HYDRODYNAMIC STUDY AND DRYING OF GRAINS IN A TAPERED FLUIDIZED BED

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Chemical Engineering

Submitted By
Y.Sai Sirisha
Roll no 20600005

Department of Chemical Engineering
National Institute of Technology
Rourkela
Orissa-769008

HYDRODYNAMIC STUDY AND DRYING OF GRAINS IN A TAPERED FLUIDIZED BED

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Chemical Engineering

Submitted By
Y.Sai Sirisha
Roll no 20600005

Under the esteemed guidance of
Prof. (Dr). K.C.Biswal

Department of Chemical Engineering
National Institute of Technology
Rourkela
Orissa-769008

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

CERTIFICATE

This is to certify that the thesis entitled " HYDRODYNAMIC STUDY AND DRYING OF GRAINS IN A TAPERED BED" submitted by Y.Sai Sirisha in partial fulfillment of the award of Master of Technology Degree in CHEMICAL Engineering with specialization in "Biochemical and Biotechnology" at the National Institute of Technology**,** Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

Date:

Prof. (Dr.) K.C.BISWAL

Dept. of Chemical Engg.

National Institute of Technology

Rourkela-769008

ACKNOWLEDGEMENT

I express my sincere gratitude to my guide, **Dr. K.C. Biswal**, Prof. of the Department of Chemical Engg., National Institute of Technology, Rourkela for giving me this great opportunity to work under his kind support, guidance and constructive criticism in the completion of my project.

I offer my deepest appreciation for people who assisted me in the experiments. I would like to thank to all those who are directly or indirectly supported me in carrying out this thesis work successfully.

Y.SAI SIRISHA

CONTENTS

Page no.

ABSTRACT

Cereal grain and food drying are done as an aid to warrant minimization of grain damage, on one side and economic feasibility on another side. Proper drying procedures can eliminate the potential of spoilage during subsequent storage and improve the quality of grain. Appropriate dryer should be designed for reducing the damage to grain and for economically feasibility. The drying method and conditions effectively determine type and characteristics of the final product. The drying performance of a tapered fluidized bed dryer on wheat grains and mustard seeds are studied. An investigation is undertaken to study the effects of temperature, time, moisture content and gas velocity on the drying performance in a tapered fluidized bed. Furthermore, the hydrodynamic aspects e.g. pressure drop and minimum fluidization velocity are also studied. The results show that the efficiency increases with increase in temperature and time of drying. This clearly indicates that the moisture transfer from the material depends strongly on the air temperature. The drying rate decreases with increase in particle size. A good agreement is obtained between the predicted hydrodynamics and the obtained results.

List of figures Page no

List of Graphs

List of Tables

CHAPTER 1

INTRODUCTION

INTRODUCTION TO TAPERED FLUIDIZED BED

Fluidization is the operation by which fine solids are transformed into a fluid like state through contact with a gas or solid. This method of contacting has a number of unusual characteristics, and fluidization engineering is concerned with efforts to take advantage of this behavior and put it to good use. The ease with which particles fluidize and the range of operating conditions which sustain fluidization vary greatly among gas-solid systems. Whether the solids are free flowing or not, whether they are liable to agglomerate, static charges, vessel geometry, gas inlet arrangement, and other factors affect the fluidization characteristics of a system.

Conical fluidized bed is very much useful for the fluidization of wide distribution of particles, since the cross sectional area is enlarged along the bed height from the bottom to the top, therefore the velocity of the fluidizing medium is relatively high at the bottom, ensuring fluidization of the large particles and relatively low at the top, preventing entrainment of the small particles. Since the velocity of fluidizing medium at the bottom is fairly high, this gives rise to low particle concentration, thus resulting in low reaction rate and reduced rate of heat release. Therefore the generation of high temperature zone near the distributor can be prevented.

Due to the existence of a gas velocity gradient along the height of a conical bed, it has some favorable special hydrodynamic characteristics. The conical bed has been widely applied in many industrial processes such as

[1] Biological treatment of waste-water,
[2] Immobilized biofilm reaction,
[3] Incineration of waste-materials,
[4] Coating of nuclear fuel particles,

[5] Crystallization, roasting of sulfide ores,
[6] Coal gasification and liquefaction,
[7] Catalytic polymerization,
[8] Fluidized contactor for sawdust and mixtures of wood residues and
[9] Fluidization of cohesive powder.

The study of the hydrodynamic characteristics of fluidization of conical beds is focused on two fields:
(1) liquid–solid systems and
(2) gas–solid systems.

When the particle weight in the top layer of the conical bed is equal to or less than the drag force by fluid flowing upward, the fully fluidized bed regime occurs. Between these two cases, the flow regime is called a partially fluidized bed regime. However, it is not easy to predict the characteristics of fluidization for the partially fluidized bed regime theoretically [2]. All these studies are based on the idealized fluidization defined by Kwauk, i.e. according to the following assumptions:

- The radial distribution of the fluid at any cross-section of the conical bed is uniform;
- There is no back mixing for the fluid phase;
- The frictional force between wall and particles is neglected.

STRUCTURE OF TAPERED BED

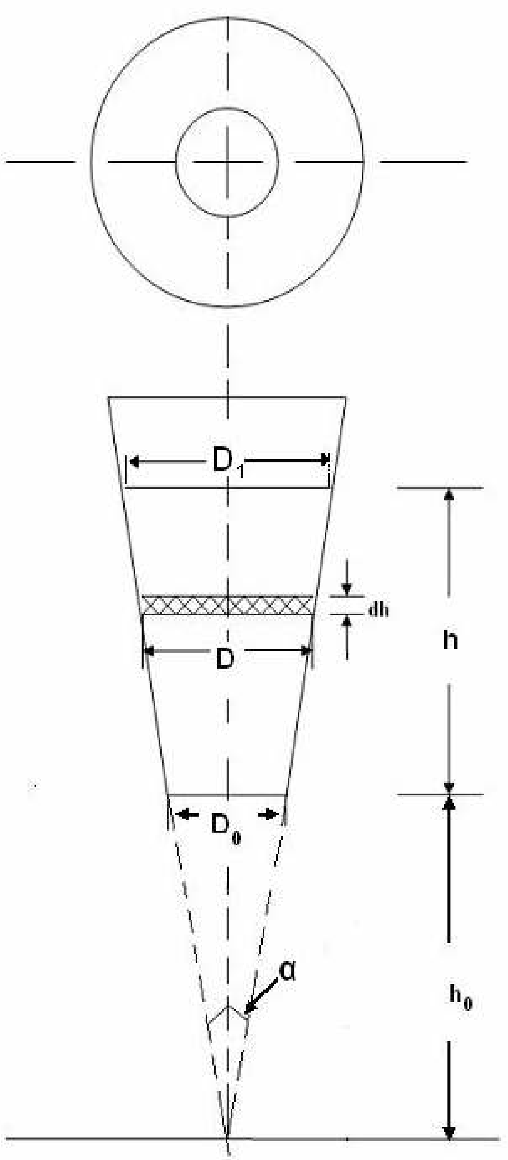


Fig-1.1

INTRODUCTION TO FLUID BED DRYING

Dehydration is a time – honored method of preserving food. Drying reduces the water activity, thus preserving foods by avoiding microbial growth and deteriorative chemical reactions. The Drying Process is an operation that aims at a reduction of the moisture content in most products, industrialized or not, to guarantee their preconservation in storage and transport. The main purposes of drying are to increase shelf life, reduce packaging and storage costs, lower shipping weights, improve sensory attributes, encapsulate flavors, and preserve nutritional value in some cases. For storage purposes, the moisture content of materials must fall within a commercially acceptable range so that they do not undergo any type of degradation or alterations in quality or appearance. To achieve the desired moisture content, the material must be dried, several types of commercial drying equipment are available.

In many practical applications, drying is a process that requires high energy input because of the latent heat of water evaporation and relatively low energy efficiency of industrial dryers. That is, expensive energy is depleted only to produce low grade heat for drying. Fluidized beds are currently used commercially for drying such materials as granular materials, cereals, polymers, chemicals, pharmaceuticals, fertilizers, crystalline products and minerals.

Factors need to be considered before selecting a drying process are

- The quality of the products in relation to requirement
- The economics of the process.
- The environment impact of the process.
- The drying time required for a given product is also a key factor in the selection of the dryer.

Classification of drying

a) Thermal drying

A gaseous or void medium is used to remove water from the material. The heat needed for drying is supplied to the material by one of the following methods.

- Radiation drying.
- Convective drying (using a drying medium, i.e., air).
- Contact drying (by conduction from a surface that is in direct contact with the material to be dried).

b) Osmotic dehydration

Solvent or solution is applied to remove water.

c) Mechanical dewatering

Physical force like centrifugal force or pressure is applied to materials with a physical barrier (i.e., membrane) to keep liquid and solid phases separated.

Dryers can be further classified in a number of ways, for example on the basis of pressure (vacuum or near atmospheric), mode of operation, and the method of handling within the dryer (e.g. stationary, agitated, fluidized, converged, falling under gravity). Dryers can be classified as batch or continuous types, depending on the mode of operation. In general, batch dryers are preferred for small-scale operations.

Factors need to be considered before selecting a drying process.

- The type of product to be dried
- Properties of the finished product desired
- The product's susceptibility to heat
- Pretreatments required
- Capital and processing cost
- Environmental factors

Drying is essentially a process of simultaneous heat and mass transfer. Heat, necessary for evaporation, is supplied to the particles of the material and moisture vapor is removed from the material into the drying medium. Heat is transported by convection from the surroundings to the particle surfaces, and from there, by conduction, further into the particle. Moisture is transported in the opposite direction as a liquid or vapor on the surface, it evaporates and passes on by convection to the surroundings.

Induced draught is created by means of blower and fresh air is sucked into the unit. This hot air stream expands the material at certain velocity and creating turbulence in the product. The phenomenon is known as fluidization and offer conditions which are almost for drying. Fluidization produces full agitation of solid particles by hot air, heat transfer is extremely high and uniform. The product is dried fast without appreciable loss of heat. Filter bags prevent particle escaping from the dryer.

Advantages of fluid bed drying are

1. Uniform product moisture content, and thus high drying air temperature can be employed with less over dried grain
2. High drying capacity due to better heat and mass transfer
3. A much smaller drying chamber and thus a significantly lower initial cost.

CHAPTER 2

LITERATURE REVIEW

TAPERED FLUIDIZED BED

Most of the gas–solid fluidization behavior studies that have been reported are for straight cylindrical or columnar fluidized bed, although a considerable proportion of the fluidized beds have inclined walls or have a tapered bottom section. A velocity gradient exists in the axial direction, leading to unique hydrodynamic characteristics. Due to this characteristic, tapered fluidized beds have found wide applicability in many industrial processes such as, waste water treatment, immobilized biofilm reaction, incineration of waste materials, coating nuclear fuel particles, crystallization, coal gasification and liquefaction and roasting sulfide ores, food processing, etc. Tapered fluidized beds are useful for fluidization of materials with a wide particle size distribution, as well as for exothermic reactions. They can be operated smoothly without any instability, i.e. with less pressure fluctuations and also for extensive particle mixing. In spite of its advantages and usefulness, not much work has been reported in literature for understanding certain important characteristics, especially minimum fluidization velocity and maximum pressure drop. Studies have been reported by researchers to determine the factors affecting minimum fluidization velocity and maximum pressure drop. But some of these results are limited to regular particles only. Some of the previous investigations include fixed bed pressure drop calculations, flow regimes, incipient condition of fluidization, voidage distribution and bed expansion calculations and development of a model for maximum pressure drop at incipient fluidization condition of a tapered fluidized bed.

For gas–solid systems in conical spouted beds, Olazer et al. [1] observed five flow regimes: fixed bed, partially fluidized bed, spouted bed, transition regime from spouted bed to jet spouted bed and jet spouted bed. The hydrodynamic characteristics for these five regimes are presented by empirical correlations [2]. The difficulty in predicting the hydrodynamics of fluidization from the theory of Peng and Fan possibly lies in the fact that the inlet diameter for the conical spouted bed is less than that of the bed bottom. The same approach by Peng and Fan [2] has been adopted by Gelperin et al. and Nishi for the incipient fluidization of gas–solid conical beds.

The model developed by Shi et al. [5] is based on Ergun's equation and neglects friction between the particles and the wall. Biswal et al. [6, 7, 8] developed theoretical models, for minimum fluidization velocity and pressure drop in a packed bed of spherical particles for gas–solid systems in conical vessels. Due to the angled walls, random and unrestricted particle movement occurs in a tapered bed with reduced back mixing. Olazer et al. [2] compared their experimental results with that calculated using the models developed by Gelperin et al. and Gorshtein and Mukhlenov [4] for maximum pressure drop and found that the predictions were not very accurate. They therefore proposed a modified equation for calculation of maximum pressure drop. Later, Peng and Fan [1] made an in-depth study of the hydrodynamic characteristics of solid–liquid fluidization in a tapered bed and derived theoretical models for the prediction of minimum fluidization velocity and maximum pressure drop, based on the dynamic balance of forces exerted on the particle. The experiments were however carried out for spherical particles only. Jing et al [9]. and Shan et al.[10] developed models for gas–solid conical fluidized beds for spherical coarse and fine particles based on the Peng and Fan models but neglected the pressure drop due to the kinetic change in the bed. Depypere et al. [11] have carried out studies in a tapered fluidized bed reactor and proposed empirical models for determination of expanded bed height by using static pressure and wall surface temperature measurements.

Levey et al, 1960 [12] have successfully used tapered beds in chemical reactions. Peng and Fan [1997] have mentioned that the beds could be used for biochemical reactions and roasting of sulfide ores. Kumar et al [1981] and Yogesh Chandra and Jagannath Rao [1981] have investigated the hydro dynamics of gas -solid fluidization in tapered vessels using single size particles.

Tapered fluidized beds have many attractive features, among which are their capabilities for handling particles with different sizes and properties (Scott and Hancher, 1976; Ishii *et al.,*1977) and for achieving extensive particle mixing (Babu *et al.,* 1973), These beds have been widely applied in various processes including biological treatment of wastewater, immobilized biofilm reaction, incineration of waste materials, coating nuclear fuel particles, crystallization, coal gasification and liquefaction, and roasting sulfide ores. Interestingly, industrial fluidized beds are, more often than not, fabricated with tapered sections at the bottom.

Nevertheless, fundamental understanding of the behavior of tapered fluidized beds appears to lag far behind their applications. Some of the previous investigations include studies on pressure drop of fixed and fluidized beds in tapered vessels (Koloini and Farkas, 1973; Biswal et al.,1984), flow regimes, incipient condition of fluidization, voidage distribution and bed expansion (Hsu, 1978), and particle mixing (Ridgway, 1965 [3]; Maruyama and Sato, (199l). A fluidized bed is formed when the particles in the bed are in dynamic equilibrium; the fluid drag force and the buoyancy force are exerted in the upward direction against the gravitational force, which pulls the particles downward (Wilhelm and Kwauk, 1948; Davidson and Harrison, 1971). This drag force is constant at any position of a columnar bed of uniform particles; however, it decreases in the upward direction in a tapered bed accompanied by the reduction in the superficial velocity of the fluid.

Thus, the particles at the lower part of the bed will first be fluidized upon an increase in the flow rate: in contrast, those at the upper part of the bed remain static. This phenomenon of partial fluidization is peculiar to the tapered fluidized bed. Relatively little has appeared in the open literature on hydrodynamic characteristics of tapered fluidized beds; the majority of what has been published deals with flow regimes and incipient condition of fluidization. Toyohara and Kawamura (1989) have reported the flow regime of partial fluidization in a gas solid tapered bed. Descriptions have been given in Kwauk's monograph (1993) on the change of the flow regime in a gas-solid tapered bed.

The incipient condition of fluidization in a tapered bed can be predicted based on the dynamic balance of forces exerted on the particle bed. This approach was adopted by Gelperin et al. (1960) and Nishi (1979) for gas-solid tapered beds, and Shi *et al.* (1984) for liquid-solid tapered beds. Nevertheless, none of these works took into account the phenomenon of partial fluidization in predicting the incipient condition of fluidization and the concomitant, maximum pressure drop.

Fluidization in tapered beds have found wide applicability in many industrial processes such as, waste water treatment (Scott and Hancher, 1976), coating of nuclear fuel particles, crystallization, coal gasification and liquification and roasting of sulfide ores (Peng and Fan, 1997), coating of food powder particles (Depypere et al., 2005), etc. Tapered fluidized beds are useful for fluidization of materials with wide particle size distribution and also for exothermic reactions. It can be operated smoothly without any instability i.e. with less pressure fluctuations (Ridgway, 1965) and also for extensive particle mixing (Babu et al. 1973, Maruyama and Sato, 1991). Various techniques including introduction of baffles, operation in multistage unit and imparting vibrations have been advocated from time to time to tackle slugging problem in conventional bed. Introduction of tapered bed instead of a conventional cylindrical one is an alternative technique in gas-solid fluidization to tackle such problem. Better solid fluid mixing and improved quality of fluidization can be achieved in a tapered bed.

The gradual decrease in superficial fluid mass velocity due to increase in the cross-sectional area in the upward direction necessitates the use of continuously decreasing size particles for smooth and stable operation of such a fluidizer. Due to angled wall, random and unrestricted particle movement occurs in tapered bed thereby reducing back mixing (Singh et al, 1992). Although some information for liquid-solid system in tapered bed is available, very little work related to gas-solid fluidization in tapered bed is available. In spite of its advantages and usefulness not much work has been reported in literature for understanding certain important characteristics, especially fluctuation ratio of the bed. Some of the previous investigations include fixed bed pressure drop calculations (Koloini and Farkas, 1973), flow regimes, incipient condition of fluidization, voidage distribution and bed expansion calculations (Hsu et al, 1978).

Maruyama and Koyanagi (1993) [13] have proposed analytical methods to predict the bed expansion and pressure drop in tapered fluidized bed. Depypere et al (2005) have carried out studies in a tapered fluidized bed reactor and proposed a model for expanded bed height by the use of static pressure and wall surface temperature measurement. Singh et. al [14] predictied minimum velocity and minimum bed pressure drop for gas–solid fluidization in conical conduits.

Fluidization operations in cylindrical column are extensively used in process industries. But, in a number of these operations, the particles are generally not of uniform size or there may be reduction in size due to chemical reactions like combustion or gasification, or attrition. In cylindrical beds, the particle size reduction results in entrainment, limitation of operating velocity in addition to the other demerits like slugging, non-uniform fluidization generally associated with such beds. These disadvantages are overcome by use of tapered beds to conduct fluidization. This is due to the gradual reduction of superficial velocity of the fluid because of increase in cross sectional area with height. Tapered fluidized beds have found wide applicability in many industrial processes such as biological treatment of waste water, immobilized biofilm reaction, incineration of waste materials, coating nuclear fuel particles, crystallization, coal gasification and liquefaction and roasting sulfide ores, and food processing .These beds are also useful for fluidization of materials with wide particle size distribution and also for exothermic reactions. Tapered bed can also reduce back mixing of particles.

Some of the previous investigations include development of a model for maximum pressure drop at incipient fluidization condition of a tapered fluidized bed. Olazer et al. proposed a correlation for calculation of maximum pressure drop in conical spouted bed. Later, Peng and Fan made an in-depth study of the hydrodynamic characteristics of solid-liquid fluidization in tapered bed and derived a theoretical model based on dynamic balance of forces exerted on the particle for the prediction of critical fluidization velocity and maximum pressure drop. Jing et al. and Shan et al. developed a model for gas-solid conical fluidized bed for spherical course and fine particles respectively based on Peng and Fan model but neglected the pressure drop due to kinetic change in the bed. But all of these works were for single type particles and uniform size particles in tapered or conical bed.

The flow of fluids of single phase has occupied the attention of scientists and engineers for many years. The equations for the motion and thermal properties of single phase fluids are well-accepted and closed form solutions for specific cases are well-documented. The state of the art for multiphase flows is considerably more primitive in that the correct formulation of the governing equations is still under debate. For this reason, the study of multiphase flows represents a challenging and potentially fruitful area of endeavor. Hence there has been an increased research activity in the experimental and numerical study of multiphase flows.

Multiphase flows can be broadly classified into four groups; gas-liquid, gas-solid, liquid-solid and three-phase flows. Gas-solid flows are usually considered to be a gas flow with suspended solid particles. This category includes pneumatic transport, bubbling/circulating fluidized beds and many others. In addition, there is also a great deal of industrial interest in pure granular flows in industrial equipment such as mixers, hoppers, ball mills, and chutes. Features of the tapered fluidized bed, especially its advantages over the columnar fluidized bed, are

The tapered fluidized bed is differentiated from the more conventional fluidized bed by a configuration that resembles an inverted, truncated bed by a cone rather than a constant cross-sectional column. Usually the size distribution of a particle system which can be employed in a columnar fluidized bed need be narrow. If the particle size distribution is too broad, small particles may be entrained and large particles may be defluidized, settling on the distributor. The cross-sectional area of the tapered fluidized bed is enlarged along the bed height from the bottom to the top. Therefore, the velocity of the fluidizing medium is relatively high at the bottom, ensuring fluidization of the large particles, and it is relatively low at the top, preventing entrainment of the small particles. Therefore, we can operate the tapered fluidized bed with particles whose size distribution is wide. This feature is especially important for an operation in which the particle size changes (coal combustion, crystallization, microbial growth, etc.).

The flow should be relatively stable through out the reactor. The taper of the column allows a wide range of flow rates without loss of bed material since the fluid velocity decreases with reactor height. As a result, the reactor can operate over a wide range of flow rates. At higher flow rates, the tapered bed simply expands into a portion of the reactor having a larger cross sectional area. At very high flow rates, the lower portion of the bed may be relatively free of the fluidized bed, since the fluid velocity may exceed the settling velocity of the particles at that point. At the same time, a lower fluid velocity further up the reactor may result in the bed being only slightly above incipient fluidization thus preventing loss of the fluidized particulates. The gradual expansion of the column also results in a stable feed introduction without gross eddies and significant backmixing. For an intensely exothermic reaction in the columnar fluidized bed the major fraction of heat is released near the distributor, creating a high-temperature zone and possibly destroying the distributor and sintering the particles. However, in the tapered fluidized bed, the velocity of the fluidizing medium at the bottom of the bed is fairly high. This gives rise to a low particle concentration, thus resulting in a low reaction rate and reduced rate of heat release. Therefore, the generation of a high temperature zone near the distributor can be prevented.

Despite recent advances, it was felt necessary to study the use of tapered fluidized bed for drying of grains and to study the effects of temperature, time of drying, gas velocity and initial moisture contact on drying performance.

FLUIDIZED BED DRYING

Recent developments of the regime of fluidization and subsequent design modifications have made fluidized bed drying a desirable choice among other dryers. However, like other types of conventional convective drying processes, fluidized bed drying is a very energy intensive process in industry. The efficiency of a conventional drying system is usually low, depending on the inlet air temperature and other conditions. It is, therefore, desirable to improve the efficiency of the drying process to reduce the overall consumption of energy.

The process of fluidization with hot air is highly attractive for the drying of powders and wet granular materials. The use of fluid bed drying for granular materials is now well established, and literally thousands of fluid bed dryers are operating throughout the food and chemical processing industries in the drying of coarse materials, grains, fertilizers, chemicals, and minerals, pharmaceuticals and food products among other solids.

Drying is essentially a process of simultaneous heat and mass transfer. In most drying operations, water is the liquid evaporated, and air is the drying medium. Heat, necessary for evaporation, is supplied to the particles of the material and moisture vapor, evaporated liquid, is removed from the material into the drying medium. Fluidized drying of granular products of solids can be either batch wise or continuous. Batch operation is preferred for small scale production and for heat sensitive materials. Fluidized bed dryers are widely used in a number of industry sectors to dry finely divided 50–5000 μm particulate materials. Compared with other drying techniques, fluidized bed drying offers many advantages. High heat and mass transfer rates between the gas and the particles are possible because of good contact or large contact area between the particles and gas, good and rapid mixing of solids, nearly uniform moisture content distribution throughout the bed, closely controllable temperature in the bed, ease in transport and handling of particles, and simplicity in construction. On the other hand, the disadvantages include high pressure drop, attrition of the solids and erosion of the containing surfaces.

Simmonds et al. [15] experimentally investigated drying of granular products in a circulation dryer and found that the rate of drying was independent of the air velocity in the range of 1.64m/s to 8.74 m/s. The rate of drying was proportional to the free moisture content of the grain, while the grain temperature was related to the moisture content at any certain stage in the drying process. Chandran et al. [16] compared the performance of batch and continuous spiral fluidized bed systems with an ion exchange resin and sand at 105°C. They found that for certain drying time, batch operations gave lower average moisture content. Abid et al. [17] performed an experimental and theoretical analysis on the mechanism of heat and mass transfer during the drying of corn kernels in a fluidized bed. They found that the humidity and velocity of the gas and the external conditions, such as the humidity, had only a small effect on the rate of drying. Hajidavaloo and Hamdullahpur [18] experimentally investigated the drying of wheat. They found that the inlet air temperature had an important effect on the magnitude of the drying rate, while the gas velocity and bed hold-up did not show significant contributions to the drying rate.

The effect of temperature was more critical than that of the other parameters and could reduce the drying time substantially. Thomas and Varma [19] experimentally investigated fluidized bed drying of granular cellular materials and compared the experimental results for batch and continuous fluidized bed drying investigated at different temperatures and flow rates of the heating medium, particle size and mass of solids in a fluidized bed type dryer. As the product is in close contact with the drying air at low temperature, and also for short duration, the physical and chemical properties of the products are generally not affected and therefore the dryer can effectively be used for heat sensitive products. Due to the continuous movements of product during drying, lump formation, case hardening etc. are minimized.

The critical moisture content was found to depend on the velocity and temperature of the heating medium, as well as the particle size and mass of solids, and fluidized drying of cellular food materials appears attractive compared to tray drying and sun drying with respect to drying time and quality of the product.

Watano et al. [20] experimentally studied the drying of wet granules in an agitating fluidized bed type dryer that has a tapered fluidized bed with an agitator blade turning on a central axis installed at the bottom of the cylindrical vessel to impart a tumbling and circulating motion to the granules. The effects of the conditions on the properties of the granules such as the mass median diameter, yield, shape and density of the granules were investigated under various air temperatures, air velocities and agitator rotational speeds. The relationships between the operating conditions and the drying rates were also examined. It was found that the mass median diameter decreases with decreasing air temperature and velocity and with an increase in agitator rotational speed, while the apparent density, shape factor and yield of fine granules increase. It can, thus, be pointed out that slow rotational speed, large air velocity and high air temperature should be selected in order to increase the drying rate. The increasing cost of energy over recent years has prompted and received great attention in order to increase the convective heat transfer rates in the process equipment.

For irregularly shaped grains such as wheat, the modeling is done generally carried out assuming that the grain is a sphere with the same volume as the grain. The wheat kernel is assumed to be spherical with an average diameter of 3.9 mm and a density of 1215 kg/m^3. Efficiency was found to be high at the initial stage of the drying process due to rapid evaporation of the surface moisture of the kernels. But it decreases exponentially during the drying from inside the kernels until the end of the drying process. The moisture diffusion coefficient of wheat is dependent only on temperature [21]. Thus, higher inlet temperatures of drying air can be used which lead to shorter drying times. The enthalpy and the entropy of drying air also increase leading to higher energy efficiency. But increasing inlet air temperature should be limited to obtain good quality dried material. It was experimentally observed by Hajidavalloo [18] that as the inlet air temperature increased the grain temperature also increases. The final temperature of the material after long time spans becomes almost equal to the temperature of inlet drying air.

The advantages of fluidized bed drying are

- The even flow of fluidized particles permits continuous, automatically controlled, large- scale operation with easy handling of feed and product.
- There are no mechanical moving parts, that is, it is low maintenance.
- By rapid exchange of heat and mass between gas and particles, overheating of heat-sensitive products is avoided.
- Heat transfer rates between fluidized bed and immersed objects, such as heating panels, are high.
- Rapid mixing of solids leads to nearly isothermal conditions throughout the fluidized bed, and thus reliable control of the drying process can be achieved easily.
- It can be operated under lower temperatures.

Disadvantages of some fluidized bed dryers [22]:

- In conventional fluidized bed, large column heights are required and formation of channels.
- The principal limitation with the superheated steam drying is the high operating temperature, large equipment like boiler for generating steam, electrical heater for converting saturated steam to super heated steam.
- Agitation fluidized bed dryer consumes high electrical energy for rotation of agitator blade.
- Freeze drying and contact adsorption drying is not suitable for large-scale production because of high operation costs.

CHAPTER 3

EXPERIMENTAL DETAILS

EXPERIMENTAL SETUP FOR HYDRODYNAMIC STUDY

The schematic diagram of experimental setup is shown below.

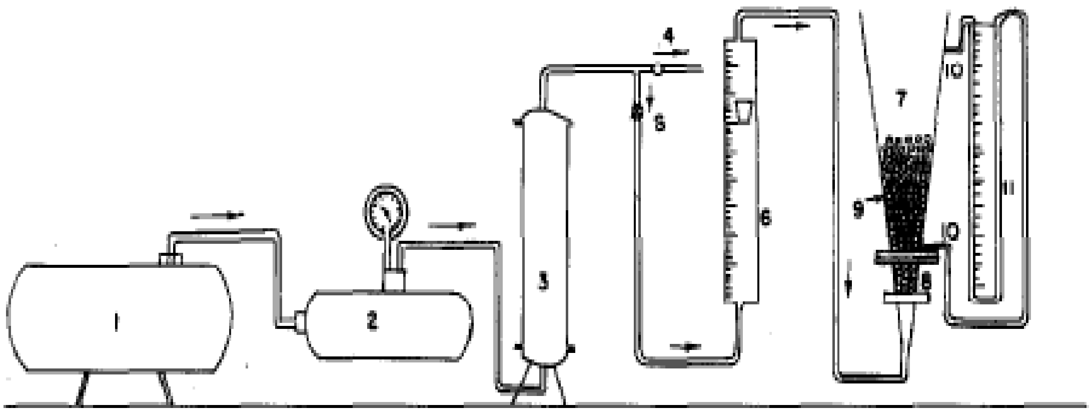


Fig 3.1 -: Experimental set-up. 1, compressor, 2 receiver, 3 silica gel tower, 4 by pass valve, 5 line valve, 6 rotameter, 7 conical fluidizer, 8 bed packing, 9 packing materials in fluidization state,
10 pressure tappings to manometer

CONSTITUENTS OF EXPERIMENTAL SETUP:

The experimental set up consists of the following parts

Air Compressor

It is multistage air compressor of sufficient capacity.

Air Accumulator

It is horizontal cylinder used for storing the compressed air from compressor. There is one G.I. pipe inlet to the accumulator and one by-pass from one end of the cylinder. The exit line also at G.I line taken from the central port of the cylinder. The purpose for using air accumulator in the line is to dampen the pressure fluctuations. The accumulator is fitted with a pressure gauge; the operating pressure in the cylinder is kept at 20psig.

Silica- Gel Column

A silica gel column is provided in the line immediately after the air accumulator to arrest the moisture carried by air from the accumulator.

Pressure Gauge

A pressure gauge in the required range (1-50psig.) is fitted in the line for measuring the working pressure.

Rotameter

Rotameter is used for the measurement of flow rate of air. Two rotameters, one for the lower range (0-20 m^3/hr) and the other for the higher range (20-120 m^3/hr) were used to measure the air flow rates.

Air Distributor

This is an important comment of the experimental setup. It is perforated plate made up of G.I sheet. The pores of 0.5cm diameter are randomly placed in the sheet. The distributor is an integral part of calming section where it is followed by a conical section. The inside hollow space of the distributor filled with glass beads of 1.5cm outer diameter, for uniform air distribution.

Conical Fluidizer

The fluidizers consists of transport Perspex column with one end fixed to flange. The flange has 6 bolt holes of 1.2cm. diameter. Two pressure tapings are provided for noting the bed pressure drop. A screen is provided in the lower flange of the fluidizer and the conical air distributor.

Quick Opening Valve and Control Valve

A globe valve of 1.25cm inner diameter attached to next to the pressure gauge for sudden release of the line pressure. A gate valve of 15mm inner diameter is provided in the line to control the airflow to the bed.

Manometer Panel Board

One set of manometer is arranged in this panel board to measure the pressure drop. Carbon tetrachloride is used as manometric liquid.

APPARATUS

The tapered columns were made of Perspex sheets to allow visual observation. The bottom diameter is 12.1 mm where as the top diameter is 21.96 mm. The reactor height is 20 mm. The tapered angle is 14°. A 60 mesh screen at the bottom served as the support as well as the distributor. The calming section of the bed was filled with glass beads for uniform distribution of fluid. Two pressure taps, one at the entrance and the other at the exit section of the bed were provided to record the pressure drops. Pressure drop was measured by manometer, which was one meter long. Carbon tetrachloride (density=1594 kg m^{-3}) was used as the manometric fluid. Air at a temperature of 26 ^{0}C ($\rho = 1.178$ kg m^{-3} and $\mu = 1.8*10^{-5}$ kg $m^{-1}s^{-1}$) used as the fluidizing medium was passed through a receiver and a silica gel tower to dry and control the air flow before being sent through the tapered column. Two rotameters, one for the lower range (0-20 m^3/hr) and the other for the higher range (20-120 m^3/hr) were used to measure the air flow rates.

MATERIALS USED

In this experimental study, wheat particles and mustard seeds were used as the test material to dry in the tapered fluidized bed dryer. Wheat (Triticum spp.) is an important human food grain. Wheat belongs to the hygroscopic materials group and has a very low mass diffusivity. In other words, wheat exhibits a dominating internal resistance to moisture transport. Wheat grains are classified as D group particles, which contain large particles that have a greater dimension than 1000µm [1]. The wheat kernels, which were tested, are approximately ellipsoidal in shape with average dimensions of 3 * 2.8* 7.5mm. Their density was about 1215 kg/m^3.

Figure 3.2: Wheat

Mustard (Brassica napus Linn) were used in drying to study the effect of particle size on drying in a tapered fluidized bed. Their density is about 1100 kg/m^3. Two different sized seeds of 1.9 mm and 2.15 mm diameter are chosen for the study.

Figure 3.3 : Mustard seeds

PROCEDURE FOR HYDRODYNAMIC STUDY

A weighed amount of material was charged to the bed and air passed through it for about five minutes till the system was stable. The initial stagnant bed height was recorded. Then the velocity of the air was increased incrementally allowing sufficient time to reach a steady state. The rotameter and manometer readings were noted for each increment in flow rate and the pressure drop and superficial velocity calculated. Air flow rate was gradually increased and the corresponding bed pressure drops were measured. When the minimum fluidization was attained, the expanded static bed height was also measured. As the bed fluctuates between two limits of gas-solid fluidization, heights of the upper and the lower surfaces of the fluctuating bed were measured for each fluid velocity higher than the minimum fluidization velocity.

PROCEDURE FOR DRYING

A known weight of the material is taken into the fluidized bed dryer column. The time, temperature and flowrate are set. The power is switched on. The dried material is taken out after the process is over and is weighed. The temperature, time, gas velocities are changed and weights of dried material is noted for three different temperatures, three different drying times, two gas velocities, two sizes of drying material and the results are studied.

TAPERED FLUIDIZED BED DRYER

The gas distributor was 2mm thick with 2mm perforations. A fine wire mesh of 0.2mm openings was spot welded ever the distributor plate to arrest the flow of solids from the fluidized bed into the air chamber. Air from the blower was heated and fed into the air chamber and into the fluidization column. The electrical heater consisted of multiple heating elements of 2 KW rating. The timer is provided in which time can be maintained from 0- 80 min.

Temperature controller

A temperature controller, provided to the air chamber, facilitated the control of air temperature to ± 0.5° C, for the operating range of 40-120° C.

Air movement:

The selection and sizing of a fan to move air through a dryer is very important. The major resistance to the flow of air comes from the grain bed. The pressure drop through the bed support is of lesser effect, particularly for deep beds. The pressure drop across a grain bed is a function of the air velocity and the grain itself. For most situations either axial flow or centrifugal fans are used.

In the tapered fluidized bed dryer, axial flow fan is used. Axial flow fan moves air parallel to its axis and at right angles to the field of rotation of its blades. Axial flow fans can be easily mounted in-line and are relatively inexpensive and are capable of operation against pressure drops of less than 1500 Pa.

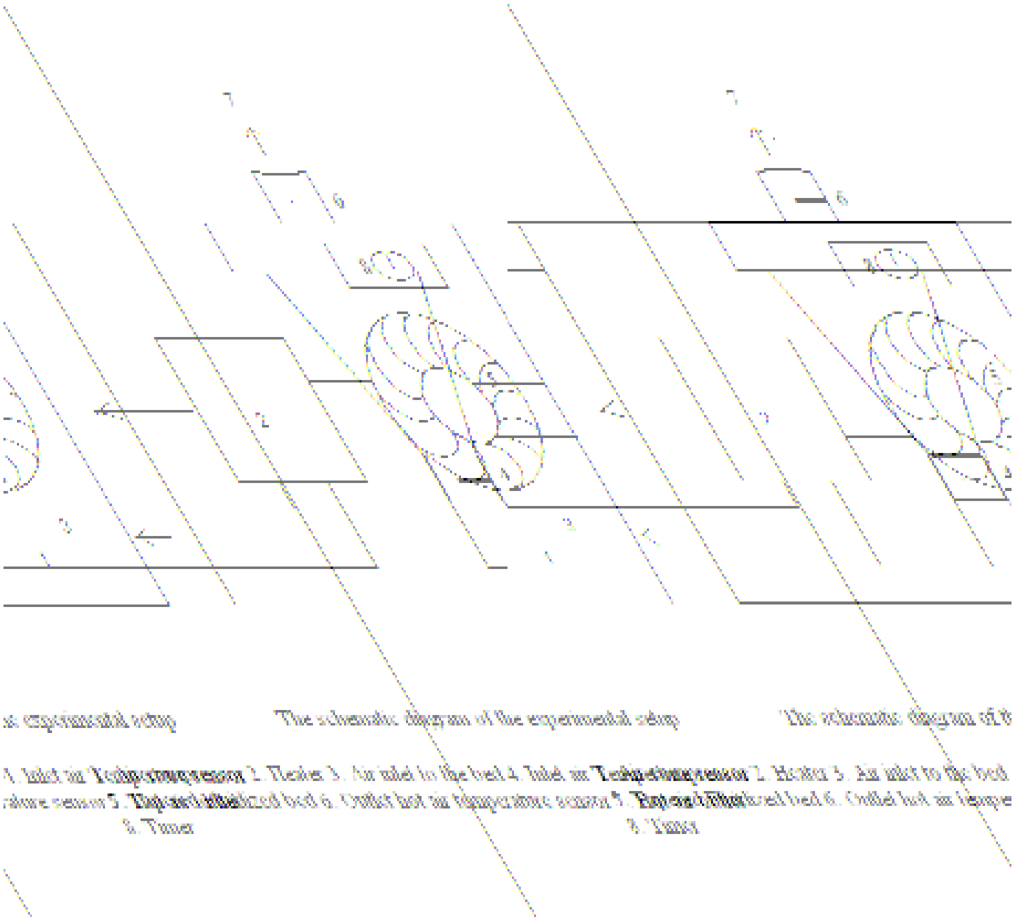


Figure 3.4: Experimental setup for drying

SPECIAL FEATURES OF TAPERED BED DRYER

- Uniformity in drying and reduction in drying time.
- Atmospheric inlet air is filtered by means of multi stage filters and micro filter 0.5 microns to prevent any fine dust to pass through the product.
- Digital temperature indicators cum controller are provided with the unit to indicate the inlet and outlet air temperature as well as to control the present inlet air temperature. Air suction and discharge dampers, provided to control the inlet and outlet air flow. An explosion safety flap of adequate capacity at the rear of dryer and a positive earthing point to prevent static charge in the machine. Timer provided to set the process time which will cut off the motor supply after pre-set time period.

Figure 3.5 : Tapered fluidized bed dryer

CHAPTER4

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

The minimum fluidization velocity and maximum pressure drop for a tapered bed were calculated using the equations (1) and (2).

$$\mathrm{Fr} = 0.2714(\mathrm{Ar})^{0.3197}(\sin\alpha)^{0.6092}\left(\frac{\varepsilon_0}{\varnothing_s}\right)^{-0.6108} \quad \text{------------------}\rightarrow (1)$$

$$\Delta P_{\max} = 7.457\left(\frac{D_1}{D_0}\right)^{0.038}\left(\frac{d_p}{D_0}\right)^{0.222}\left(\frac{H_s}{D_0}\right)^{0.642}\left(\frac{\rho_s}{\rho_f}\right)^{0.723} \quad \text{-----}\rightarrow (2)$$

The hydrodynamic behavior of fluidization in tapered beds is best described by the plot of pressure drop across the bed versus superficial velocity of the fluid at the entrance. Such a plot is shown in Figure 1. From point A to point B, the pressure drop increases with the increase of superficial gas velocity. The transition from fixed bed to partially fluidized bed occurs at point B. From point B, the pressure drop decreases with the increase of superficial gas velocity and from point C it remains constant. Point B to point C is called partially fluidized bed and thereafter it is called fully fluidized bed.

The efficiency of the dryer can be calculated using the equation (3)

$$\eta_e = \frac{W_d\,[\,h_{fg}\,(\Delta M_p) + c_m\,(T_{m2} - T_{m1})\,]}{m^{\cdot}_{da}\,(h_1 - h_0)\,\Delta t} \quad \text{------------------------}\rightarrow (3)$$

The specific heat of the wheat grain[36] is given by the equation (4)

$$c_m = 1398.3 + 4090.2[M_p/(1 + M_p)] \quad \text{---------------------}\rightarrow (4)$$

where M_p is moisture content of grain.

The moisture content, Mp is given by

$M_p = (W_b - W_d) / W_d$ ------------→ (5)

In this study, the drying characteristics of wheat in a fluidized bed were experimentally observed with three different temperatures, three different times of drying, different initial moisture contents and two different gas velocities. The specific heat for the material and efficiency of dryer were calculated for each moisture content, drying time and temperature.

The hydrodynamic aspects e.g. pressure drop and minimum fluidization velocity showed an error of about 6.52%, 5.28% and 2.94% respectively (Table 2) for maximum pressure drop and an error of about 7.65%, 3.2% and 3.78% respectively (Table 3) for wheat and mustard seeds of two sizes. The plots of pressure Vs fluidization velocities are shown in Graphs 1, 2, 3.

Effect of temperature, time and initial moisture content on drying are shown in Graphs 4,5. The effect of temperature and time of drying on dryer performance is shown in Graph 6. The effect of gas velocity on efficiency of drying of wheat is shown in Graph7. The effect of particle size on drying rate for mustard seeds is shown in Graph 8.

The inferences are

1. Effect of Temperature on drying

   As the temperature increases, the drying of the grains also increases. Increasing drying air temperature will increase efficiency on the drying process but there is a practical limitation due to damage of the material caused by the extent of stress cracking. For wheat, the drying temperature should not be more than 65 °C.

2. Effect of drying time

As the drying time increases, the amount of water evaporated increased.

3. Effect of Initial moisture content

The efficiency is slightly higher for the grain material with higher initial moisture content.

4. Effect of gas velocity on efficiency

The increase of gas velocity from 1.95 m/s to 3.8 m/s, shows that it would be advantageous to use air velocity as low as possible.

5. Effect of particle size

An increase in particle size decreases the drying rate. This reduction is due to reduction in surface area per unit weight of solids.

CHAPTER 5

CONCLUSION

CONCLUSION:

The hydrodynamic features of the tapered fluidized bed are very different from those of the columnar fluidized bed; therefore, the known relations for the columnar bed cannot be used in calculating those for the tapered bed. Correlations have been developed for the calculation of critical fluidization velocity and maximum bed pressure drop for binary mixture of regular and irregular particles in gas-solid system in tapered beds. The experimental values for gas-solid systems in tapered beds were found to fit well with the proposed correlations. This indicates that the proposed correlations is valid and are of practical use. The average absolute percentage errors are within 10%, it needs more work to improve the working conditions and to minimize the errors.

In this study, the drying characteristics of wheat in a fluidized bed were experimentally observed with three different temperatures, three different times of drying, different initial moisture contents and two different gas velocities. Temperature has a more important effect on the drying when compared with that of the mass flow rate. That is, the mass flow rate of air has not played an important role on drying performance as much as the temperature, since moisture extraction rate is only slightly enhanced by an increase in air mass flow rate when compared with an increase in temperature. Thus, in order to increase the drying performance, the higher air temperatures should be preferred rather than higher air mass flow rates. However, further work is required for developing the model equations for drying and determining the optimal conditions of drying.

APPLICATIONS:

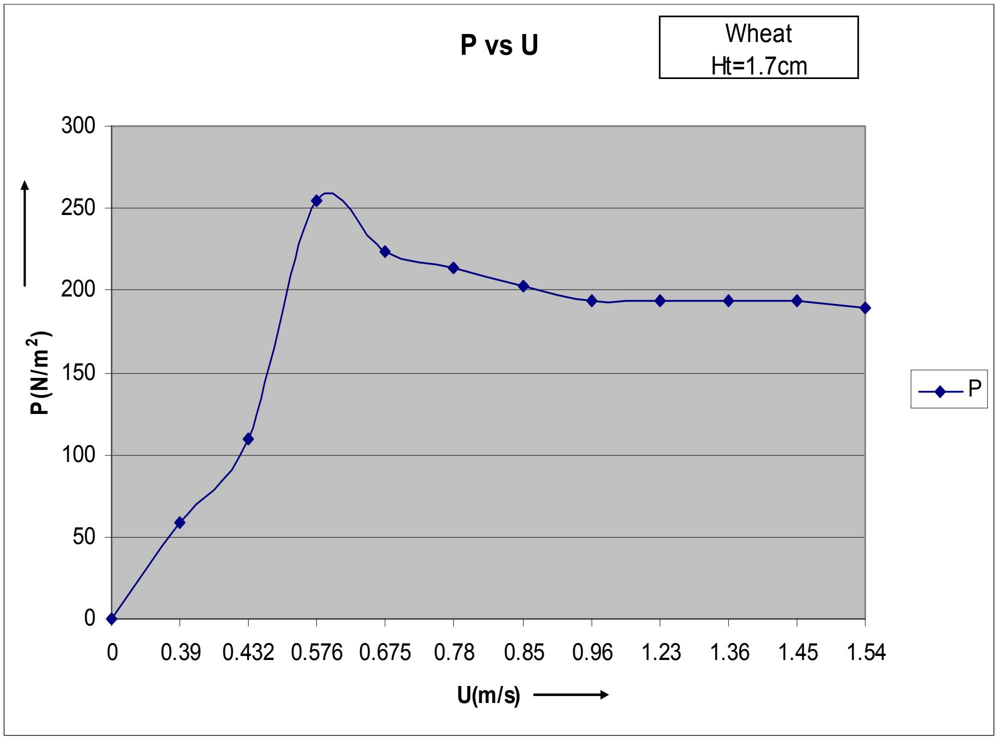
The study is helpful in using the tapered fluidized bed dryer in the

1. Drying of cereal grains
2. Drying of food products
3. Replacement of conventional fluidized bed with the tapered fluidized bed for drying purposes in biological applications.

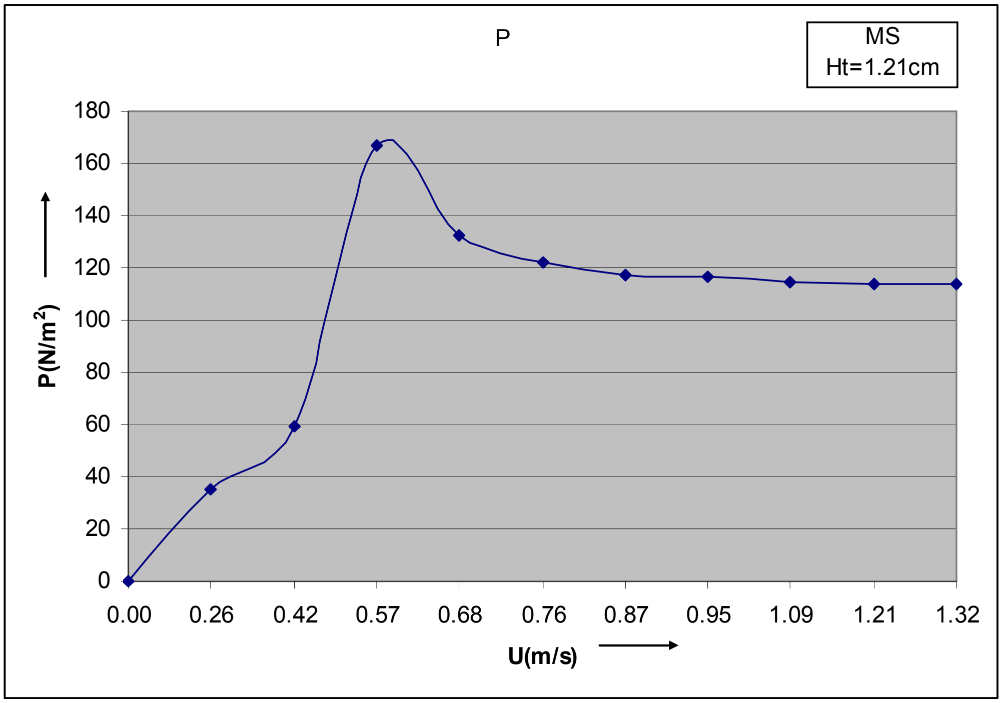
CHAPTER 6

GRAPHS

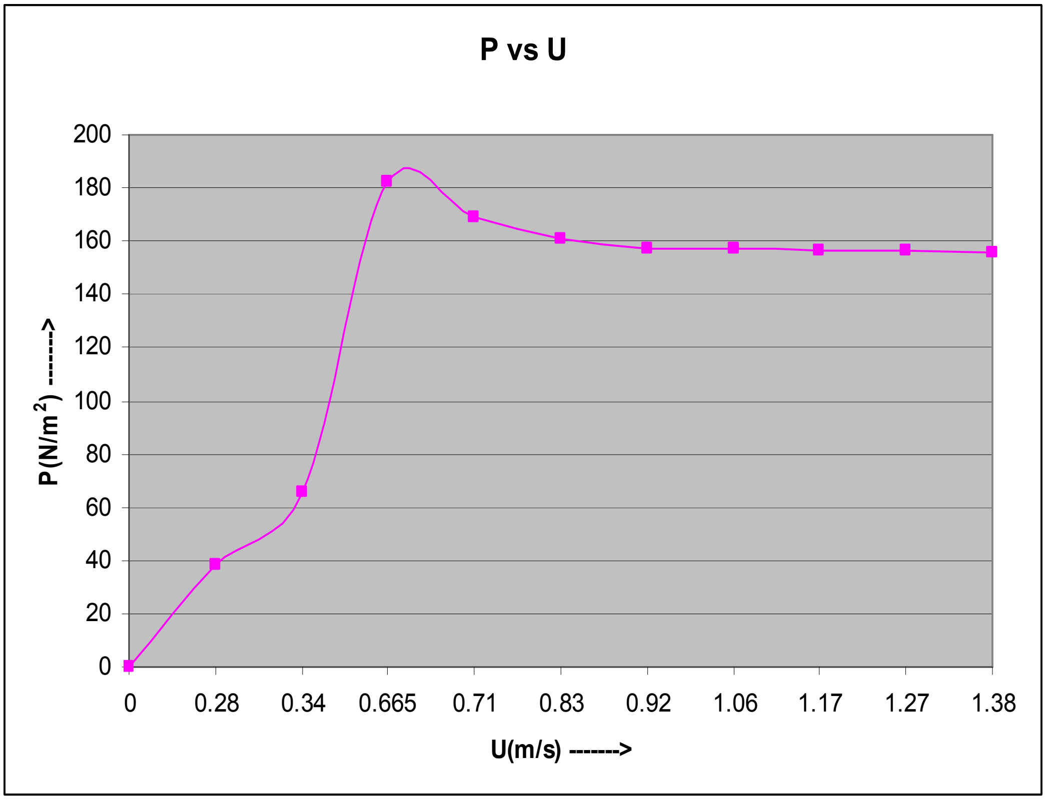
GRAPHS:



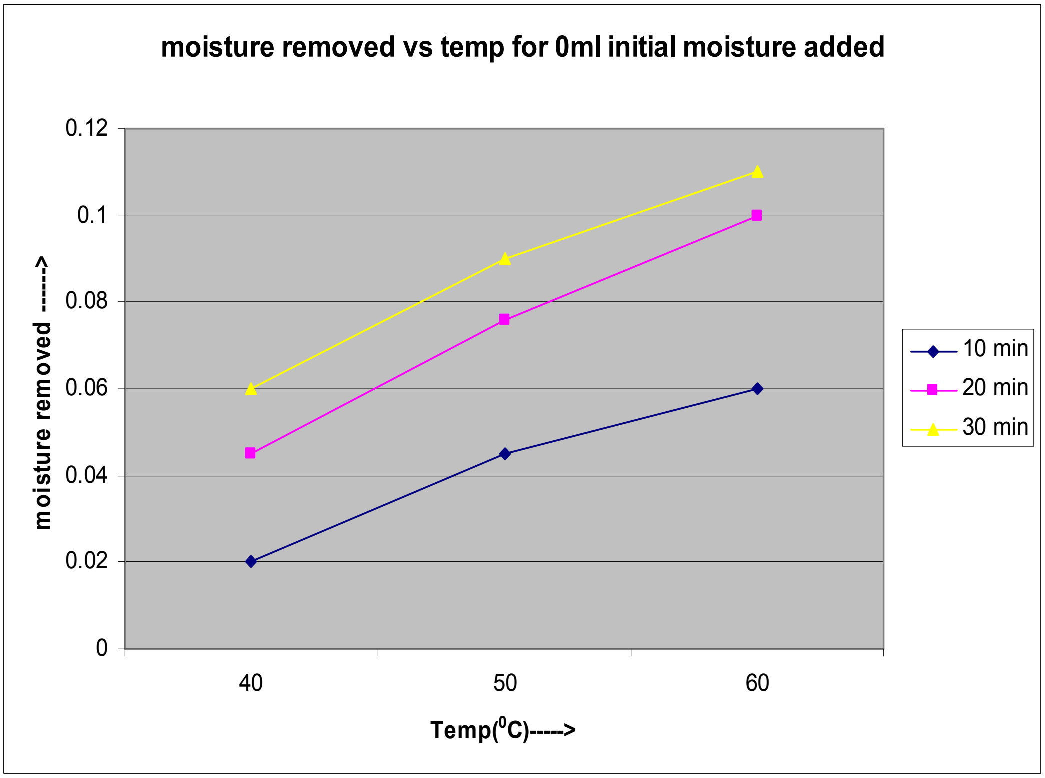
Graph 1: Pressure drop Vs Fluidization velocity for Wheat grains



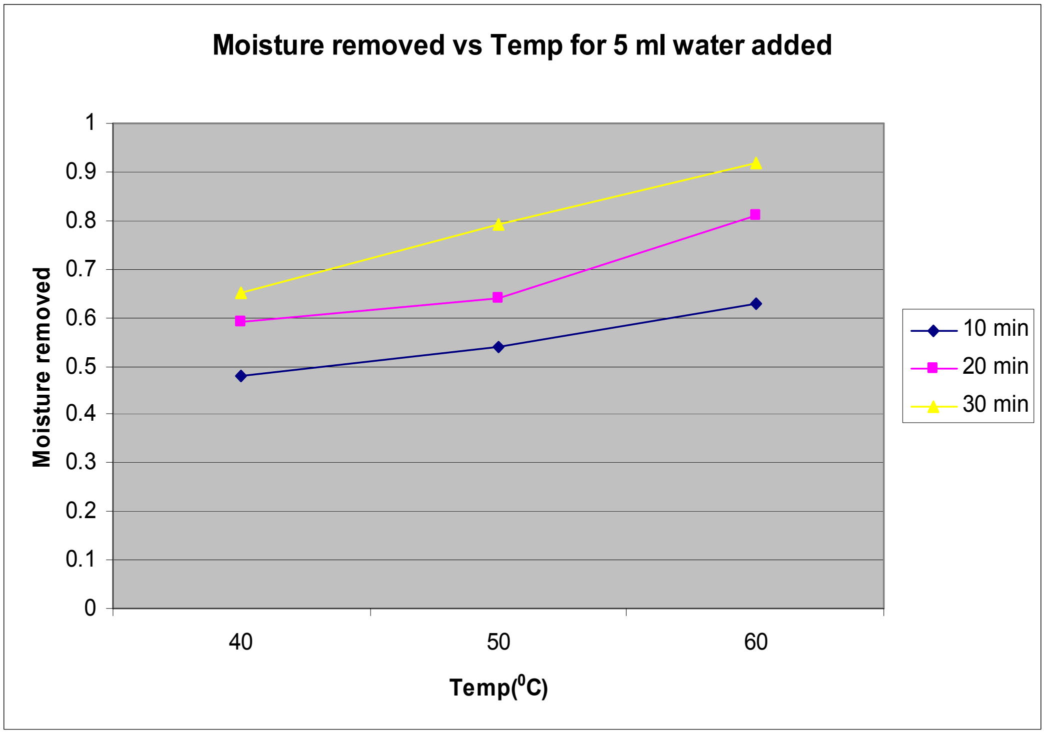
Graph 2: Pressure drop Vs Fluidization velocity for mustard seeds of diameter 1.9mm



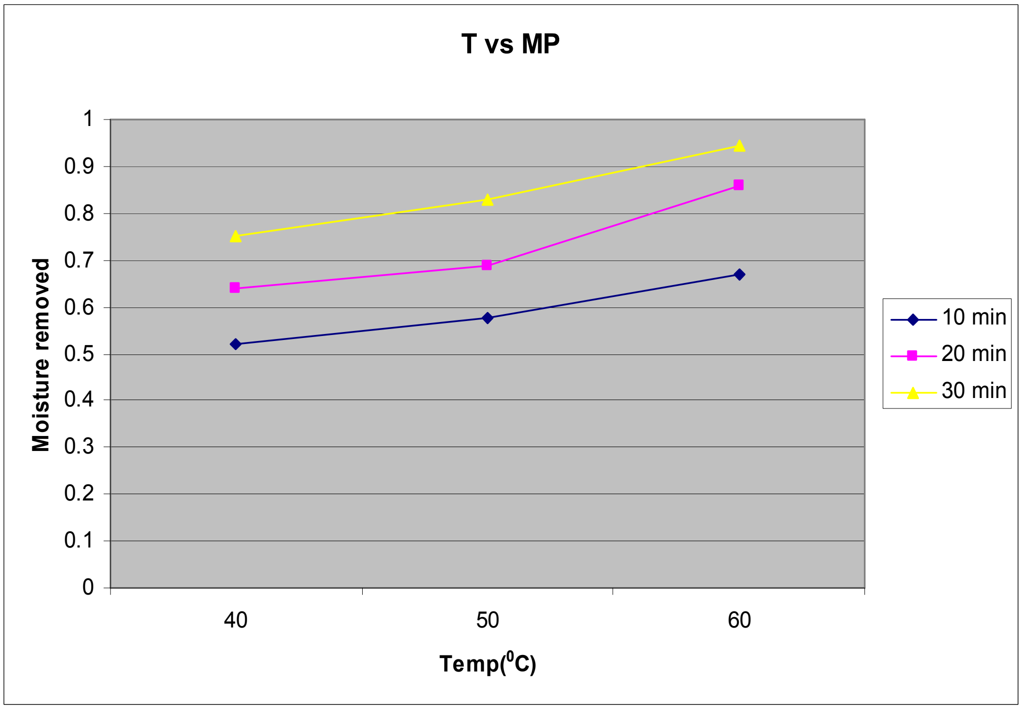
Graph 3: Pressure drop Vs Fluidization velocity for mustard seeds of diameter 2.15 mm



Graph 4:

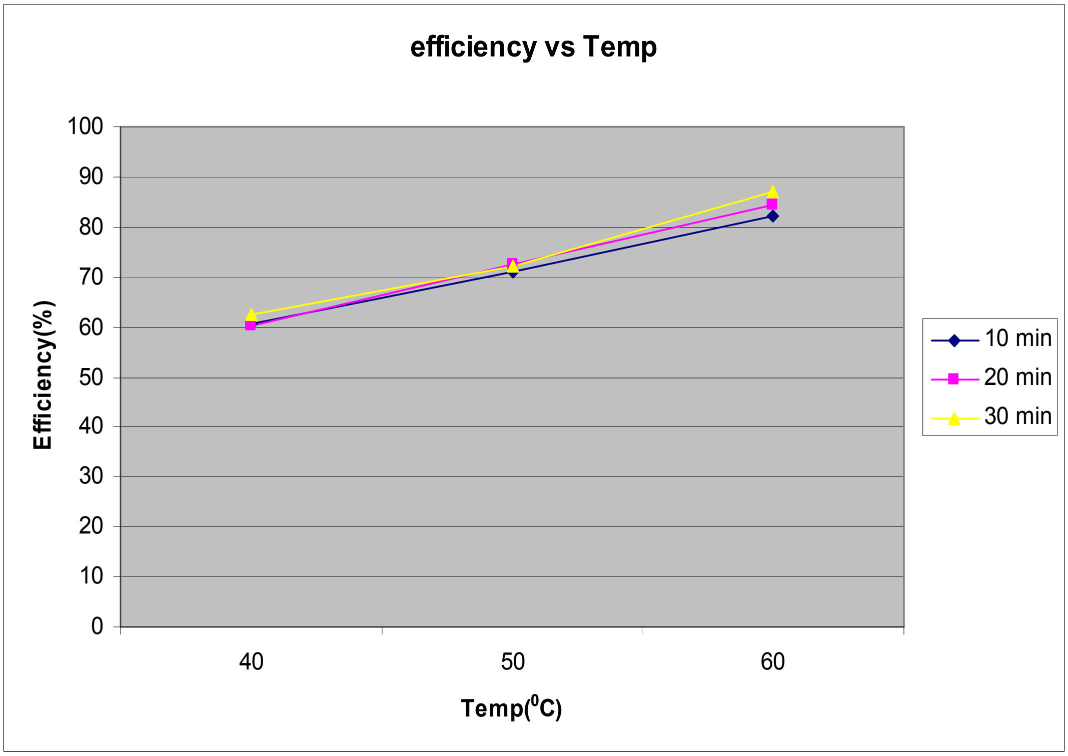


Graph 5:

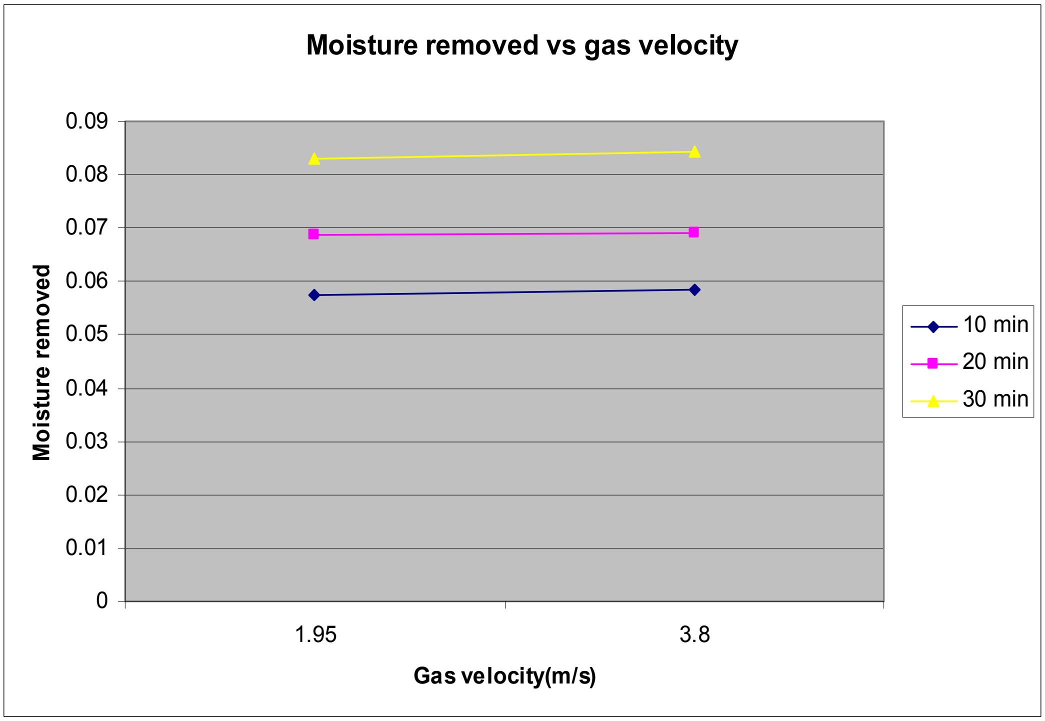


Graph 6

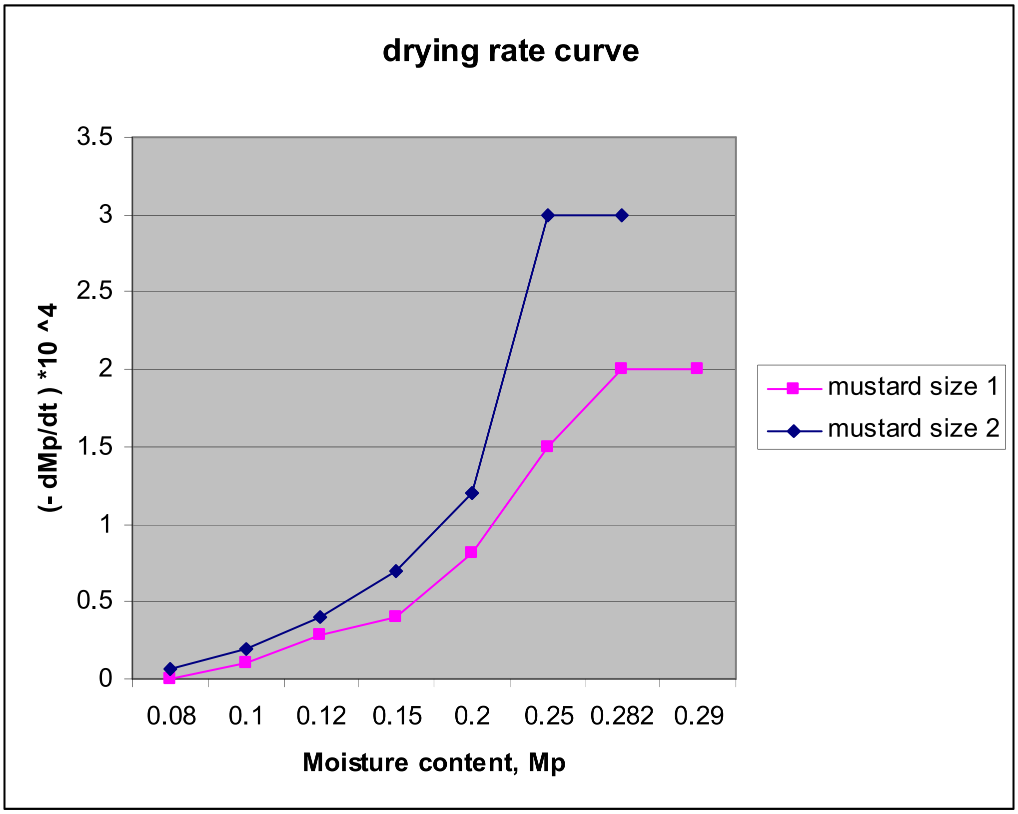
Graph 4, 5 & Graph 6: Effect of temperature, time and initial moisture content on drying



Graph 7: Effect of temperature and time on drying in a tapered fluidized bed drying



Graph 8: Effect of gas velocity on moisture removed



Graph 9: Effect of particle size on drying rate for mustard seeds

CHAPTER 7

TABLES

TABLES

Table 1: Properties of particles

Material	Diameter (mm)	Density (kg/ m^3)
Wheat grains	3.9	1215
Mustard seeds	1.7-2.15	1100

Table 2: Minimum fluidization velocity experimental Vs predicted

Material	Experimental (m/s)	Predicted (m/s)	Error (%)
Wheat grains	0.756	0.71	6.52%
Mustard seeds (1.9mm diameter)	0.568	0.54	5.28%
Mustard seeds (2.15mm diameter)	0.665	0.646	2.94%

Table 3: Maximum Pressure drop experimental Vs predicted

Material	Experimental	Predicted	Error (%)
Wheat grains	265.5	244.98	7.65%
Mustard seeds(1.9 mm diameter)	167.13	161.95	3.2%
Mustard seeds(2.15 mm diameter)	182.45	175.83	3.78%

NOMENCLATURE

D_0	Bottom diameter of the tapered fluidized bed, m
D_1	Top diameter of the tapered fluidized bed, m
D_p	Particle diameter, m
U	superficial velocity of the fluidizing fluid, m/s.
U_{mf}	minimum fluidization velocity based on bottom diameter of the bed, m/sec.
G_f	mass velocity of fluid at fluidization condition, kg/m-hr
G_{mf}	mass velocity of fluid at minimum fluidization condition, kg/m-hr
g	gravity , ms^{-2}
h_1	specific enthalpy at inlet, kJ/kg
h_2	specific enthalpy at outlet, kJ/kg
Hs	initial stagnant height of the particle bed, m
U_c	critical fluidization velocity based on the diameter of entrance of the bed, ms^{-1}
ΔP_{max}	maximum pressure drop through the particle bed (Pa)
h_{fg}	Latent heat of vaporization of wheat, kJ/kg water
c_m	specific heat of the material, kJ/ kg.K

Greek letters

ρ_f	fluid density, kg/m^3
α	tapered angle, deg
μ_f	fluid viscosity, kg m^{-1} s^{-1}
ρ_s	solid density, kg/m^3

REFERENCES:

1. M.Olazer, M.J.San Jose, A.T.Aguayo, J.M.Arandes, J.Bilbao, Pressure drop in conical spouted beds, The Chemical Engineering Journal 51 (1993) 53 – 60
2. Peng.Y, Fan L.T., Hydrodynamic characteristics of fluidization in liquid-solid tapered beds, Chemical Engineering Science, vol 52, no 14, 1997, p 2277 – 2290.
3. Ridgway. K, The tapered fluidized bed—a new processing tool, Chem. Process. Eng. 6 (1965) 317–321.
4. A.E. Gorshtein, I.P. Mukhlenov, Hydraulic resistance of a fluidized bed in a cyclone without a grate. II. Critical gas rate corresponding to the beginning of a jet formation, Zh. Prikl. Khim. (Leningrad) 37 (1964) 1887–1893.
5. Shi Y.F., Yu Y.S., Fan L.T., Incipient fluidization condition for a tapered fluidized bed, Ind. Eng. Chem. Fundam. 23 (1984) 484–489.
6. Biswal K.C., Bhowmik T., Roy G.K., Prediction of minimum fluidization velocity for gas–solid fluidization of regular particles in conical vessels, Chem. Eng. J. 30 (1985) 57–62.
7. Biswal K.C., Bhowmik T., Roy G.K., Prediction of pressure drop for a conical fixed bed of spherical particles in gas–solid systems, Chem. Eng. J. 29 (1984) 47–50.
8. Biswal. K.C, Samal B.B., Roy G.K.(1984), ‘Dynamics of gas-solid fluidization of regular particles in conical vessels’, The Journal the IE (India), Vol. 65, CH-1, 15 -17.
9. Jing S., Hu Q., Wang J., Jin Y., Fluidization of coarse particles in gas–solid conical beds, Chem. Eng. Process. 39 (2000) 379–387.
10. Shan J., Guobin C., Fan M., Yu B., Jingfu W., Yong J., Fluidization of fine particles in conical beds, Powder Technology 118 (2001) 271 – 274.

11. Depypere F., Pieters J.G., Dewettinck K., Expanded bed height determination in a tapered fluidized bed reactor, Journal of Food Engineering 67 (2005) 353 – 359.
12. R L Levey, A D L Garga, S C Jacobs, H M Heidt and D E Trent. 'Fluid Bed Conversion of UO_3 to UF_4', Chemical Engineering Progress, vol 56, no 3, 1960, p 43.
13. Maruyama T and Koyanagi T, Fluidization in Tapered Vessels, Chemical Engineering Journal, vol 52, 1993, p 121.
14. Singh R.K., Suryanarayana A., Roy G.K., Prediction of minimum velocity and minimum bed pressure drop for gas–solid fluidization in conical conduits, Can. J. Chem. Eng. 70 (1992) 185–189.
15. Simmonds W.H.C, Ward G.T, McEwen E, The drying of wheat grain, Part 1: The mechanism of drying, Trans Inst Chem Eng 1953; 32:265–78.
16. Chandran A.N, Subba Rao S, Varma Y.B.G, Fluidized bed drying of solids, AIChE J 1990; 36(1):29–38.
17. Abid M, Gibert R, Laguerie C, An experimental and theoretical analysis of the mechanisms of heat and mass transfer during the drying of corn grains in a fluidized bed, Int Chem Eng 1990; 30(4):632–42.
18. Hajidavaloo E, Hamdullahpur F, Thermal analysis of a fluidized bed drying process for crops. Part 2: Experimental results. Int J Energy Res 2000; 24:809–20.
19. Thomas P.P, Varma Y.B.G, Fluidized bed drying of granular food materials, Powder Technology 1992; 69:213–22.
20. Watano S, Yeh N, Miyanami K, Drying of granules in agitation fluidized bed, J Chem Eng Japan 1998; 31(6):908–13.
21. Analia. L. Gaston, Argentina, 'Wheat drying kinetics. Diffusivities for sphere and ellipsoid by finite elements'.
22. Srinivasa Kannan C., et. al Drying of solids in Fluidized beds, Department of Chemical Engineering, IIT Madras, Journal of Industrial Engineering Chem Res., 1995, Vol 34, no 9, p 3068-3077.

23. Ambrosio M.C.B., et. al The Drying of solids in a modified fluidized bed, Brazilian Journal of Chemical Engineering, Vol 10, No.3, pp 355-358, July – Sept 2002.
24. Ozbey M., Soylemez M.S., Effect of swirling flow on fluidized bed drying of wheat grains, Energy Conversion and Management 46 (2005) 1495–1512.
25. Arun .S. Mujumdar, Handbook of Industrial Drying, Third edition, 'Grain drying', pg 563- 574, 'Grain property Values and Their measurement', pg 575-604.
26. Second law analysis of drying: - modeling and simulation of fluidized bed grain drying, drying 2004 – proceedings of the 14th international drying symposium (ids 2004) são paulo, brazil, 22-25 august 2004, vol. a, pp. 301-308.
27. H.A. Becker, A study of diffusion in solids of arbitrary shape, with application to the drying of the wheat kernel, J. Appl. Polym. Sci. 1 (2) (1959) 212–226.
28. Geldart D. Gas Fluidization technology, New York, Wiley, 1986.
29. Kazarian EA ; Hall CW (1965) Thermal properties of Grain. Trans of the ASAE 8 : 33-37.