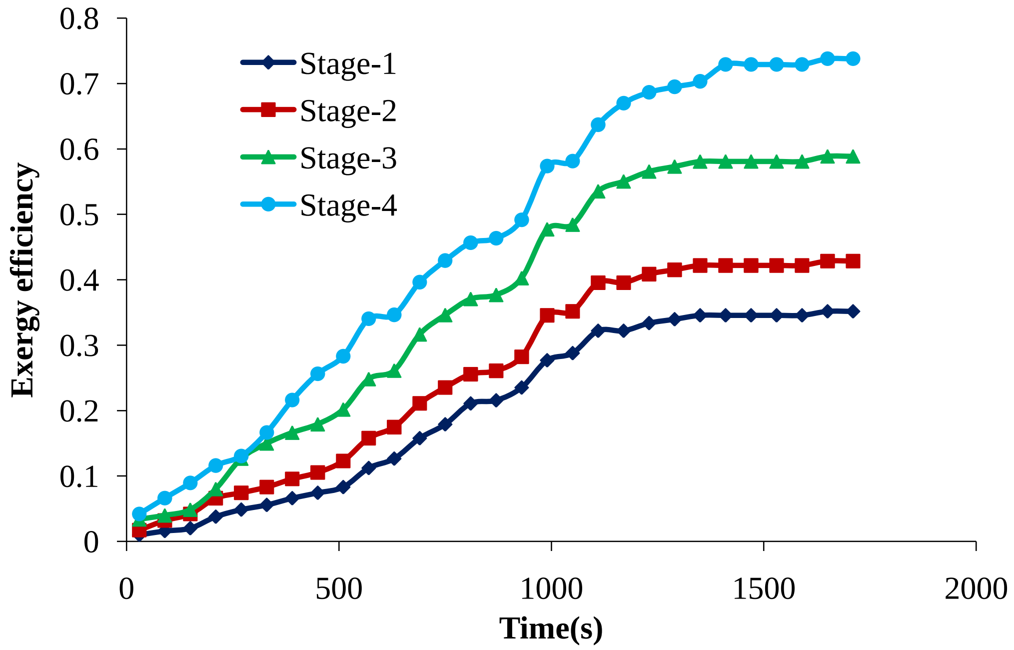


Figure 4. 52 Stage wise exergy efficiency of MFBD

(T_w-313 K, V- 1.01 m/s, S_F-6.7 kg/h, H_d -50 mm)

4.4.3.2 Exergy efficiency of MFBD at different air velocities

To find the influence of velocity of air on exergy efficiency of the dryer, the experimental work was done using MFBD by operating air velocities with a range of 1.01 - 1.3 m/s and other conditions kept in constant mode. The exergy efficiencies of dryer at different air velocities of the dryer are reported in Fig 4.48. The figure shows increment in exergy efficiency of MFBD with increase in velocity of air.

4.4.3.3 Exergy efficiency of MFBD at different solids flow rates

To examine the influence of solids flow rate on exergy efficiency of MFBD, multistage drying of Barnyard millet grains was done with MFB dryer by operating the flow rate of solids in the range of 5 - 10 kg/h and keeping other conditions under constant mode. From the exergy efficiency profiles in Fig 4.49, the decrement in exergy efficiency of MFBD was observed when the solids flow rate was increased. The reverse trend was observed for exergy loss profiles with the increase in solids flow rate.

4.4.3.4 Exergy efficiency of MFBD at different downcomer heights

To examine the influence of downcomer height on exergy efficiency of MFBD, multistage drying of Barnyard millet grains was done with MFB dryer at different downcomer heights ranging from 50 to 70 mm and keeping other conditions under the constant mode. From the exergy efficiency profiles reported in Fig 4.50, the influence shows the decrement in exergy efficiency of MFBD with an increase in downcomer height in the dryer.

The present study shows that the increment in exergy efficiency of MFBD from 0.45 to 0.64 with increasing wall temperatures of stages from 313 to 328K and increment of 0.45 to 0.72 when there is the increase in velocity of air from 1.01 to 1.3 m/s. Similar reports were observed from Karaguzel et al. (2012) study, that the exergy efficiency of the batch fluidized bed dryer increased from 30 to 50% with chickpea and beans with an increase in air temperature. Also from Akpinar (2007) study, it was seen that the exergy efficiency of the cyclone type dryer with strawberry increased from 20 to 80% when the increase in temperature of the air was from 333 to 358 K and velocity of air from 0.5 to 1.5 m/s. The present study showed similarities in the trends as seen from the study of Azadbakht et al. (2017) and Nazghelichi et al. (2010) studies, where there is an increment in solids holdup with increasing height of downcomer and flow rate of solids. Here in this study, exergy efficiency of MFBD was found to be decreasing from 0.45 to 0.38 with increasing height of downcomer from 50 to 70 mm, from 0.5 to 0.371 with the increasing flow rate of solids from 5 to 10 kg/h. The reports of Nazghelichi et al. (2010) showed the decrement in exergy efficiency from 75 to 50% with the increasing bed height of carrot cubes from 3 to 9 cm in batch fluidized bed dryer. Similarly, Azadbakht et al. (2017) reported decrement in exergy efficiency with increase in bed depth from 1.5 to 3 cm of potato cubes in batch fluidized bed dryer.

4.5. Continuous hot air multistage fluidized bed dryer

4.5.1 Drying characteristics of solids in MFBD

Experiments were conducted in continuous multistage fluidized bed dryer by changing air temperature from 313 to 353 K and remaining parameters solids flow rate, downcomer height and air flow rate kept in constant mode. The drying characteristics of 0.6 mm sand particles were determined in continuous hot air multistage fluidized bed dryer. The Fig 4.53 shows that the drying rate of solids increase with increase in air inlet temperature and equilibrium moisture content decreased with increase in air inlet temperature of multistage fluidized bed dryer.

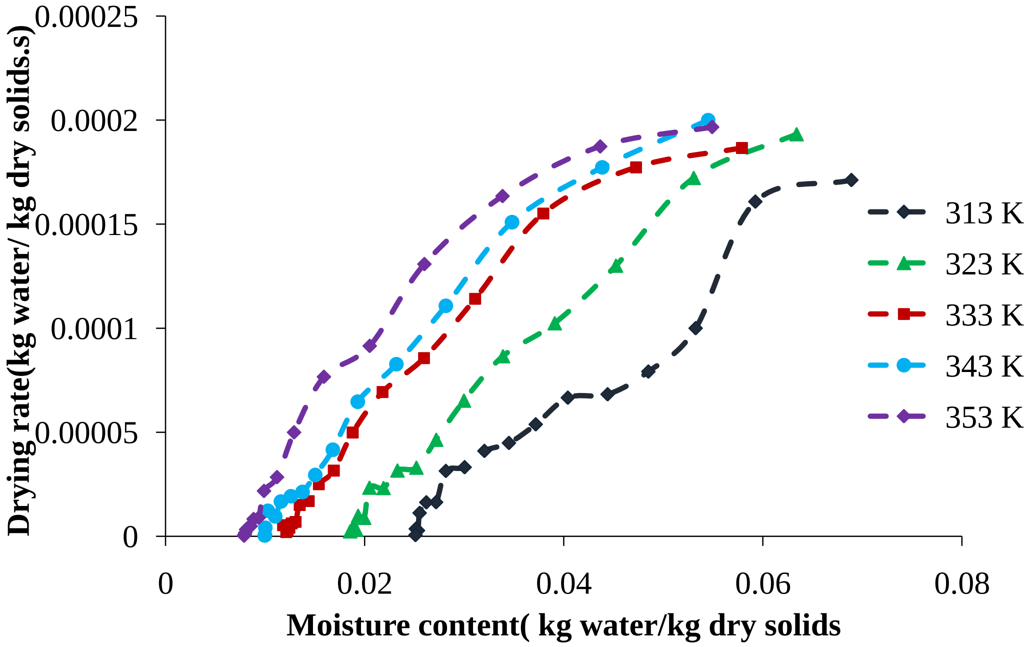


Figure 4. 53 Effect of temperature on multistage drying characteristics of solids (Air flow rate- 50 kg/h, S_F-10 kg/h, IMC-10%)

4.6 Aspen simulation studies on Continuous hot air single stage fluidized bed dryer

4.6.1 Effect of distributor configuration

4.6.1.1 Effect of orifice diameter

Simulations were conducted with orifices of different diameters ranging from 0.4 to 1.4 mm with an increment of 0.1 mm using uniformly sized particles of size 1.3 mm keeping the number of orifices constant. The simulated results of solid outlet temperature, varying orifice diameter have been presented in Fig 4.54. From the results, it can be observed that with the increase in orifice diameter, solids outlet temperature increases up to a certain range and then found to be almost constant. With an increase in orifice diameter from 0.4 to 1 mm, the solid outlet temperature has been found to be increasing and a further increase in orifice diameter above 1 mm, the solid outlet temperature is found to be almost constant. In general, the solids outlet temperature is directly proportional to the drying rate and hence higher the solids outlet temperature, the higher the drying rate (Appendix- Data f).

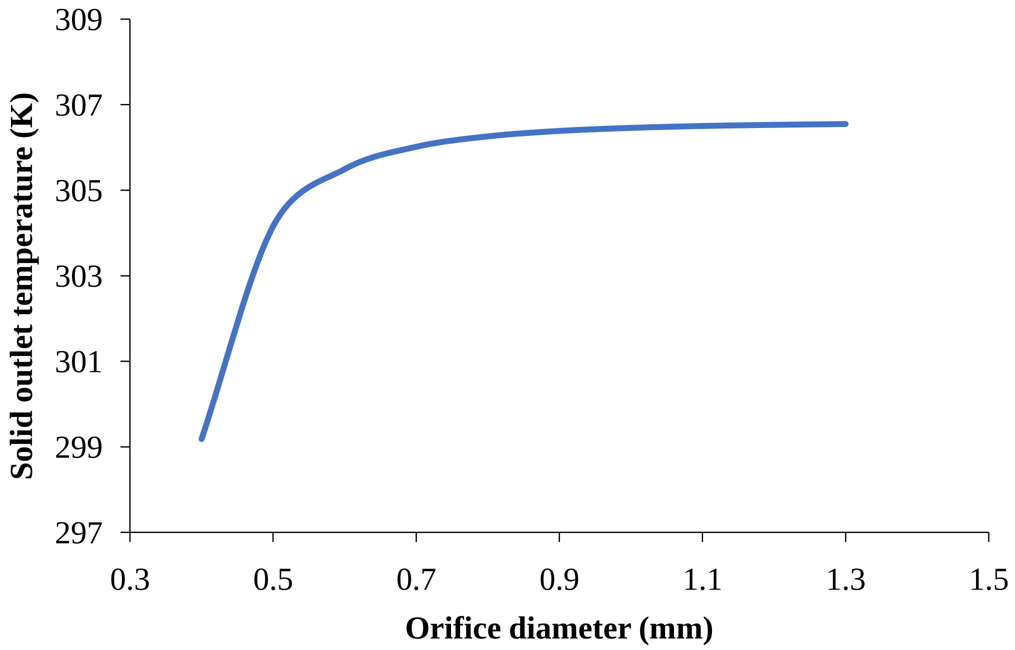


Figure 4. 54 Solid outlet temperature at different orifice diameters
(Initial moisture content-10%, solid flow rate -10 kg/h, air flow rate-50 kg/h, air inlet temperature 323 K)

4.6.1.2 Effect of number of orifices

In the design of the distributor plate, the opening area plays an important role, being mainly responsible for good gas to solid contact. In the present study, the number of orifices has been varied from 50 to 600 with an increment of 10 and the orifice diameter was kept constant at 1 mm. The simulation results of solid outlet temperature by numbers of orifices are presented in Fig. 4.55. From the figure, it can be observed that with an increase in the number of orifices, the solids outlet temperature is found to be increasing up to the certain number of orifices and then after it remains constant. The solids outlet temperature is proportional to the drying rate. Hence the maximum drying rate can be achieved at particular number of orifices that is 190 in the present study. It may vary based on the fluidized bed dimensions and the orifice diameter.

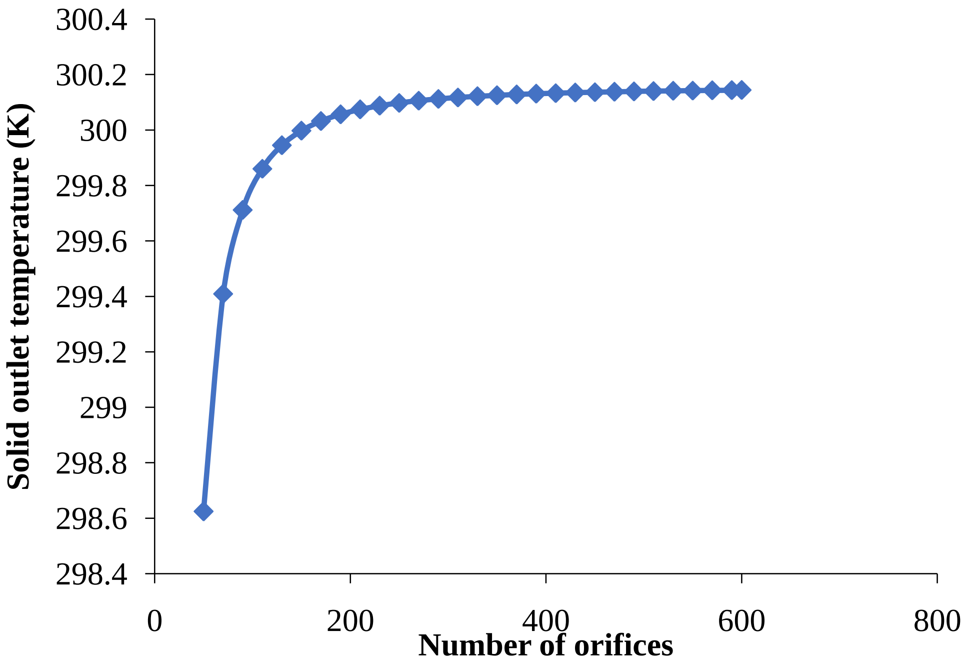


Figure 4. 55 Solid outlet temperature at different number of orifices
(Initial moisture content-10%, solid flow rate -10 kg/h, air flow rate-50 kg/h, air inlet temperature 303 K)

4.6.1.3 Effect of air inlet temperature

Simulations were conducted at different gas inlet temperatures ranging from 303 to 353 K with an interval of 5 K using the fluidized bed dryer model of ASPEN PLUS (Appendix-Data G). Results of solids outlet temperature and outlet moisture content at different air inlet temperatures have been reported in Figs 4.47 and 4.48. From Fig 4.56 it can be observed that with the increase in air inlet temperature the solids outlet temperature increases, hence the drying rate also increases. In the present simulation, it is noticed that the minimum solids outlet moisture content is obtained as 1.5% corresponding to the gas stream temperature of 353 K as seen from Fig 4.57.

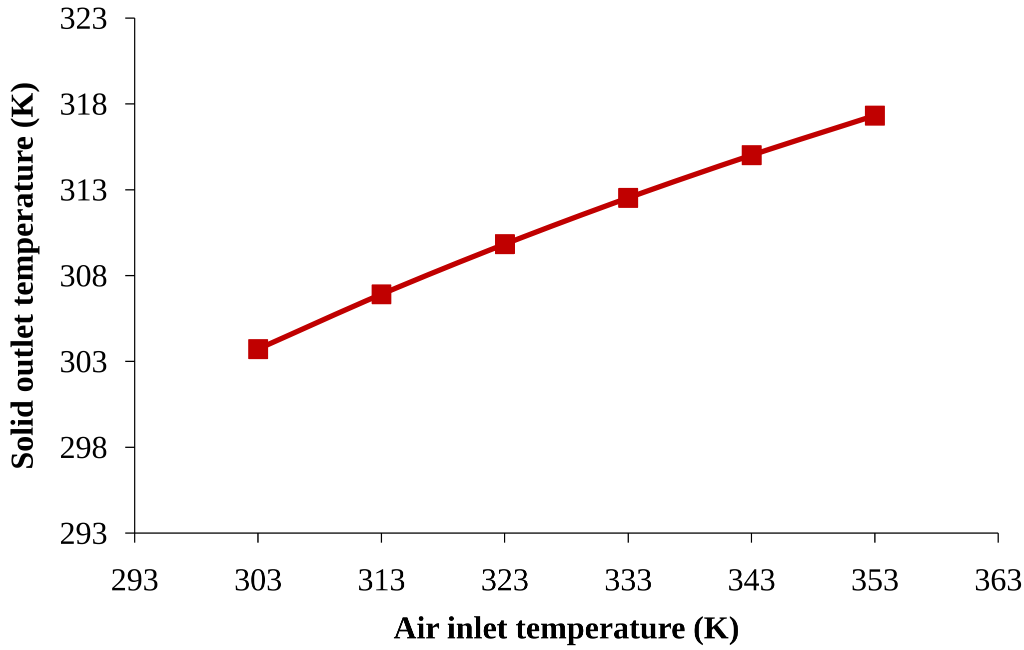


Figure 4. 56 Effect of air inlet temperature on solid outlet temperature
(Initial moisture content-10%, solid flow rate -10 kg/h, air flow rate-50 kg/h)

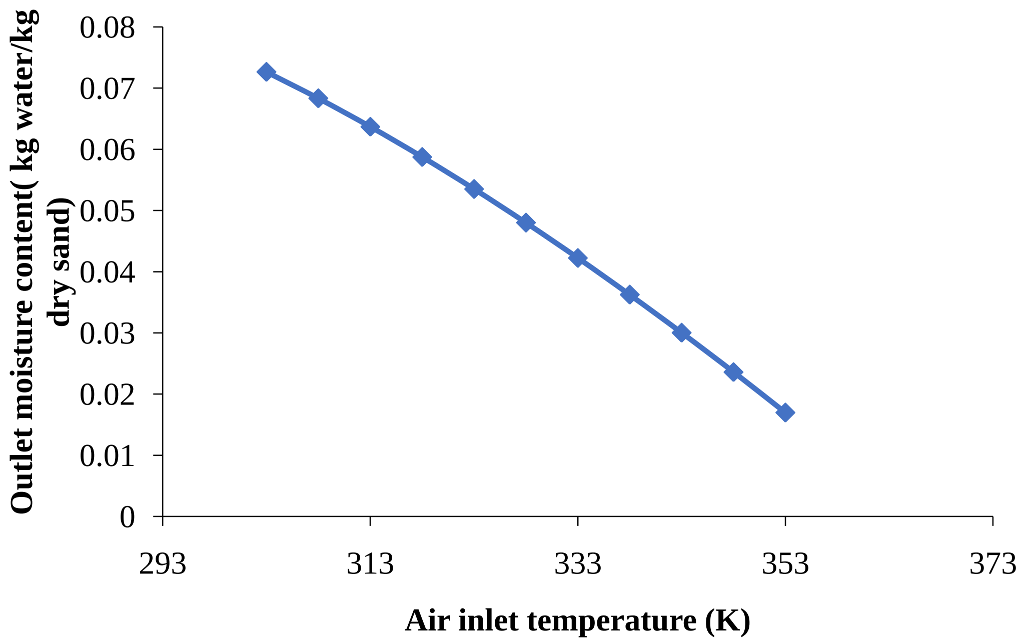


Figure 4. 57 Effect of air inlet temperature on outlet moisture content

(Initial moisture content-10%, solid flow rate -10 kg/h, air flow rate-50 kg/h)

4.6.1.4 Comparison with literature reports

Amer (2006) studied on air distributor influence on heat transfer in the fluidized bed. From their study, it has understood that the heat transfer coefficient of bed increased with increasing opening area of distributor plate in the fluidized bed. Ouyang and Levenspiel (1986) have studied with using the spiral distributor to know the effect of opening area of the distributor in a fluidized bed and from their results, it is found that the heat transfer coefficient increases with increasing opening area of spiral distributor. The simulation and experimental results in the present study also showed similar trend as seen from literature. Here the results from simulation and experimental study show that the solid outlet temperature increased with increasing opening area of distributor due to heat transfer between solid and gas which increased with increasing opening area. and reached maximum at particular opening area and orifice diameter of the distributor plate. In the present study, the heat transfer coefficient is calculated at this condition of distributor using Equation 4.4.1 (Ouyang and Levenspiel, 1986). From the simulation results, it can be observed that the maximum heat transfer coefficient is 533.5 W/m^2.K in steady state fluidized bed dryer. From the experimental results, the heat transfer coefficient is found to be 503.8 W/m^2.K in continuous fluidized bed dryer.

$$h = \frac{m_a c_p (T_{aout} - T_{ain})}{A(T_{sout} - T_{aout})} \qquad (4.4.1)$$

Here h = heat transfer coefficient, A = heat transfer area

Sutar and Sahoo (2011) presented in their results that the drying behavior increased with increasing size of orifices of distributor plate in batch fluidized bed drying. The results from the present study also show similar trend. The drying rate of solids increased with increasing orifices size and number of orifices in continuous fluidized bed dryer and after attaining particular condition, further increase did not affect much.

4.7 Aspen simulation studies on Continuous hot air multistage fluidized bed dryer

4.7.1 Exergy loss

4.7.1.1 Exergy loss of MFBD with change of air temperature

Simulation studies were conducted to examine the air temperature influence on exergy loss of continuous multistage fluidized bed model by varying air temperature from 313 to 353 K with an increment of 5 K at constant flow rate of air as 50 kg/h and solids flow rate as 10 kg/h with initial moisture content of the material as 10% (Appendix- Data H). It can be observed from Fig 4.58, that the exergy loss has increased with an increase in air temperature in the multistage fluidized dryer. Increasing air inlet temperature increases the exergy loss of multistage dryer because higher air temperatures result in higher exergy inflow and exergy utilization also increases for the evaporation of solids moisture in the multistage dryer.

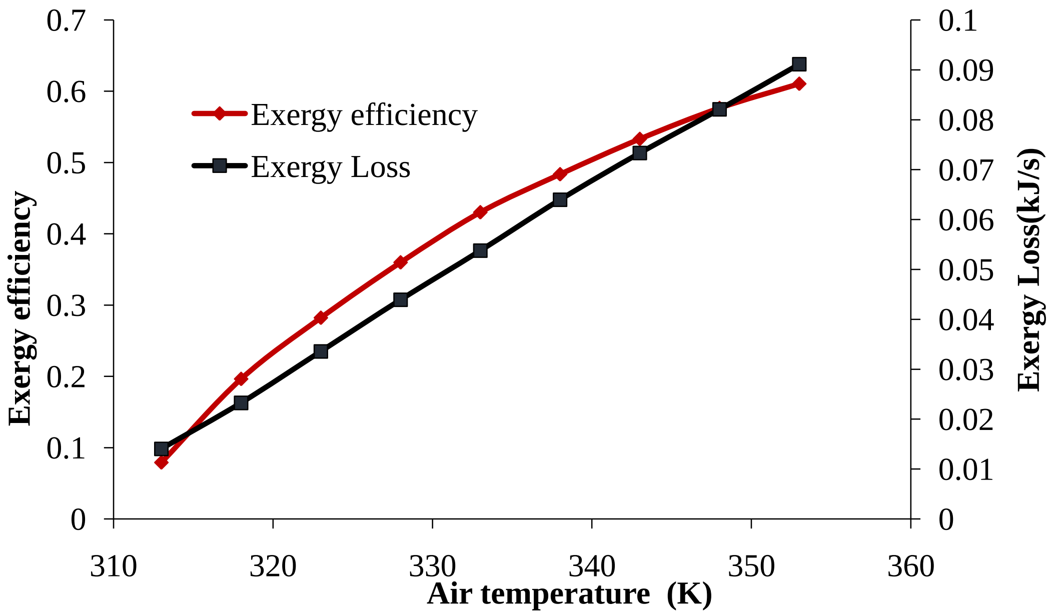


Figure 4. 58 Profiles of exergy loss and exergy efficiency with inlet air temperatures (Air flow rate- 50 kg/h, S_F-10 kg/h, IMC-10%)

4.7.1.2 Exergy loss of MFBD with change in air flow rate

Simulations studies were conducted to examine the air flow rate influence on exergy loss of continuous multistage fluidized bed model by varying mass flow rate of air from 35 to 80 kg/h with an increment of 5 kg/h. It can be observed from Fig 4.59, that the exergy loss increased with an increase in mass flow rate of air of multistage fluidized bed dryer. The exergy loss profiles have shown similar trends as reported in the literature. it has been noticed from Karaguzel et al. (2012) study, that the exergy loss showed increment from 0.002 to 0.013 kJ/s with the change in air temperature from 308 to 333 K at air velocity of 5.4 m/s in hot air fluidized bed dryer during bean drying. Similar trends were noticed in Azadbakht et al. (2017) study, that the exergy loss increased with increasing temperature of air from 318 to 328 K of batch fluidized bed dryer. The simulation results on exergy loss of continuous multistage dryer with increase in mass flow rate of air were reported by Akpinar (2007) study, where it has been observed that the exergy loss increased from 0.1 to 0.7 kJ/s with increasing velocity of air from 0.5 to 1.5 m/s and temperature of air from 318 to 328 in cyclone type dryer In this study, it has been found that the exergy loss showed increment from 0.014 to 0.091 kJ/s with increase in temperature of air from 313 to 353 K and increased from 0.03 to 0.0369 kJ/s when the air flow rate was increased from 40 to 80 kg/h for multistage fluidized bed dryer.

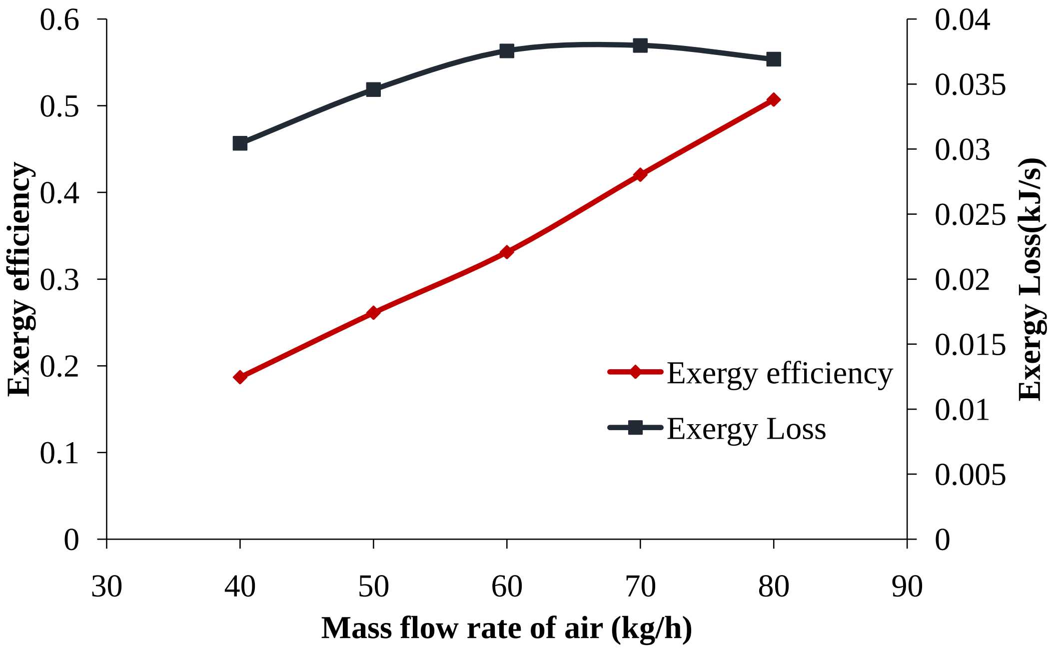


Figure 4. 59 Profiles of exergy loss and exergy efficiency with mass flow rates of air (T_{ain} - 323 K, S_F-10 kg/h, IMC-10%)

4.7.1.3 Exergy loss of MFBD with change in solids flow rate

Simulation studies were also conducted to determine the solids flow rate influence on exergy loss of continuous multistage fluidized bed model by varying flow rate of solids from 6.7 to

12.5 kg/h. It can be seen from Fig 4.60 that the exergy loss showed the increasing trend with increase in the flow rate of solids of multistage fluidized dryer. The increment of solids flow rate increases the solids holdup in the dryer which leads to more exergy loss. With the increase of solids holdup in the dryer, the bed moisture increases (subjected to drying) and outlet air temperatures of the dryer decreases. The increase in solids holdup increases the supplied exergy utilization for multistage drying and the minimal amount of exergy was obtained from the air at outlets of the dryer.

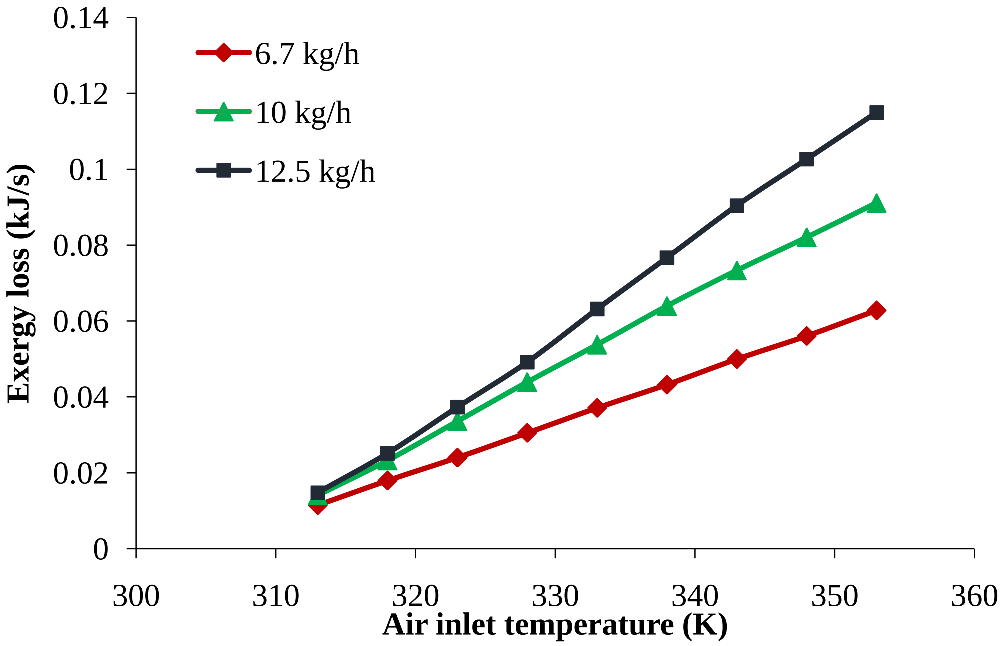


Figure 4. 60 Exergy loss profiles of MFBD at different solids flow rates (Air flow rate- 50 kg/h, IMC-10%)

4.7.1.4 Exergy loss of MFBD with change of feed moisture percentage

Simulation studies were conducted to examine the feed moisture influence on exergy loss of dryer by varying solids inlet moisture from 7.5% to 12.5% of the multistage fluidized bed dryer. It can be noticed from Fig 4.61, that the exergy loss increased with an increase in initial moisture content of solids of multistage fluidized dryer. The feed moisture increased which increases the amount of moisture subjected to drying and which decreases outlet air temperature of the dryer.

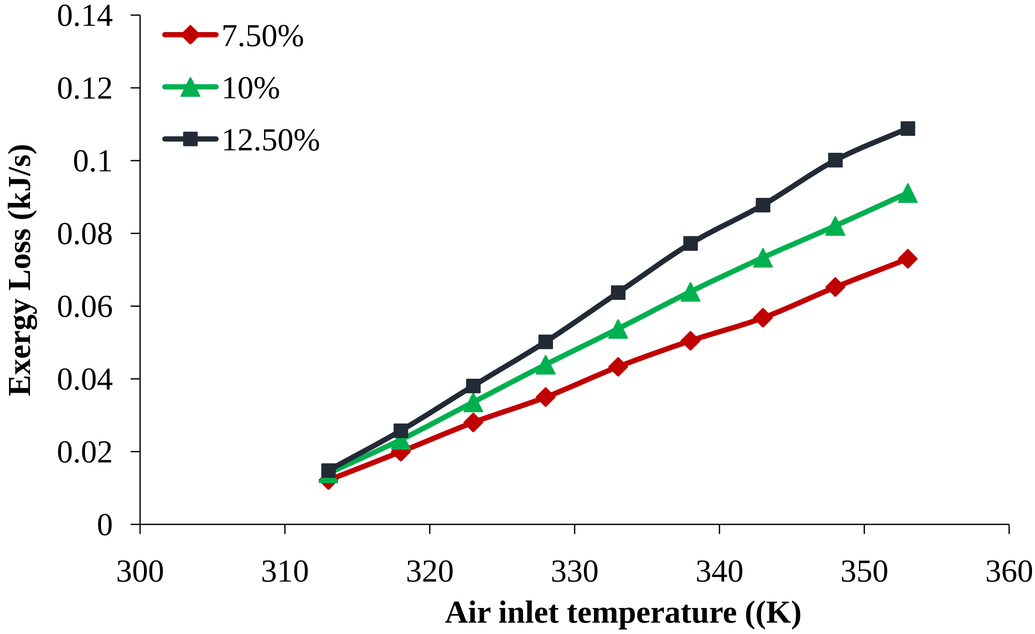


Figure 4. 61 Exergy loss profiles of MFBD at different feed moistures
(Air flow rate- 50 kg/h, S_F-10 kg/h)

In the study of Nazghelichi el al. (2010), it has been reported that the increment of exergy loss was from 0.2 to 0.8 kJ/s with increase in bed depth of carrot cubes from 3 to 9 cm in batch fluidized bed dryer. The influence of initial moisture content on exergy loss showed agreement with Akpinar (2007) results, that the more exergy loss of dryer was found at high solid moisture content. In this study, the exergy loss obtained is in the range of 0.0629 to 0.114 kJ/s for solids flow rate range of 6.7 to 12.5 kg/h and the exergy loss is in the range of 0.0741 to 0.108 kJ/s with the increase in initial moisture content from 7.5 to 12.5 % for multistage fluidized bed dryer.

4.7.2 Exergy efficiency

4.7.2.1 Exergy efficiency of MFBD with change in air temperature

Simulation studies were made to examine the influence of temperature of inlet air on multistage fluidized bed dryer model exergy efficiency by varying it from 313 to 353 K with an increment of 5 K at constant flow rate of air as 50 kg/h with feed moisture of 10% at 10 kg/h solids flow rate. It can be perceived from Fig 4.58, that the exergy efficiency showed increment with increasing air inlet temperature of multistage fluidized dryers.

4.7.2.2 Exergy efficiency of MFBD with change in air flow rate

Simulation studies were executed to examine the influence of the mass flow rate of air on exergy efficiency of the continuous multistage fluidized bed dryer by varying mass flow rate of air from 40 to 80 kg/h. It can be seen from Fig 4.59, that the exergy efficiency showed increment with increasing mass flow rate of air of the multistage fluidized bed dryer.

Exergy results obtained from simulation studies have shown trends similar to Nikbakht (2014) and Darvishi (2018) studies. From Nikbakht (2014), it has been seen that the increment in exergy efficiency of pomegranate arils was from 0.44 to 0.83 with the increase in temperature of the air from 50 to 343 K and velocity of air from 0.5 to 1.5 m/s in microwave treatment. From Darvishi (2018) study, it is noticed that the exergy efficiency of fluidized bed dryer showed increment with increasing velocity of air and temperature of air. In this study, the exergy efficiency of multistage fluidized bed dryer showed increment from 0.07 to 0.61 with increase temperature of air from 313 to 353 k and showed increment from 0.18 to 0.50 with increasing flow rate of air from 40 to 80 kg/h.

4.7.2.3 Exergy efficiency of MFBD with change in solids flow rate

The simulation studies to examine solids flow rate influence on exergy efficiency for continuous multistage fluidized bed dryer has been made by maintaining the flow rate in the range of 6.7 to 12.5 kg/h. The results shown in Fig 4.62 indicate that the exergy efficiency showed decrement with increasing the solids flow rate of the multistage fluidized dryer, because the increase in solids holdup decreases the exergy efficiency due to high exergy loss which occurs at higher beds (from section 4.5.2.3). It was observed from Nazghelichi et al. (2010) results that the batch fluidized bed dryer exergy efficiency showed decrement from 0.75 to 0.5 with the increase in carrot cubes bed height from 3 to 9 cm. Also, Azadbakht et al. (2017) showed similar trends as seen in this study with the change of bed heights in batch fluidized bed dryer. In this study, the exergy efficiency decreased from 0.73 to 0.50 with an increase in solids flow rate from 6.7 to 12.5 kg/h.

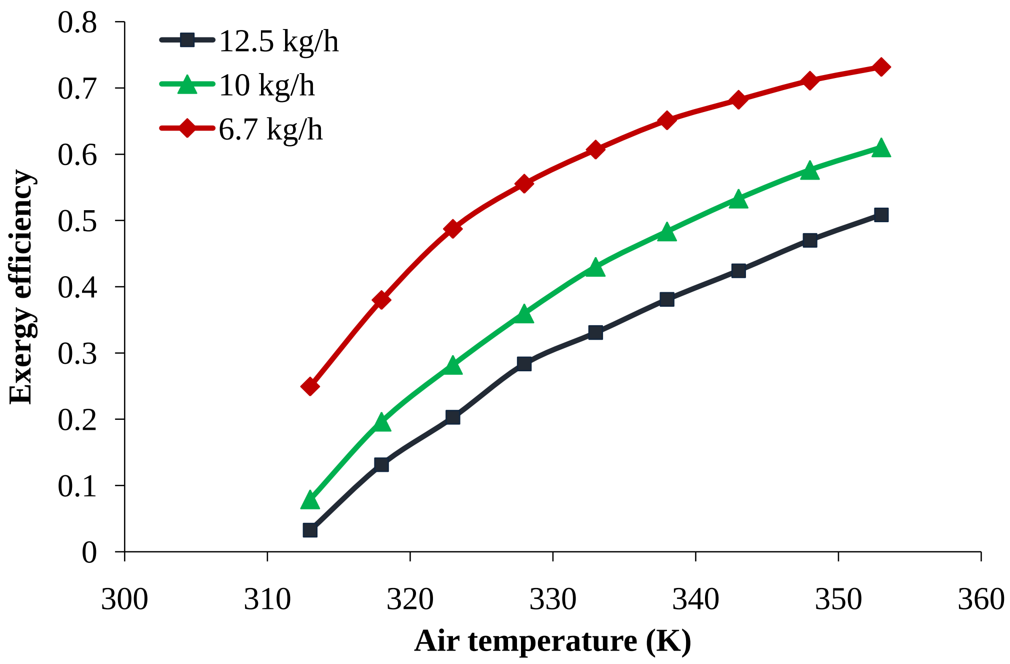


Figure 4. 62 Exergy efficiency of MFBD at different solids flow rates (Air flow rate- 50 kg/h, IMC-10%)

4.7.2.4 Exergy efficiency of MFBD with change in feed moisture percentage

Simulation studies were conducted to examine the feed moisture influence on multistage dryer exergy efficiency by changing the solids inlet moisture from the 7.5% to 12.5% of multistage fluidized bed dryer. It can be observed from Fig 4.63 that the exergy efficiency of dryer showed decrement with increasing initial moisture content of solids. From the results of simulation studies, it is seen that exergy efficiency decreased from 0.68 to 0.53 with the increase in initial moisture content from 7.5 to 12.5% in multistage fluidized bed dryer.

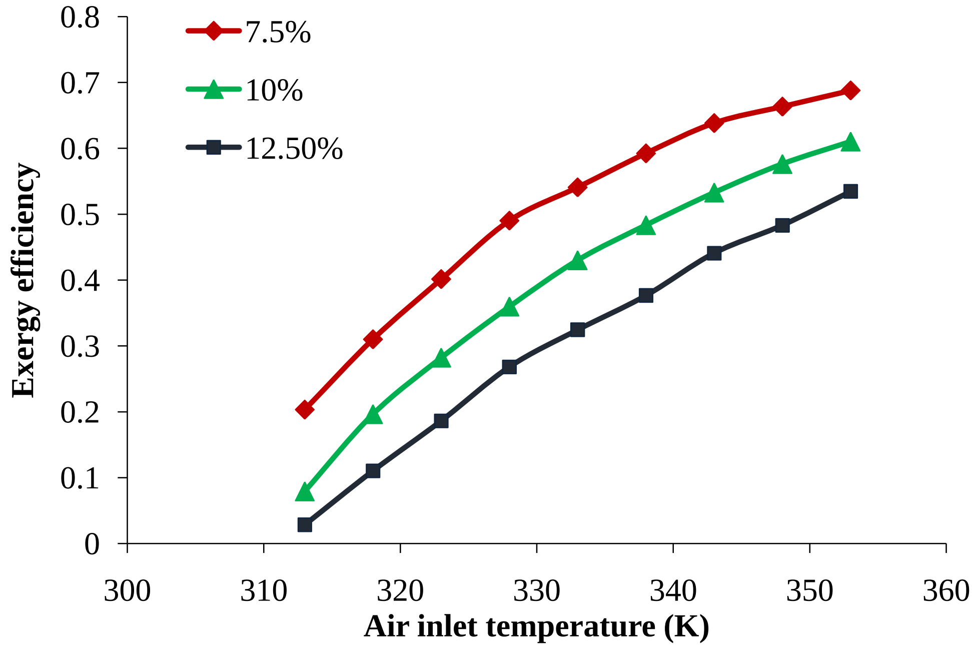


Figure 4. 63 Exergy efficiency of MFBD at different feed moistures

(Air flow rate- 50 kg/h, S_F-10 kg/h, Multistage- Four stages)

4.7.3 Comparison with Single stage fluidized bed dryer

Simulations were carried out with single stage fluidized bed dryer for comparison with multistage dryer varying air flow rate from 40 to 80 kg/h with an increment of 10 kg/h and keeping air temperature as 353 K, feed moisture at 10% and using solids flow rate of 10 kg/h. From Fig 4.64, it can be observed that the exergy losses are high in the multistage dryer than single stage dryer. From the results, it can also be seen that the exergy loss of multistage dryer does not show much variation with the increase in air flow rate compared to that for a single stage fluidized bed dryer. From Fig 4.65, it can be noticed that the exergy efficiency of the multistage dryer is higher than that for single stage.

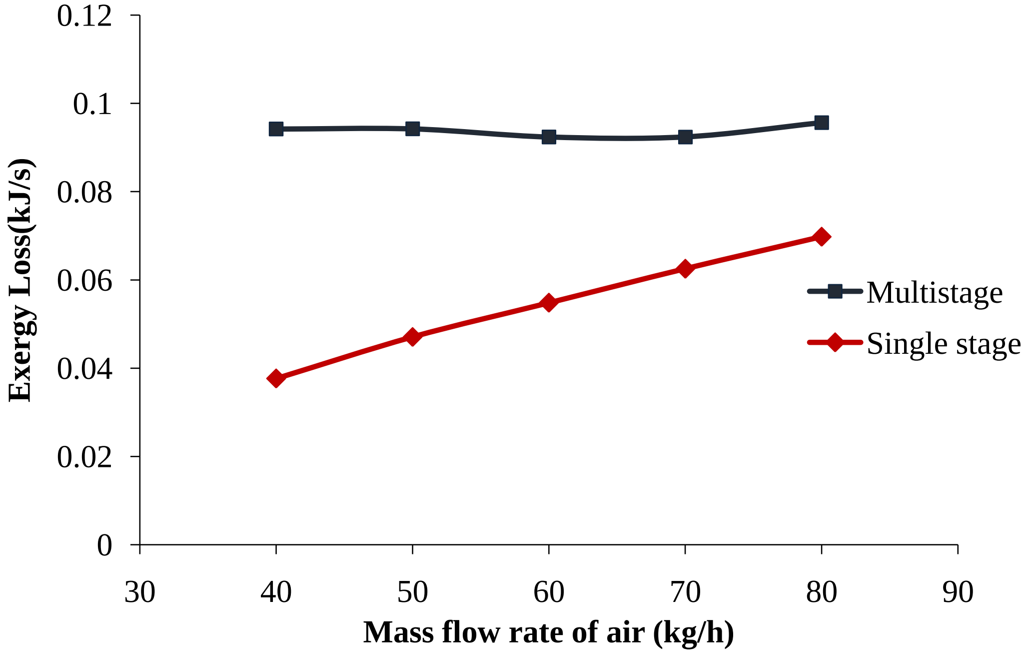


Figure 4. 64 Comparison of MFBD exergy loss profiles with single stage at different air flow rates (T_{ain}- 353 K, S_F-10 kg/h, IMC-10%, Multistage- Four stages)

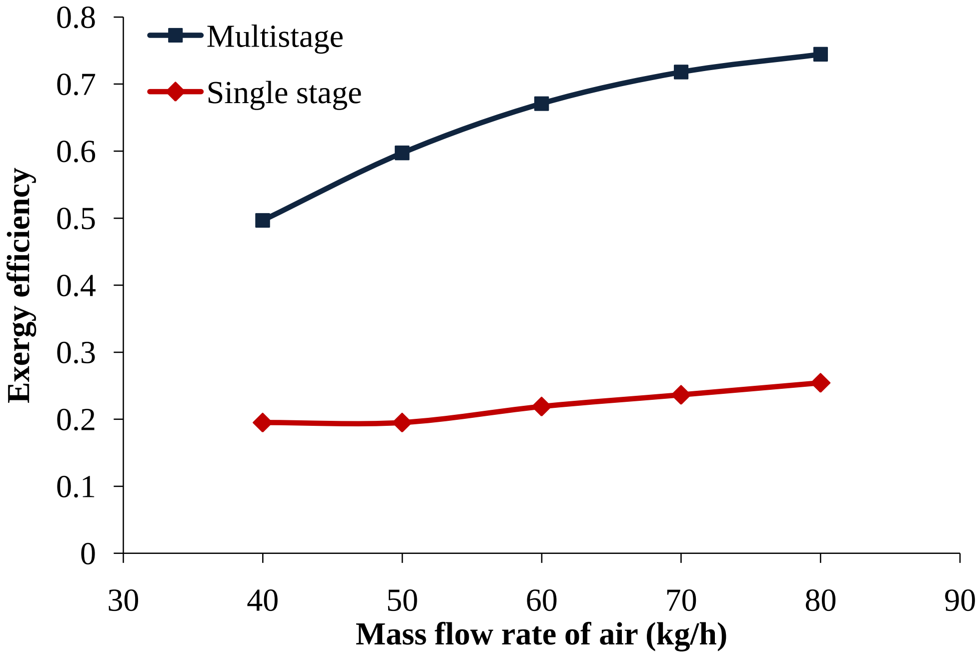


Figure 4. 65 Comparison of MFBD exergy efficiency profiles with single stage at different air flow rates

(T_{ain} - 353 K, S_F-10 kg/h, IMC-10%, Multistage- Four stages)

4.7.4 Comparison with experimental results

The experimental results have shown similar trend with simulation results (Appendix- Data I). Fig 4.66 shows the variation of the equilibrium moisture content of solids with air temperature, which shows the similar trends for both simulation and experimental studies. In the experimental study, it has noticed that the influence of air temperature at higher values of temperature on moisture content is less compared to that at lower temperatures. The similar trend is noticed in the simulation study also, where it is found that the increase in air temperature at higher temperatures does not alter the moisture content. From Figs 4.67 and 4.68, it can be noticed that the exergy loss and exergy efficiency profiles show similar trends with simulation results.

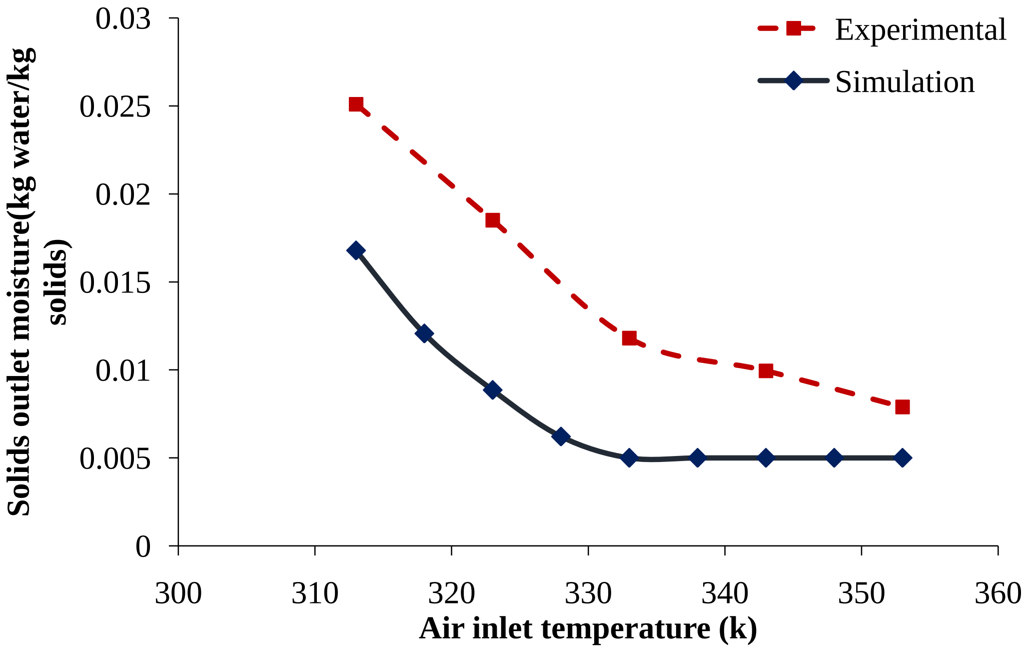


Figure 4. 66 Comparison of simulation and experimental solids outlet moisture of MFBD (Air flow rate- 50 kg/h, S_F-10 kg/h, IMC-10%)

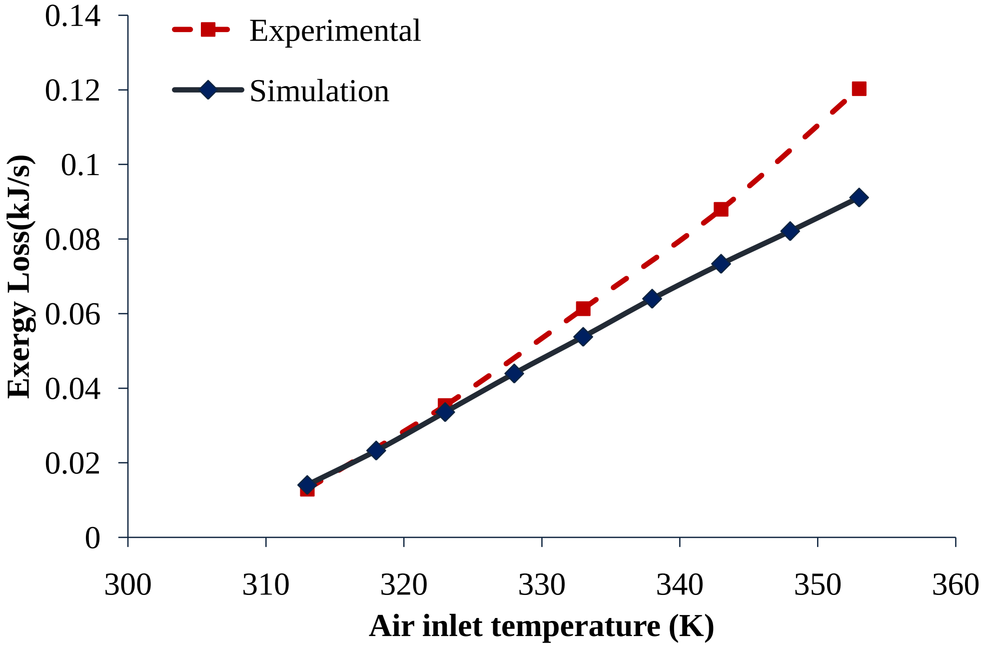


Figure 4. 67 Comparison of simulation with experimental exergy loss of MFBD (Air flow rate- 50 kg/h, S_F-10 kg/h, IMC-10%)

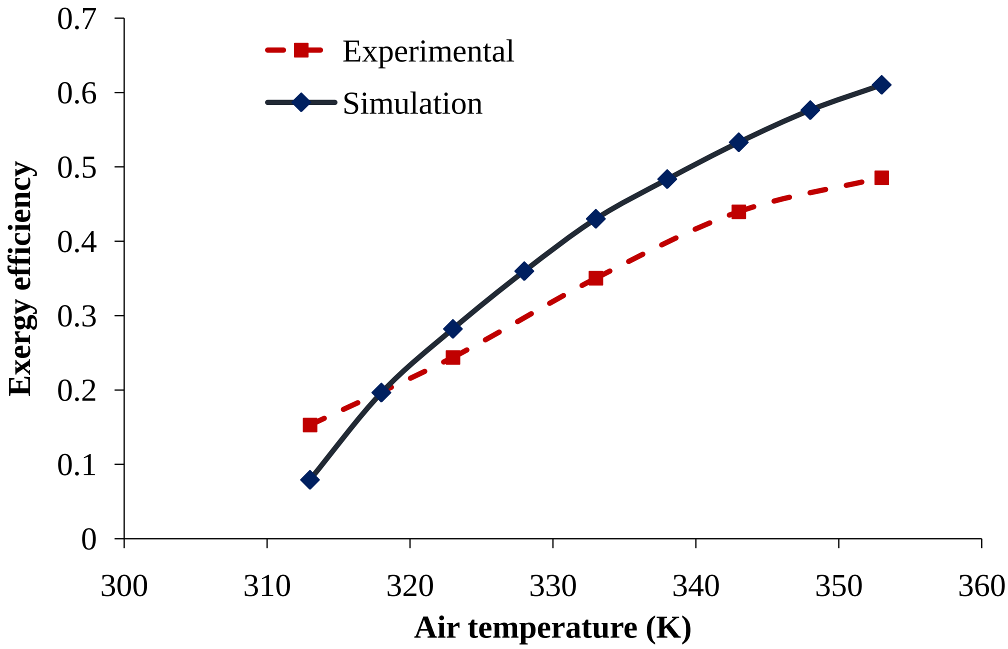


Figure 4. 68 Comparison of simulation with experimental exergy efficiency of MFBD (Air flow rate- 50 kg/h, S_F-10 kg/h, IMC-10%)

4.8 Comparison of results with literature reports

The comparison of findings of present work with literature report were given in the tables presented in Appendix-II of the thesis. In tables, the critical findings of each objective were reported with their independent, dependent variables and with supported literature.

Also the comparison is given in Table A2, from the literature finding it was observed that the most efficient independent parameters are temperature and velocity on exergy efficiency. In this study also it was proved that the wall temperature affects exergy efficiency of dryer. The present reports showed that in batch wall heated fluidized bed Kodo millet drying, best exergy efficiency was 72% at (Tw-333K, V-1.3 m/s,H-4 cm,IMC-10%) and 75% at (Tw-323K, V-1.7 m/s,H-4 cm,IMC-10%) and for Fenugreek seeds drying 71% at (Tw-333K, V-1.3 m/s,H-4 cm,IMC-10%) and 74% at (Tw-323K, V-1.7 m/s,H-4 cm,IMC-10%). Similarly in multistage fluidized bed dryer also it showed best exergy efficiency as 64% at wall temperature of 328K among the all parameters.

While earlier reports were made using hot air fluidized bed dryers, the present study involves use of wall heated bed dryer where the operation can be done at minimal temperatures. Also there are no reports on exergy analysis of drying of millets.

The final or equilibrium moisture content is important for millet preservation. Various studies shown in Table A1 indicate the influence of independent variables on reduction of moisture content. Maintaining lower moisture is preferable for millet preservation. In food drying methods, the temperature affect plays a major role in moisture removal, but low temperatures are preferable for drying to avoid the property changes of millets. Literature shows that the major independent variables that affect drying are velocity and air temperature. In the present study, the independent variables are wall temperature and air velocity which play a major role in moisture reduction and these drying results showed better performance compared to literature reports. Hence wall heating, multistage drying methods met the conventional drying standards and gave higher moisture removal at lower temperatures. The literature simulation reports compared with present simulation results in Appendix II Table A3.

CHAPTER 5: CONCLUSIONS AND SCOPE OF FUTURE WORK

5.1 Conclusions

Experiments have been performed to investigate the drying behavior of food materials using batch and continuous multistage fluidized bed dryers. Exergy and energy analyses were conducted on dryers to analyze thermal efficiency of dryers. Simulation and experiments were carried out to determine the effect of the distributor on continuous fluidized bed dryer performance and to study the exergy aspects of continuous multistage fluidized bed dryer. Following are the conclusions drawn from the study.

From the Batch wall heated fluidized bed drying results, the drying rates of Kodo millet and Fenugreek seeds increased with an increase in wall temperature (313 to 333 K), air velocity (1.01 to 1.7 m/s) and decreased with an increase in bed height (3 to 5 cm), initial moisture content (10 to 20% db). Energy utilization ratio, exergy loss and exergy efficiency of both materials Kodo millet and Fenugreek seeds were reported. From the results, it can be noticed that

Kodo millet drying:

- The energy utilization ratio of kodo millet drying has increased from 0.68 to 0.82, 0.6 to 0.9, 0.68 to 0.85 and 0.79 to 0.92 with an increase in wall temperature, air velocity, bed height, initial moisture content .
- The exergy loss has increased from 0.0018 to 0.0038 kJ/s, 0.002 to 0.004 kJ/s and 0.002 to 0.0041 kJ/s with increasing wall temperature, bed height and initial moisture content and decreased 0.0035 to 0.002 kJ/s with increasing air velocity.
- The exergy efficiency increased from 0.58 to 0.72, 0.61 to 0.75 with increasing wall temperature, air velocity and 0.78 to 0.57, 0.68 to 0.54 decreased with increasing bed height and initial moisture content.

Fenugreek seeds drying:

- The energy utilization ratio of Fenugreek seeds drying has increased from 0.6 to 0.72, 0.59 to 0.78, 0.55 to 0.8 and 0.65 to 0.75 with an increase in wall temperature, air velocity, bed height, initial moisture content .

- The exergy loss has increased from 0.002 to 0.004 kJ/s, 0.002 to 0.0038 kJ/s and 0.002 to 0.0041 kJ/s with increasing wall temperature, bed height and initial moisture content and decreased 0.0038 to 0.0021 kJ/s with increasing air velocity.
- The exergy efficiency increased from 0.58 to 0.72, 0.61 to 0.75 with increasing wall temperature, air velocity and 0.78 to 0.57, 0.68 to 0.54 decreased with increasing bed height and initial moisture content.

From the results, the energy utilization ratio and exergy losses decreased with drying time and exergy efficiency increased with drying time. The highest exergy efficiency has been found to be around 0.75 and 0.74 in batch wall heated fluidized bed drying of Kodo millet and Fenugreek seeds respectively.

The multistage drying results were reported by stagewise and comparisons were made with single and multistage fluidized bed dryers with changing parameters. From the results, the 0influence of wall temperature (313 to 328 K), air flow rate (1.01 to 1.3 m/s), bed height (50 to 70 mm) on drying rate of pearl millet in multistage fluidized bed dryer is similar to that of batch wall heated fluidized bed dryer and the drying rate of solids decreased with increase in downcomer height and solids flow rate in both single and multistage dryer.

- The drying rate of solids and bed temperature were found to be higher in a multistage dryer.
- The drying rate increased with increase in the number of stages and equilibrium moisture content reduced with an increase in the number of stages of the fluidized bed.
- From the study, Kodo millet showed better drying rates than Fenugreek seeds in batch process. In multistage drying the Barnyard millet showed better drying rates than Pearl millet.

The experimental results were validated for various models by minimizing errors and model parameters were reported with R^2 (regression coefficient) and RMSE (root mean square errors) values. Diffusion equation was used to model the drying kinetics of the bed material in a multistage fluidized bed dryer. Effective diffusivities of solids were estimated and reported. Effective diffusivities were found to increase from 0.64×10^{-9} to 1.59×10^{-9} m^2/s with an increase in the number of stages in the dryer. Effective diffusivity increased with increase in wall temperature and air velocity and also it was found to be higher for lower downcomer height and lower solid flow rates. The activation energies were found to be 17.56 kJ/mol and 24.34 kJ/mol for single and multistage fluidized bed dryers respectively.

To study the exergy and energy analyses of wall heated continuous multistage fluidized bed drying, the experiments were performed with Barnyard millet grains. From the experimental results, it was noticed that the influence of wall temperature (313 to 328 K) and air velocity (1.01 to 1.3 m/s) on energy utilization ratio, exergy loss and exergy efficiency of multistage fluidized bed dryer is similar to that of batch wall heated fluidized bed dryer.

- The EUR values at steady state have increased from 0.36 to 0.46 with an increment of wall temperature (313 to 328 K), from 0.36 to 0.43 with increasing air velocity (1.01 to 1.3 m/s), from 0.36 to 0.41 with an influence of downcomer height (from 50 to 70) and showed increment from 0.25 to 0.41 by increment of solids flow rate (5 to 10 kg/h) for Barnyard millet grains in continuous multistage fluidized bed dryer.
- The exergy loss of multistage dryer at steady state increased from 0.009 to 0.014 kJ/s with an increment of wall temperatures, increased from 0.009 to 0.010 kJ/s with increase in downcomer height, increased from 0.0082 to 0.0103 kJ/s with an increment of solids flow rate, showed decrement from 0.0090 to 0.0059 kJ/s with increasing air velocity for Barnyard millet grains drying.
- The present study shows increment in exergy efficiency of MFBD from 0.45 to 0.64, 0.45 to 0.72 with increasing wall temperatures, air velocity and found to be decreasing from 0.45 to 0.38, 0.5 to 0.371 with increasing height of solids flow rate.
- The highest exergy efficiency of multistage fluidized bed drying of Barnyard millet grains was found as 0.64 (ie., 64%) at steady state from the results.
- It has been noticed that higher exergy loss was due to heat input of each stage and simultaneously exergy efficiency increased due to high drying phenomena. The multistage fluidized bed drying of feed materials showed better drying performance with good exergetic efficiency.
- The EUR and Exergy efficiency values have been found to be increasing (0.30 to 0.70) with increase in number of stages (one to four) in dryer.

In a continuous fluidized bed dryer, the influence of various parameters such as orifice diameter, number of orifices and the opening area of the distributor plate on the performance of fluidized bed dryer have been studied through simulation and experimentation. If the orifice diameter is very small clogging may happen and if the orifice diameter is the large uneven distribution of the gas stream in the fluidization can result in the fluidized bed. From literature, we can see that the solid temperature in bed is directly proportional to drying behavior. It can be observed from experimental results that with the increase in orifice diameter up to 5 mm and number orifices of the distributor plate up to 60, the solid outlet temperature increases, then after with further increase in the orifice diameter and number of orifices the change in the solid outlet temperature observed was little. The same trend has been observed from simulation results also. With an increase in the orifice diameter and the number of orifices, i.e. with an increase in the opening area of the distributor plate, drying rate increases due to increase in gas to solid contact and with further increase the change in the drying rate observed is small (upto 22% opening area).

The simulation runs for exergy study of multistage fluidized bed dryer using Aspen Plus has been executed and results were reported.

From the simulation study of multistage fluidized bed dryer,

- Exergy loss showed increment from 0.014 to 0.091 kJ/s with increase in temperature of air from 313 to 353 K and increased from 0.03 to 0.0369 kJ/s and increase when the air flow rate was increased from 40 to 80 kg/h, increased in 0.0629 to 0.114 kJ/s, 0.0741 to 0.108 kJ/s for solids flow rate range of 6.7 to 12.5 kg/h and initial moisture content from 7.5 to 12.5 % increment for multistage fluidized bed dryer.
- The exergy efficiency of multistage fluidized bed dryer showed increment from 0.07 to 0.61, 0.18 to 0.50 with increase air temperature and with air flow rate and decreased from 0.73 to 0.50, 0.68 to 0.53 with the increase in solids flow rate and feed moisture content.
- The exergy loss and exergy efficiency of the multistage fluidized dryer are higher than single stage fluidized dryer.
- The simulation results showed similar trends with experimental results of multistage fluidized bed dryer.

5.2 Contributions

This thesis contributes to the area experimental and simulation of fluidized bed drying. Specially, it gives the information of new drying techniques in the field of grain drying. The studies related to exergy and energy analysis give the information of work potential assessment of drying systems.

The principle contribution of this thesis

- The drying studies were conducted on Kodo millet, Pearl millet, Barnyard millet grains and Fenugreeks in single and multistage fluidized bed dryers. This helps the maintain quality of product with long term usage.
- Effective diffusivity studies of millets give information for parameter effect on diffusion and this information helps to design appropriate dryer for grains.
- The exergy analysis of batch wall heated fluidized bed dryer and multistage fluidized bed dryer help to find the performance and wastage of energy in a drying system. This study helps for energy study importance for the drying system like wall heating and multistage drying.
- The distributor study gives the information of how the air flow distribution affects drying of wet solids in fluidized bed dryer and it helps in the design with appropriate flow condition for dryer.
- The simulation study of multistage fluidized drying gives the information of new drying techniques and also helps the practical feasibility for designing a appropriate dryer.

5.3 Limitations

The limitations of batch wall heated fluidized bed drying and multistage fluidized bed drying are

- The experiments should be conducted above minimum fluidization velocity and below the terminal velocity for better solids fluidization.
- In continuous operation, due to particle agglomeration, solids stuck in hopper at higher solids flow rate.
- The wall temperature should be maintained based on bed materials used to avoid the material property damage.

5.4 Recommendations

- In pharmaceutical industry, Drying is still one of the important operations because of the issue of providing high quality assurance. It is also needed to improve product efficiency and for increasing the applications, simulation studies help to acquire the results and for designing of the equipment. It is also needed to study the drying behavior of pharmaceutical products of multistage fluidized bed dryer with exergy analysis using CFD simulations.
- To study the dryer with recycling of dehumidified exhaust air from one stage outlet to another stage inlet in multistage fluidized bed dryer. It helps to improve the energy efficiency by heat transfer from exhaust air passages.
- The present challenge is reducing energy usage from non renewable sources and hence, increase the renewable energy usage is needed. Study with solar assisted continuous multistage fluidized bed dryer can also be made for higher efficiency with minimal energy consumption.

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Nomenclature

c_{pa}	specific heat of air (kJ/kg.K)
m_a	mass flow rate of air (kg/h)
m_w	evaporation rate of moisture (kg/s)
r	radius of particle (m)
t	time (s)
w_t	weight of sample at time (kg)
w_d	dry sample weight (kg)
η_{Ex}	exergy efficiency
A	area of fluidized bed (m^2)
D_{eff}	effective diffusivity (m^2/s)
D_{eff}	pre exponential factor (m^2/s)
E_a	activation energy(kJ/mol)
E_{out}	energy utilization of dryer (kJ/s)
E_{in}	energy input of dryer (kJ/s)
E_{mwout}	energy utilization of wall heated MFBD (kJ/s)
E_{mwin}	energy input of wall heated MFBD (kJ/s)
Ex_{ain}	exergy of inlet air (kJ/s)
Ex_{aout}	exergy of outlet air (kJ/s)
Ex_w	exergy rate of wall heater (kJ/s)
Ex_{din}	total exergy inflow of the dryer(kJ/s)
Ex_L	exergy loss of dryer (kJ/s)
Ex_{mwin}	total exergy inflow of the wall heated MFBD (kJ/s)
Ex_{mwout}	total exergy outflow of the wall heated MFBD (kJ/s)
Ex_{mwLoss}	exergy loss of the wall heated MFBD (kJ/s)
η_{Exmw}	exergy efficiency of wall heated MFBD
η_{mhEx}	exergy efficiency of hot air MFBD
Ex_{mhi}	exergy inflow of hot air multistage dryer(kJ/s)
Ex_{mho}	exergy out flow of hot air multistage dryer (kJ/s)
Ex_{mhL}	exergy loss of the hot air multistage dryer (kJ/s)
MFBD	multistage fluidized bed dryer
H	Bed height (cm)

H_d	down comer height (mm)
EUR	energy utilization ratio
FBD	fluidized bed dryer
L_g	latent heat of vaporization (kJ/kg water)
MR	moisture ratio
M_i	initial moisture content
M_e	equilibrium moisture content
M_t	moisture content of solids with respect to time
R	gas constant (8.314 J/mol.K)
RH	Relative humidity
s_F	solids flow rate (kg/h)
T_{ain}	inlet air temperature (K)
T_{aout}	outlet air temperature (K)
T_{∞}	ambient temperature (K)
T_w	wall temperature (K)
T_{sin}	solids inlet temperature (K)
T_{sout}	solids outlet temperature (K)
Q_w	wall heat flux (kW/m^2)
V	velocity of air (m/s)
W_i	humidity ratio of inlet (kg water/kg dry air)
W_o	humidity ratio of outlet (kg water/kg dry air)

Subscripts

1	Corresponding to Stage-1
2	Corresponding to Stage-2
3	Corresponding to Stage-3
4	Corresponding to Stage-4
e	equilibrium
exp	experimental
i	initial
a	air
d	dry
Ex	exergy
F	flow rate

in	inlet/inflow
out	outlet/outflow
mw	wall heated multistage fluidized bed
mh	hot air multistage fluidized bed
pre	predicted
t	clock time (s)
w	wall

Appendix-I

Typical observation data

Data A. Batch wall heated fluidized bed dryer (Kodo millet drying)

T_w= 333 K,T_{ain} =298 K, %RH in= 25.8, IMC=10%, V=1.35 m/s, H=4 cm, E_{in}=0.125 kW, Ex_{din}=0.0131 kW, T_∞ =298 K

Time(s)	Moisture content	%RH	T_{aout}
30	0.0852	30.5	33.3
60	0.0738	27	34.9
90	0.0654	23.5	36.5
120	0.0585	21	37.2
150	0.0535	18.8	38.9
180	0.0491	17.3	40
210	0.0450	15.5	41
240	0.0415	14.4	41.6
270	0.0391	14	42
300	0.0369	13.1	43.3
330	0.0350	12.2	43.9
360	0.0335	11.4	44.9
390	0.0329	10.5	46
420	0.0324	10	47
450	0.0318	9.8	47.8
480	0.0312	9.5	48.2
510	0.0308	8.9	48.9
540	0.0301	8.4	49.3
570	0.0294	8.3	49.6
600	0.0289	8.1	49.9
630	0.0281	8	50.1
660	0.0275	7.9	50.5
690	0.0271	7.8	50.8
720	0.0270	7.8	50.8
750	0.0269	7.8	50.8
780	0.0269	7.8	50.8
810	0.0268	7.8	50.8

Data B. Batch wall heated fluidized bed dryer (Fenugreek seeds drying)

T_w= 333 K,T_{ain} =298 K, %RH (inlet of dryer) = 25.8, IMC=10%, V=1.35 m/s, H=4 cm, E_{in}=0.125 kW, Ex_{din}=0.0131 kW, T_∞ =298 K

Time(s)	Moisture content	%RH(outlet)	T_{aout}
30	0.0877	31.8	31.8
60	0.0765	28.5	33
90	0.0686	25.5	34.5
120	0.0623	23.4	35.4
150	0.0572	20.1	37.5
180	0.0529	18.7	38.8
210	0.0493	17	39.8
240	0.0462	14.9	41.8
270	0.0433	14	42.5
300	0.0409	12.9	43.4
330	0.0392	12.5	43.9
360	0.0381	12.1	44.4
390	0.0366	11.4	45.4
420	0.0356	11	45.8
450	0.0349	10.1	47.1
480	0.0341	10	47.3
510	0.0334	9.8	47.5
540	0.0325	8.9	48.8
570	0.0317	8.6	49.2
600	0.0310	8.4	49.8
630	0.0303	8.1	50.3
660	0.0295	8.1	50.3
690	0.0288	8	50.6
720	0.0284	8	50.6
750	0.0282	8	50.6
780	0.0281	8	50.6
810	0.0281	8	50.6

Data C. Continuous hot air single stage fluidized bed dryer

Particle dp - 1.35 mm (sand)

IMC-4%, Distributor opening area-3.4 to 40%, Solids flow rate- 10 kg/h, air flow rate- 40 kg/h, T_{ain}-323 K

Time(s)	Moisture content				
	3.4%	7.8%	14%	22%	40%
0	0.0380	0.0380	0.0380	0.0380	0.0380
30	0.0349	0.0344	0.0341	0.0337	0.0339
60	0.0323	0.0315	0.0310	0.0303	0.0305
90	0.0300	0.0292	0.0285	0.0277	0.0277
120	0.0280	0.0271	0.0265	0.0254	0.0254
150	0.0263	0.0253	0.0247	0.0237	0.0235
180	0.0248	0.0237	0.0232	0.0221	0.0218
210	0.0235	0.0224	0.0219	0.0207	0.0203
240	0.0223	0.0211	0.0207	0.0196	0.0190
270	0.0212	0.0201	0.0195	0.0184	0.0177
300	0.0202	0.0193	0.0185	0.0175	0.0166
330	0.0195	0.0185	0.0176	0.0166	0.0157
360	0.0188	0.0178	0.0168	0.0158	0.0148
390	0.0181	0.0171	0.0160	0.0151	0.0141
420	0.0175	0.0165	0.0153	0.0144	0.0135
450	0.0169	0.0159	0.0146	0.0137	0.0129
480	0.0163	0.0153	0.0140	0.0131	0.0125
510	0.0157	0.0147	0.0134	0.0125	0.0120
540	0.0152	0.0142	0.0128	0.0120	0.0116
570	0.0147	0.0136	0.0123	0.0114	0.0112
600	0.0142	0.0132	0.0118	0.0109	0.0109
630	0.0138	0.0127	0.0113	0.0104	0.0106
660	0.0133	0.0122	0.0109	0.0100	0.0103
690	0.0129	0.0118	0.0103	0.0096	0.0101
720	0.0125	0.0114	0.0099	0.0093	0.0097
750	0.0122	0.0110	0.0095	0.0090	0.0095
780	0.0118	0.0106	0.0091	0.0087	0.0092
810	0.0115	0.0103	0.0088	0.0084	0.0090
840	0.0112	0.0100	0.0085	0.0082	0.0088

Data D. Continuous wall heated fluidized bed dryer (Pearl millet drying)

T_w= 313 K, IMC=14.5%, V=1.01 m/s, H_d=50 mm, S_F = 6.7 kg/h

Time(s)	Moisture content			
	Stage-1	Stage-2	Stage-3	Stage-4
0	0.145	0.1355	0.1037	0.0860
60	0.1370	0.1261	0.0939	0.0756
120	0.1290	0.1170	0.0839	0.0662
180	0.1215	0.1086	0.0759	0.0604
240	0.1150	0.1015	0.0695	0.0556
300	0.1093	0.0952	0.0640	0.0515
360	0.1040	0.0900	0.0593	0.0478
420	0.0990	0.0852	0.0558	0.0443
480	0.0945	0.0808	0.0531	0.0415
540	0.0901	0.0767	0.0505	0.0390
600	0.0864	0.0731	0.0481	0.0370
660	0.0830	0.0701	0.0460	0.0351
720	0.0802	0.0676	0.0442	0.03407
780	0.0775	0.0653	0.0425	0.0330
840	0.0749	0.0629	0.0413	0.0325
900	0.0725	0.0608	0.0402	0.0321
960	0.0703	0.0588	0.0392	0.0321
1020	0.0682	0.0568	0.0385	0.0320
1080	0.0661	0.0550	0.0380	
1140	0.0640	0.0533	0.0379	
1200	0.0621	0.0518	0.0377	
1260	0.0604	0.0506	0.0375	
1320	0.0587	0.0496		
1380	0.0571	0.0486		
1440	0.0555	0.0477		
1500	0.0541	0.0471		
1560	0.0529	0.0467		
1620	0.0518	0.0465		
1680	0.0509	0.04649		
1740	0.0501			
1800	0.0495			
1860	0.0494			
1920	0.0492			

Data E. Continuous wall heated fluidized bed dryer (Barnyard millet drying)

T_w= 328 K, IMC=14.5%, V=1.01 m/s, H_d =50 mm, S_F = 6.7 kg/h, T_{ain} =300 K,

%RH (inlet of dryer) = 23.5, E_{mwin}=0.464 kW, Ex_{mwin}=0.0396 kW, T_∞ =300 K

Time(s)	%RH (outlet)				T_{aout}			
	Stage-1	Stage-2	Stage-3	Stage-4	Stage-1	Stage-2	Stage-3	Stage-4
30	34	34.5	33.3	33	29.7	29.8	30.8	31.7
90	33	33	32	31.5	30.2	30.8	31.2	32.4
150	32	31.5	30	31	30.5	31.2	32.4	33.1
210	30	29.5	27.5	27.5	31.5	32.1	33.8	34.9
270	28	27	24.3	24.5	33.2	33.9	35.7	36.8
330	26	25.7	23	23.5	33.7	34.5	37.4	38.1
390	25.6	24.5	21.5	20.8	34.1	35.3	38.1	39.4
450	25	23.8	21	18.3	34.4	35.6	38.4	41.7
510	24	23	20.1	17.5	34.7	36.1	38.9	42.2
570	22.8	21.5	19	16.4	35.6	37.8	40.25	43.2
630	21.9	18.8	18.3	15.4	36	38.6	40.5	44.1
690	20.5	18.5	17	14.5	37	39.4	41.5	44.9
750	19.9	18	15.9	13.9	37.7	39.9	43	45.4
810	18.5	17.5	14.8	13.2	38.4	40.3	44	46.4
870	18.4	16.8	14.7	13	38.5	41	44.1	46.5
930	17.8	16	14.2	12.6	38.9	41.4	44.5	46.9
990	16.8	15	13.3	12.3	39.7	42.5	45.6	47.2
1050	16	14.2	13	12	40.3	43.4	45.7	47.3
1110	15.5	13	12.5	11.5	41.3	44.7	46.4	48
1170	14.9	13	12	11	41.4	44.8	47.1	48.5
1230	14.7	12.9	11.7	11.2	41.8	45.2	47.5	48.9
1290	14.3	12.8	11.5	11	42.1	45.3	47.6	49.4
1350	14.3	12.1	11	10.5	42.2	46	48.5	49.5
1410	14.3	12.3	11	10.5	42.2	46.1	48.6	49.8
1470	14	12.1	11	10.3	42.3	46.1	48.7	49.9
1530	14.3	12.1	11	10.3	42.3	46.2	48.8	50
1590	14	12.1	11	10.3	42.4	46.3	48.9	49.9
1650	14	12.1	11	10	42.4	46.4	49	50
1710	14	12.1	11	10	42.4	46.4	49	50

Data F. Continuous hot air single stage fluidized bed dryer- Simulation (Effect of orifice diameter)

Particle dp - 1.35 mm (sand)

IMC-10%, Solids flow rate- 10 kg/h, air flow rate- 50 kg/h, T_{ain}-323 K

Orifice Size (mm)	Outlet Solid temperature (K)
0.4	299.18
0.5	304.15
0.6	305.49
0.7	306.01
0.8	306.26
0.9	306.38
1	306.46
1.1	306.50
1.2	306.53
1.3	306.54
1.4	306.56

Data G. Continuous hot air single stage fluidized bed dryer- Simulation Effect of air inlet temperature

Particle dp - 1.35 mm (sand), IMC-10%, Solids flow rate- 10 kg/h, air flow rate- 50 kg/h, Orifice size-1 mm, number of orifices-190

T_{ain}(K)	Outlet Solid temperature (K)
303	303.72
313	306.91
323	309.83
333	312.52
343	315.01
353	317.32

Data H. Continuous hot air multistage fluidized bed dryer (Simulation)

Particle dp – 0.6 mm (sand)

IMC=10%, air flow- 50 kg/h, S_F = 10 kg/h

T_{ain}	Exergy inflow (kJ/s)		Exergy outflow (kJ/s)					Solid moisture (kg/kg) -At stage 4
	Single	MFB (Four stages)	Stage-1	Stage-2	Stage-3	Stage-4	Multistage	
313	0.0038	0.015271	4.53E-06	2.22E-05	0.00019	0.00099	0.0013	0.0167
318	0.0072	0.028967	0.0003	0.0005	0.00157	0.00316	0.0057	0.0120
323	0.0117	0.0468	0.0009	0.0015	0.00394	0.00672	0.0132	0.0088
328	0.0171	0.068643	0.0020	0.0033	0.00753	0.01175	0.0247	0.0062
333	0.0235	0.094376	0.0033	0.0060	0.01252	0.01866	0.0406	0.005
338	0.0309	0.123881	0.0050	0.0093	0.01878	0.02668	0.0599	0.005
343	0.0392	0.157048	0.0071	0.0137	0.0264	0.03639	0.0837	0.005
348	0.0484	0.193772	0.0092	0.0197	0.0356	0.04709	0.1117	0.005
353	0.0584	0.23395	0.0122	0.0266	0.0459	0.05793	0.1429	0.005

Data I. Continuous hot air multistage stage fluidized bed dryer- At steady state

Particle dp – 0.6 mm (sand)

IMC-10%, Solids flow rate- 6.7 kg/h, air flow rate- 50 kg/h

T_{ain}	Exergy		Stage-4
	Inflow	Outlflow	Moisture content
313	0.01528	0.0024	0.0251
323	0.0468	0.0114	0.0185
333	0.09438	0.0330	0.0118
343	0.15705	0.0690	0.00995
353	0.2339	0.1136	0.00789

Appendix-II

Table A1. Comparison of the final moisture content results with literature reports.

Type of dryer	Bed material	Operating conditions	Final moisture content	Reference
Batch hot air fluidized bed dryer	Finger millet	T- 333 to 373 K V-1.2 to 1.6 m/s at IMC- 42%	4.2 to 1.1% 2.9 to 2.9%	(Srinivasakannan and Balasubramaniam, 2006)
Batch fluidized bed dryer	Corn particles	V- 0.43 to 0.67 m/s, T- 318 to 348 K IMC-16%	11 to 7% 11 to 5%	(Zhang et al., 2018)
Batch hot air fluidized bed dryer	Pearl millet	T-313 to 338 K IMC-22%	5 to 3%	(Srinivasakannan and Balasubramanian, 2009)
Continuous hot air multistage fluidized bed dryer	Pearl millet	T-308 to 368 K S_F-2.5 to 5.4 kg/s	13 to 5% 5 to 11%	(Choi et al., 2002)
Batch wall heated fluidized bed dryer	Kodo millet Fenugreek seeds	T_w-313 to 333K, H-3 to 5 cm, V-1 to 1.7 m/s IMC- 10 to 20% T_w -313 to 333K, H-3 to 5 cm, V-1 to 1.7 m/s IMC- 10 to 20%	3.5 to 2.6% 2.3 to 3.3% 3.7 to 2.3% 3 to 4.5% 3.7 to 2.9% 3.3 to 2.3 % 3.9 to 2.9% 3.6 to 4.7%	Present study
Continuous wall heated multistage fluidized bed dryer	Pearl millet	T_w -313 to 328K, H-50 to 70 mm, V-1 to 1.3 m/s	4.8 to 2.6% 3.2 to 4.8% 4.8 to 2.8%	Present study

		S_F-5 to 10 kg/h	2.9 to 5.4%	
	Barnyard millet	T_w -313 to 328K, H-50 to 70 mm, V-1 to 1.3 m/s S_F-5 to 10 kg/h	4.5 to 2.9% 2.3 to 4.5% 4.5 to 2.6% 2.5 to 5.2%	

Table A2. Comparison of exergy efficiency with literature reports

Dryer	Bed material	Variables	Exergy efficiency	Reference
Hot air batch fluidized bed dryer	Carrot cubes	T-323 to 343 K, H- 3 to 9 cm	0.6 to 0.8 0.75 to 0.6	Nazghelichi et al. (2010)
Tray dryer	Broccoli florets	T-323 to 343 K V-0.5 to 1.5 m/s	0.74 to 0.69 0.75 to 0.81	(Icier et al., 2010)
Solar-assisted fluidized Paddy bed dryer integrated	Paddy	334 to 351 K	0.47 to 0.49	Yahya et al. (2017)
a) Tray dryer b) Hot air Fluidized bed dryer	Plums (Prunus domestica Insititia)	318 to 328 K	0.37 to 0.39 0.24 to 0.22	(Hepbasli et al., 2010)
Tray dryer	cassava starch	313 to 333 K	0.14 to 0.22	(Aviara et al., 2014)
Batch wall heated fluidized bed dryer	Kodo millet and Fenugreek seeds	T-313 to 333K, H-3 to 5 cm, V-1.01 to 1.7 m/s	0.58 to 0.72 (Kodo) 0.59 to 0.71(Fenugreek) 0.78 to 0.57(Kodo) 0.74 to 0.55(Fenugreek) 0.61 to 0.75(Kodo) 0.58 to 0.74(Fenugreek)	Present study

		IMC- 10 to 20%	0.68 to 0.54(Kodo) 0.67 to 0.45(Fenugreek)	
Continuous wall heated multistage fluidized bed dryer	Barnyard millet	T-313 to 328K H-50 to 70mm V-1.01 to 1.3 m/s S_F-5 to 10 kg/h	0.45 to 0.64 0.45 to 0.38 0.45 to 0.63 0.50 to 0.37	Present study

Table A3. Comparison of simulation reports with literature findings.

Dryer	Material	Modeling approach	Operating conditions	Findings	References
FBD	Granules	Mathematical modeling	T-343 K IMC-60%	Final moisture content:10% Solid temperature: 303 to 340 K	(Poos and Szabo, 2017)
Plug flow FBD	Shelled corn	Mathematical modeling	T-323 to 373 K	Final moisture content: 25 to 15%	(Khanali et al., 2018)
Continuous single stage fluidized bed dryer	Sand 1.35 mm	ASPEN PLUS	T-313 to 353 K Mass flow rate-40 to 80 kg/h	Final moisture content: 7 to 1.5 % Solid temperature: 303 to 320 K	Present study
FBD	Soybeans	Mathematical modeling	T-303 to 333 K V-1.2 to 2.2 m/s H-3 to 6 cm	Exergy efficiency: 0.09 to 0.12 0.10 to 0.09 0.10 to 0.09	(Ranjbaran and Zare, 2013)
Infrared drying process	Biomass	Mathematical modeling	Mass flow rate-0.036 to 1.1 kg/s	Exergy efficiency: 28 to 10%	(Aghbashlo, 2016)
Hot air multistage fluidized bed dryer	Sand -0.6 mm	ASPEN PLUS	T-313 to 353 K Mass flow rate-40 to 80 kg/h	Exergy efficiency: 0.07 to 0.61 0.18 to 0.5	Present study

Appendix III

Sample calculation for uncertainty:

Taking any three readings of instrument , Example: Temperature readings are noticed as 40.1, 40.5 and 40.3.

Mean of the readings O_m is 40.3 and from that uncertainty value was found to be ±0.4 using equations 3.9.1 to 3.9.3.

Actual exergy equation $Ex_{aout} = m_a . c_{pa} .[(T_{aout} - T_\infty) - T_\infty . \ln(T_{aout} / T_\infty)]$ (3.8.3)

For equation 3.8.3, the uncertainties for the three independent variables are

$\Delta m = 0.5$ (air flow), $\Delta T_{aout} = 0.4$ and $\Delta T_\infty = 0.4$

For first term (subtraction term for independent variables)

$\sqrt{(\Delta Taout)^2 + (\Delta T\infty)^2}$ =0.56, for the $(T_{aout} - T_\infty)$ term……………… (a)

For division

$\sqrt{\left[\frac{\Delta Taout}{Taout}\right]^2 + \left[\frac{\Delta T\infty}{T\infty}\right]^2}$ =0.19, for the (T_{aout} / T_∞) term

For $T_\infty . (T_{aout} / T_\infty)$ the value will be the 0.254………………………. (b)

Then a and b will be the 0.61

Then entire equation $\sqrt{\left[\frac{\Delta m}{m}\right]^2 + [0.61]^2}$

$\Delta m = 0.5$ and m will be the average value than $\Delta m/m = 0.061$

Final exergy uncertainties for single stage batch wall heated bed dryer are found ±0.61% and Similarly the exergy uncertainties for batch wall heated multistage fluidized bed dryer are found ±1.56%

Publications and Conferences

List of Publications

- D Yogendrasasidhar, G Srinivas, Y Pydi Setty. "Effect of distributor on performance of a continuous fluidized bed dryer". **Heat and Mass Transfer** 2018;Vol 54, pp:641–649. doi:10.1007/s00231-017-2169-2 (SCI Indexed)
- D Yogendrasasidhar, Y Pydi Setty. "Drying kinetics, exergy and energy analyses of Kodo millet grains and Fenugreek seeds using wall heated fluidized bed dryer". **Energy** 2018; Vol 151, pp:799–811 (SCI Indexed)
- D Yogendrasasidhar, Y Pydi Setty."Experimental studies and thin layer modeling of pearl millet using continuous multistage fluidized bed dryer staged externally". **Engineering Science and Technology–An internation Journal** 2019; Vol 22, pp: 428-438. doi:10.1016/j.jestch.2018.10.010 (SCOPUS Indexed, ESCI Indexed)
- D Yogendrasasidhar and Y Pydi Setty, "Energetic and exergetic analyses of Barnyard millet drying using continuous multistage fluidized bed dryer". **Journal of Food Process Engineering**. (Accepted) DOI.10.1111/JFPE.13247.

Book chapter

- D Yogendrasasidhar, Y Pydi Setty. "Studies on Heat and Mass Transfer Coefficients of Pearl Millet in a Batch Fluidized Bed Dryer". **Numerical Heat Transfer and Fluid Flow**, Lecture Notes in Mechanical Engineering (SCOPUS Indexed) doi: 10.1007/978-981-13-1903-7_50

Conferences proceedings

- D.Yogendrasasidhar, Y.Pydi Setty, An experimental investigation on pearl millet with wall heated Fluidized bed dryer, PBSI-2016 International Conference, Bombay Convention & Exhibition Centre, Mumbai, India, October 13-15, 2016.
- D Yogendrasasidhar, G Srinivas and Y Pydi Setty, "Experimental Investigation on Drying Characteristics of Geldart Group B and Group D Particles in a Fluidized Bed Dryer", PGBSIA-2016, Jaipur, Rajasthan, India, December 1-3, 2016.
- D Yogendrasasidhar and Y Pydi Setty, "Heat and mass transfer studies of pearl millet using a fluidized bed dryer", International Conference on Numerical Heat Transfer &

Fluid flow (NHTFF-2018), Warangal, National Institute of Technology Warangal, January 19-21, 2018.

- D Yogendrasasidhar and Y Pydi Setty, "Studies on heat and mass transfer for Geldart B particles using batch fluidized bed dryer", Fifth International Conference on Computational Methods for Thermal Problems (THERMACOMP 2018), Indian Institute of Science, Bangalore, India, July 9-11, 2018.
- D Yogendrasasidhar and Y Pydi Setty, "Experimental energy studies and artificial neural network modeling for continuous wall heated fluidized bed dryer", International Conference on Advance materials, Energy and Environmental Sustainability (ICAMEES-2018), University of Petroleum and Energy Studies, Dehradun, India, Dec-14 and 15,2018.
- D Yogendrasasidhar and Y Pydi Setty, "Simulation of continuous multistage fluidized bed dryer for exergy analysis using Aspen Plus simulator", 11th International Exergy, Energy and Environment Symposium (IEEES11-2019), SRM University, Chennai, India, July 14-18, 2019.