BATCH DRYING STUDIES OF SOLIDS IN A MULTIPLE DRAFT TUBE SPOUTED BED

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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D E C L A R A T I O N

I hereby *declare* that the Research Thesis entitled **"Batch drying studies of solids in a multiple draft tube spouted bed"** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in the Department of Chemical Engineering, is a *bonafide report of the research work carried out by me*. The material contained in this Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify that the Research Thesis entitled **“Batch drying studies of solids in a multiple draft tube spouted bed”** submitted by Mr. Rajshekhara S (Register Number: 135027CH13F03) as the record of the research work carried out by him, is *accepted as the Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy.**

Research Guide

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ABSTRACT

Solids drying is a unit operation carried out with solids either in immobile state (as packed bed) or in an agitated state. Since this operation involves simultaneous transfer of heat and mass, it will be beneficial when the bed of solids is kept in continuous circulation in order to improve the transfer rates. Freshly harvested agricultural grains are typically coarse, granular and fibrous in nature. Fluidised beds and spouted beds can be considered for drying solid materials. However, when coarse granular solids like agricultural grains, whose particle sizes are more than 1mm, fluidised beds are not efficient, whereas spouted beds seem to be more suitable.

A conventional Spouted Bed (CSB) have some inherent limitations for scale up. A Multiple Spouted Bed (MSB) can handle larger capacities and provision of draft tubes (DTs) in the bed can help in overcoming the limitation of maximum spoutable bed depth(MSBD). In addition, DTs act as vertical baffles to avoid hydrodynamic instability of MSB when it is to be operated at higher gas velocities as well as help in achieving better control of gas residence times and solids cycle times. Presence of holes on DTs leads to movement of gas into annulus, which will be useful in an operation like solids drying.

A multiple porous draft tubes spouted bed (MPDTSB) was considered as a gas-solid contactor for carrying out experimental studies on grain drying. The focus of this research work was to find the applicability of proposed design of the contactor as a grain dryer and consider it for scale up to large-scale application. In addition, two different single porous draft tube spouted bed (SPDTSB) dryers were used for comparing the performance of multiple and single spouted bed dryers.

Drying experiments were carried out using ragi (*Eleusine coracana*), barley and wheat grains at temperatures of 40,45, 50, 55 and 60 ^{0}C, inlet air flow rates of 30, 33 and 36 m^3/h. The initial moisture contents of grains used were 0.15, 0.20, 0.25, 0.30 and 0.35 kg moisture/ kg dry solids with bed mases varying between 1 and 8 kg. The fluid inlet sizes used were 8, 15 and 21 mm. Three different draft tubes having inside diameters of 21, 26 and 39 mm having hole sizes of 2 and 4 mm were used in the study. Also, non-porous draft tubes were used in the study.

The batch drying times, moisture diffusivities in grains, thermal efficiencies and gas - solid heat transfer coefficient were evaluated. They were influenced by the operating

variables, design variables and properties of grains. In addition, the performance of multiple porous draft tube spouted bed dryer was compared with the performance of two different single porous draft tube spouted bed dryers. Using the experimental data an empirical equation was proposed to predict batch-drying times in MPDTSB.

The following important conclusions could be drawn based on the results obtained in this study.

- It was possible to overcome MSBD limitation and larger bed masses could be handled in multiple porous draft tube dryer.
- The operating parameters influenced the batch drying time. A higher air inlet temperature and air rate resulted in lower batch drying times.
- The batch drying time would decrease with increase in draft tube diameter and hole size/ area.
- Porous draft tubes helped in reducing the batch drying time.
- Batch drying time decreased as the fluid inlet size decreased for a given bed mass.
- The moisture diffusivities were found to be dependent on both operating and design variables of the dryer.
- The thermal efficiencies and gas-solid convective heat transfer coefficients for MPDTSB were found to be higher when compared to those for SPDTSBs.
- The overall performance of the proposed design of Multiple Porous Draft Tube Spouted Bed seemed to be good for solids drying. Scale up of this design for large-scale operations should be possible.

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NOMENCLATURE

CSA	Cross Sectional Area
CSB	Conventional Spouted Bed
DT	Draft Tube
DT ID	Draft Tube Inner Diameter
MSB	Multiple Spouted Bed
MPDTSB	Multiple Porous Draft Tube Spouted bed
NPDT	Non-Porous Draft Tube
SPDTSB	Single Porous Draft Tube Spouted bed
a_s	Specific surface area, m^2/kg
a_v	Specific grain surface m^2/m^3
C_H	Humid heat KJ/Kg dry air, K
C_{ps}	Specific heat capacity, KJ/Kg ^0C
D_{eff}	Effective diffusivity coefficient
d_i	Fluid inlet diameter, mm
d_h	Hole diameter, mm
d_t	Draft tube diameter, mm
d_p	Particle size, mm
E_f	Thermal efficiency, %
h_T	Gas – Solid heat transfer co-efficient, W/m^2K
m_b	Bed mass, kg
R	Universal gas constant J/mol K
t_d	Drying time, Seconds
T_a	Inlet air temperature, °C
T_{av}	Average outlet air temperature, ^0C
T_s	Solid temperature, °C
v_o	Air flow rate, m^3/h
W_a	Mass flowrate of inlet dry air, kg/h
W_s	Mass of dry sample, Kg
X	Moisture content of the solids, kg Moisture/kg bone dry solids

X_0	Initial moisture content of the solids, kg Moisture/kg bone dry solids
Xe	Equilibrium moisture content of the solid, kg Moisture/kg bone dry solids
X_f	Final moisture content of the solids, kg Moisture/kg bone dry solids
λ_g	Latent heat of vaporisation of sample, KJ/Kg

CHAPTER 1

INTRODUCTION

Solids drying involves removal of a relatively small quantity of liquid from a solid material. It is a unit operation involving simultaneous heat and mass transfer, where heat transfer occurs from a hot gas to the solids such that the liquid present in the solids gets evaporated and vapour gets carried away by gas. In most cases the liquid happens to be water and the gas is air. This operation is carried out typically as a final step to maintain the product quality during storage or packing. This operation is used in industry to dry materials like soaps, detergents, dyestuffs, fertilizers, drugs, pharmaceuticals, biological materials and agricultural grains. It may be carried out either at ambient pressure, under vacuum, or as freeze drying. Batch as well as continuous operations are used in industrial practice.

The solids to be dried may be in different forms, having widely differing liquid contents as well as other properties; these include powders, crystals, granular flakes, slabs or sheets. In general, these solids may be divided into two major classes on the basis of their drying behaviour. (Foust, *et al*. 1981)

I. Granular or crystalline solids
II. Amorphous, fibrous or gel like solids

The solids in Class I hold moisture in the interstices between particles or in shallow open surface pores; the moisture movement in the solids is relatively unhindered and occurs as result of interplay of gravitational and surface tension or capillary forces. The materials in this class are usually inorganic in nature and are relatively unaffected by the presence of liquid and therefore are largely unaffected by the drying process; as a result, drying conditions can be chosen on the basis of convenience and economics without worrying about the effect of operating conditions on properties of the dried products.

Most organic products fall into Class II; these materials hold liquid or moisture as an integral part of the solid structure or trapped within the fibrous structure or within the fine interior pores. The moisture movement in these solids is slow and probably occurs by molecular diffusion through the structure of solids. As a result, the drying curves of these materials show very short constant rate periods, ending at high values of critical moisture content. Since the water/liquid is the integral part of the solid structure these materials are affected by the removal of liquid or moisture. The surface layer tends to dry more rapidly than the interior. If the drying rate is high it may cause such differences in moisture content through the solid that warping or cracking can occur; in other cases, it may cause formation of a relatively impervious and partly dry shell, which can further inhibit drying in the interior portion of solid structure and as a consequence the solids may deteriorate. Because of this behaviour, the conditions under which the drying is carried out are critical for this class of solid materials. So the operating conditions for drying these solids need to be chosen keeping the product quality in mind, and operating convenience and economics obviously becomes secondary. All the agricultural grains fall into this class. The freshly harvested agricultural grains typically contain about 30 – 35% moisture and they are to be dried to about 13% moisture for safe storage (Cruz and Diop. 1989).

The Relative Humidity (RH) of air is an important variable in solids drying operation. When solids having a given moisture content are exposed to a large quantity of air having a constant temperature and humidity for a sufficiently long period, the solids attain a constant value of moisture, and it is referred to as Equilibrium Moisture Content (EMC). The EMC will greatly vary with the type of material for a given RH.

Agricultural grains are typically hygroscopic in nature and will lose or gain moisture until equilibrium is reached with the surrounding air. The relationship between EMC, RH and temperature for various agricultural grains are reported in literature (Brooker et al, 1976). Under no circumstances, it is possible to dry given solids to a moisture content lower than the EMC associated with temperature and humidity of the drying air.

Heat supply is necessary in a drying operation to evaporate moisture from the grain and air flow over the solids is needed to carry away the evaporated moisture. Basically, two mechanisms are involved in drying process - the migration of moisture from interior of grains to the grain surfaces and evaporation of moisture from the surfaces to the surrounding air. The rate of drying is determined by the moisture content of solids and temperature of the grains, as well as the temperature, relative humidity and velocity of the air in contact with the grains. Drying occurs under constant - rate conditions initially, followed by a falling - rate period. Convective mass transfer plays an important role when drying occurs under constant-rate conditions, whereas under falling-rate conditions mass transfer occurs by molecular diffusion. However, in the case of agricultural grains drying occurs mostly under falling-rate conditions.

Freshly harvested agricultural grains are typically coarse, granular and fibrous in nature. These materials contain fixed amounts of initial moisture which need to be reduced to specified levels for safe storage. In order to avoid damage of these grains they are to be dried at specified temperatures. The initial moisture contents, maximum temperature to be used for drying and the desirable final moisture contents for storage are reported in literature (Tiwari and Mishra, 2011).

Solids drying may be carried out keeping the wet solids either in a packed state as in the case of tray driers and tunnel driers, or in an agitated state like in rotary driers, fluidized bed driers and spouted bed driers. The choice of an appropriate drier depends on factors like properties of the solids to be dried, operating conditions to be used, operational convenience, energy efficiency and economics.

Since the solids drying operation involves transfer of both heat and mass it will be beneficial to keep the solids in an agitated state to achieve higher transfer rates of heat and mass. So, fluidized beds and spouted beds can be considered for solids drying.

1.1 Fluidized beds

In chemical process industries fluidized beds are widely used as fluid - solid contacting devices to carry out several unit operations and unit processes and one such application is drying of solids. The fluidized bed driers are used to dry solid materials like Chinese lignite coal, sawdust, sand, semolina, baker’s yeast, ammonium chloride, ammonium sulphate, silica gel, zeolite etc. When relatively finer solids (less than 1 mm size) are to be dried, fluidized beds are perhaps suitable. However, when coarse granular solids like agricultural products, whose particle sizes are more than 1mm, fluidized beds are not efficient. Gas – solid systems typically lead to aggregative fluidization, where in problems like bubble formation, segregation, slugging is encountered. As a result, fluid-solid contact becomes poor leading to low rates of heat and mass transfer and the process becomes inefficient. As the solids to be processed become coarser these problems can become more acute. It is in this context spouted bed becomes useful as an efficient fluid-solid contacting device, when the granular particulate solids are coarser (above 1 mm size). In fluidized beds the minimum fluidization velocity is independent of static bed height as well as vessel diameter, but it is influenced by the properties of fluid and solids. However, the bed pressure drop depends on bed height as well as the properties of the fluid and solids. These two hydrodynamic parameters are important in the context of design and operation of fluidized beds.

1.2 Spouted beds

The spouted bed technique was developed by Mathur and Gishler (1955). It was originally developed to dry wheat and later found to be useful to carry out several other operations (Mathur and Epstein 1974, Epstein and Grace 2011).

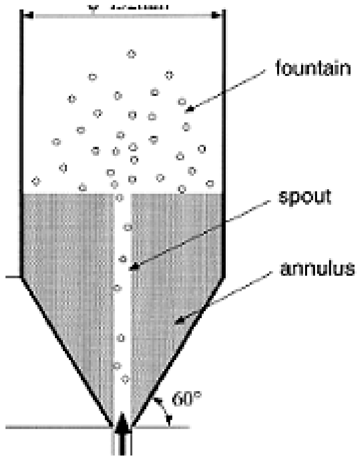


Figure 1.1. Spouted bed

As shown in Fig. 1.1 it consists of a central core called **spout**, a surrounding annular region called **annulus**, and solids above the bed surface entrained by the spout; the region where the solids above the bed surface are entrained by the gas and then fall into the annular region is referred to as **fountain**. A systematic recirculation of solids and absence of any bubble formation or slugging in the bed are typical features of a spouted bed. A spouted bed may be constructed using a circular column fitted with a conical bottom and the fluid inlet located at the cone apex; the role of conical bottom is essentially to avoid stagnancy of solids at the bottom of the vessel. It is also possible to have a rectangular or square column or an entirely conical vessel to achieve spouting. The minimum spouting velocity as well as spouting pressure drop depends on vessel diameter, fluid inlet size, static bed height and properties of fluid and solids. In addition, a stable bed operation is not possible beyond a static bed depth called "**maximum spoutable bed depth**" (MSBD), which is a typical characteristic of a conventional spouted bed (CSB). Such a maximum limit does not exist in the case of fluidized beds.

1.3 Draft tube spouted beds

In a CSB the spout has direct contact with annular solids over entire height of the bed and as a result continuous percolation of gas from the spout region to the annular region exists. If the operational bed height is larger than the MSBD, the spout cannot support the bed leading to its collapse and the bed transforms into a poor quality fluidized bed (Berghel and Renström 2014). However, when a draft tube is axially located in the bed the spout can efficiently become a vertical transport riser thereby overcoming the MSBD limitation and it becomes useful for large scale operations. Also, a draft tube helps to achieve an accurate control of fluid residence time as well as solid cycle time(Sahoo et al. 2011).

1.4 Multiple spouted beds

The commercial scale processes would generally require larger capacities and single spout beds are not suitable for large scale operations. From the economic view point, the fixed cost of one large bed would be lower than that of a set of smaller units having the same throughput as pointed out by Mathur and Epestein (1974); they also mentioned that two factors would weigh against the single spout bed of very large capacity.

- The large bed height required for effective spouting in a large diameter column (Height/column diameter = 2 – 3) would call for a gas supply at a correspondingly high discharge pressure.
- The particle cycle times would be longer in large deep beds, which are undesirable in certain operations like drying of heat sensitive solids.

An alternative to overcome these limitations, Mathur and Epstein (1974) suggested the use of multiple fluid inlets within the same bed as shown in Fig.1.2. There are several investigations related to multiple spouted beds reported in literature, which are discussed in Chapter 2.

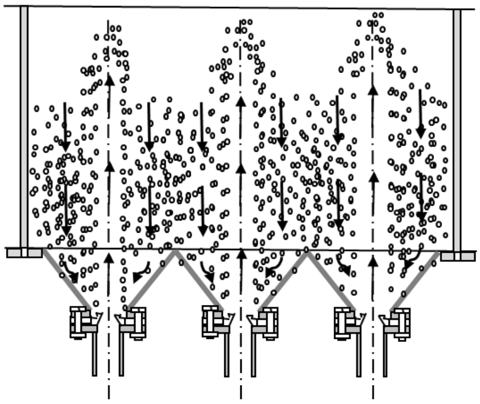


Figure 1.2. Multiple spouted bed

CHAPTER 2

LITERATURE REVIEW

Solids drying is a unit operation which may be carried out with solids either in immobile state (as packed bed) or in an agitated state. Since this operation involves simultaneous transfer of heat and mass it will be beneficial when the bed of solid are kept in continuous circulation in order to improve the transfer rates. The fluid in a fluidized bed and spouted bed keeps the solids in a constant motion and these contactors can be used for solids drying. These two devices have the potential to be used for drying of agricultural grains and food materials. Since the objectives of this research work was to study the suitability of a proposed design for large scale grain drying application, the review presented here focuses on literature related to fluidized beds and spouted beds.

2.1 Fluidized beds

Fluidized beds are widely used for solids drying and a considerable volume of literature is available on fluidized bed dryers. A few works reported in literature during the last 15 years are discussed here.

Inprasit and Noomhorm (2001) used a 10 t/h capacity fluidized bed dryer for drying paddy and studied the effect of drying temperature, exposure time and water removal rate on rice quality, head rice yield and water absorption.

Jenkins et al. (2002) assessed the performance of fluidised bed dryer by drying saturated zeolite pellets. The drying was reported to be faster than in conventional fan assisted oven.

Senadeera et al. (2003) studied the influence of shapes of selected vegetable materials on drying kinetics during fluidised bed drying. They reported the drying to take place in falling rate period for all the materials they studied. Page model described the drying behaviour more accurately. The drying constant values for peas were reported to be lower than beans and potatoes.

Mujumdar (2004) summarized about fluidized bed dryers in his article on Research and Development on Drying.

Rordprapat et al. (2005) studied the fluidised bed drying of paddy using hot air and super-heated steam. Steam provided superior heat transfer and condensation in early stages and aided in better gelatinisation; as a result, it was possible to obtain better head rice yield than that dried by hot air. Whiteness of paddy dried by super-heated steam was lower than that dried by hot air.

Wiset et al. (2005) studied the effect of high temperature drying on physicochemical properties of various cultivars of rice in a fluidized bed dryer. They reported that among the quality parameters considered the head rice yield appeared to increase with drying temperature, but the yellowing showed the opposite trend without significantly affecting the appearance of rice.

Özbey and Söylemez (2005) reported that temperature had much important role to play in drying than the flow rate of air for drying wheat in a swirl fluidised bed.

Srinivasakannan and Balasubramaniam (2006) investigated and modelled drying of ragi in fluidised bed. They observed that drying rate increased significantly with increase in temperature and marginally with flowrate of heating medium; it decreased with increase in solid hold up. Drying was found to occur under falling rate period. Also, they tested their drying kinetics data with various simple and exponential decay models, evaluated moisture diffusivities.

Nitz and Taranto (2007) studied drying of beans in a pulsed fluid bed dryer and reported that air consumption was less when compared to conventional fluidized bed dryer.

Nazghelichi et al. (2010) carried out a thermodynamic analysis of fluidised bed drying of carrots. They reported the influence of air temperature, bed depth and particle size on energy utilization.

GAZOR and MOHSENIMANESH (2010) modelled the drying kinetics of canola in a fluidised bed dryer. They tested their experimental data for various drying kinetics models and also evaluated moisture diffusivities.

Meziane (2011) studied the drying kinetics of the olive pomace in a fluidised bed at various air temperatures and bed depths. The evaluated moisture diffusivities were found to be increasing with temperature and bed depth.

Srinivasakannan et al. (2011) evaluated the kinetic parameters for drying of black pepper in fluidised bed and reported the drying kinetic parameters and moisture diffusivities.

Srinivasakannan et al. (2012) studied continuous fluid bed drying with and without internals. They reported that use of spirals as internals changed the solids mixing from mixed flow to plug flow behaviour. The drying rate was fond to be better for continuous fluidised bed drier with internals when compared to continuous fluidised bed drier without internals.

Bakal et al. (2012) studied the kinetics of potato drying using fluidised bed dryer. They reported the moisture content decreased with increase in drying air temperature and drying was found to happen in falling rate period. Rate of drying was found to decrease as the moisture content of the potato decreased and the moisture diffusivity was found to increase with increase in air temperature.

Subramanian et al. (2013) studied the drying characteristics of ragi using circulatory fluidised bed. They observed that the pressure drop increased linearly with increase in gas mass flux and solid circulation rate. They reported that drying occurred under falling rate period and the rate of drying was influenced by the initial moisture content, flow rate and temperature of the heating medium.

Shingare and Thorat (2013) studied the effect of drying temperature and pre-treatment on protein content and colour changes during fluidised bed drying of finger millets sprouts. Their results showed that drying occurred in falling rate period; they reported moisture diffusivities at various temperatures.

Irigoyen and Giner (2014) studied the kinetics of drying – toasting of pre-soaked soya beans, and observed that drying occurred under falling rate period. An unsteady state diffusional model was proposed with strict internal control to the mass transfer rate. Also, they reported moisture diffusivities.

Reyes et al. (2014) studied drying of carrots in a fluidised bed. They proposed a correlation to evaluate effective moisture diffusivity as a function of temperature.

2.2 Conventional spouted beds

Since its development as an efficient fluid-solid contacting device, spouted bed was found to be useful for varieties of process applications like granulation, coal gasification, combustion, pyrolysis of hydrocarbons, pneumatic conveying, and solids drying. Also, many modifications of the original conventional spouted bed, as developed by Mathur and Gishler (1955), were reported in literature. Epstein and Grace (2011) presented a review of some single spouted bed configurations applied to drying of particulate solids; these included conventional spouted bed, conical spouted bed, two-dimensional spouted bed, triangular spouted bed, parabolic-cylindrical spouted bed, spout-fluidized bed, rotating jet sprayed bed and jet spouted bed. Further modifications reported in literature were those of multiple spouted beds and draft tube spouted beds. Some of the works related to solids drying in spouted beds reported in last 15 years are presented here.

Hung-Nguyen et al. (2001) carried out drying of high moisture content paddy in a pilot scale triangular spouted bed dryer. They reported that it would be better to dry high moisture content paddy by employing two temperature levels – a high temperature level of 140^0 C – 160^0 C, followed by a low temperature level.

Marreto et al. (2006) studied the applicability of spouted bed for drying pharmaceuticals and concluded that it would provide a range of operational conditions that would allow a good preservation of active ingredients and adequate moisture content in dry powder. Further the drying of microcapsules in a spouted bed seemed to be an interesting alternative to spray drying.

Markowski et al. (2010) studied drying kinetics of barley in spouted bed. They found that drying occurred under falling rate conditions. Also, they reported that the estimated moisture diffusivities influenced by both temperature and kernel shape.

Kahyaoglu et al. (2012) compared spouted bed and microwave assisted spouted bed drying of parboiled wheat and found that drying occurred in falling rate period.

Microwave-assisted spouted bed drying was found to be energy efficient with large reduction in drying time.

Feng et al. (2012) compared various drying techniques with and without microwave assistance for drying lettuce cubes. The quality of drying was assessed in terms of rehydration ratio, chlorophyll content, colour, and sensory evaluation. They found that Microwave assisted spouted bed – dried samples were all better than those obtained by hot air dried, spouted bed dried, and vacuum microwave dried. Microwave assisted spouted bed drying took considerably lesser time than vacuum freeze drying, yielding product with similar hydration and chlorophyll content.

2.3 Comparison between fluidised beds and spouted beds

A comparison between fluidized and spouted beds as given by Cui and Grace, (2008) is mentioned below.

Table 2.1 A comparison between fluidized and spouted beds

Property	Fluidized bed	Spouted bed
Mean particle size. Particle size distribution	0.3–3 mm; usually<1mm. Usually broad	0.6–6 mm; usually >1 mm. Usually narrow
Pressure drop/height within the bed	96–100% of that needed to support the particles,	Less than75% of that needed to support the weight of the particles,
Pressure drop across entry orifices	Usually30–50% of that across the bed	As small as possible consistent with satisfying the other constraints
Axial gradient of pressure	Virtually independent of height in the column	Varies with height
Temperature gradient	Very uniform temperature over entire fluidized bed	Significant temperature gradients both axially and radials
Column geometry	Usually cylindrical columns	Usually diverging conical base with or without cylindrical portion above
Orifice diameter	No restriction	Must not exceed 25 times of mean particles diameter
Gas motion	Less ordered; depends on flow regime and specific geometry	Out wards from the spouts into the dense phase, except just above inlet
Particle motion	Complex flow regimes and particle motion. Region surrounding the gas entry orifices is usually fluidized with few particle–particle contacts	Systematic circulation patterns, up the spout and slowly downward in the annulus. Annulus is a moving packed bed flow with substantial particle–particle contacts
Particle segregation	Very little segregation provided that particles are well fluidized	Significant segregation according to both size and density of particles
Attrition	Normally little except in cyclone or jet regions	Significant in spout region and in fountain above
Bed depth	Broad range of depths, e.g. from 0.1to 20 m dense bed depth	More limited range of depths, usually between 0.2and2.0m
Superficial gas velocity	Broad range, typically: $(U\text{-}U_{mf})$ = 0.2- 10 m/s	More limited range, typically:1-1.8U_{ms}
Orifice velocity variation	Some variation with time across each individual orifice as bubbles form and leave the orifice or jet	Essentially steady as flow is controlled to fluid inlet from an upstream valve
Internals	Common in fluidized bed processes	Rare in spouted bed processes, except for some use of draft tubes and heat transfer coils

2.4 Multiple spouted beds

In order to use spouted beds for large scale operations, one of the alternatives suggested was to use multiple fluid inlets in the bed. The reported investigations related to multiple spouted beds are those of Peterson (1966), Foong et al. (1975), Huang and Chayang (1993), Murthy and Singh (1994,1996), Saidutta and Murthy (2000), Hu et al. (2008). Li et al. (2012), Chen et al. (2013) Chen et al. (2014).

In order to maintain a required rapid circulation of solids in a large-scale operation Peterson (1966) used six spouts within the same bed. He could establish several individual spouting cells, each with its own spout and annulus in a large bed, by an appropriate choice of spacing between fluid inlets. However, he found the operation tending to become unstable except with a shallow bed. So, in order to overcome this problem, he provided vertical baffles, extending upward from the base of the vessel and covering one-half to seven-eighths of the height of the bed. This seemed to have brought about a marked improvement in spouting stability, perhaps because of cutting off lateral flow of gas between neighbouring cells. But the solids exchange between the cells was still permitted in the upper un-partitioned portions of the bed. He operated a continuous unit with a maximum solids feed rate of 590 kg/h and a mean residence time of about 12 minutes without any noticeable effect on spouting behaviour and achieving a nearly perfect solid mixing.

A comparison of observed performance sextuple spouter of Peterson with the estimated properties of two hypothetical single spout bed, one having the same bed volume as the sextuple unit and the other the same air flow rate was given by Mathur and Epstein (1974); that comparison is shown in Table 2.2 They pointed out that a multi – spout system would provide a more vigorous agitation of a given mass of solids than the equivalent single spout bed, but at the expense of higher gas consumption; also, it would allow a shorter gas residence time. To achieve the same flow rate of gas as in a sextuple unit, the single spout bed required would be much larger and would provide slower solid turn over and longer gas residence time, and would require gas supply at a higher pressure. Hence the choice between a multi – spout and a single spout system would depend on the requirements of given process with respect to solid turnover rate and gas

Table 2.2 Comparison between multiple – spouts and single – spout beds air – wheat

	Single Spouter (Peterson's observed data)	Estimated values for equivalent single spout beds	
		Same bed volume	Same volumetric air flowrate
size			
Cross Section	41 cm X 61 cm	46 cm diameter	76 cm diameter
Cross – sectional area (m^2)	0.25	0.16	0.46
Bed Depth (cm)	76	107	190
Bed volume (m^2)	~0.14	0.14	0.68
Minimum spouting air flow			
Volumetric (m^3/sec)	0.219	0.097	0.219
Superficial velocity (m/sec)	0.88	0.58	1.2
Average gas residence time (sec)	0.9	1.8	1.6
Solid circulation			
Particle velocity at wall (m/sec)	27.9	17.8	12.7
Particle cycle time (sec)	22	60	150
Solids mass flow (kg/sec)	5.44	2.28	4.53
Bed pressure drop (kN/m^2) = 2/3 (bed mass/ cross sectional area)	4.2	5.8	10.4

residence time on one hand, and the economics of gas supply on the other. For example, a multiple spouted bed would be preferred for drying heat sensitive solid materials where rapid turnover is of critical importance.

Foong et al (1975) carried out experiments in a flat bottom half sectional bed having three and two fluid inlets, as well as a three-dimensional flat bottom column having seven spouts arranged on a triangular pitch with the central spout surrounded by six spouts. Based on their experimental work they concluded that the multiple spouted beds were inherently unstable due to the tendency of the spouts towards pulsation and regression. They found that the bed stability was dependent on the ratio of diameter of particle to diameter of gas inlet orifice and also on bed height.

Huang and Chyang (1993) used two-dimensional flat bottom columns having three as well as seven gas inlets. They mapped phase diagrams to identify the operational regimes, which include static bed, partial spouting, jetting, in coherent spouting, steady spouting and interacted spouting. They found that the stability of the multiple spouts was affected by bed height, superficial gas velocity, particle size, interaction between adjacent spouts and operativeness of the orifices.

Murthy and Singh (1994, 1996) conducted experiments in three dimensional rectangular columns having 2, 3 and 4 spout cells; each spout cell was of square cross section and was provided with an inverted pyramid. Air and water were used as fluids to spout six distinctly different solid materials. Based on their experimental findings they identified five different regions in the operation of multiple spout system – static bed, partial spouting, stable spouting, oscillations and interface of spouts, and chaotic bed. In addition, they reported that for a given column, fluid, solids and bed depth there existed a maximum superficial velocity beyond which stable spouting was not possible; the minimum spouting velocity was found to be independent of number of spout cells in a given column, but depended on bed depth, particle size and fluid properties. Also, they compared the performance of their multiple spouted beds with two cases of hypothetical single spout beds, one – a circular column having a cross sectional area equal to that of a square cell in the multiple spouted bed and two – a circular column having a cross sectional area equal to that of all square cells in a given multiple spouted bed; that comparison is given in Table (2.3) Based on such a comparison they concluded that for the same bed volume a multi – spout system needed much higher fluid flow rate when compared to a single spout unit; however, the spouting pressure drop would be lesser in multiple spouted beds and also the average gas residence time would be smaller.

It is to be noted here that Murthy (1991) reported that for a given solid material spouted by a fluid in a column having a given number of spout cells and fluid inlets, there existed a "maximum spoutable bed depth" beyond which steady spouting was not possible.

Table 2.3 Comparison of performance between four – spout bed and single spout beds $^{\text{air – ragi seed}}$

Sl no		Four spouted bed	Single Spouted bed	
			Case 1	Case 2
1	Column			
	Size	150 cm X 150 cm	dia. = 8.46cm	dia. = 16.93cm
	Cross Sectional area, cm^2	225	56.25	225
	Bed depth, cm	20	75.5	25.6
	Bed volume, cm^3	4092	4092	4092
2	Fluid inlet			
	Size, mm	8	8	16
	Total flow area cm^2	2.01	0.5	2.01
3	Minimum spouting Velocity, cm/sec	38.3	88.5	25.8
4	Volumetric flow rate litre/sec	8.61	4.98	5.28
5	Spouting pressure drop N/m^2	424	5534	1481
6	Average gas residence time, sec	0.52	0.85	0.99

Case 1: A hypothetical single spouted bed in a circular column having a cross sectional area equal to that of a single square cell in a multiple spouted bed

Case 2: A hypothetical single spouted bed in a circular column having a cross sectional area equal to that of all square cells in a multiple spouted bed.

Saidutta and Murthy (2000) studied the mixing behaviour of solids in multiple spouted beds having continuous flow of solids and air. They used same column configurations as that of Murthy and Singh (1994, 1996). The “plug flow – mixed flow in series” model was used to fit their experimental data. From their results, they concluded that the solids flow would be a combination of mixed flow and plug flow with more of mixed flow volume in the bed.

Gong et al. (2006) studied the hydrodynamic characteristics of novel annular spouted bed with multiple air nozzles; they concluded it was possible to spout larger volume and mass of particles for the given air supply using the novel design having multiple nozzle.

Hu et al. (2008) studied flow patterns and transitions in a novel annular spouted bed with multiple air nozzles. Three distinct stable flow patterns and two transitional flow patterns, i.e. internal jet, jet- spouting, fully developed spouting, single internal jet, and single jet-spouting were identified. With increasing spouting gas velocity, the flow pattern transitions from the fixed bed to single internal jet and then to entire internal jet. They also found that the interaction of spout gases from different nozzles causes the jets to distort or coalesce.

Chen et al. (2013) studied the stability of slot-rectangular spouted beds with multiple slots. Based on their experimental results they concluded that the bed behaviour would be significantly affected by the interaction between adjacent spouts. Interchange of particles and gas in the fountain zone would be the main factor affecting the interactions. They felt that suspended vertical partitions would successfully stabilise the multiple spouting flows and hence suggested that an assembly of slot-rectangular chambers separated by suspended partial baffles would provide a successful means of realising scale-up of spouted beds.

A three-dimensional computational fluid dynamics model, coupling with two-fluid model approach was adopted by Chen et al. (2014) to investigate the interactions of spout jets and to evaluate the effects of baffles in a multiple-spouted bed. They considered the simulation of triple spouted bed having a rectangular geometry, both with out and with vertical baffles in the column. Their simulation results seemed to indicate that the presence of baffles in the bed would improve the hydrodynamic stability of a multi spout system.

2.5 Draft tube spouted bed dryer

It was pointed out that a conventional spouted bed would have the following limitations

- There would exist a maximum spoutable bed depth beyond which proper spouting would not be possible (Mathur and Gishler,1959). As a result, scale up of the bed to large scale operations would not be feasible.
- The solids would enter the spout from annulus at all levels resulting in random behavior of these particles. As a result, it would be difficult to closely control the particle history in the bed (Ishikura et al., 2003).

  An alternative suggested to overcome these limitations was to provide an axially positioned draft tube in a conventional spouted bed. However, it was pointed out that in operations where the spouting fluid would be expected to play an active role, like in the case of solids drying or carrying out a chemical reaction, a non-porous draft tube would bring in a potential limitation (Ishikura et al., 2003).It would be because the lateral/radial transport of fluid would get prevented, and as a result an efficient contact between fluid and solids would not be achieved in the bed as a whole; this in turn would lower the transfer rates of heat and mass. Hence use of porous draft tube would be beneficial in such operations, which would still retain the means of controlling the particle history (Ishikura et al., 2003).

  Some of the reported works related to draft tube spouted beds are presented here.

Madhiyanon et al.,(2001) carried out paddy drying studies on an industrial scale proto type spouted bed dryer with a capacity of 3500 kg/h. The dryer consisted of vertical rectangular chamber, a slanting base, a rectangular slit as an air inlet and draft plates. They reported that the dryer performance was found to be satisfactory.

Madhiyanon et al. (2001) developed a two-region mathematical model for batch drying of grains in a two-dimensional spouted bed having draft plates and it was validated with experimental results of corn drying. Their results showed that heating and drying occurred in both the spout and down-comer regions.

Madhiyanon et al., (2002) developed a mathematical model for continuous drying of grains in a spouted bed dryer having draft plates and also investigated the dryer behaviour experimentally. They reported that absence of air flow in down-comer would lead to tempering of grains in the down-comer and intense heat and mass transfer would occur in spout due to high flow rates prevailing in the spout.

Ando et al. (2002) studied the drying of solid particles in a spouted bed with draft tube both theoretically and experimentally; the theoretical model successfully explained the influence of various operating parameters on drying of particles. The validity of their theoretical model was confirmed with the experimental data.

Ishikura et al. (2003) employed a porous draft tube spouted bed to obtain hydrodynamic data of binary mixtures of glass beads (a small quantity of finer particles and large quantity of coarser ones) for a range of operating conditions and design factors. Their results showed that the gas flow rate through the annulus increased by increasing the distance between the gas inlet and bottom of the draft tube (entrainment zone), but decreased with increasing draft tube diameter and mass fraction of finer particles. The porous draft tube showed a higher gas flow rate through the annuls than non-porous draft tube, particularly in the case of low height of the entrainment zone. The solids circulation rate increased with increasing gas velocity, the height of entrainment zone and porous draft tube diameter. Moreover, they found that the porous draft tube lead to a higher solids circulation rate than the non-porous draft tube.

Madhiyanon and Soponronnarit (2005) studied the high temperature drying of paddy with varied down comer air flows and moisture contents and reported their effects on drying kinetics, critical moisture content and milling quality. The experimental dryer used by them was a two-dimensional spouted bed batch dryer; it included a vertical rectangular chamber, a slant base chamber and two draft plates. Hot air was distributed at the bottom of slant base chamber through three air inlets – a central rectangular inlet serving for spout region and two round inlets, located in slant base, for the down-comer regions. They reported that both spout and down comer regions contributed for moisture reduction and believed that evaporative cooling was cause for moisture and bed temperature reduction, along with the downward movement of grains within the down-comer. Their results demonstrated that down-comer air flows had important role in effective moisture reduction, which increased with increase in down-comer air flow. Two stage drying with intermediate tempering was best suited for spouted bed paddy drying considering the quality of product obtained. Further they reported that spouted bed provided significantly better product quality than fluidised bed; however, the specific drying rates (kg water evaporated $h^{-1}m^{-3}$) of both were comparable. They recommended paddy drying from very high to low moisture content be carried out in two stages with temperature tempering in between from the product quality viewpoint.

Shuyan et al. (2010) carried out simulation studies of flow behaviour of gas and particles in spouted bed with a porous draft tube. Results of simulation indicated that the predicted gas flow rate into annulus increased along with porosity of the draft tube followed by increase in solid circulation. Similar results were reported by Azizi et al. (2010)

Olazar et al. (2011) developed a model for batch drying of sand in a draft-tube conical spouted bed. They concluded that conical spouted beds fitted with a draft tube would perform well for drying fine solids, and it would be an interesting alternative to standard but more expensive and less efficient rotary driers. They reported that air leaving the annulus would be close to saturation, but that leaving the spout would not be. The moisture content in the solids at a given time would be similar in the three zones indicating that the solids would be well mixed.

Makibar et al. (2012) investigated on selection of draft tube and its hydrodynamic behaviour of a pilot scale conical spouted bed pyrolysis reactor. They reported that presence of draft tube would enhance solid recirculation rate when compared to conventional beds under identical conditions. A draft tube would widen the range of stable operating condition and would influence the distribution of flow into annulus and spout.

Nagashima et al. (2013) investigated the hydrodynamic behaviour of spouted beds with different types of draft tubes and reported that the bed pressure drop, minimum spouting velocity, the annulus gas flow rate and the solid recirculation reached a maximum using a conical – cylindrical porous draft tube. Further it was reported that the gas bypassing into the annulus and solid recirculation were higher with a conical – cylindrical porous draft tube which would contribute to efficient gas-solid contacting.

Berghel and Renström (2014) studied the influence of using draft tube in a continuous spouted bed drier; they conducted several tests for drying saw dust in the unit with nine different draft tube designs. Their results showed that an increase in draft tube length and disengagement height decreased the flow rate of dry substances throughout the dryer. The results also showed that the mass of the material in the dryer was approximately same in all the tests, which meant that the sizes of draft tubes did not influence the amount of material in the dryer.

Ishikura et al. (2003) compared spouted beds with out and with draft tubes, as given n Table 2.4.

Table 2.4 Comparison of characteristics of a spouted bed without and with a draft tube

Type of bed	Advantages	Limitations	Applications
Conventional spouted without a draft tube	Simple grid design. Regular solid circulation. Good solid mixing for coarse solids. Low pressure drops. Good fluidisation for sticky or lumpy solids.	Limitation on geometry and operation. Limitation of bed height. Somewhat narrower particle size. Poor spouting for fine particle.	Drying of grains and suspensions. Coating of particles. Granulation of particle. Gas cleaning. Coal gasification. Chemical products.
Spouted bed with a non-porous draft tube	No limitation of bed height and particle size uniformity. Greater operation flexibility. Lower gas flow and pressure drop. Narrower spread of solid RTD. More control of solid circulation.	Complex design. Reduced mixing Plugging of draft tube. Reduced contact between gas and solids. Lower heat and mass transfer.	Drying of grains and suspensions. Coating of particles. Granulation of particles. Coal gasification. Combustion. Pyrolysis of hydrocarbons. Pneumatic conveying
Spouted bed with a porous draft tube	All advantages of non-porous draft tube is retained. More control of gas percolation through annulus. Higher heat and mass transfer.	More complex design. Plugging of draft tube.	Drying of grains and chemical products. Thermal disinfestation process.

2.6 Spout – fluidised beds

Spout-fluidized beds were suggested as yet another modification to conventional spouted beds. Supply of additional/auxiliary fluid into the annulus region could be done without sacrificing the basic features of spouting. This could be beneficial in operations involving simultaneous transfer of heat and mass such as solids drying. A good volume of literature is available on spout-fluidized beds and a few are presented here.

Osorio-Revilla et al.(2004) conducted batch experiments in a half-sectional spout-fluid bed column with draft tube for cleaning and drying of guava seeds. They concluded that the amount of additional air sent through the annular region in the range used had no significant effect on the drying time. They stated that variables that had major effect on the drying time were the spout and annular air temperatures and more specifically the average temperature between them. They proposed a regression model for predicting drying time.

Cunha et al. (2006) studied the effects of process temperature, feed flow rate and gas velocity in spout and annulus on drying of mango pulp in a spout- fluidized bed. They carried out the process with an intermittent paste flow rate since the high sugar content of the fruit led to bed collapse when continuous feed was used. They assessed the dryer performance by the efficiency of powder production, product moisture, feed and process time and reported that high process temperatures provided better performance and product quality Also, they stated that higher air flow rates at the annulus and feed mass also contributed to an improvement in product quality and process efficiency.

Marmo (2007) studied low temperature drying of pomace in conventional spouted bed as well as spout- fluid bed equipped with a draft tube. The spouted bed was operated batch wise, whereas the spout- fluid bed was operated continuously. It was demonstrated that an optimal temperature of the inlet air could be found to optimise the overall energy consumption.

Zielinska and Markowski (2007) studied the drying behaviour of carrots in a spout–fluidized bed. They reported that a high air velocity at the beginning of drying cycle and a lower velocity at later stages were required. They observed that the intensity of heat and mass transfer during drying was dependent on the drying temperature; when a higher drying temperature was applied higher values of heat and mass transfer coefficients were observed. It was also observed that internal resistances of mass transfer had a crucial effect on the drying process from the start to the end of drying. They developed a correlation to calculate the effective moisture diffusivity for dried carrot cubes as a function of moisture content and temperature of the material.

Sutkar et al. (2013) critically analysed the recent advances in experimental and numerical studies of spout- fluidized beds and made a comparison of fluidized beds, spouted beds and spout- fluidized beds.

Jittanit et al. (2013) studied the drying behaviour of fluidized bed and spout- fluidized bed dryer using rice and wheat grains at different initial moisture contents and different temperatures. They compared the results from both types of dryers and found that spouted bed dryer was better in terms of specific energy consumption, whereas the fluidised bed dryer gave a faster drying rate. However, they stated that the main limitation of spouted bed dryer would be its minimum and maximum spoutable bed height, which would constrain the scalability of spouted bed.

The following points were noted from the literature survey.

- Fluidized beds were found to be popular to be used for drying solids because of their numerous favourable features. When relatively finer solids (less than 1 mm size) were to be dried, fluidized beds could be perhaps suitable. However, when coarse granular solids like agricultural grains, whose particle sizes are more than 1mm, fluidized beds would not be efficient. Gas – solid systems typically would lead to aggregative fluidization, where in problems like bubble formation, segregation, slugging would be encountered. As a result, fluid-solid contact would become poor leading to lower rates of heat and mass transfer and the process could become inefficient. As the solids to be processed become coarser these problems could become more acute.
- Spouted beds, which were essentially modified version of fluidized beds, could be suitable for coarse solid particles belonging to Group D in Geldart's Classification (Geldart, 1973). These devices with their typical features would be suitable for drying of agricultural grains.
- A conventional single spouted bed would have the limitation of MSBD and this would restrict its scalability for large scale operations. Also, it would be difficult to closely control the particle history in the bed.
- A multiple spouted bed could be considered for large scale drying operations. However, these units also would have the limitation of MSBD and limited

operational regime to maintain stable spouting. Vertical baffles provided in a multiple spouted bed would help to overcome the problem of hydrodynamic instability of the bed.

- Provision of draft tube(s) in either a single or multiple a spouted bed would help to overcome the limitation of MSBD and also achieve close control of particle history in the bed. The draft tubes in multiple spouted beds would act as vertical baffles and would help in overcoming the problem of hydrodynamic instability. So, as a result scalability to large scale operations would be possible.
- A non-porous draft tube would prevent lateral/radial transport of fluid from spout to annulus, and as a result an efficient contact between fluid and solids would not be achieved in the bed as a whole; this in turn would lower the transfer rates of heat and mass. So, this could become a potential limitation for an application like solids drying.
- Use of porous draft tube would be beneficial in such operations, which would help in supply of hot air into annulus from spout region and still retain the means of controlling the particle history.

Based on the points discussed above, it was felt that providing porous draft tubes in a multiple spouted bed should be useful for solids drying. Hence a Multiple Porous Draft Tubes Spouted Bed was considered for this study with the following objectives.

1. Conduct batch drying experiments to study drying kinetics of different agricultural products under varied conditions of air temperature, air flow rate, initial moisture content of the solids and bed mass.
2. Finding the influence of operating variables on drying rate and batch drying time.
3. Study the influence of different operating variables on drying rate and batch process time for each of the solid material chosen.
4. Study the influence of fluid inlet size on batch drying time.
5. Study the influence of draft tube parameters like draft tube diameter, hole size and hole pitch.

6. Estimation of moisture diffusivities in grains and understanding the influence of operating variables and design parameters of the dryer on these diffusivities.
7. Estimation of thermal efficiencies of the dryer and studying the influence of operating variables and design parameters of the dryer on thermal efficiencies.
8. Estimation of gas solid convective heat transfer coefficients in MPDTSB and two SPDTSBs.
9. Comparison of performance of MPDTSB and two SPDTSBs.
10. Development of mathematical model to predict batch drying time.

CHAPTER 3

EXPERIMENTAL WORK

A multiple porous draft tube spouted bed was considered as a gas-solid contactor for carrying out experimental studies on solids drying. The contactor assembly was envisaged keeping in mind some flexibility such that experiments could be conducted under varied conditions. However, the column/spout cell dimensions and number of spout cells were chosen to be constant. It should be noted here that the focus of this research work was to find the applicability of the proposed contactor design as a grain dryer and whether this design could be considered for scale up to large scale application. Also, two different single porous draft tube spouted bed columns were used for conducting drying experiments for comparing the performance of multiple and single spouted bed dryers.

The details of various parts and assembly of the contactor, a schematic diagram of experimental rig used and experimental procedure followed are presented in this chapter.

3.1 MPDTSB dryer assembly and specifications

The dryer consisted of a rectangular column, spout assembly, air inlets and draft tubes. The rectangular column housed the bed of grains. The column dimensions were 225 mm × 75 mm such that three-square spout cells of 75 mm × 75 mm could be accommodated. The spout cell configuration as shown in Fig.3.1 was used in the work. The column had three sections such that depending upon the bed mass to be loaded either one, two or three sections (200, 300, 470 mm respectively) could be assembled. The broader sides of each section were made of transparent acrylic sheets so that the bed behaviour could be observed visually during experiments.

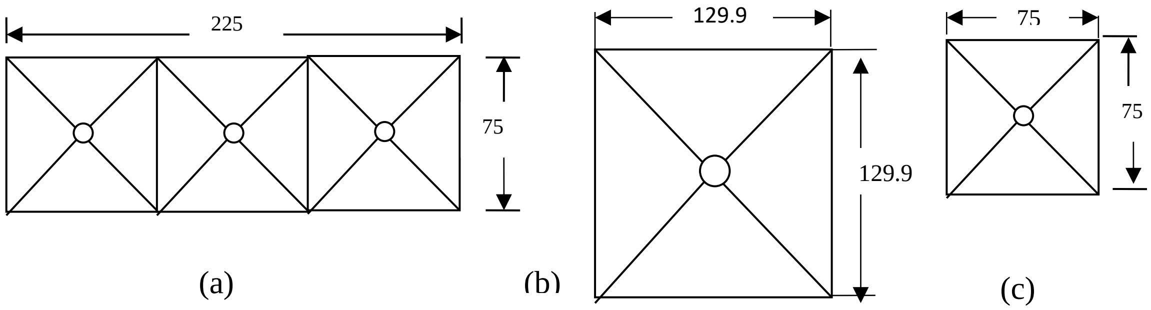


Figure 3.1 Spout cell configurations (All dimensions are in mm).

a – MPDTSB; b – SPDTSB1; c – SPDTSB2

Each spout cell was provided with an inverted frustum (apex angle = 60^0) as base and an axially located draft tube. The fluid inlet orifices were located at the base of each frustum. The spout assembly as shown in Fig.3.2 and 3.3 was used in the study. The fluid inlet diameters used in the study were 8, 15 and 21 mm.

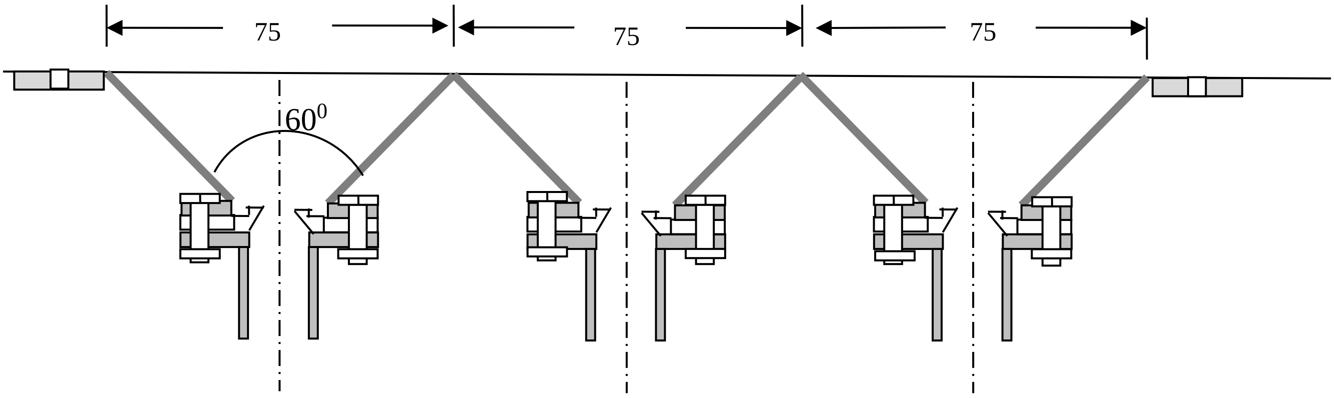


Figure 3.2 Spout cells assembly for multiple porous draft tube spouted bed.

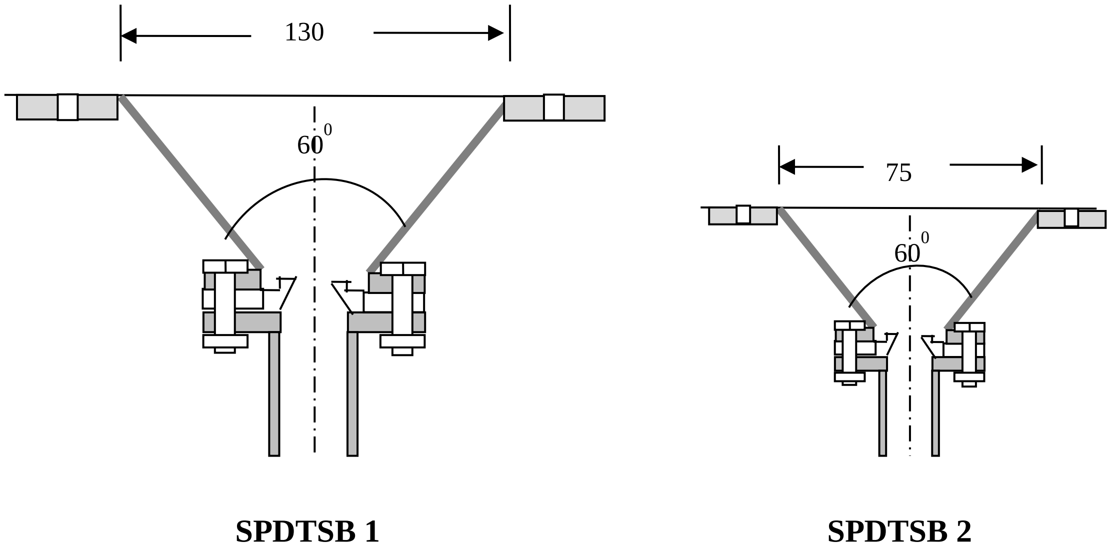


Figure 3.3 Spout cell assemblies for single porous draft tube spouted beds.

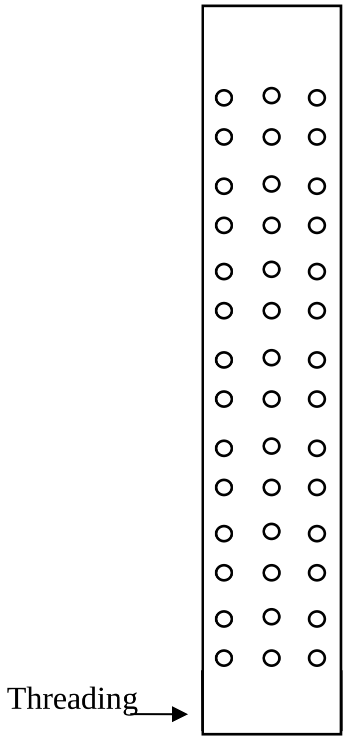


Figure 3.4 Porous draft tube.

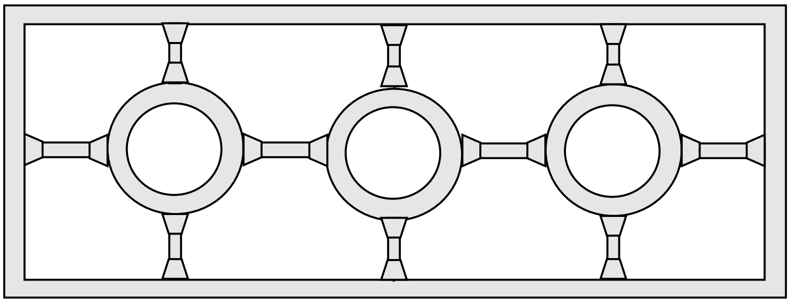


Figure 3.5 a: MPDTSB Top plate.

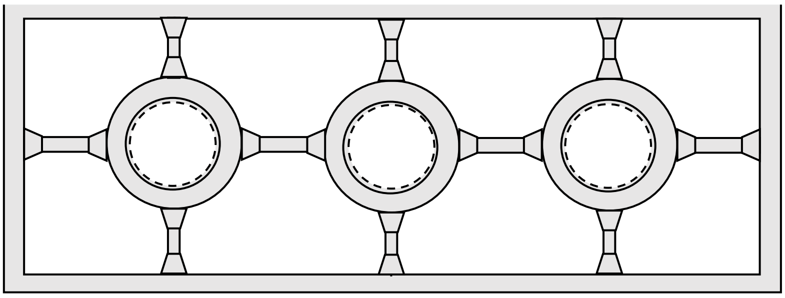


Fig 3.5 b: MPDTSB Bottom plate.

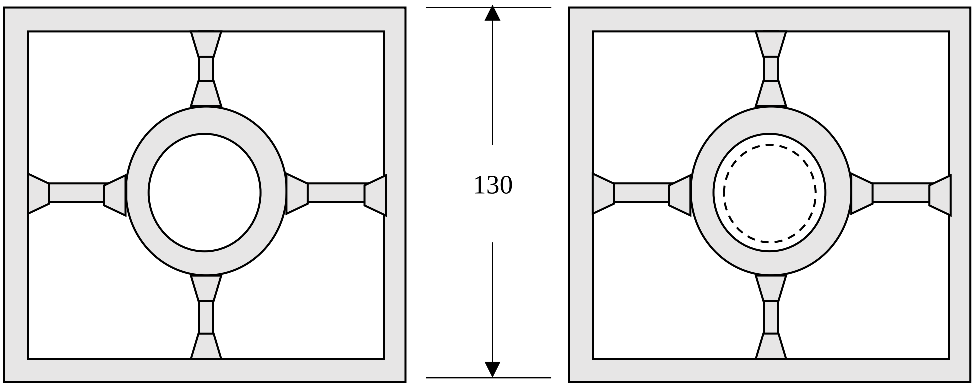


Figure 3.6 SPDTSB1 Top and bottom plate.

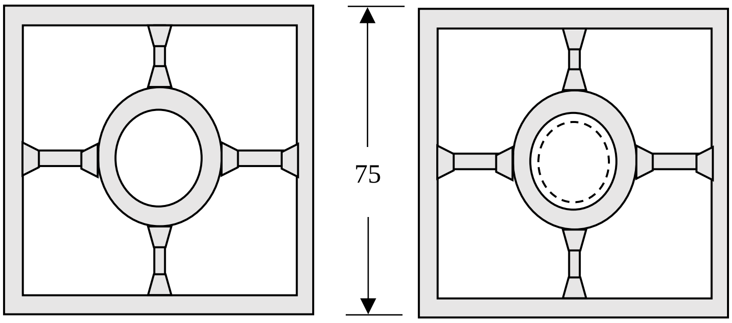


Figure 3.7 SPDTSB2 Top and bottom plate.

Each draft tube was made of PVC pipe having appropriate inside diameter and length. Two plates, as shown in Figures 3.5 to 3.7, were used to keep the draft tubes in appropriate axial location of each spout cell; threads were provided at the lower end of each draft tube for housing the tubes in lower plate. Also, these threads were useful to adjust the gap between the fluid inlet and bottom of each draft tube such that required circulation of solids could be achieved; a gap of around 28 mm was maintained in all the experiments. Enough free areas were provided in both the plates for free movement of grains at the top and bottom.

Both non-porous and porous draft tubes were used in the study. In the cases of porous draft tubes holes were provided in a rectangular configuration such that the number of holes per unit length were same in all the tubes used in this study. Fig. 3.4 shows the sketch of a typical porous draft tube. However, for cases where the total hole areas were to be varied different pitches were used. A nylon mesh was tightly wrapped over 4 mm holes on DT to prevent clogging of holes by solids; also, the mesh prevented movement of solids between spout and annulus. Mesh was not used for 2 mm holes.
The specifications of MPDTSB are given in Table 3.1. The assembly of MPDTSB is shown in Fig. 3.8.a.

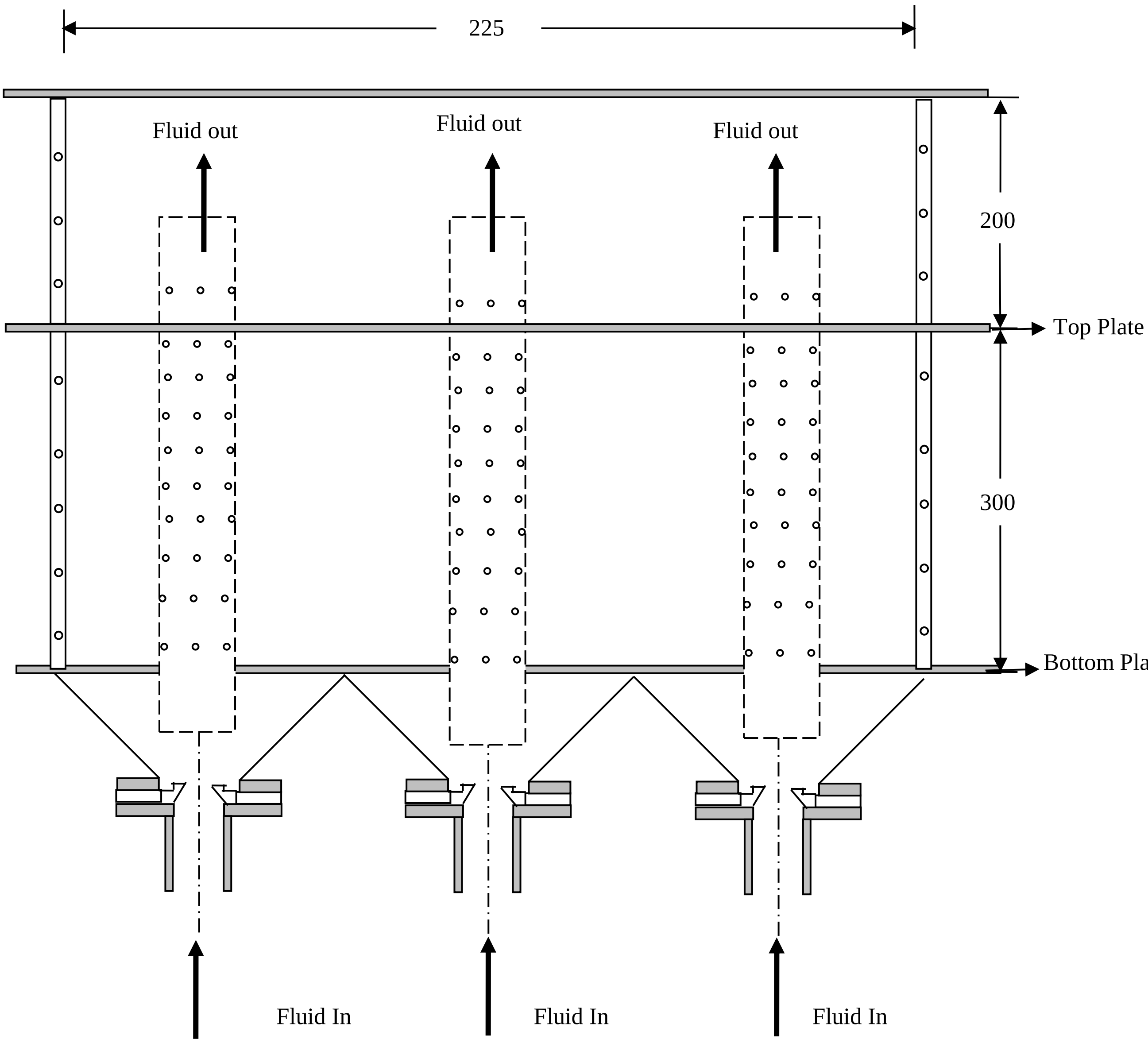


Figure 3.8.a Contactor assembly (MBDTSB).

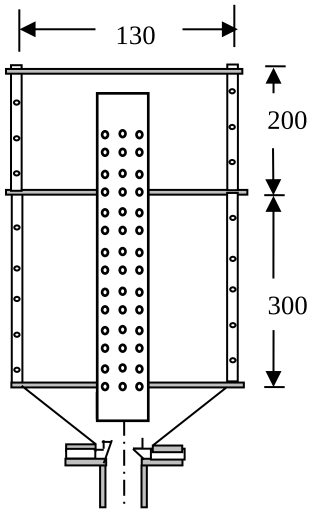


Figure 3.8.b Contactor Assembly (SBDTSB1)

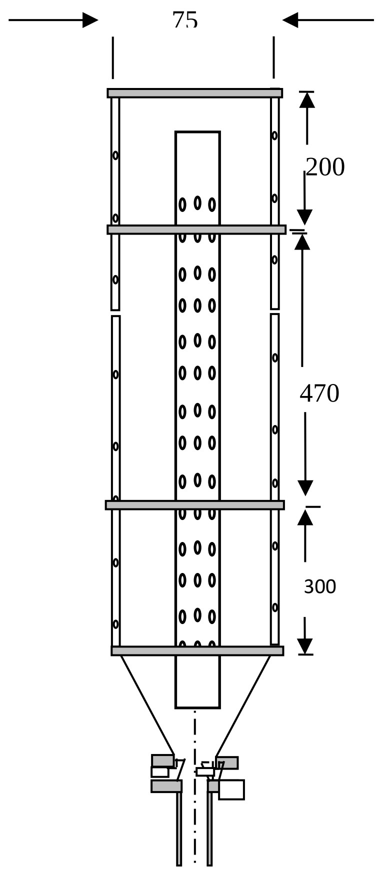


Figure 3.8.c Contactor Assembly (SBDTSB2)

3.2 SPDTSB dryer specifications

The assemblies of SPDTSBs used were similar to MPDTSB. The details of dryers used for comparison, the bed masses and corresponding static bed depths of solids used are given in Table 3.1.

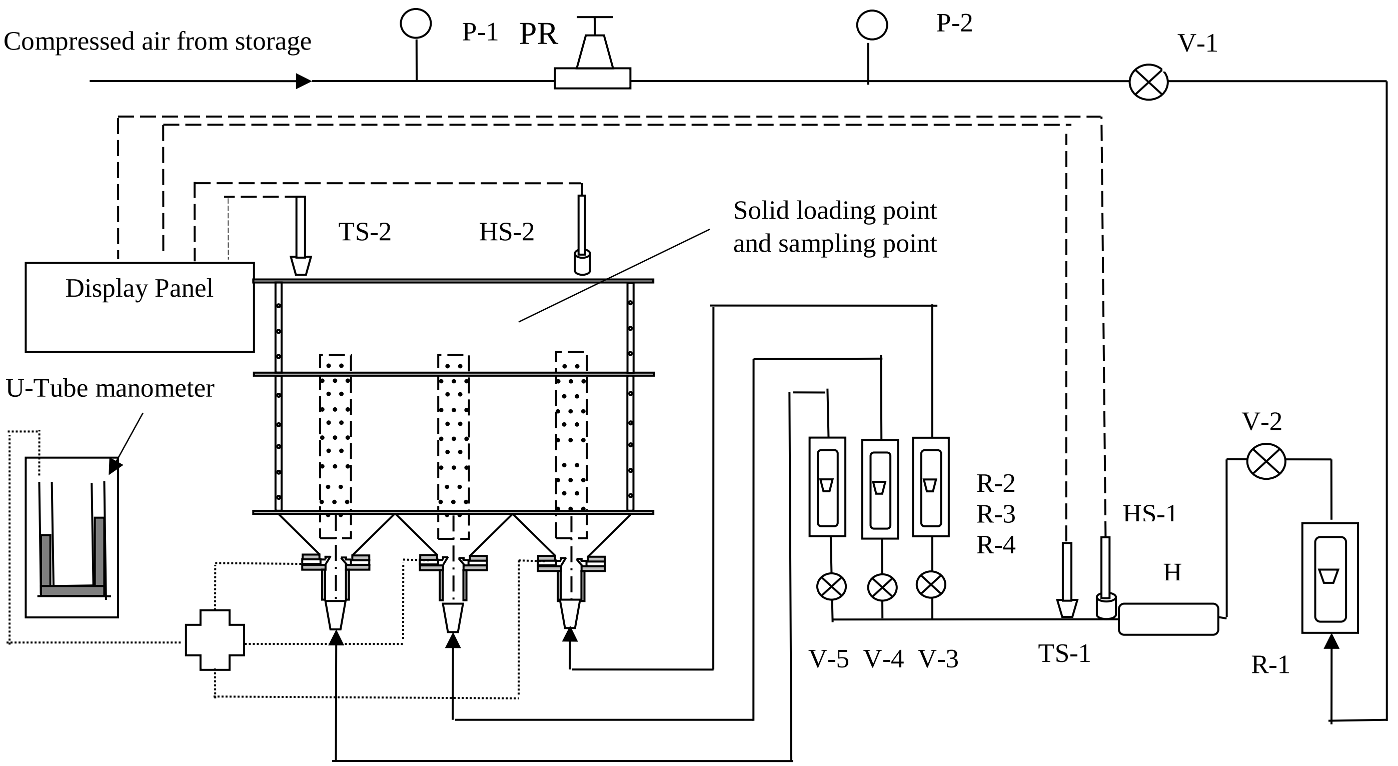
SPDTSB1 had column cross sectional area (CSA) and fluid inlet area equivalent to that of MPDTSB, but the CSA of DT in SPDTSB1 was three times less compared to MBDTSB. So, the air jet velocities in MPDTSB and SPDTSB1 were same, but the air superficial velocity in DT in SPDTSB1 was three times higher than that in MPDTSB. The SPDTSB2 had three times less column CSA, fluid inlet area and CSA of DT compared to MPDTSB. So, the air jet velocities as well as air superficial velocities in DT of SPDTSB2 were three times more compared to MPDTSB. The static bed depths for a given bed mass of all the grains are approximately same for MPDTSB and SPDTSB1, whereas about three times more for SPDTSB2. The spout cell assemblies, top and bottom plated for housing draft tubes and contactor assemblies for SPDTSBs are shown in Figures 3.6,3.7, 3.8.b and 3.8c

3.3 Description of experimental rig

A schematic diagram of the experimental rig is shown in Fig 3.9(a); a photograph of the dryer is shown in Fig 3.9(b).

Compressed air passing through a constant pressure regulator was supplied to the main rotameter was at 28^0C and 101.32 kPa(g). A 3-kW electric heater was used to make hot air to be supplied to the dryer. Valves were provided appropriately to adjust flow rate to each spout cell as well as total flow rate. Rotameters were provided in individual spout lines for flow measurement. Humidity and temperature sensors were located for measuring air conditions at required locations (each one at hot air inlet and exit). A U – tube manometer was used for measuring bed pressure drop. The bed masses reported and the corresponding static bed depths were for dry solids at ambient conditions. The flow rates, bed pressure drops and MSBD were measured at ambient conditions.

Three different grains were used in the study and their properties are given in Table 3.2. The details pertaining to various draft tubes used are given in Table 3.3. The various operating conditions used and design variable considered are given in Table 3.4



P-1, P-2 =Pressure gauge; PR=Pressure Regulator; V-1, V-2, V-3, V-4, V5, = Globe Valves; R1, R2, R3, R4, = Rotameters; H = Heater;

HS-1, HS-2 = Humidity Sensors; TS-1, TS-2 =Temperature Sensors

Figure 3.9 (a) Schematic line diagram of experimental

Figure 3.9 (b) Photographs of experimental rig.

3.4 Experimental procedure

Solids of required mass and water of appropriate quantity were thoroughly mixed to obtain wet solids batch needed for a given experimental run. Air flow was adjusted to the required value and it was heated to required temperature and supplied to empty dryer. Wet solids batch was loaded into the column after it attained steady state. Solid samples were taken from the top of dryer using a scoop at regular time intervals. The solids samples were taken in a beaker (fixed to a wooden stick). The sample size was around 15g. The samples were kept in desiccators and their masses were noted. These samples were kept in oven maintained at 70^0C for ragi, 102^0C for wheat and barley for sufficiently long times so that they became bone dry. The temperatures and times for different samples were selected for oven drying based on independent preliminary experiments. They were chosen such that thermal damage of grains would not occur and at the same time bone drying would be achieved. Using the mass differences, the moisture content of each sample at a given time was found. Moisture content versus time plots were prepared for all runs; from these plots batch-drying times needed to achieve a final moisture content of 0.10 kg moisture/kg dry solids from a given initial moisture content were obtained.

The grain temperatures at bed top were measured at regular time intervals by taking a small sample at bed top in a beaker and the solids temperature was quickly measured using a Pt 100 thermocouple.

Table 3.1 Details of dryers used in the study.

	MPDTSB	SPDTSB1	SPDTSB2
Column cross-section, mm x mm	225 x 75	129.9 x 129.9	75 x 75
Column height, mm	500	500	970
Size of each spout cell, mm x mm	75 x 75	129.9 x 129.9	75 x 75
Number of the spout cell(s)	3	1	1
Column Dimensions, mm	75 x 225	129.9 x129.9	75 x 75
Column cross sectional area, m^2	16.875×10^{-3}	16.875×10^{-3}	5.625×10^{-3}
Fluid inlet diameter(s), mm	8, 15, 21	26	15
Details of the dryers used for performance comparison			
Fluid inlet diameter, mm	15	26	15
Cross sectional area of fluid inlet(s), mm^2	529.9	530.6	176.7
Air jet velocity through fluid inlet, m/s	18.87	18.87	56.61
DT id, mm	26	26	26
Cross sectional area of DT(s), mm^2	1592	530.6	530.6
Air superficial velocity through DT, m/s	6.28	18.87	18.87
DT Height, Pitch, mm	380, 15x17	380, 15x17	380, 15x17

Table 3.2 Properties of the grains used.

Physical properties	Ragi	Barley	Wheat
Inherent moisture contents of grains, kg moisture/kg dry solids	0.113	0.11	0.12
Initial moisture contents used, kg moisture/kg bone dry solids	0.15, 0.2, 0.25, 0.3, 0.35.	0.15, 0.2, 0.25.	0.15, 0.2, 0.25.
Grain sizes, mm	1.35	2.98	Minor axis=3.42 Major axis =7.17
Bulk density, kg/m^3	793.4	826.4	795.8
True density, kg/m^3	1243.2	1343.4	1296.6
Specific grain surface, m^2/kg	3.5751	1.4992	1.1729

Table 3.3. Details of draft tubes used.

Inside diameter, mm	Outside diameter, mm	Pitch, mm	Length, mm	No. of holes
21	26	15x14	380/760	114/228
26	31	15x17	380	114
39	44	15x24	380	114

Table 3.4. Variables considered for drying studies in MPDTSB.

Variable	Values
T_a, °C	40,45,50,55,60
v_0, m^3/h	30,33,36
X_0, kg/kg	0.15, 0.20, 0.25, 0.30, 0.35
m_b, kg	1 – 8
d_i, mm	8,15, 21

CHAPTER 4

RESULTS AND DISCUSSIONS

The batch drying times, moisture diffusivities in grains and thermal efficiencies were the parameters considered for study. They would be influenced by the operating variables, design variables and properties of grains. The operating variables considered were inlet air temperature (T_a), initial moisture content of grains (X_0), air flow rate(v_0) and bed mass (m_b). The design parameters considered were inside diameter(d_t) of draft tube(DT), diameter of holes (d_h) in DTs and fluid inlet diameter(d_i). Three different grains having different particle sizes and specific surface areas were used in the study. The influence of different variables on these three parameters were studied experimentally and the results are presented and discussed here.

In addition, the performance of multiple porous draft tube spouted bed dryer was compared with the performance of two different single porous draft tube spouted bed dryers, one having same CSA as that of MPDTSB and the other having CSA of a single spout cell of MPDTSB. The comparison was made based on the batch drying times, moisture diffusivities and thermal efficiencies. The gas-solid convective heat transfer coefficients were also estimated for these three different dryers for comparison.

The influence of these operating variables and design parameters on batch drying time for all three materials in MPDTSB and SPDTSBs are presented in table 4.1.1 to 4.1.6. The experimental data was checked for reproducibility by conducting duplicate runs for some typical experiments and the deviations are found to be with in ±2%. Typical plots of error analysis are shown in appendix – VII.

The solids used were amorphous and fibrous in nature. The moisture was held as an integral part of grain structure and its movement through grain would be by molecular diffusion, which would be a very slow process. As a result, drying would be occurring under falling rate period only. The results obtained indicated that for all the three types of grains used did not exhibit constant rate periods and drying occurred under falling rate periods. The drying rate curves are shown in Figures 4.1 to 4.16

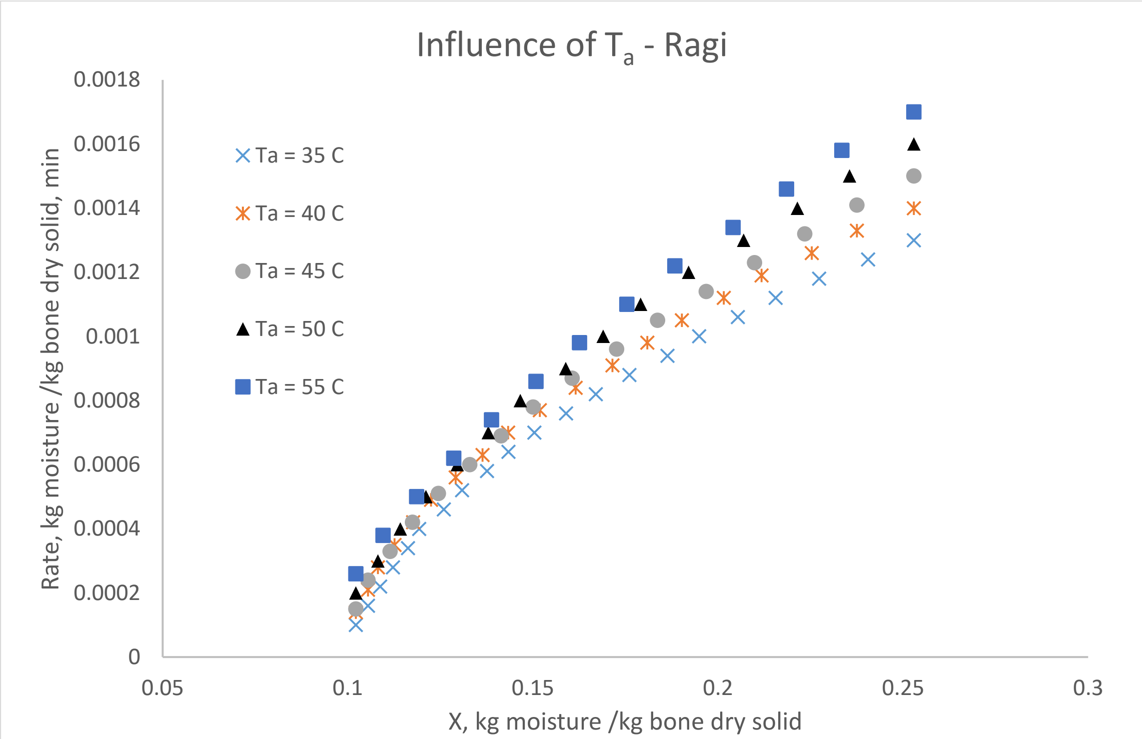


Figure 4.1 Effect of inlet air temperature on rate of drying.

(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 2.5 kg, d_t,= 26 mm, d_i = 21mm, d_h = 2 mm)

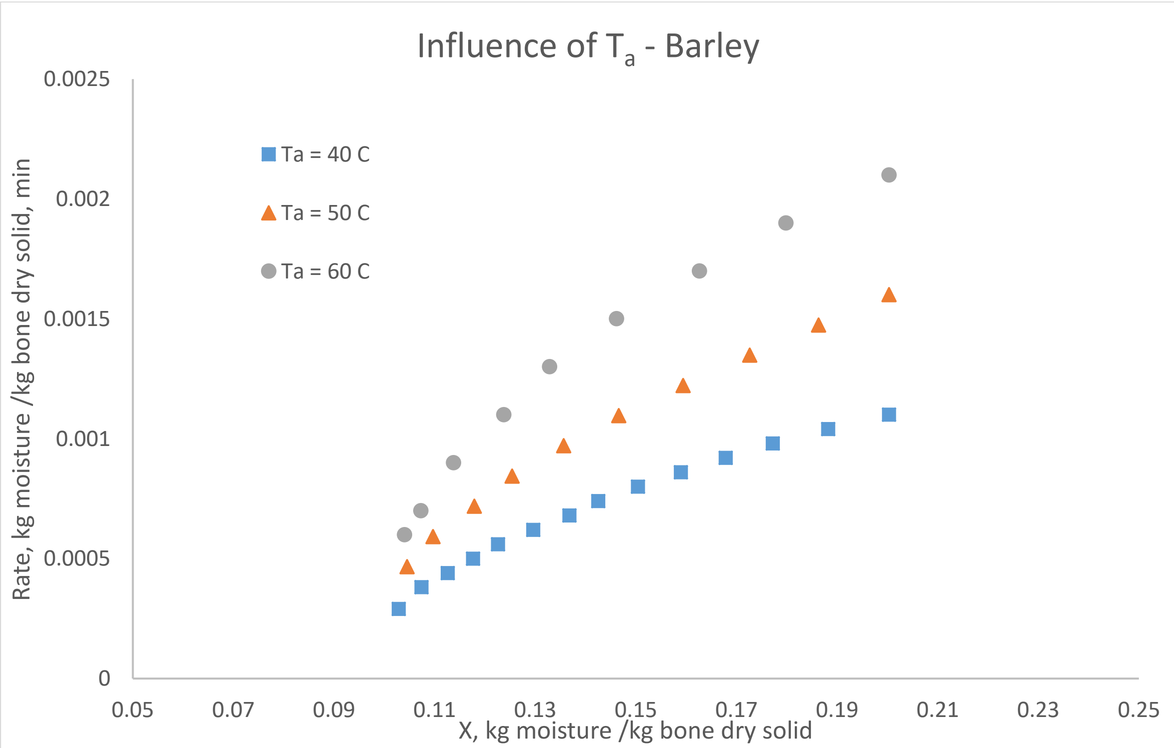


Figure 4.2 Effect of inlet air temperature on rate of drying.

(X_0 = 0.2 kg/kg, v_o = 36 m^3/h, m_b = 2 kg, d_t,= 26 mm, d_i = 21mm, d_h = 2 mm)

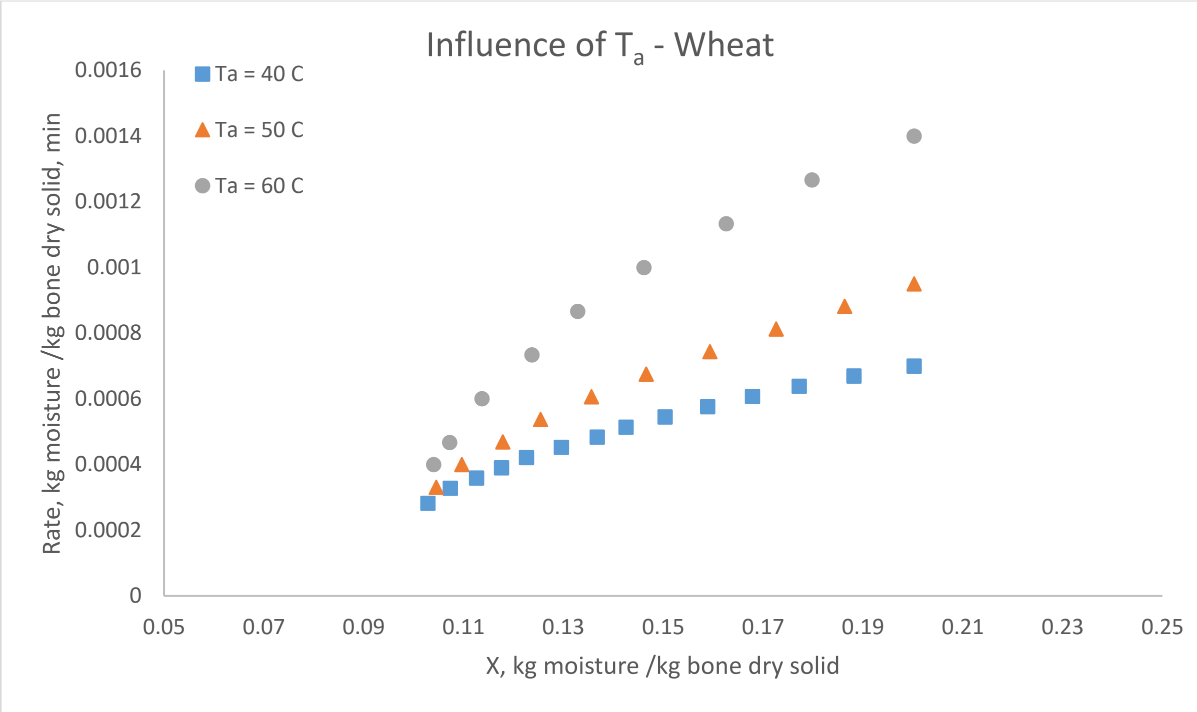


Figure 4.3 Effect of inlet air temperature on rate of drying.

(X_0 = 0.2 kg/kg, v_o = 36 m^3/h, m_b = 2 kg, d_t, = 26 mm, d_i = 21mm, d_h = 2 mm)

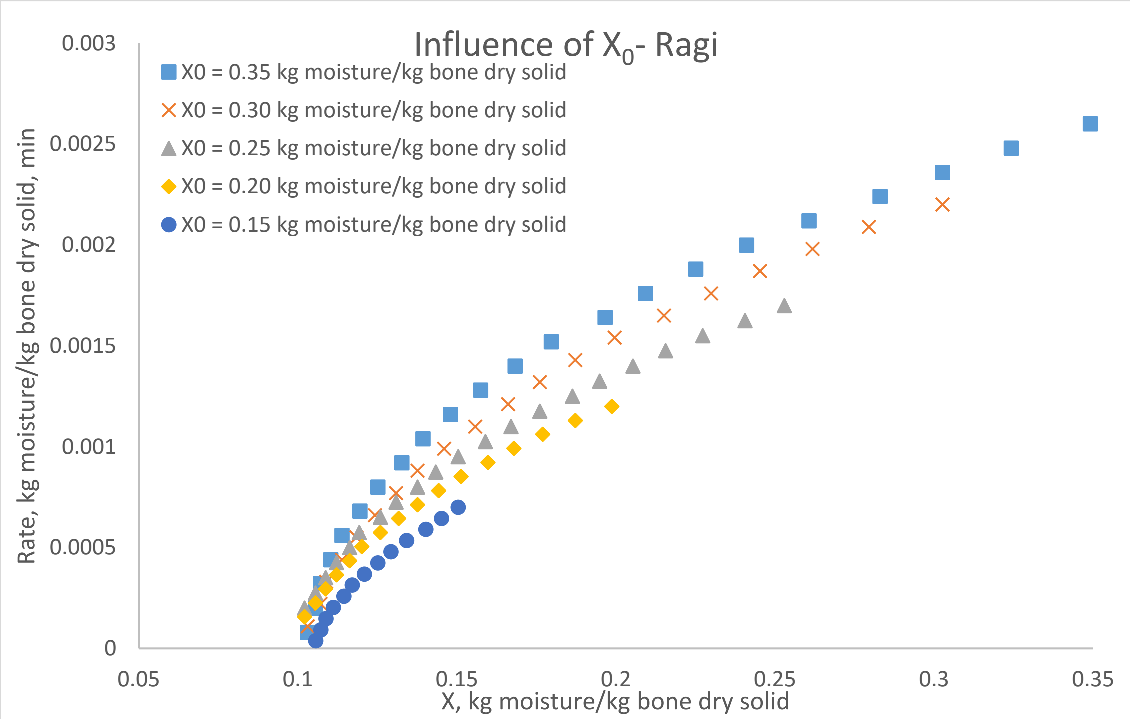


Figure 4.4 Effect of initial moisture content on rate of drying.

(T_a = 50 ^{0}C, v_o = 30 m^3/h, M_b = 2.5 kg, d_t,= 26 mm, d_i = 21 mm, d_h = 2 mm)

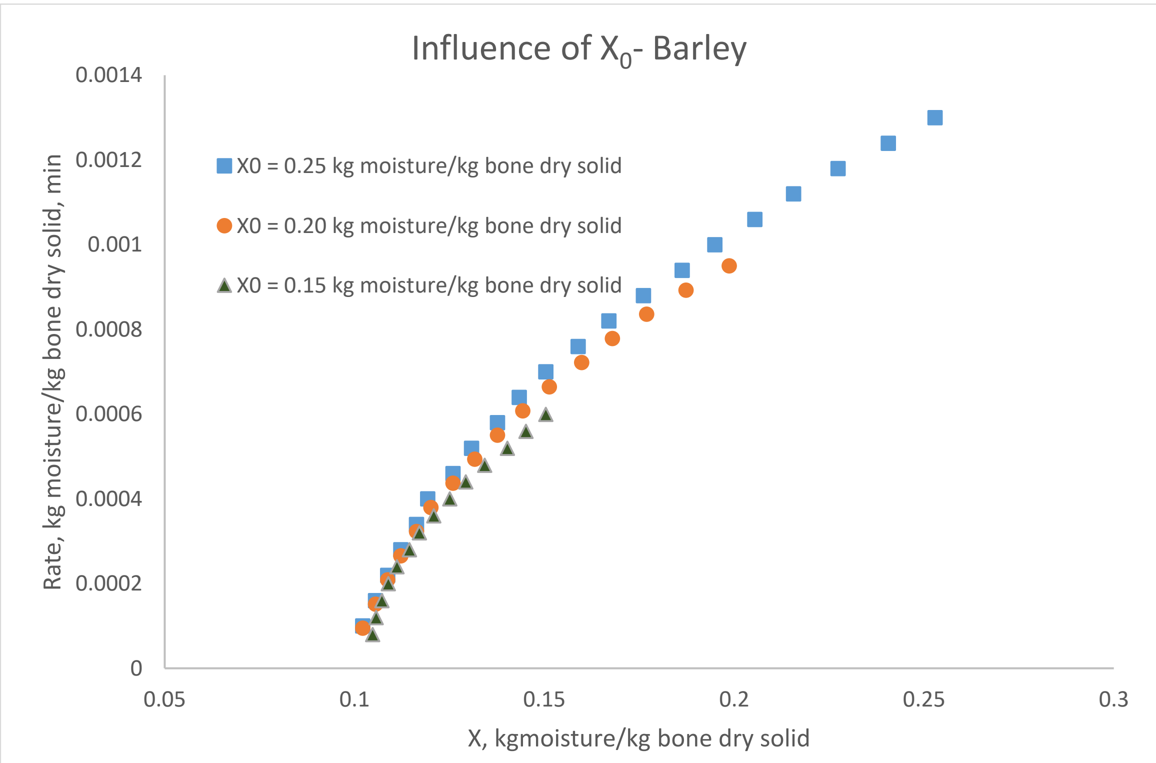


Figure 4.5 Effect of initial moisture content on rate of drying.

(T_a = 50 ^{0}C, v_o = 36 m^3/h, M_b = 4 kg, d_t,= 26 mm, d_i = 15 mm, NPDT)

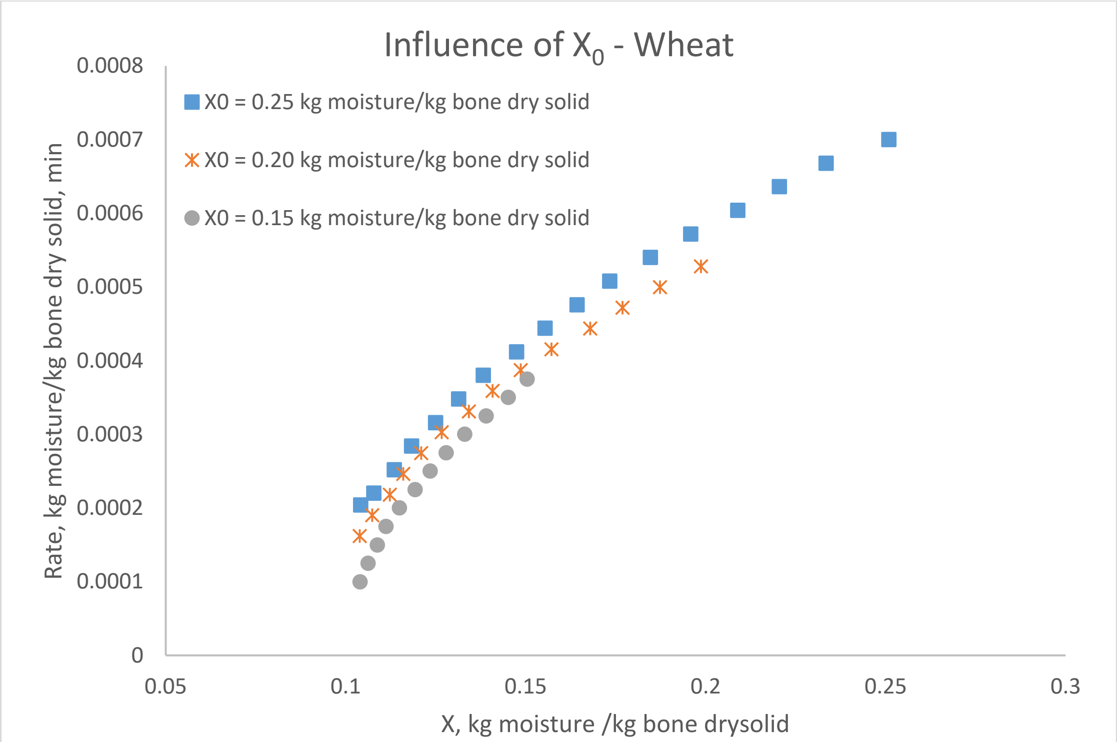


Figure 4.6 Effect of initial moisture content on rate of drying.

(T_a = 50 ^{0}C, v_o = 36 m^3/h, m_b = 4 kg, d_t,= 26 mm, d_i = 15 mm, NPDT)

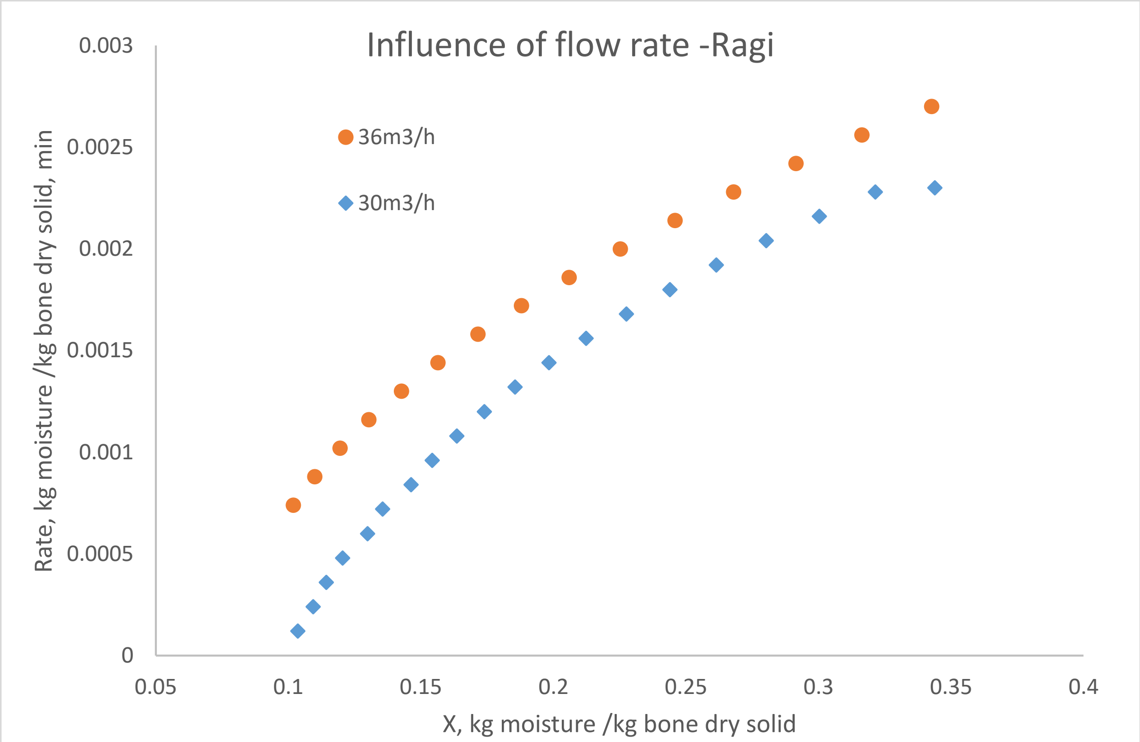


Figure 4.7 Effect of inlet air flowrate on rate of drying.

(T_a= 55 ^{0}C,,X_0=0.35kg/kg, m_b = 2.5kg ,d_t= 26mm, d_i = 21mm, NPDT)

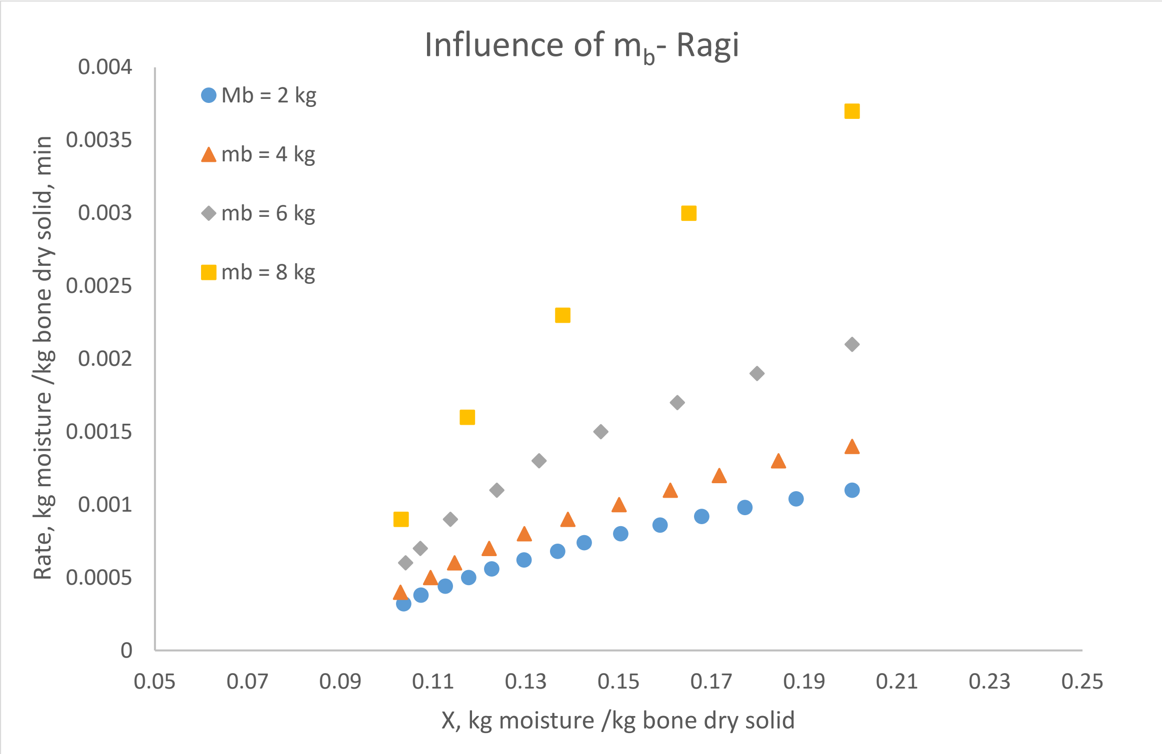


Figure 4.8 Effect of bed mass on rate of drying.

(T_a = 50 ^{0}C, X_0 = 0.2 kg/kg, v_o = 36 m^3/h, $d_{t,}$ = 21 mm, d_i = 21 mm, d_h = 4 mm)

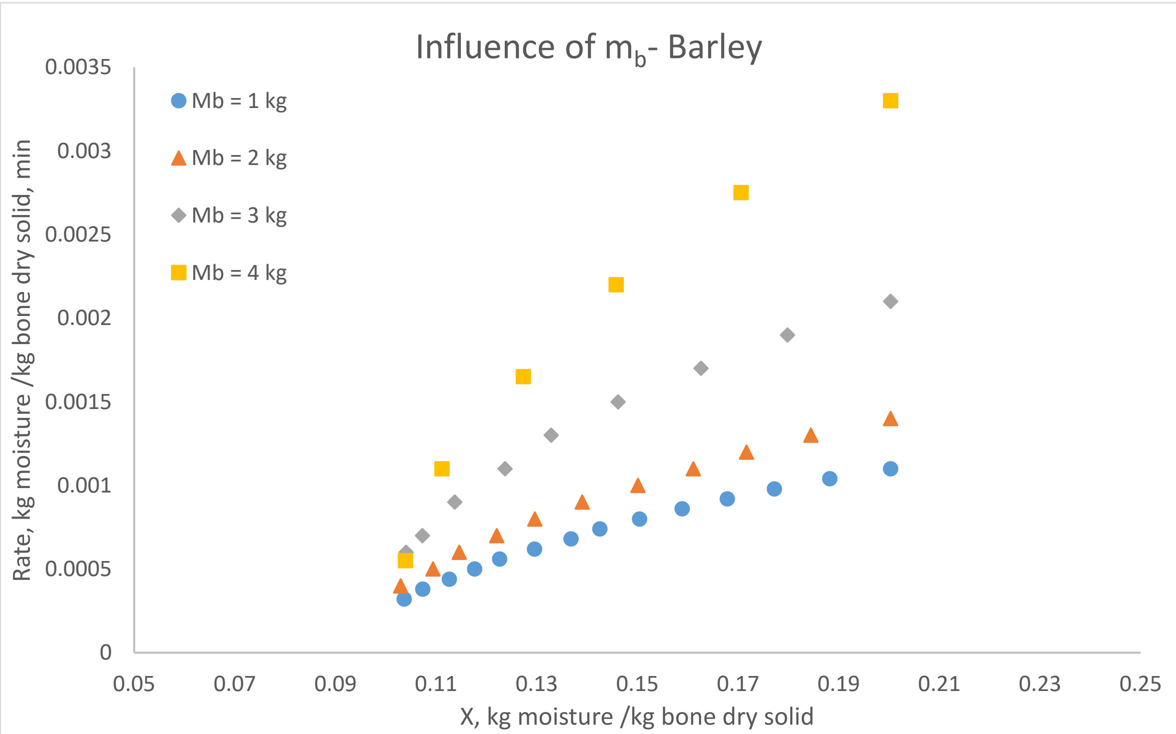


Figure 4.9 Effect of bed mass on rate of drying.

(T_a = 60 ^{0}C, X_0 = 0.2 kg/kg, v_o = 36 m^3/h, $d_{t,}$= 21 mm, d_i = 15 mm, NPDT)

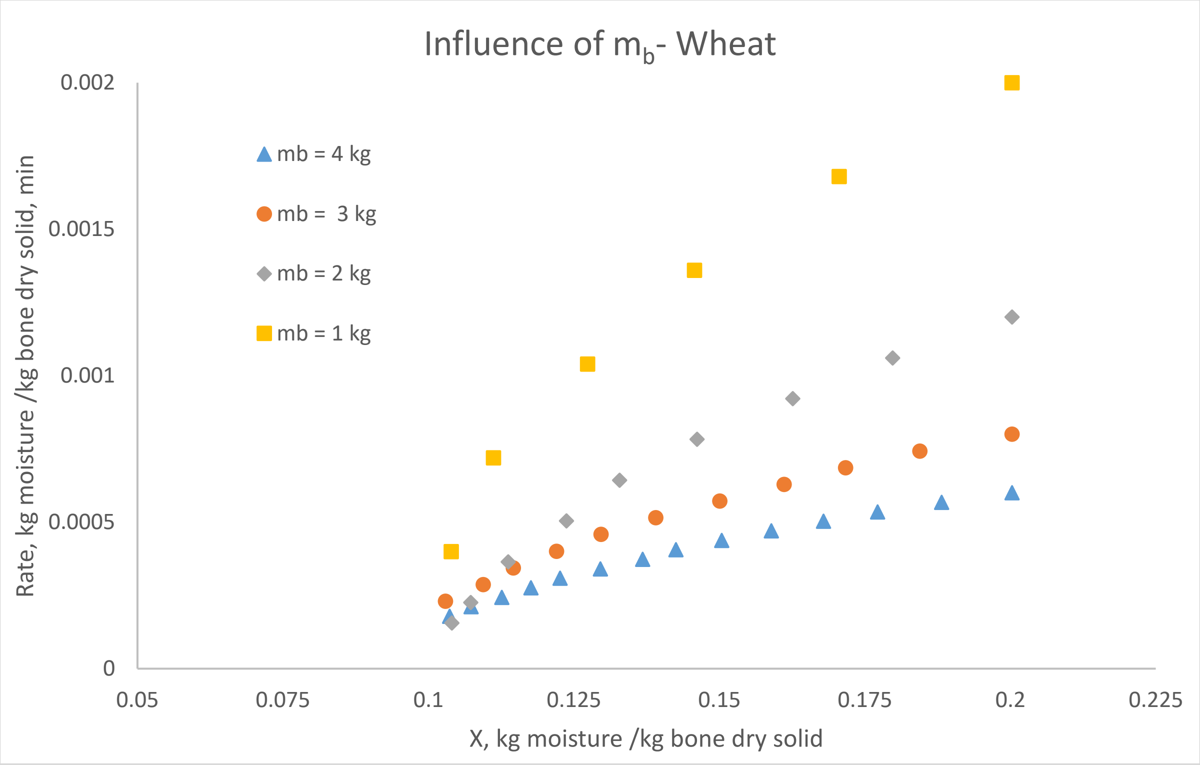


Figure 4.10 Effect of bed mass on rate of drying.

(T_a = 60 ^{0}C, X_0 = 0.2 kg/kg, v_o = 36 m^3/h, $d_{t,}$= 21 mm, d_i = 15 mm, NPDT)

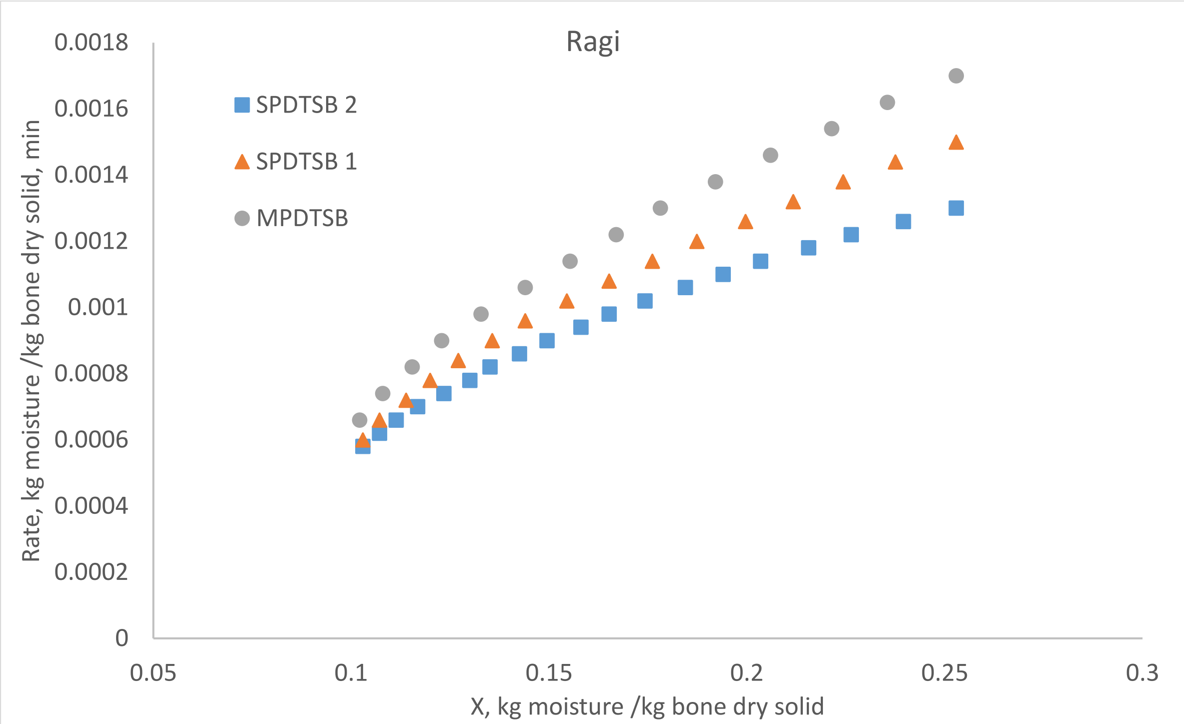


Figure 4.11 Comparison of drying rates in MPDTSB and SPDTSBs.

($T_a = 40^0C$, $X_0 = 0.25$kg/kg, $v_o = 36\ m^3/h$, $m_b = 2$ kg, d_t,=26 mm, d_h =2 mm)

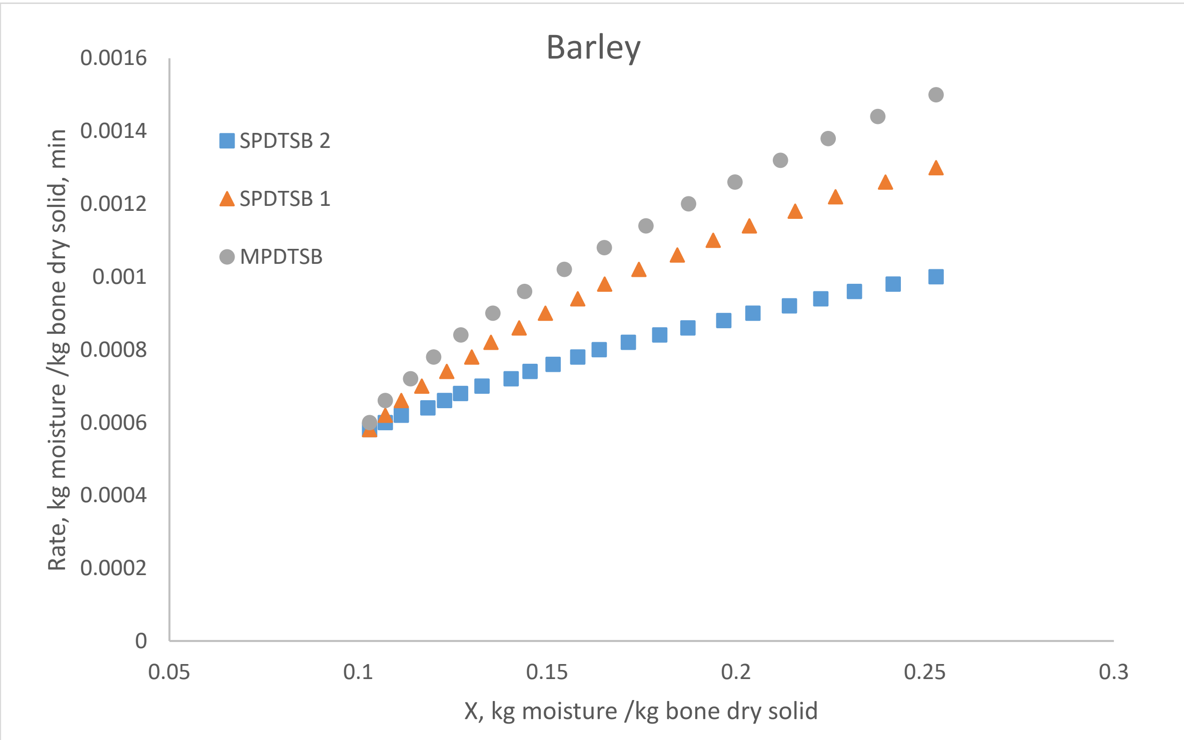


Figure 4.12 Comparison of drying rates in MPDTSB and SPDTSBs.

($T_a = 40^0C$, $X_0 = 0.25$kg/kg, $v_o = 36\ m^3/h$, $m_b = 2$ kg, d_t,=26 mm, d_h =2 mm)

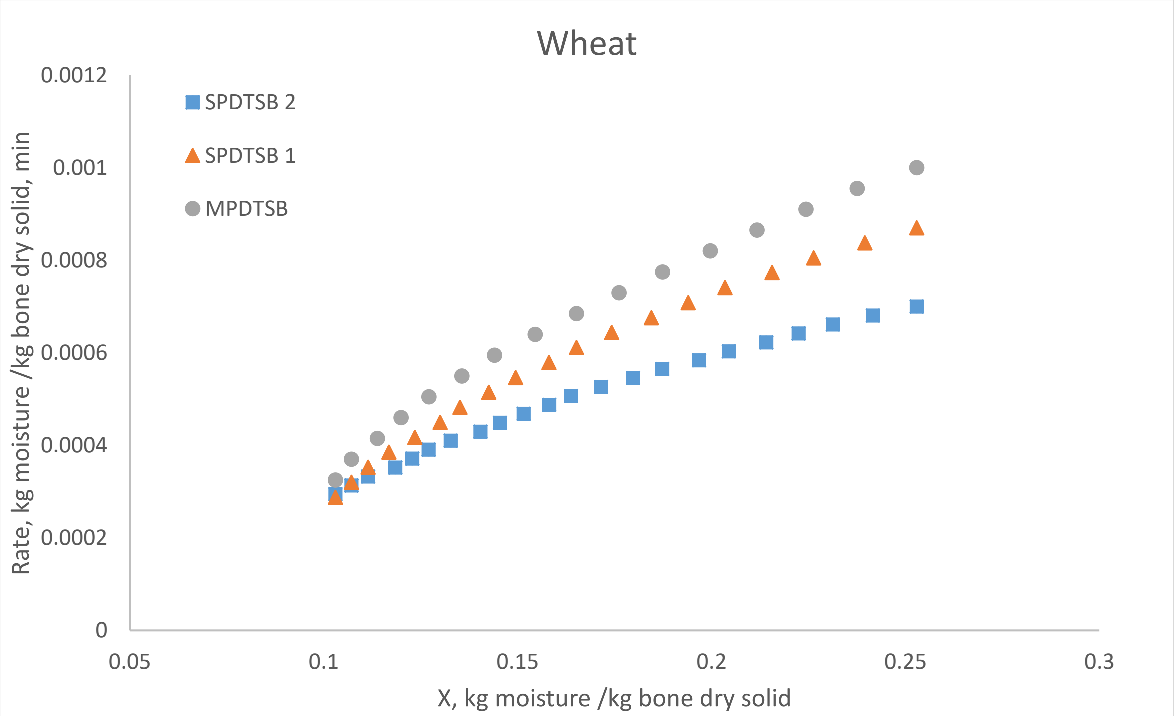


Figure 4.13 Comparison of drying rates in MPDTSB and SPDTSBs.

($T_a = 40^0C$, $X_0 = 0.25$kg/kg, $v_o = 36\ m^3/h$, $m_b = 2$ kg, $d_{t,}$=26 mm, d_h =2 mm)

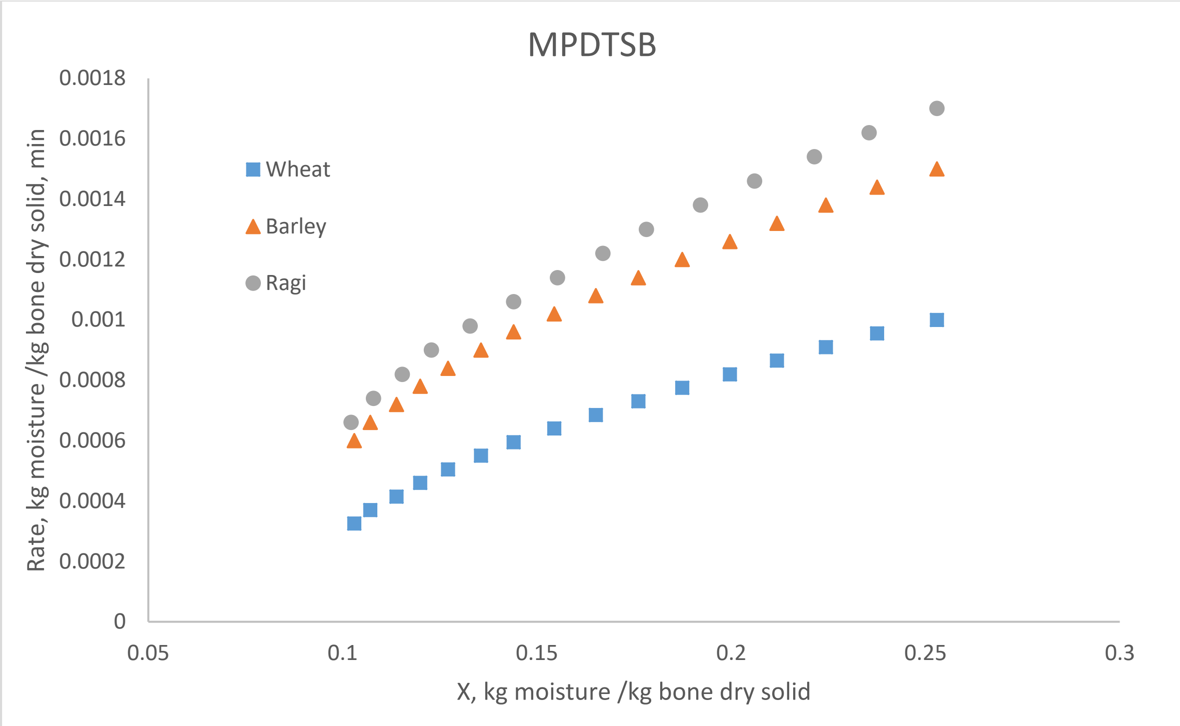


Figure 4.14 Comparison of drying rates for different grains in MPDTSB.

(T_a=40^{0}C, X_0=0.25 kg/kg, v_o=36 m^3/h, m_b =2 kg, d_t=26 mm, d_i =15 mm, d_h =2 mm)

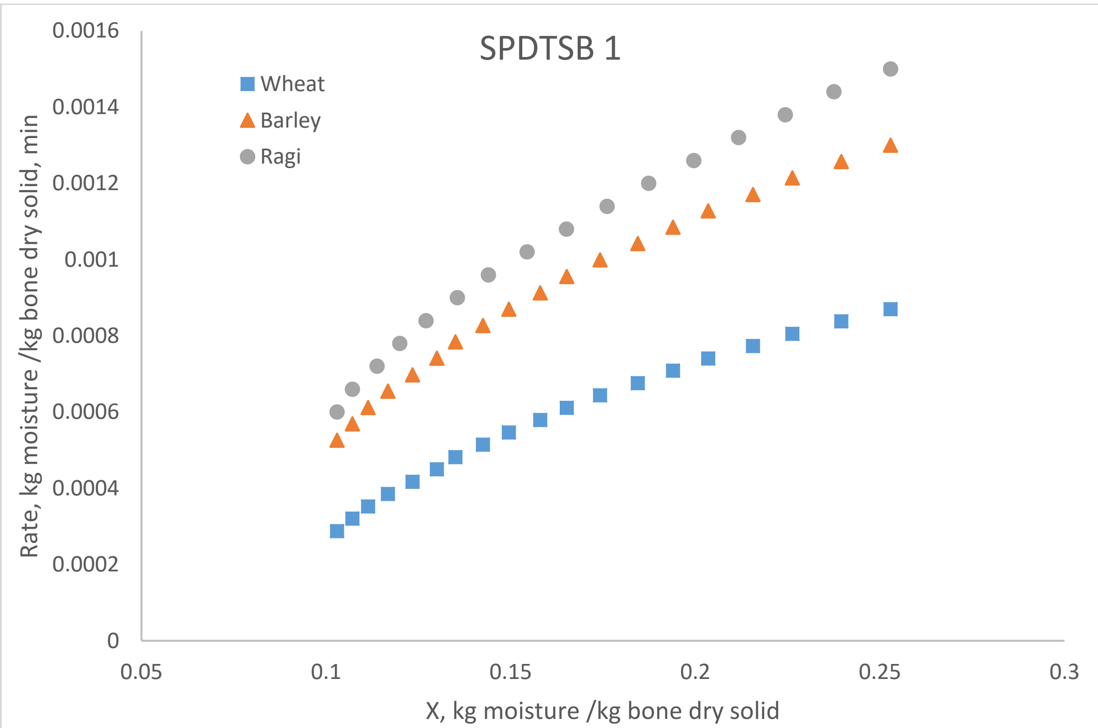


Figure 4.15 Comparison of drying rates for different grains in SPDTSB1.

(T_a =40^{0}C, X_0=0.25 kg/kg, v_o=36 m^3/h, m_b =2 kg, d_t=26 mm,d_i=26 mm,d_h = 2 mm)

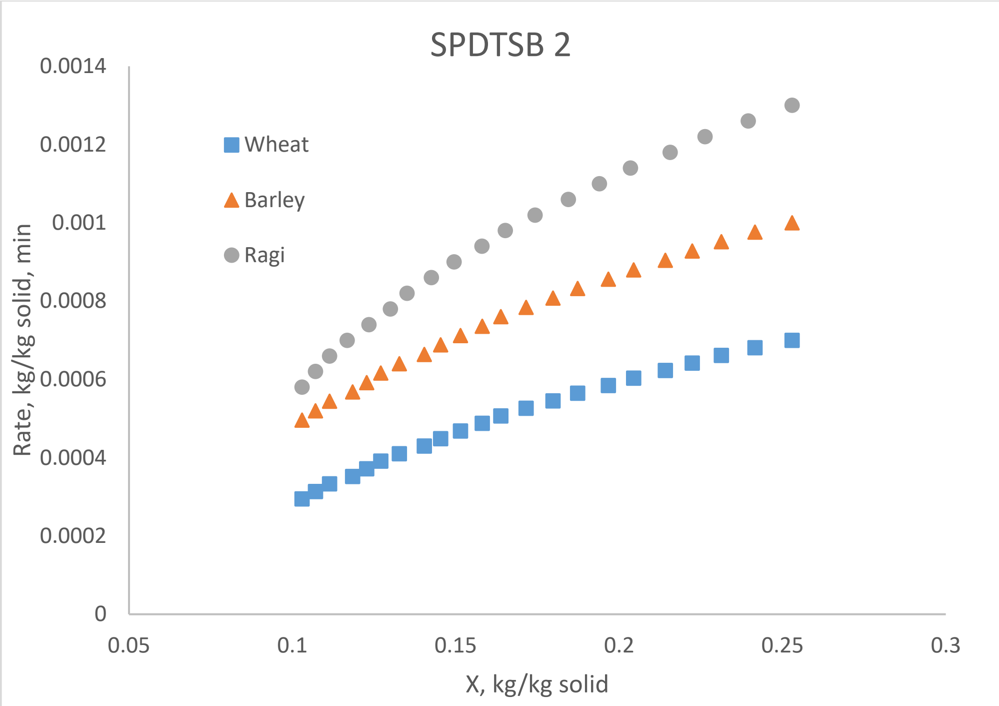


Figure 4.16 Comparison of drying rates for different grains in SPDTSB2.

(T_a=40^{0}C, X_0 =0.25 kg/kg, v_o=36 m^3/h, m_b=2 kg,$d_{t,}$=26 mm, d_i =26 mm, d_h = 2 mm)

4.1 Influence of operating variables on drying

4.1.1 Influence of air inlet temperature on drying rate and batch drying time

Since the drying occurred under falling rate conditions the moisture diffusion through grain would control the overall process and the diffusion rate would be temperature dependent. The grain temperature attained would influence the diffusion rate here. The grain temperature would be dependent on dry bulb temperature of air. Since the inlet air temperature could be an easily measurable operating variable, its influence on drying rate was studied. The results shown in Figures 4.1-4.3 and 4.17 – 4.19 indicated that the drying rate increased and batch drying time decreased as the inlet air temperature increased when all other variables were kept constant. An increase in air inlet temperature increased the grain temperature. The energies possessed by water molecules present in grain structure would be increasing with increase in grain temperature resulting in enhancement of diffusion rate of moisture with in the grains; this lead to lower batch drying times.

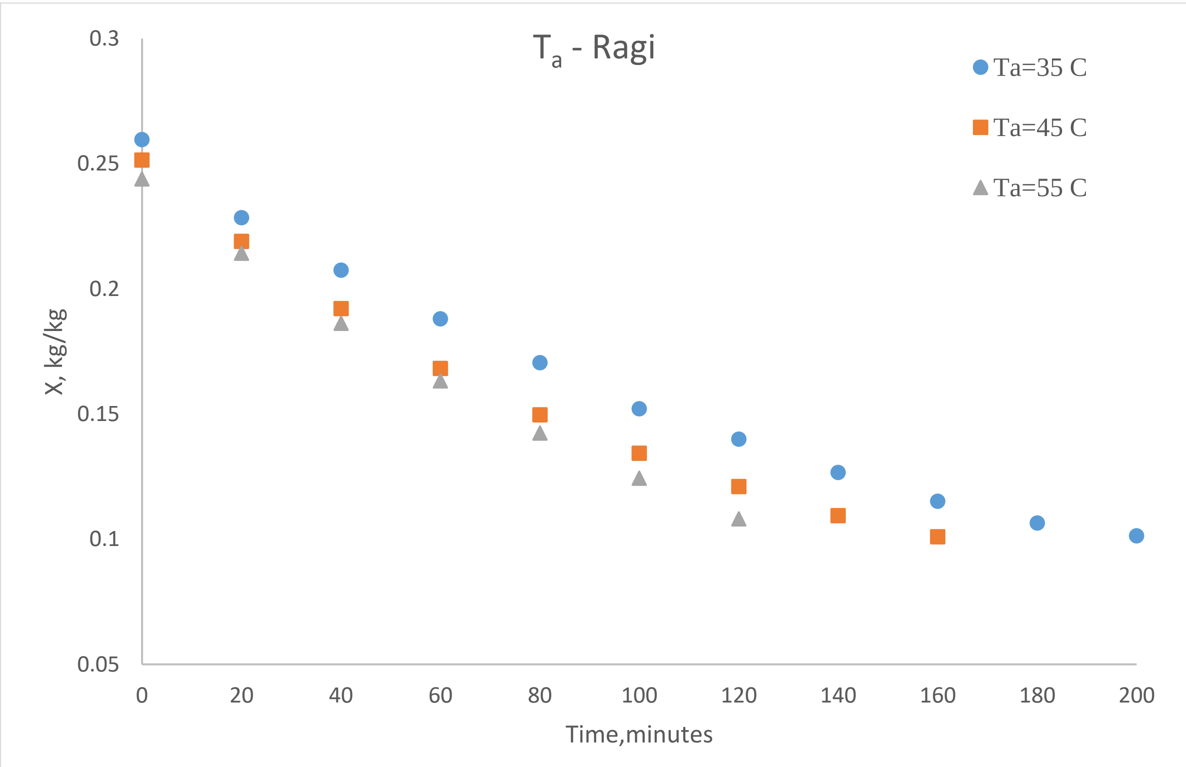


Figure 4.17 Effect of inlet air temperature on batch drying time.

(X_0=0.25kg/kg, v_0 =36 m^3/h, m_b = 2.5 kg, d_t= 26mm, d_i = 21mm, NPDT)

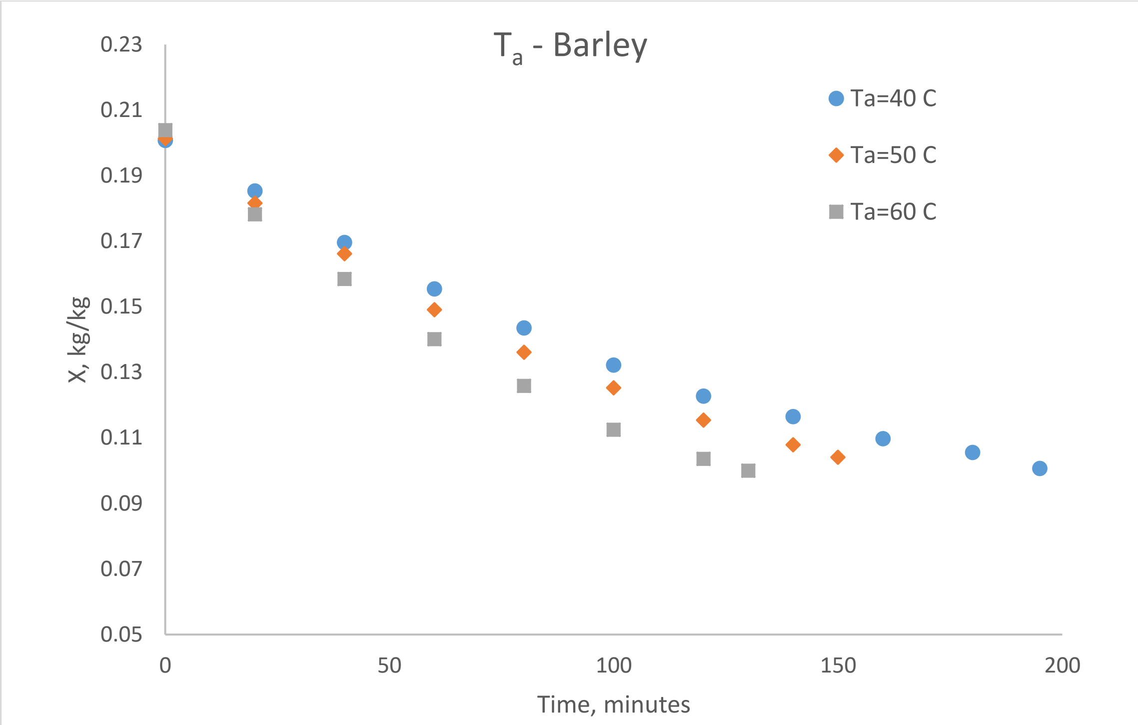


Figure 4.18 Effect of inlet air temperature on batch drying time.
(X_0=0.2kg/kg, v_0 =36 m^3/h, m_b = 4 kg, d_t= 26mm, d_i = 15mm, NPDT)

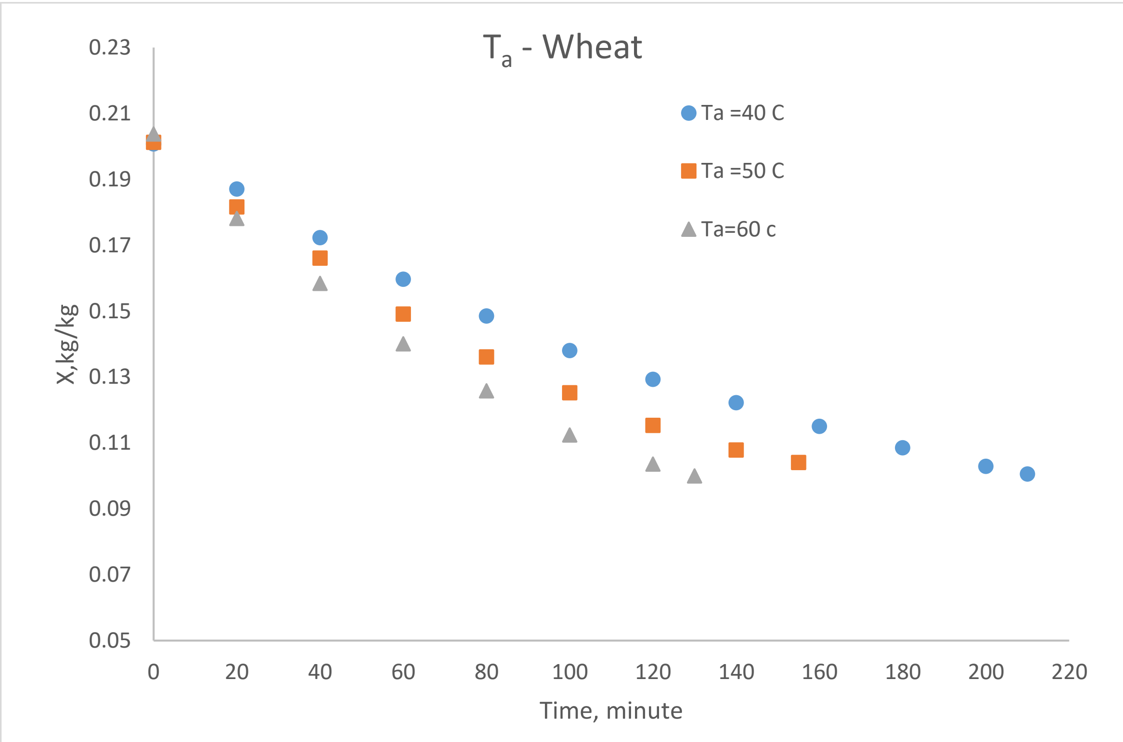


Figure 4.19 Effect of inlet air temperature on batch drying time.
(X_0=0.2kg/kg, v_0 =36 m^3/h, m_b = 2 kg, d_t= 26mm, d_i = 15mm, NPDT)

4.1.2 Influence of initial moisture content of grains on drying rate and batch drying time

The results shown in Figures 4.4 – 4.6 and 4.20 – 4.22 indicated that the drying rate decreased and batch drying time increased as the initial moisture content of grains increased at a given set of conditions. For a given final moisture content of 0.1kg moisture/ kg bone dry solid, as the initial moisture content increased the total amount of moisture to be removed would be increasing and also the total wet bed mass would be more, leading to slower bed recirculation rates and hence longer batch times were needed.

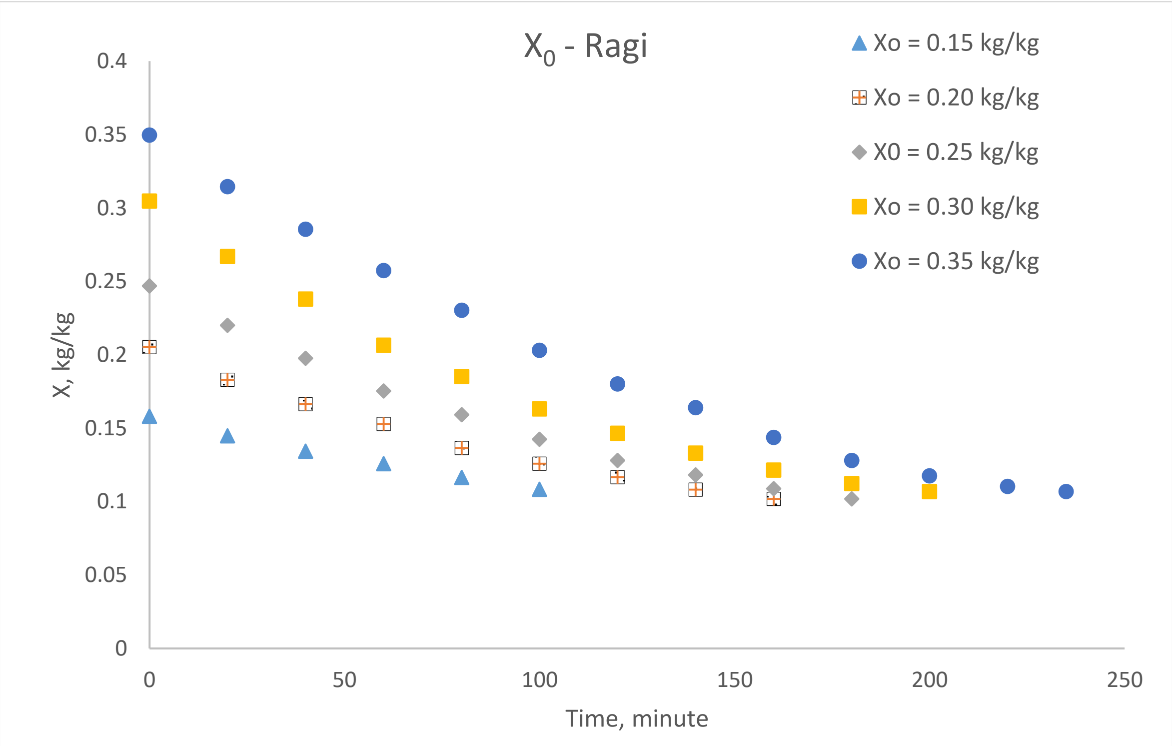


Figure. 4.20 Effect of initial moisture content on moisture removal.

(T_a= 45 ^{0} C, v_0 = 30 m^3/h, m_b = 2.5 kg, d_t=21mm, d_i =21mm, NPDT)

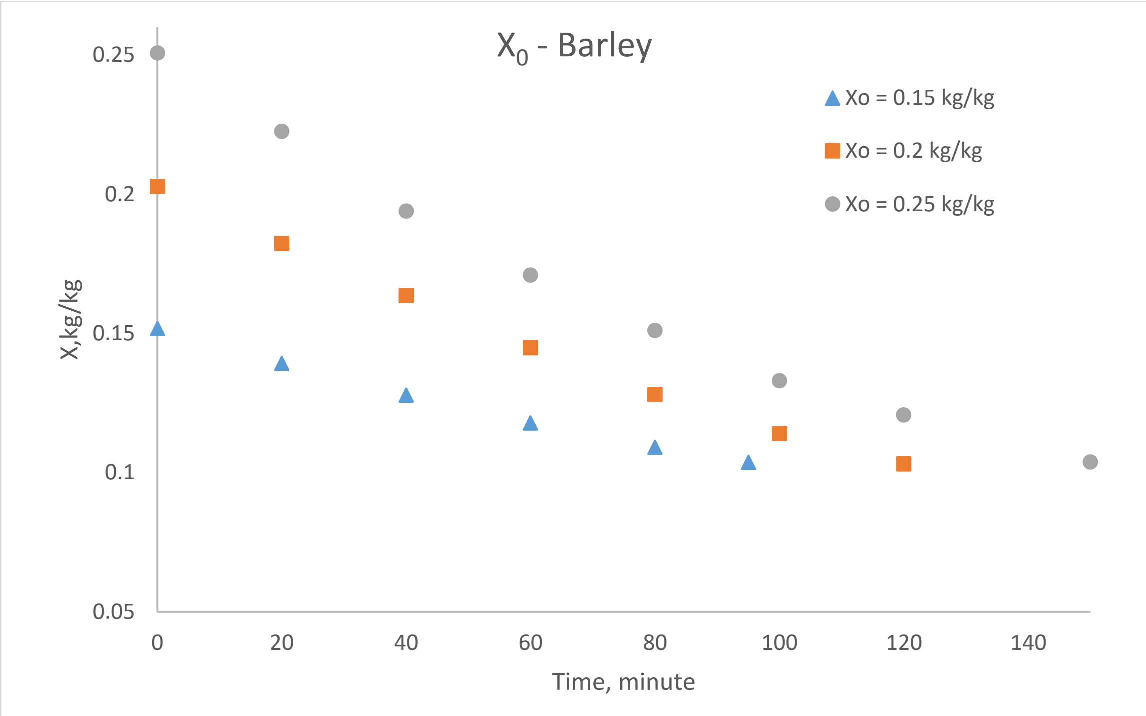


Figure. 4.21 Effect of initial moisture content on moisture removal.

(T_a= 40 ^{0} C, v_0 = 36 m^3/h, m_b = 2 kg, d_t=26mm, d_i =15 mm, d_h=2mm)

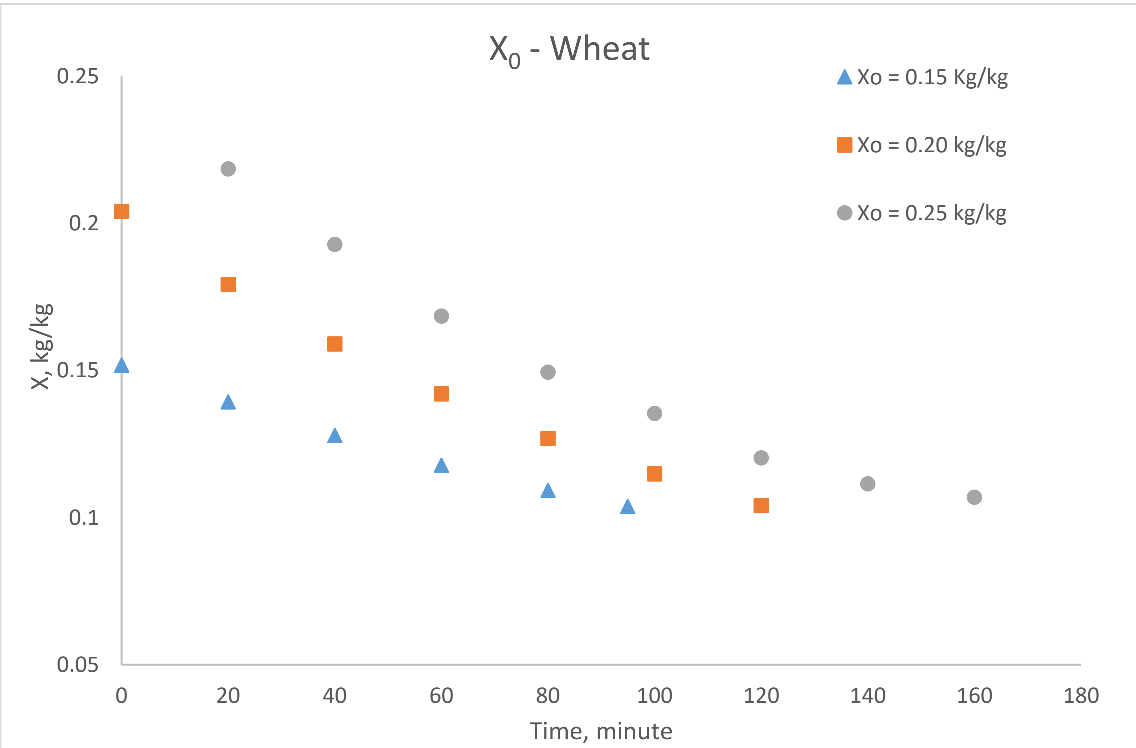


Figure 4.22 Effect of initial moisture content on moisture removal.

(T_a= 60 ^{0} C, v_0 = 36 m^3/h, m_b = 2 kg, d_t=26mm, d_i =15 mm, d_h=2mm)

4.1.3 Influence of air flow rate on drying rate and batch drying time

An increased air flow rate would lead to increase in solids circulation and also increased heat supply rate to bed, which in turn should lead to better transfer rates of heat and mass. The results given in Figures 4.7 and 4.23 indicted that the drying rate marginally increased and batch drying time marginally decreased with an increase in air flow rate at a given set of operating conditions; this could be because the convective mass transfer did not play any significant role here due to the following reasons.

- Moisture diffusion through grain controled the overall process here.
- The grains quickly attained the temperature of surrounding air when turbulent flow conditions prevailed in the dryer at the air flow rates used here.
- The heat transfer from air to grain was much faster when compared to mass transfer (moisture transport) within the grains.
- The thermal response of the grains would be much quicker. For example, Robbins and Fryer (2003) measured the thermal responses of barley grains and found them to be within 10 s, whereas their model response gave thermal equilibrium within 15 s.

It should be noted here that the influence of inlet airflow rate was studied using ragi grains only; but similar trends could be expected with wheat and barley.

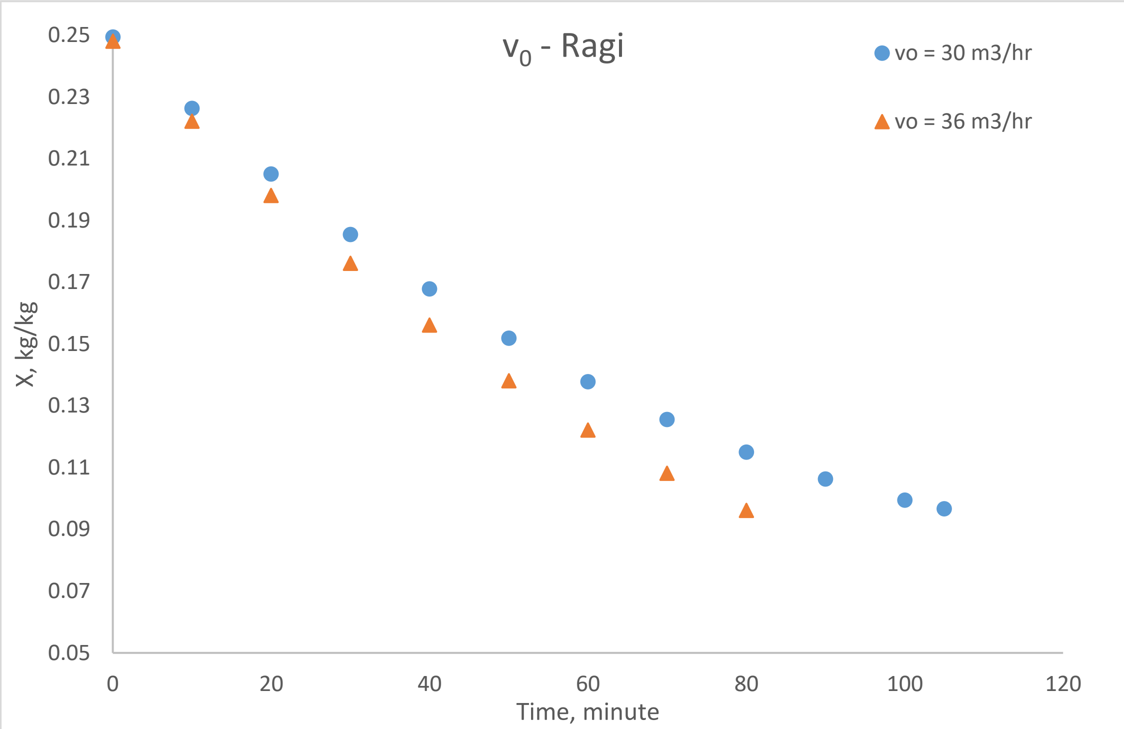


Figure 4.23 Effect of air flow rate on moisture removal.

(T_a=55^{0}C, X_0= 0.25 kg/kg, m_b = 2 kg, d_t= 21mm, d_i = 21mm, d_h= 2mm)

4.1.4 Influence of bed mass on drying rate and batch drying time

As the bed mass increased the bed depth would increase and the gas-solid contact times in DTs would increase which resulted in better heat transfer between gas and grains. However, the hot grains from DTs had to travel through deeper annuli for larger bed depths and would get cooled to lower temperatures; this lowered the diffusion controlled moisture removal. Also, at a given air flow rate, the solids circulation would decrease when bed mass increased. Further, as the bed mass increased for a specified initial moisture content, the total amount of moisture to be removed would be increasing. These factors lead to lower drying rates and longer drying times for larger bed masses as shown in Figures 4.8 – 4.10 and 4.24 – 4.26.

The results on the influence of operating variables on drying indicated that a higher air inlet temperature, lower initial moisture content of grains, higher air flow rate and lower bed masses lead to faster drying rates and lower batch drying times. However, it should be noted here that operation with higher air inlet temperature and air flow rate would increase the operating costs; more number of batches would be handled when bed masses are lower. The initial moisture contents of fresh agricultural grains would be fairly fixed.

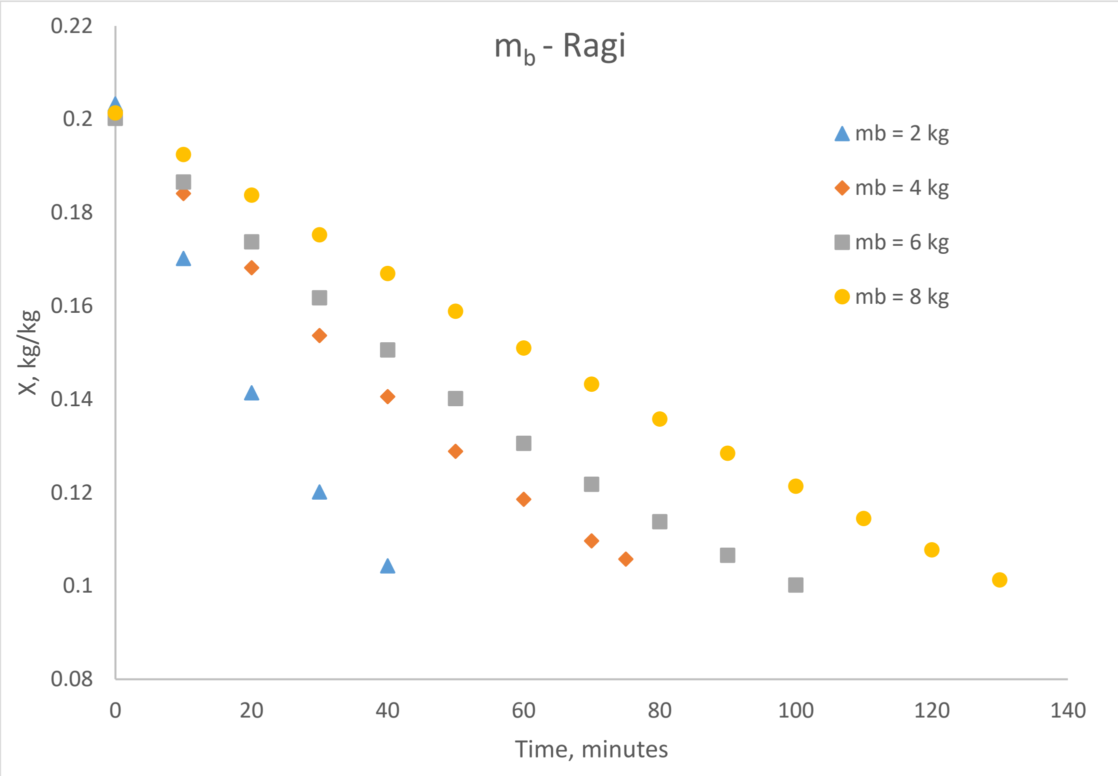


Figure 4.24 Effect of bed mass on moisture removal

(T_a=50^{0}C, X_0= 0.2kg/kg, v_0 = 36 m^3/h, d_t= 21mm, d_i = 21mm, d_h= 4mm)

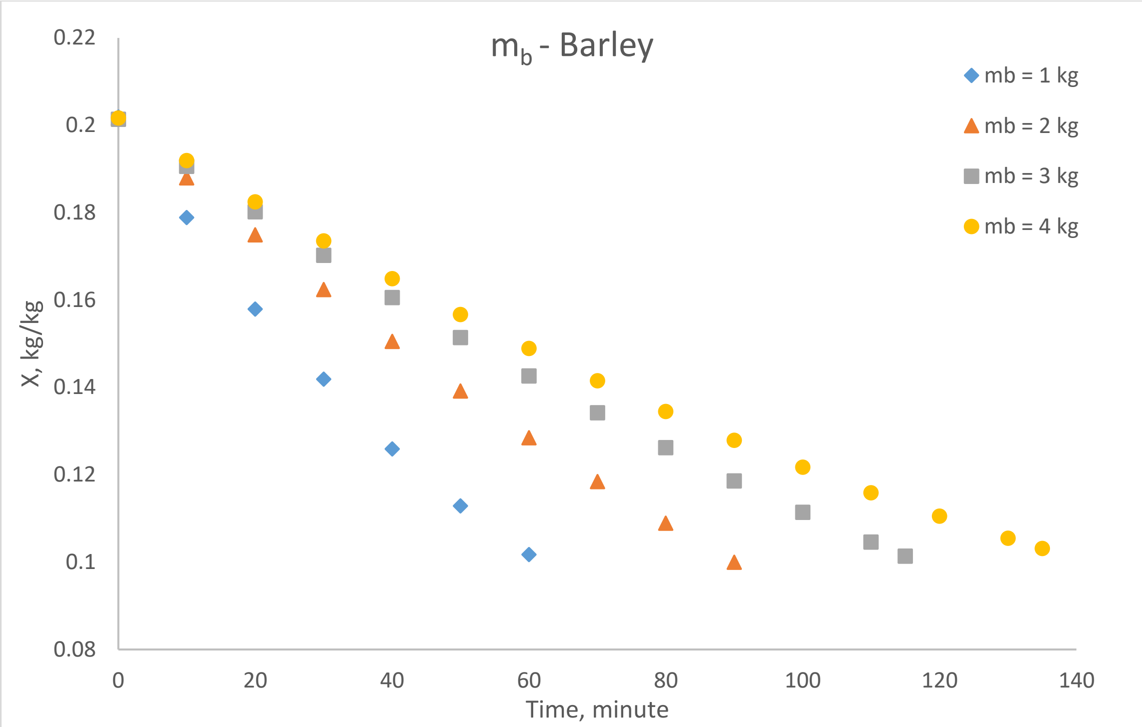


Figure. 4.25 Effect of bed mass on moisture removal

(T_a=50^{0}C, X_0= 0.2kg/kg, v_0 = 36 m^3/h, d_t= 26mm, d_i = 15mm, d_h= 2mm)

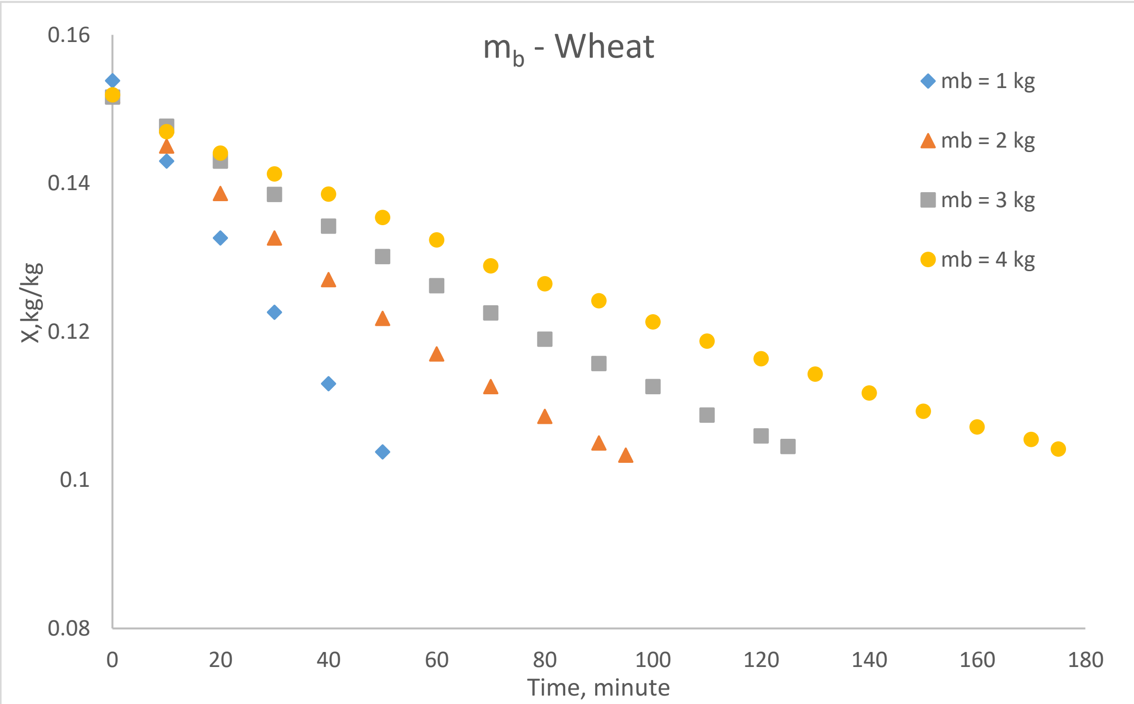


Figure 4.26 Effect of bed mass on moisture removal

(T_a=60^{0}C, X_0= 0.15kg/kg, v_0 = 36 m^3/h, d_t= 26mm, d_i = 15mm, d_h= 2mm)

4.2 Influence of design parameters on batch drying time

Since the DTs help in overcoming the MSBD limitation and facilitate in scale up for large scale operations, the DT parameters play an important role in the design of this type of dryer. So, in order to understand the influence of DT ID and hole size on batch drying time, experiments were conducted using both non-porous and porous DTs.

When non-porous DTs (NPDTs) were provided in a MSB the hot air would contact the solids present in DTs and would leave the bed through the fountains without contacting the solids in annuli. As a result, drying could be occurring mostly within DTs and to some extent in fountains also. However, porous DTs facilitated hot air supply into annulus regions where bulk of the drying could be occurring. Grains would typically pick up heat while they transverse through DTs, and while coming down through annuli they would exchange heat with fellow grains and also receive heat from hot air flowing through DT holes leading to better heat and mass transfer.

So, it was expected that the batch drying times for MSB with porous DTs should be less when compared to cases with non-porous DTs, as reflected in the results shown in Tables 4.2 – 4.4.

4.2.1 Influence of DT diameter on batch drying time

As the id of DT increased for a given DT length the volume fraction of total bed present in DT would increase and for a given air rate the superficial velocity of air would decrease; this resulted in increase in gas-solid contact time with more bed fraction present in DTs. An increased gas-solid contact time lead to better heat transfer between gas and solids in DTs and better mass transfer from solids to gas in the bed as a whole. So, the results as given in Tables 4.5 – 4.7 indicated that the batch drying times decreased as the DT ID increased. However, it should be noted here that there would be an upper limit for DT ID for a given set of operating conditions. For a given air flow rate and other conditions, an increase in DT ID would decrease the superficial velocity within DT and under a limiting condition spouting would not be possible.

4.2.2 Influence of DT hole diameter on batch drying time

The results given in Tables 4.8 – 4.10 indicated that the batch drying time decreased as the hole diameter in porous DTs increased. This could be because of increased hot air supply into annuli as the hole size increased, leading to better moisture removal rates.

4.2.3 Influence of DT hole area on batch drying time

The hot air supply into annulus regions would be dependent on the total hole area provided on a given DT. The chosen hole diameter and hole pitch would decide the hole area that would be available for a given DT length. In order to understand the influence of hole area on batch drying time a few experiments were conducted for different hole areas. The results obtained as given in Table 4.11 indicated that the batch drying times decreased as the hole areas increased. This could be because of increased hot air supply into annuli as the hole area increased, leading to better drying rates.

Madhiyanon and Soponronnariit (2005) studied paddy drying in a two-dimensional spouted bed having draft plates; hot air was supplied to the spout region as well as down-comer. They concluded that moisture removal occurred in both spout and down-comer regions. They believed that evaporative cooling could be the main cause for moisture reduction. In addition, they demonstrated that down-comer air flows played an important role in drying and moisture removal increased with increasing down-comer air flow. The down-comer air flow in their dryer could be considered similar to hot air supply through DT holes to annulus regions in the MPDTSB dryer used in this work. An increase in hole area, through an appropriate choice of hole diameter and pitch for a given DT length, lead to more hot air supply into annuli and faster drying.

The following points are to be noted here in the context of porous DT design.

- As the DT ID increased the superficial velocity of air would decrease for a given air rate; also, as the particle size increased the air velocity needed for spouting would increase. So, when much coarser grains were to be spouted in larger diameter DTs, higher air flow rates would be needed. Ragi grains were smaller when compared to wheat and barley and hence all three DTs could be used for ragi, whereas DTs having 39 mm id could not be used for wheat and barley because of air supply limitations in this work.

- Since the DT holes helped in hot air supply into annuli, an appropriate choice of hole diameter and hole pitch for a given DT length would become necessary. However, for a given air flow rate a large diversion of air through holes into annuli could lead a situation where the vertical velocity component of air in DT would not be sufficient for proper spouting to occur unless the air flow rate would be increased.
- In the context of design, when relatively smaller sized grains are to be handled, DTs having smaller id and larger holes may be used. However, for larger sized solids, DTs having larger id and larger holes may be preferred to avoid chocking of DTs.

4.2.4 Influence of fluid inlet diameter on batch drying time

Epstein and Grace (2011) mentioned that the fluid inlet diameter would play an important role for effective spouting. They stated that an upper limit for fluid inlet diameter could exist for a given particle size and the requirement could be that the ratio of fluid inlet diameter to particle size should not exceed about 25 to 30, irrespective of particle density. This condition was satisfied for all cases used in this study. As the fluid inlet diameter increased the superficial fluid velocity would decrease for a given fluid flow rate. At the lower end, the fluid velocity should just be sufficient to lift the particles and contribute for stable spouting; however, a too large fluid inlet would lead to a lower spout jet velocity which might not be sufficient to achieve spouting.

When the fluid inlet diameter decreased, the fluid jet velocity would increase leading to lower gas-solid contact times; however, higher jet velocities would increase the bed recirculation rate which would help in enhancing the drying rate. Yet very high fluid jet velocities might lead to particle attrition and damage. Thus, it would be important to choose a proper fluid inlet diameter considering both particle properties and other design parameters of spouted bed.

The results presented in Tables 4.12 – 4.14 indicted that the batch drying times decreased as the fluid inlet size decreased for a given bed mass. However, grain damage was observed for all three types of grains with 8 mm fluid inlets. The damage was found to be considerable for ragi when compared to wheat and barley; this could be because of distinctly different grain structures of these solids. When 15 and 21mm fluid inlets were used, no damage was observed for all three types of grains.

So, a proper choice of fluid inlet size would become important wherever grain damage is undesirable. However, in situations where the grains were to be ground to make powder and size reduction during drying could be tolerable, one could take advantage of lower drying times with smaller fluid inlets. Also, higher jet velocities with smaller fluid inlets would help in de-husking and polishing the grains.

4.3 Influence of grain properties on batch drying time

Since the drying occurred under falling rate condition diffusions of moisture through grins would control the drying process. Therefore, the grain properties such as particle size, specific surface area and grain structure would influence the drying rate. McDonough et al (1986) studied the structural and chemical features of ragi utricles in detail. Casada (2002) while reporting about the moisture absorption characteristics of wheat and barley discussed about the structural features of these grains. It could be concluded from these reported studies that these three different grins essentially consisted of seed coat surrounded by a pericarp; however, these grains seemed to be having distinctly different non-homogeneous internal structures. The pericarp in the case of ragi grains would not be fused to seed coat and hence could be easily removed by rubbing action even though the seed coat would contain several layers. The pericarp and seed coats in wheat and barley grains would have tight arrangements of cells, which would offer high resistance to moisture diffusion with in the grains. The structural differences apart, the grain sizes and their specific areas were also different for these three grains. Hence, the results obtained in this study indicated different drying rates for these three different grains. The results as given in Tables 4.15 – 4.17 indicated that the batch drying times for ragi grains were less when compared to barley and wheat under identical conditions. This could be because ragi grains were smaller in size having larger surface specific area leading to higher diffusion rates. Therefore, when coarser grains with lower specific area are to be dried, appropriate operating conditions like higher inlet air temperature and also appropriate design parameters of the dryer are to be chosen to achieve higher drying rates and lower drying times.

4.4 Estimation of moisture diffusivities in grains

Since drying occurred under diffusion controlled conditions, estimation of moisture diffusivity in grains would be useful. The unsteady state diffusion equation for solids can be used for estimating moisture diffusivity.

Becker (1959) derived the following equation as an approximation for unsteady-state diffusion in solids.

$$\bar{M} = \frac{X - X_e}{X_0 - X_e} = 1 - \frac{2}{\sqrt{\pi}} X'' + \frac{f''(0)}{2} X^2 \qquad \text{………… (4.1)}$$

Where $X'' = a_v\sqrt{D_{eff} t}$ and $f''(0) = 0.588$ for wheat and 0.661 for spherical particles.

He used this equation in the range of $0.2 < \overline{M} < 1.0$ to calculate moisture diffusivities in wheat from drying data.

Giner and Mascheroni (2001) reviewed the simplified diffusive short time expression of Becker (equation 4.1) and concluded that it could be used in ‘thin layer drying’ studies of agricultural grains. However, Irigoyen and Giner (2014), while studying drying-toasting kinetics of pre-soaked soybeans in fluidised bed, concluded that equation 4.1 was not suitable for high initial moisture-high temperature process, particularly above 100^0 C, but found that the complete analytical solution of unsteady state diffusion equation provided accurate prediction of drying curve above 100^0 C.

The experimental drying data were used to estimate moisture diffusivities by solving equation 4.1 using nonlinear least squares method. The following points were considered in the analysis.

- The surface moisture of grain was taken as equal to equilibrium moisture.
- Negligible grain shrinkage occurred during drying.
- The moisture content and temperature of grain were initially uniform within the grain.
- A flat temperature profile would prevail within the grain.

- The experimental data used in this analysis correspond to $0.2 < \overline{M} < 1.0$ and the maximum inlet air temperature used was 60^0 C.
- $f''(0)$ was taken as 0.588 for wheat and 0.661 for ragi and barley since they were spherical particles as given by Becker (1959).

The solids drying would involve heat transfer from hot air to solids and mass transfer (moisture removal) from solids to air. In a single spouted bed dryer without a draft tube, the heat transfer would essentially occur in the spout region and mass transfer in annulus. The moisture diffusion through grain played a significant role when drying occurring entirely under falling rate period. Because the diffusional rate would be strongly temperature dependent, the temperature attained by grains in dryer would become important. In the MPDTSB used in this study, heat transfer from hot air to grains could be occurring mostly in the DTs, but the annulus regions also could be contributing to heat transfer since hot air would enter annuli through holes provided in DTs. The grains temperature would be increasing as they moved up in DTs, reaching maximum at the top of each DT. As these hotter grains move through fountains and annuli, moisture removal would occur and their temperatures would be decreasing, reaching lowest values at the bottom during each cycle. The presence of multiple DTs in the bed prevented entry of relatively colder solids from annuli into spout regions and provide equal times of travel for all particles that would enter DTs at bottom and pass through to fountains. As a result, the gas to solids heat transfer could be better and solids in DTs could heat up to relatively higher temperatures during each cycle. Since the heat transfer would play an important role for the grains to attain the required final temperatures and moisture contents in the dryer, it was felt that the operating variables and design parameters of MPDTSB should influence the moisture diffusivities as revealed by the results obtained in this study. The results are given in Tables 4.18 – 4.28.

The moisture diffusivity could be strongly influenced by grain structure and grain temperature. Since the operating and design variables of the dryer influenced the grain temperatures, the diffusivities also varied accordingly as revealed by the results obtained in this study.

- For a given solid material, the diffusivities were found to be increasing with an increase in air inlet temperature, when all other conditions were kept constant as shown in Tables 4.18 – 4.20. An increase in air temperature would lead to an increase in grain temperature. The energies possessed by water molecules present in grain structure would be increasing with increase in grain temperature resulting in higher diffusivities.
- For a given air inlet temperature, air flow rate and initial and final moisture contents of grains in a batch operation, the final temperatures of grains to be attained would be fixed. Hence the quantum of heat to be transferred to the grains per unit mass of moisture to be removed would be fixed. When the initial moisture of grains increased for a given bed mass or when bed mass increased for a given initial moisture of grains, the required quantity of moisture to be removed would be more to reach the given final moisture content. So, in both cases, for the fixed quantum of heat to be transferred per unit mass of moisture to be removed the rate of increase in grain temperature would be lower and the time needed to reach the required final grain temperature and moisture content would increase. So, the diffusivities could be lower for higher bed masses (Tables 4.19 – 4.21) and for higher initial moisture contents (Tables 4.22 – 4.23) as observed here.
- The diffusivities were found to be marginally increasing with increase in inlet air flow rate, keeping all other conditions constant; this could be because the convective mass transfer did not play any significant role here as explained in section 4.1.3. The influence of inlet airflow rate on moisture diffusivities were studied using ragi grains only and the results are given in Table 4.18; similar trends could be expected with wheat and barley also.
- An increase in DT ID would help to increase the gas-solid contact times resulting in higher grain temperatures in shorter times. As a result, the diffusivities increased with increase in DT id as observed in Table 4.22.
- Since hot air supply into annulus region would be possible with porous DTs, an increase in diameter of holes on DTs would increase hot air supply into annuli. As a result, the reduction in solids temperature, as they move down from top to bottom, could be less and relatively hotter solids could be re-entering the DTs

at bottom for the following cycle of heating. This would result in achieving higher grain temperatures in shorter times. As a result, the diffusivities increased with increase in hole size as observed in Tables 4.23 – 4.25.

- As the fluid inlet diameter decreased for a given bed mass and air rate the bed recirculation rates would increase to help in achieving better heat transfer and higher solids temperatures in shorter times. This could result in increased diffusivities with decrease in fluid inlet size as reported in Tables 4.26 – 4.28.
- The grain properties would influence the diffusion process in a given grain. The moisture gradient within the grain would depend on its size, whereas the specific surface area of grain would influence the moisture removal rate from grain. The grain structure would influence the moisture diffusivity. The estimated diffusivities for the three grains used in this study were found to be different as given in Tables 4.15 – 4.17. The diffusivities for wheat were found to be higher when compared to ragi, with those of barley lying in between. Since the grain structures of these three solid materials were distinctly different the moisture diffusivities in these grains could be different under identical conditions.

4.4.1 Comparison between experimental results and predicted values of dimensionless moisture contents

The dimensionless moisture contents were predicted under varied conditions of operation for three different grains using simplified diffusive short time expression of Becker (equation 4.1). The results are represented in the Figures 4.27 – 4.32. The results indicated that there was reasonably good agreement between the experimental and predicted values when the drying times were lower; however, the deviations were found to be more at higher drying times. It was felt that if complete equation for unsteady state diffusion in solids, instead of equation 4.1, were used to predict the dimensionless moisture contents, the agreement with experimental would have been better.

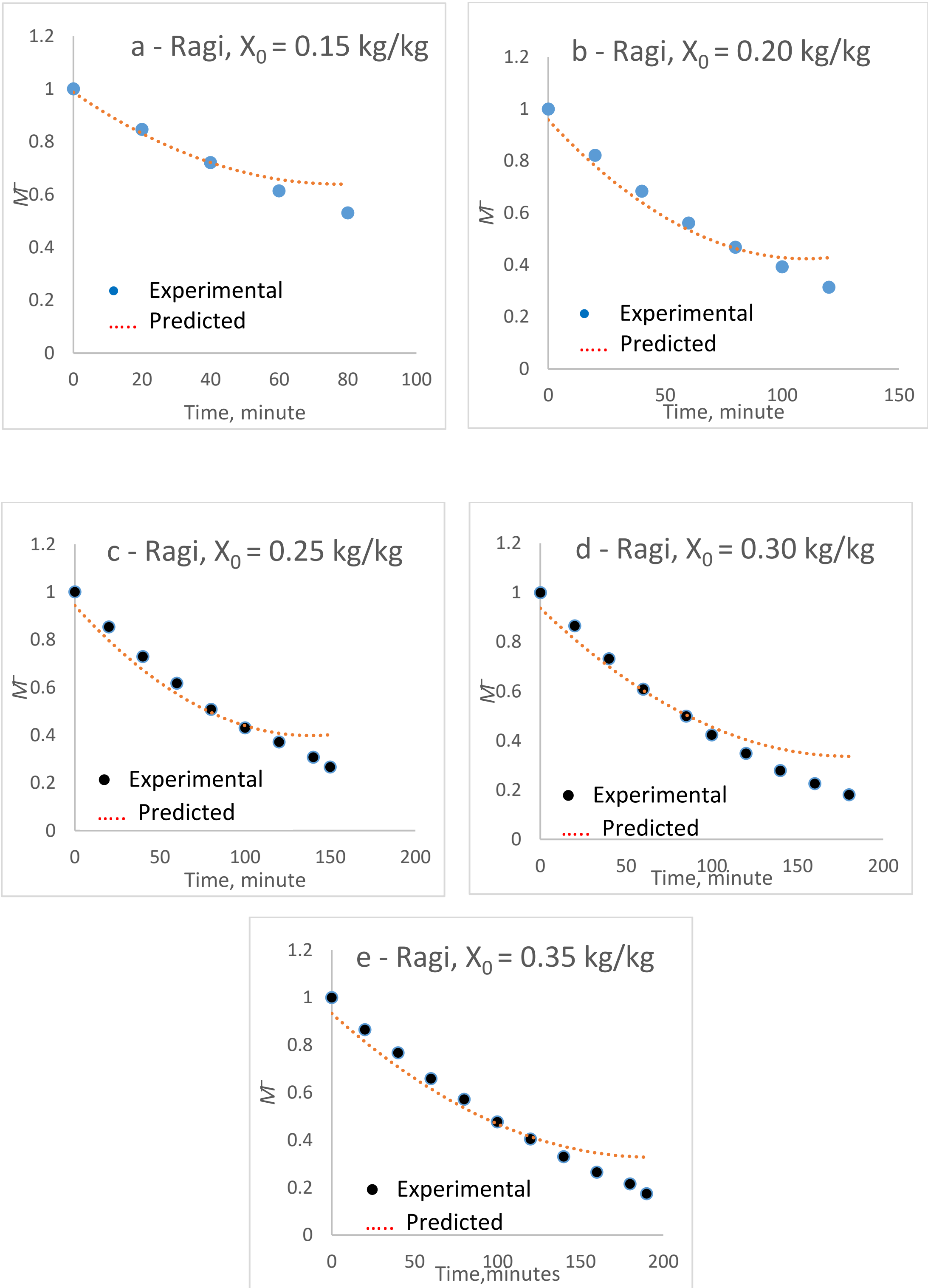


Figure 4.27 Comparison of experimental dimension less moisture ratio with predicted value; Influence of initial moisture content – ragi

(T_a =50^0C, v_o = 33 m^3/h, Mb = 2.5 kg, dt, = 26 mm, d_i = 21mm)

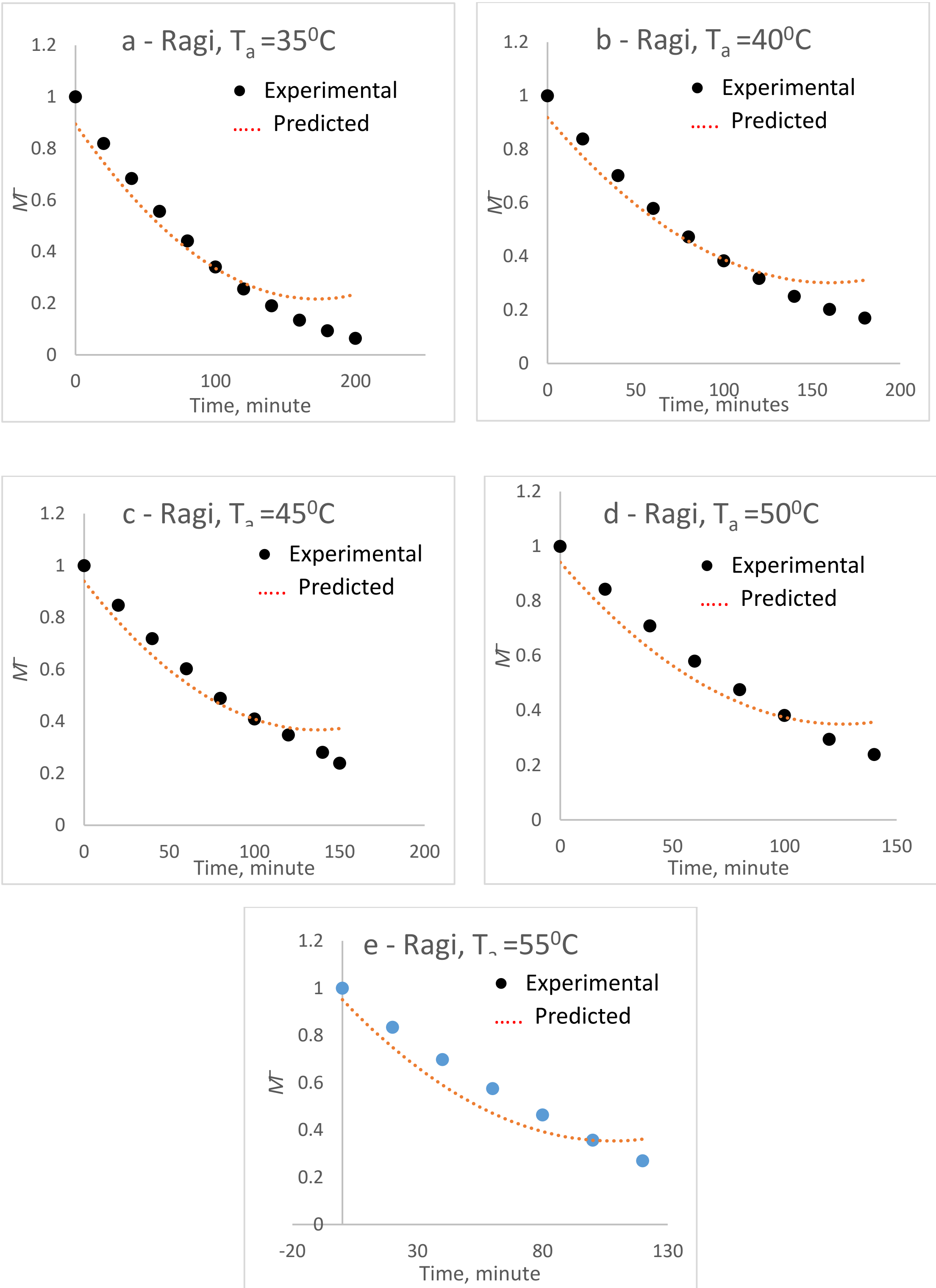


Figure 4.28 Comparison of experimental dimension less moisture ratio with predicted value; Influence of inlet air temperature – ragi

(X_0 = 0.25 kg/kg, v_o = 33 m^3/h, Mb = 2.5 kg, dt, = 26 mm, d_i = 21mm)

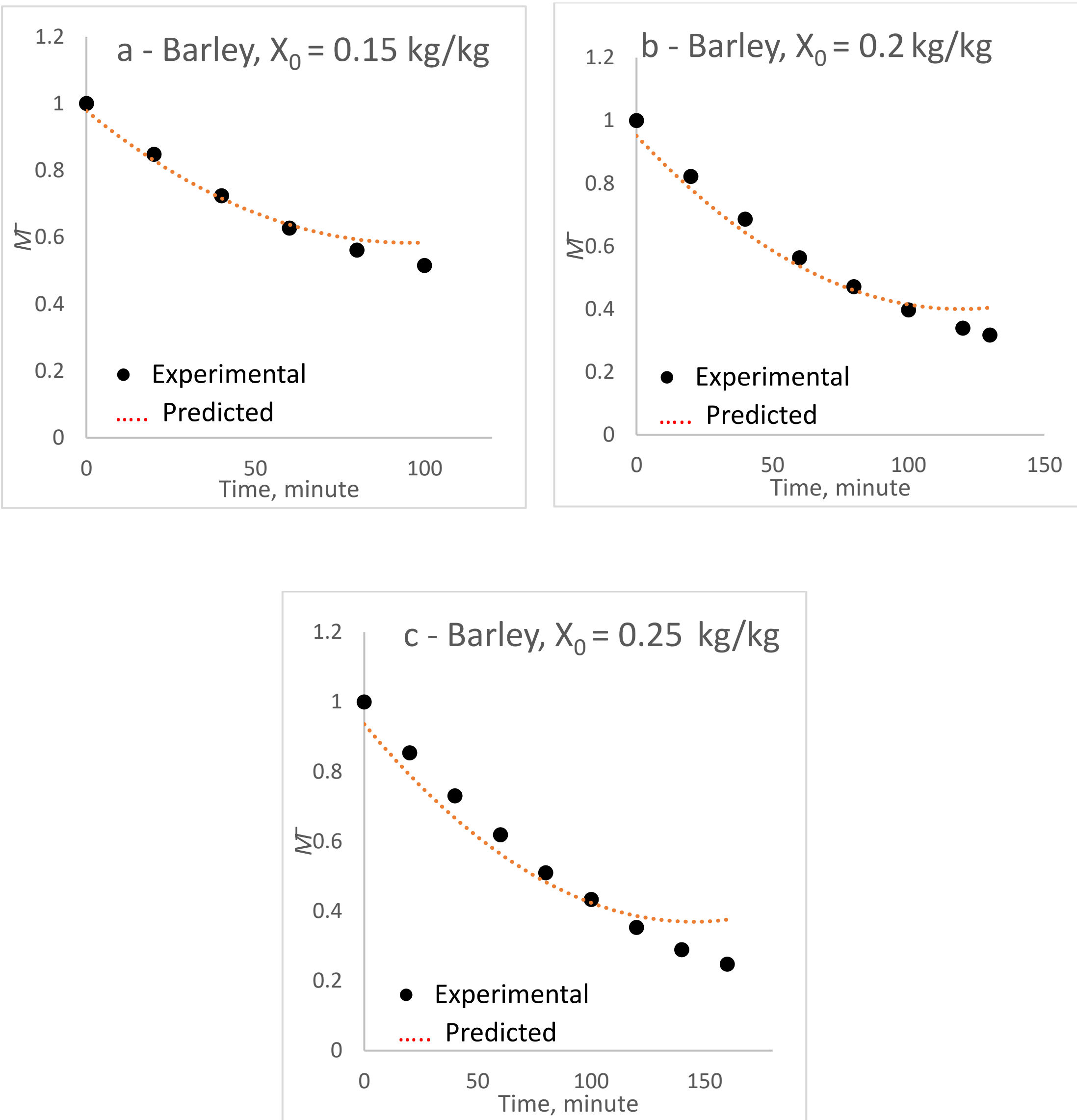


Figure 4.29 Comparison of experimental dimension less moisture ratio with predicted value; Influence of initial moisture content – barley

(T_a =60 ^{0}C, $v_o = 36m^3/h$, m_b = 4kg, $d_{t,}$= 26mm, d_i = 15mm)

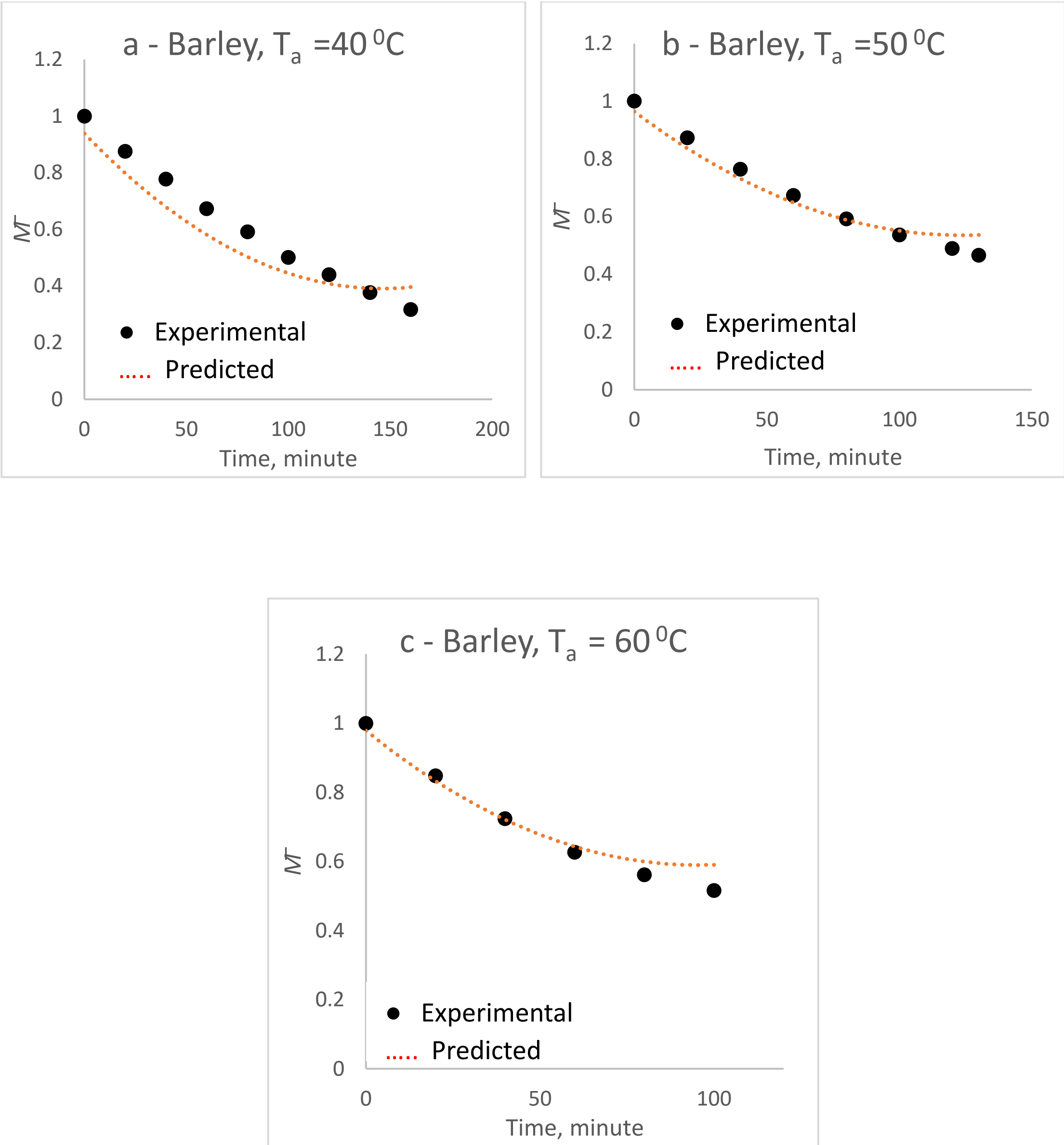


Figure 4.30 Comparison of experimental dimension less moisture ratio with predicted value; Influence of inlet air temperature – barley

($X_0 = 0.15$ kg/kg, $v_o = 36m^3/h$, $m_b = 4kg$, $d_{t,} = 26mm$, $d_i = 15mm$)

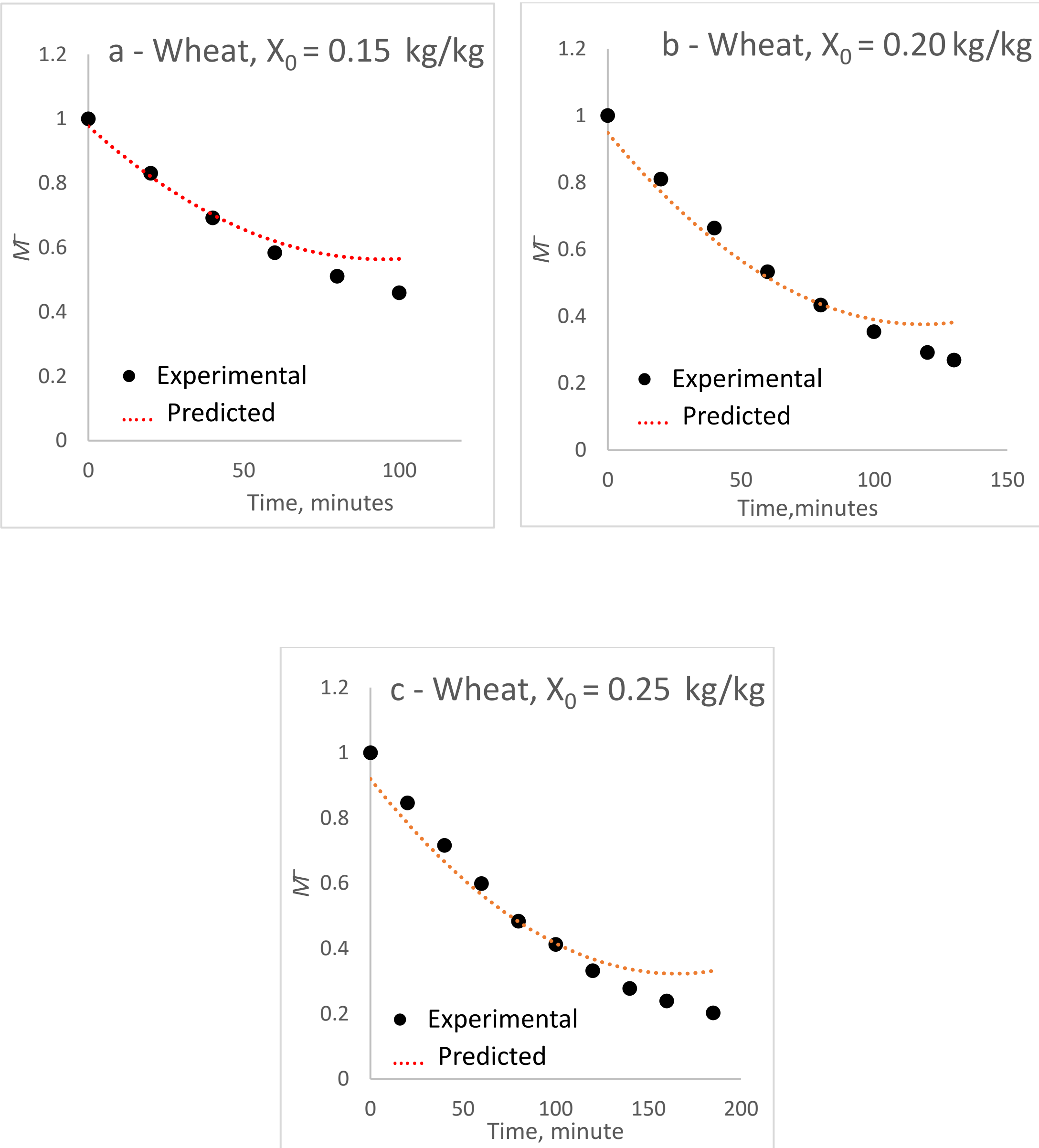


Figure 4.31 Comparison of experimental dimension less moisture ratio with predicted value; Influence of initial moisture content – wheat

(T_a =60 ^{0}C, $v_o = 36m^3/h$, m_b = 2kg, $d_{t,}$= 26mm, d_i = 15mm)

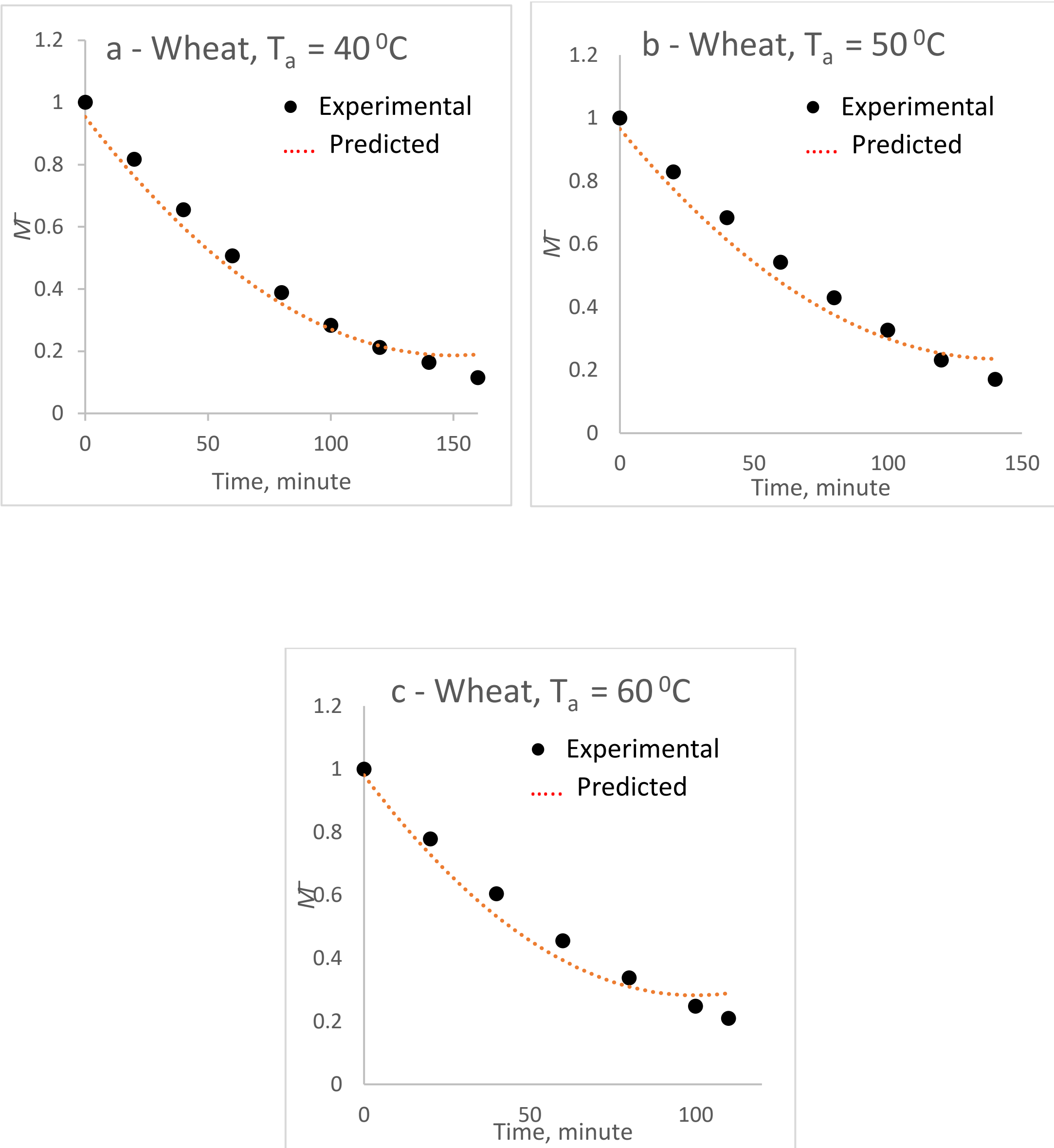


Figure 4.32 Comparison of experimental dimension less moisture ratio with predicted value; Influence of inlet air temperature – wheat

(X_0 = 0.25 kg/kg, v_o = 36m^3/h, m_b = 1 kg, $d_{t,}$= 26mm, d_i = 15mm)

4.4.2 Evaluation of Activation energy

The operating temperature of dryer would strongly influence the moisture removal rate when drying would occur under falling rate conditions. Therefore, development of a relation between diffusivity and temperature would be useful for modelling or simulation of grain drying process in a given dryer. Several researchers correlated moisture diffusivity data of agricultural grains using Arrhenius type of equation and reported in literature. Some of them used the grain temperatures, while others used inlet air temperatures in the correlation. The grain temperature would have a direct influence on moisture diffusivity when diffusion process would be occurring in the grain, but an accurate measurement of it would be difficult. However, the inlet air temperature would be an easily measurable and controllable operating variable of a dryer; therefore, it would be convenient to correlate moisture diffusivity data in terms of inlet air temperature, assuming that the grain temperature would be equal to the surrounding air temperature. Such an assumption could be a good approximation because of the following reasons.

- The operating airflow rates in grain dryers would lead to turbulent flow conditions and hence the grains would quickly attain the temperature of surrounding air.
- The heat transfer from air to grain would be much faster when compared to mass transfer (moisture transport) within the grain.
- The thermal response of the grains would be much quicker. For example, Robbins and Fryer (2003) measured the thermal responses of barley grains and found them to be within 10 s, whereas their model response gave thermal equilibrium within 15 s.

The estimated moisture diffusivities of the grains were correlated as function of temperature for some typical cases. The Arrhenius type of plots are shown in figures 4.33 – 4.35. The activation energies evaluated from the slopes of these plots were compared with those values reported in literature as shown in Table 4.29. The results were found to be in a reasonable agreement with literature.

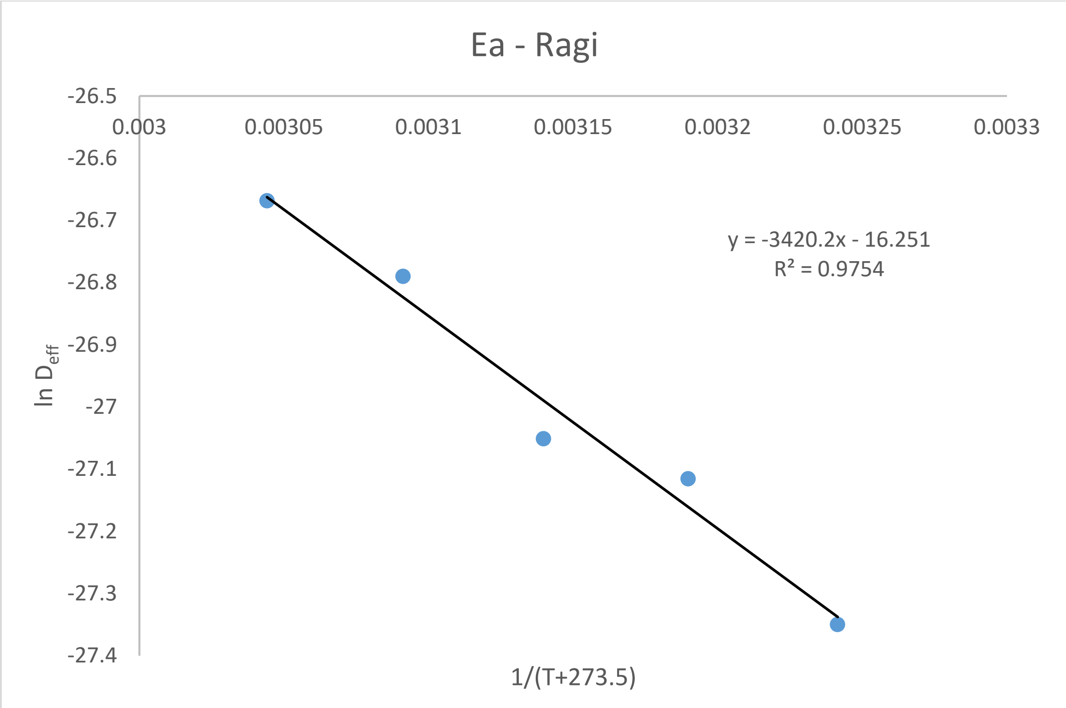


Figure 4.33 Arrhenius-type relationship between effective diffusivity coefficient and temperature.
(T_a = ^{0}C, X_0 = 0.25 kg/kg, v_o = 36m^3/h, m_b = 2.5 kg, d_t,= 26 mm, d_i = 21mm, NPDT)

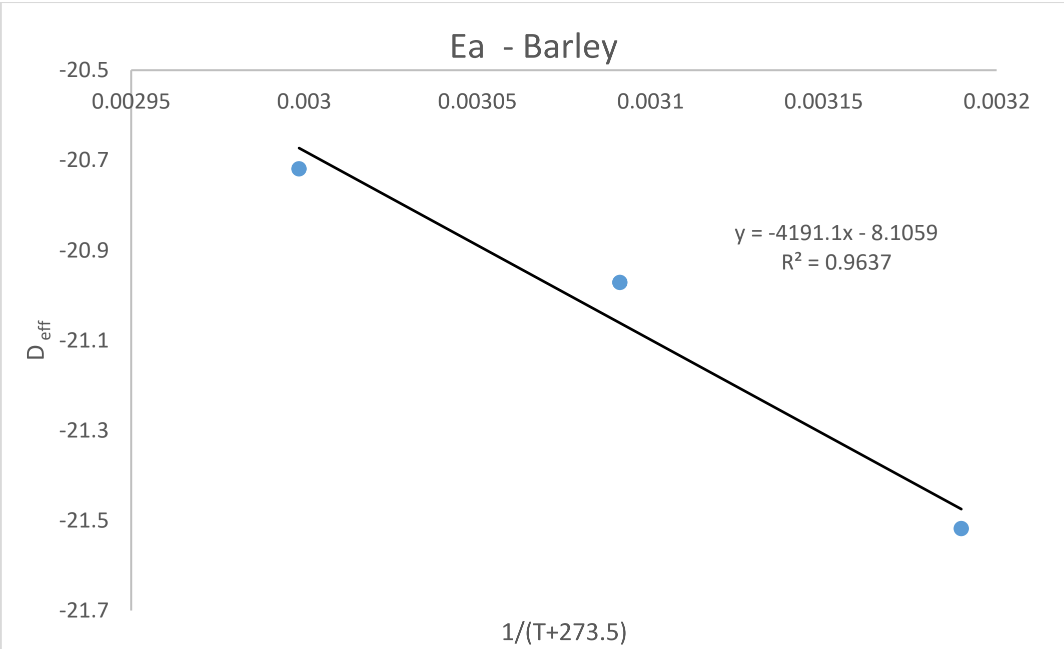


Figure 4.34 Arrhenius-type relationship between effective diffusivity coefficient and temperature.

(X_0 = 0.2 kg/kg, v_o = 36m^3/h, m_b = 2 kg, d_t,= 26 mm, d_i = 21 mm, d_h = 2 mm)

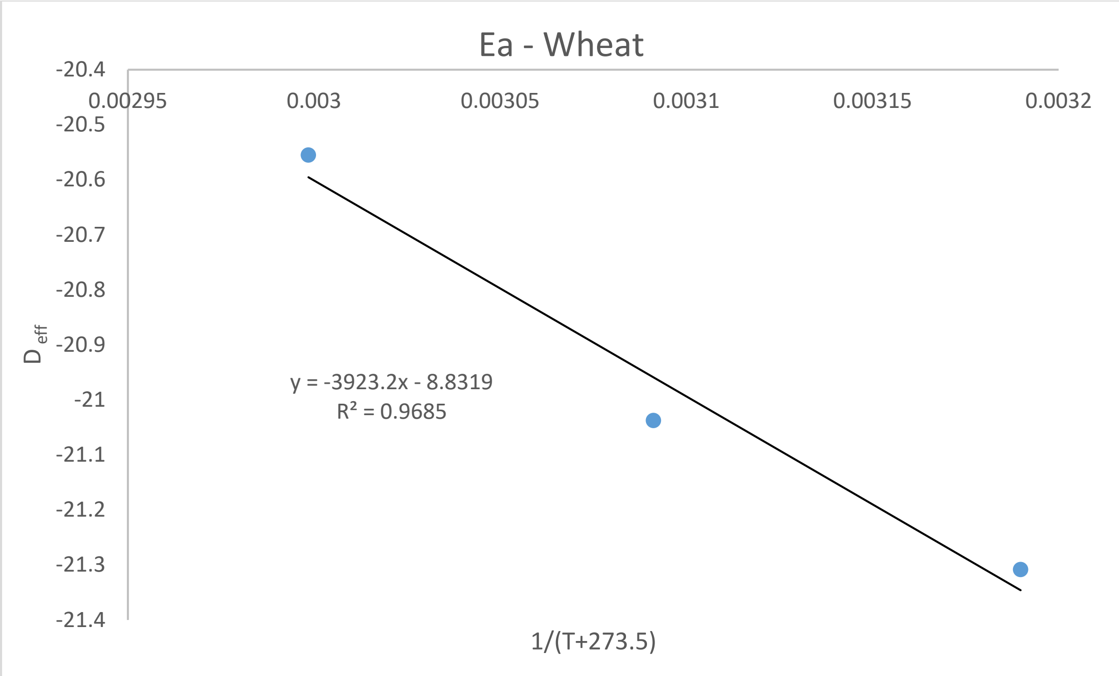


Figure 4.35 Arrhenius-type relationship between effective diffusivity coefficient and temperature.

(X_0 = 0.2 kg/kg, v_o = 36m^3/h, m_b = 2 kg, $d_{t,}$= 26 mm, d_i = 21 mm, d_h = 2 mm)

4.5 Estimation of thermal efficiency

Grain drying involves transfer of heat as well as mass. The moisture removal from grain depends on heat transfer from hot air to gain. Several types of efficiencies are reported in literature to evaluate the performance of dryers used for solids drying and thermal efficiency is one of them. Torrez Irigoyen and Giner (2016) used the following definition for computing thermal efficiency of a fluidized bed dryer.

$$\text{Thermal efficiancy} = \frac{\text{Latent heat required to evaporate the moisture in grains}}{\text{Heat supplied to grains by hot air}}$$

It can be written as the following equation

$$E_f = \frac{W_s(X_0 - X_f)\lambda_g}{W_a C_H (T_{a1} - T_{av}) t_d} \qquad \text{…………………(4.2)}$$

The operating and design variables of the dryer and also the grain characteristics would influence the gas-solid heat transfer; hence the thermal efficiency would also vary accordingly as revealed by the results obtained in this study. The estimated thermal efficiencies are shown in Tables 4.30 to 4.39.

- For a given solid material, the thermal efficiencies were found to be increasing with an increase in air inlet temperature, as observed in Tables 4.30 – 4.32, when all other conditions were kept constant. As the air inlet temperature increased the heat input rate to the bed of solids would increase; this helped the grains attaining the required final temperature much faster, resulting in lower drying time and higher thermal efficiency.
- The thermal efficiencies were found to be increasing with increase in either bed mass or initial moisture content, when all other conditions were kept constant. The heat supply rate would be fixed for a given set of conditions maintained. When either the initial moisture content of grains or bed mass increased, the total amount of moisture to be removed would be increasing. So, for a fixed heat

supply rate when more moisture could be removed, the thermal efficiency would be higher as reported in Tables 4.31 – 4.35.

- In a porous DT the grains would typically pick up heat while they transverse through DT, and while coming down through annuli they would exchange heat with fellow grains and also receive heat from hot air flowing through DT holes leading to better heat and mass transfer. Since there would not be any hot air supply into annulus regions with non-porous DTs, the thermal efficiencies with porous DTs would be higher. Further, as the DT hole diameter increased the hot air supply into the annulus regions would increase leading to higher thermal efficiencies as observed in Tables 4.34 and 4.36.
- An increase in DT ID would help to increase the gas-solid contact times resulting in higher grain temperatures in shorter times. As a result, the thermal efficiencies increased with increase in DT id as observed in Table. 4.35.
- As the fluid inlet diameter decreased for a given bed mass and air rate the bed recirculation rates would increase to help in achieving better heat transfer and higher solids temperatures in shorter times. This resulted in increased thermal efficiencies with decrease in fluid inlet size as reported in Tables 4.37 – 4.39.
- The thermal efficiencies for ragi were found to be higher when compared to wheat, with barley in between, as shown in Table 4.15 – 4.17. Because of the grain properties (explained in Section 4.3), the grains of ragi attained the required final temperatures much faster leading to better thermal efficiencies.

4.6 Estimation of gas – solid heat transfer coefficient

Mathur and Epstein (Chapter 9, 1974) stated that in a CSB the time spent by a solid particle in spout region would be much less compared to that in annulus and in the context of heat transfer the annulus would serve as a heat sink for recirculating solids which would pick up heat from spouting gas during each cycle; the mass transfer in spout region would be negligible relative to that in annulus. So, in the case of solids drying which would involve both heat and mass transfer, bulk of the drying could be occurring in the annulus, more so when it would be occurring under falling rate conditions. The moisture diffusion through grain would play a significant role when drying occurred entirely under falling rate period. Because the diffusional rate would be strongly temperature dependent, the temperature attained by grains in dryer becomes important in the context of dryer design and operation. For a given final moisture content of grains there would be a fixed final temperature of grains to be attained.

In a MPDTSB used in this study heat transfer from hot air to grains could be occurring mostly in the DTs, but the annulus regions also could be contributing to heat transfer since hot air would be supplied to annuli through holes provided in DTs. The grains temperature would be increasing as they move up in DTs, reaching maximum at the top of each DT. As these hotter grains move through fountains and annuli moisture removal would occur and their temperatures would be decreasing, reaching lowest values at the bottom during each cycle. The presence of multiple DTs in the bed would prevent entry of relatively colder solids from annuli into spout regions and provide equal times of travel for all particles which would enter DTs at bottom and pass through to fountains. As a result, the gas to solids heat transfer was better and solids in DTs were heated to relatively higher temperatures during each cycle. Since the grain temperatures attained in the dryer depend on the gas-solid convective heat transfer coefficient, its estimation would be useful. It was estimated using the macroscopic heat balance equation given below. The following assumptions were made while writing this equation.

- The moisture content and temperature of grain were initially uniform within the grain.
- The grain temperature would be uniform at a given time instant. It meant that the temperature profile within the grain would be flat. So, it could be considered that the transfer of heat from hot air to solid could be solely by convection.
- The shrinkage of grain during dying was neglected.

The macroscopic heat balance in the grain can be written as

Heat transfer rate from hot air to grain = Sensible heat change of grain + Latent heat for moisture removal from grain

The equation is

$$W_s C_{ps} \frac{\partial Ts}{\partial t} = h_T (W_s a_s)(T_a - T_s) - W_s \left(-\frac{dX}{dt}\right) \lambda_g$$

………….. (4.3)

It is rearranged as

$$h_t = \frac{C_{ps} \frac{\partial Ts}{\partial t} + \left(-\frac{dX}{dt}\right) \lambda_g}{a_s (T_a - T_s)}$$

…………... (4.4)

Equation 4.4 was used to evaluate the variation of heat transfer coefficient with batch drying time under varied conditions. The specific surface area of grains used were those of dry grains, which were measured experimentally. The heat capacities of different grains were estimated using available literature (Rahman and Kumar, 2006). The variation of latent heat of vaporization of water with temperature was accounted for in the above equation. The experimental data of moisture removed (dry basis) and grain temperature at various times were fitted to higher order polynomials and the resulting equations were differentiated to obtain the derivatives of dX/dt and dT_s /dt needed in equation 4.4. A detailed specimen calculation is given in Appendix – II

The following points are to be noted here. During each drying run, grain samples were taken at fixed time intervals for moisture measurement. At the same times grain and air temperatures were measured at the top of bed as explained in Section 3.4 of Chapter 3. So, the estimated values of heat transfer coefficients correspond to the conditions prevailed at the bed top and do not correspond to the bed as a whole. The grain and air temperatures vary along the bed depth at a given time instant, and the mean heat transfer coefficients for the bed as a whole at various time instants could be different from the estimated values here. The estimated heat transfer coefficients for MPDTSB and SPDTSBs are given in Figures 4.36 to 4.38.

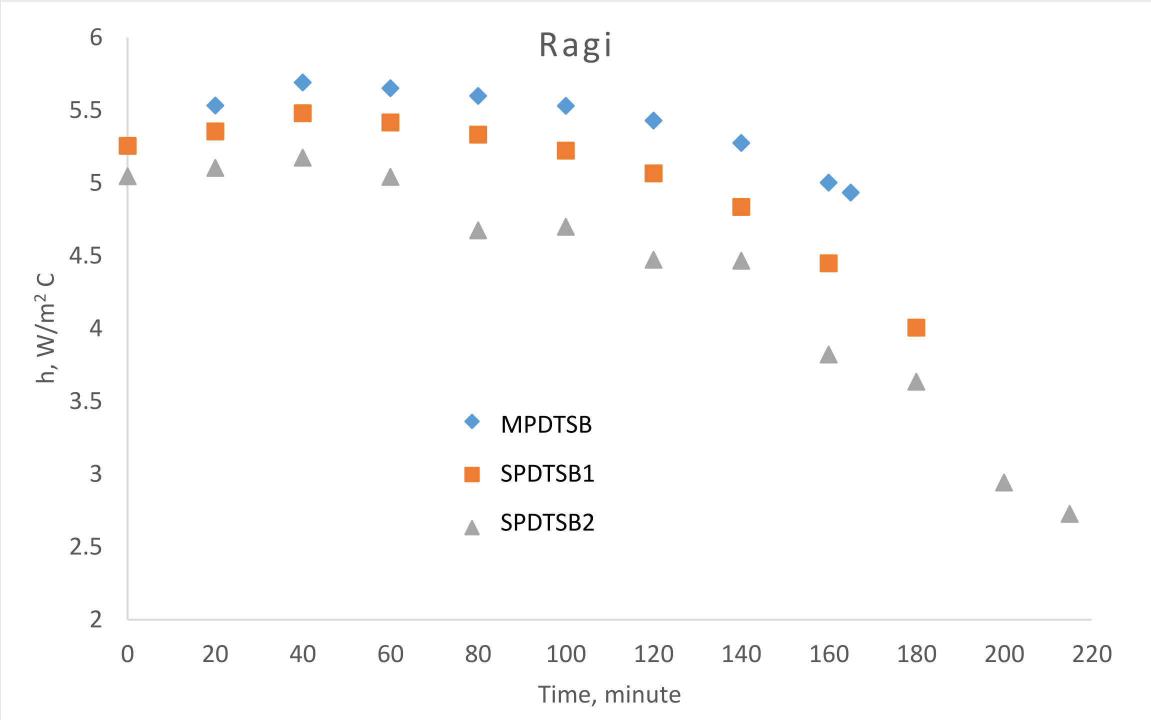


Figure 4.36 Comparison of heat transfer coefficient in different rigs.

(T_a= 40^{0}C, X_0= 0.25kg/kg, v_0 = 36m^3/h, m_b =4 kg)

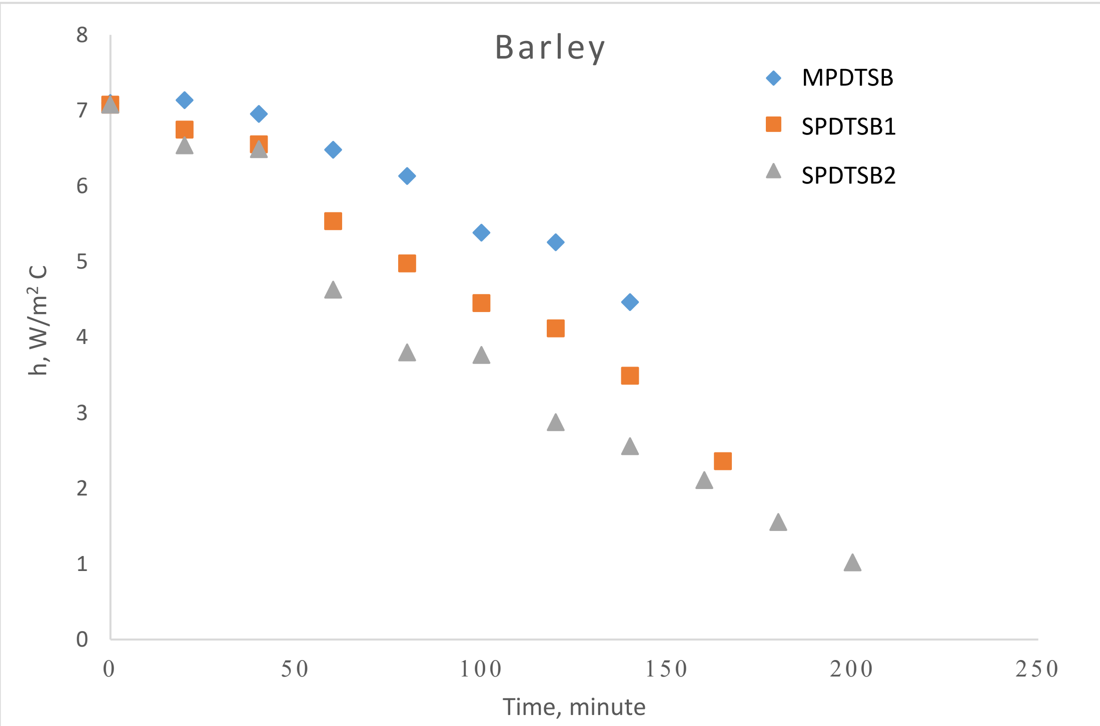


Figure 4.37 Comparison of heat transfer coefficient in different rigs.
(T_a= 40^{0}C, X_0= 0.2kg/kg, v_0 = 36m^3/h, m_b =2 kg)

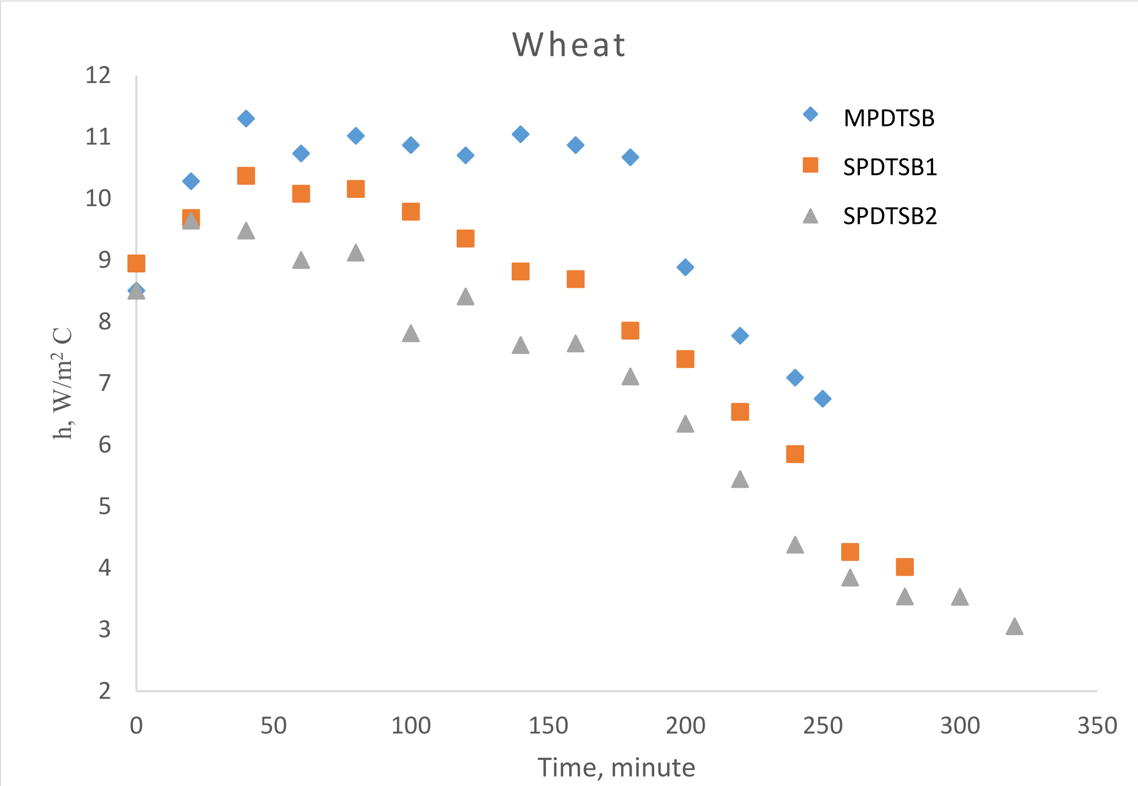


Figure 4.38 Comparison of heat transfer coefficient in different rigs.
(T_a= 40^0C, X_0= 0.2kg/kg, v_0 = 36m^3/h, m_b =2 kg)

The heat transfer coefficients for MPDTSB were found to be higher when compared to the two SPDTSBs used. Also, it was found that the measured air and grain temperatures (as shown in Figurers 4.39 – 4.44) at bed top were found to be increasing with time and the corresponding estimated heat transfer coefficients were found to be decreasing with time; such trends were expected since it was a batch operation. We could expect that similar trends would be prevailing even when the measurements and estimations were done for the bed as a whole.

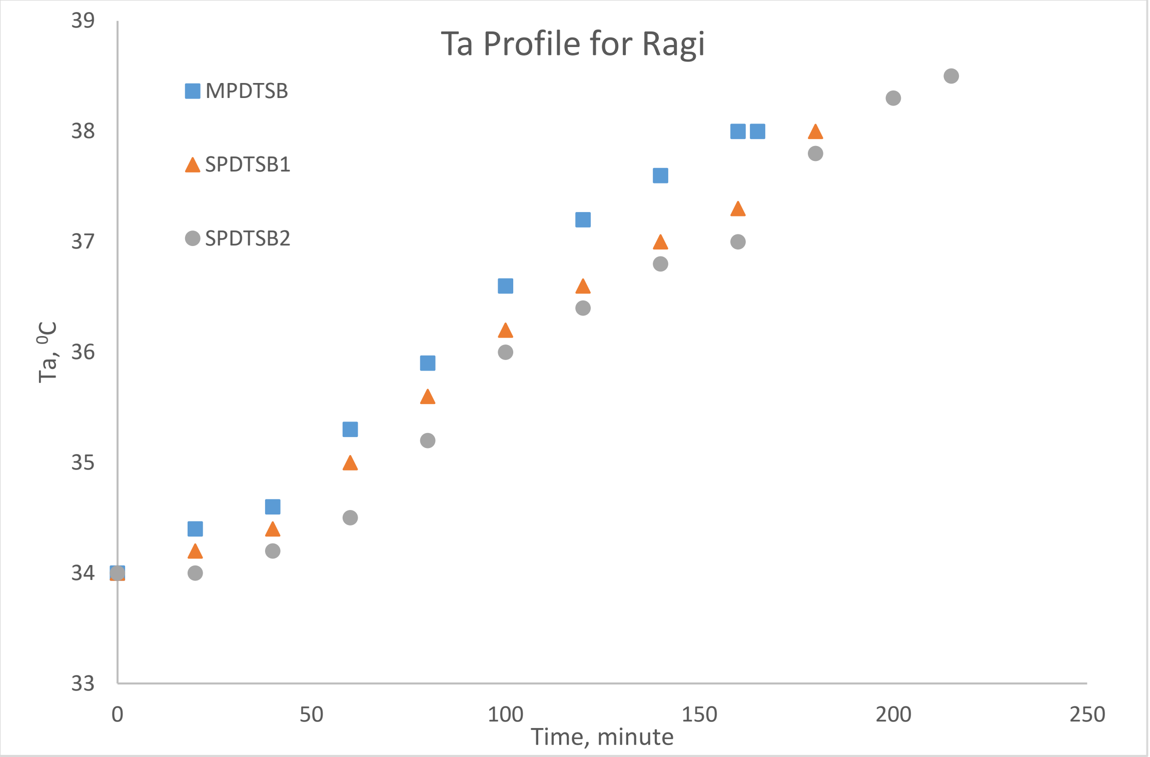


Figure 4.39 Hot air temperature profile during batch drying.
(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 4 kg)

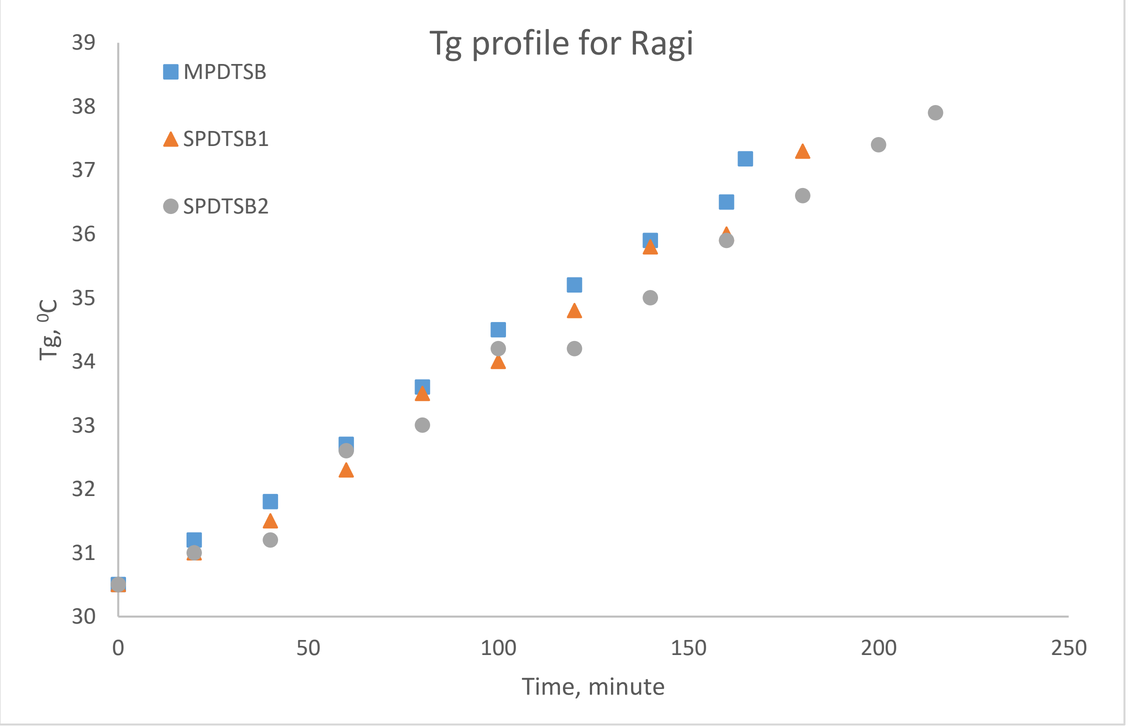


Figure 4.40 Grain temperature profile during batch drying.

(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 4 kg)

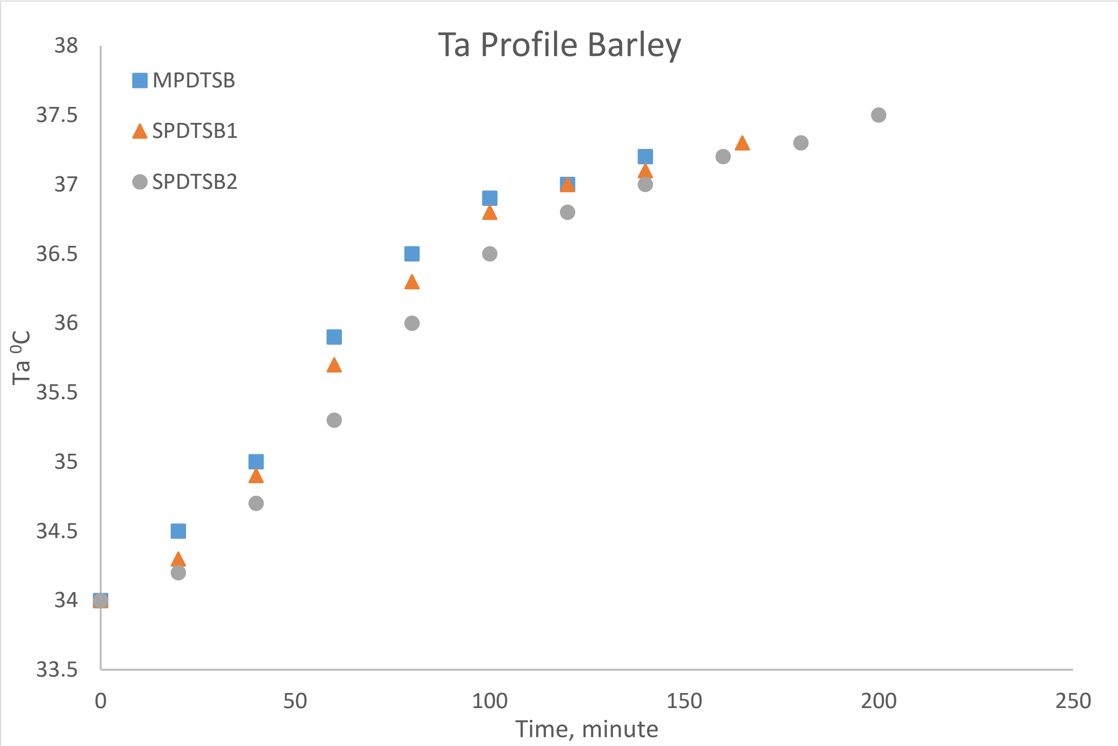


Figure 4.41 Hot air temperature profile during batch drying.

(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 4 kg)

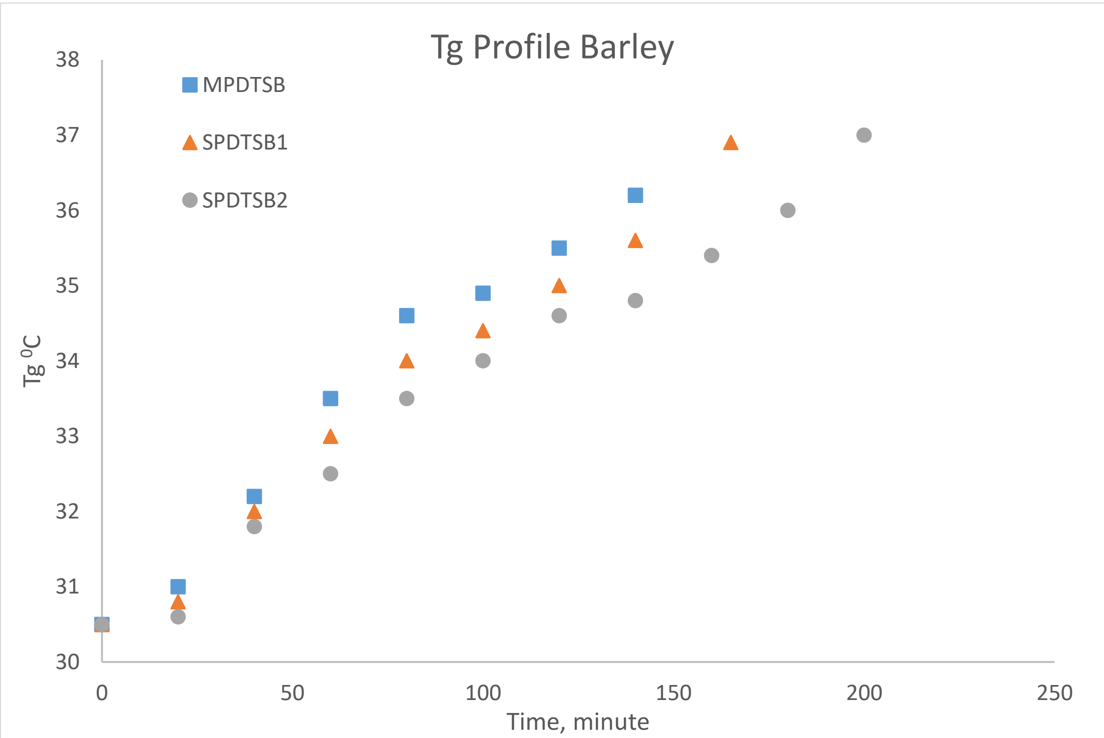


Figure 4.42 Grain temperature profile during batch drying.

(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 4 kg)

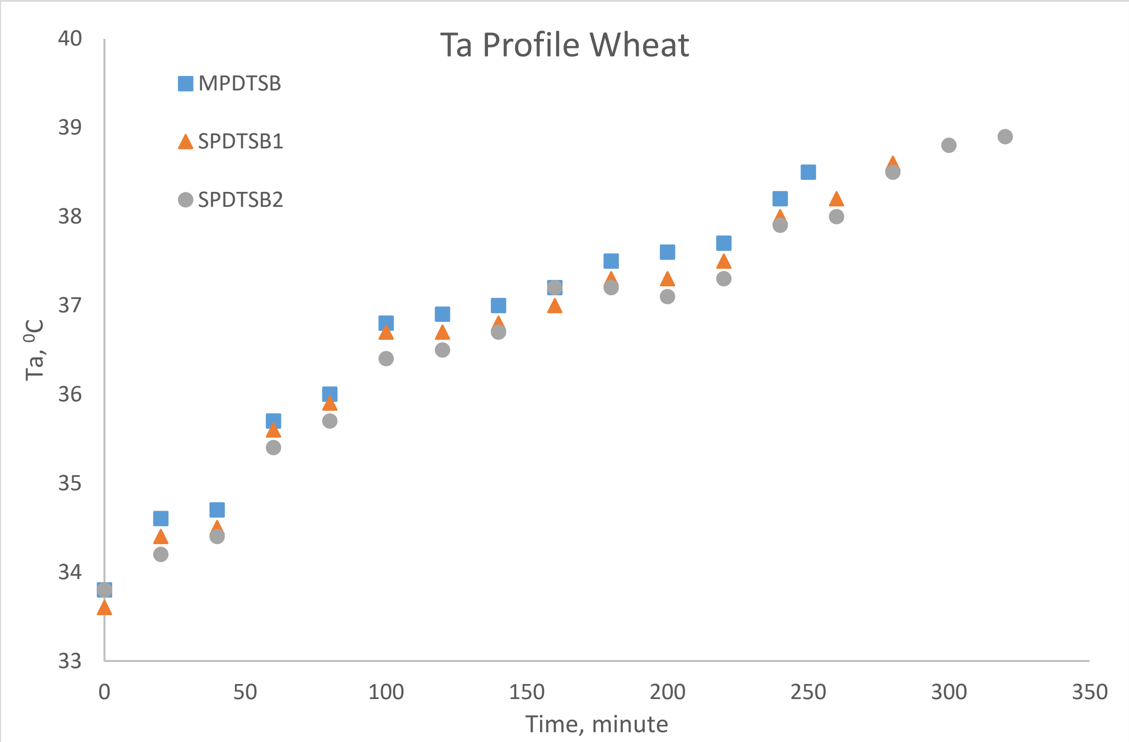


Figure 4.43 Hot air temperature profile during batch drying.
(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 4 kg)

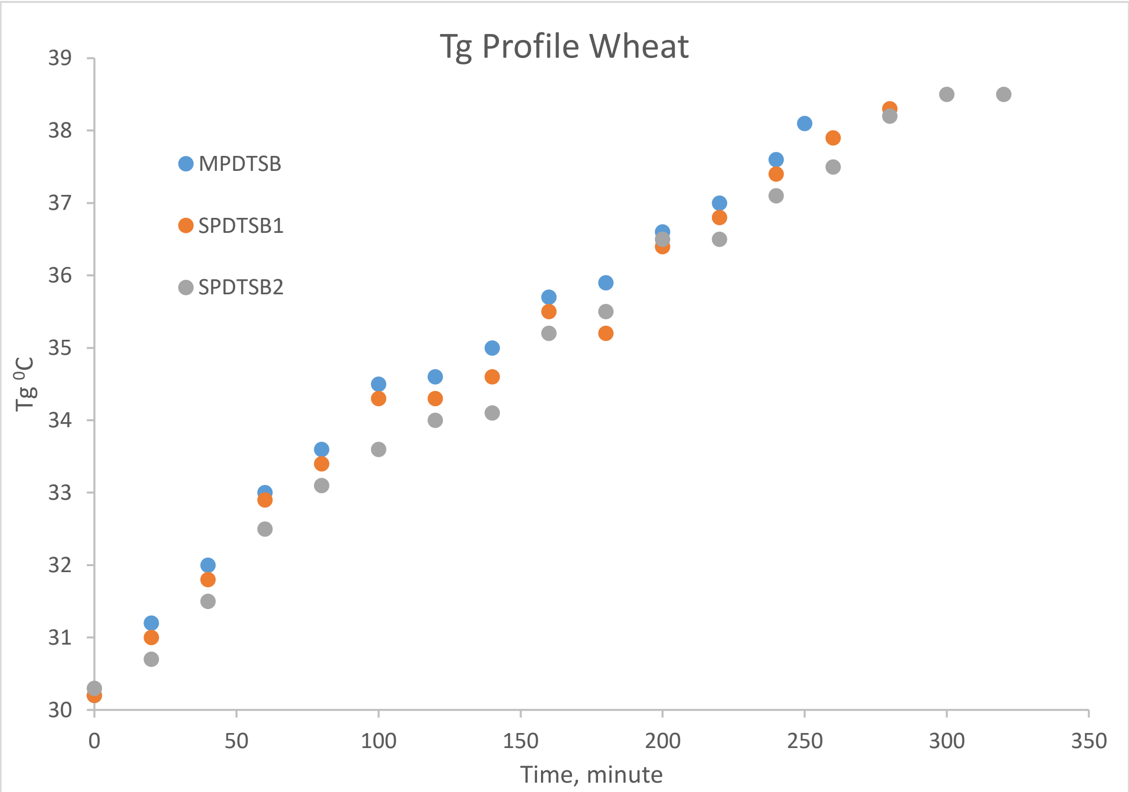


Figure 4.44 Grain temperature profile during batch drying.

(X_0 = 0.25 kg/kg, v_o = 36 m^3/h, m_b = 4 kg)

4.7 Comparison of performance between MPDTSB and SPDTSB

In order to compare the performance of MPDTSB dryer with that of SPDTSB dryer two single spout beds were considered for study. The details of systems used for comparison, the bed masses and corresponding static bed depths of solids used are given in Tables 3.1. The results of drying times, thermal efficiencies and diffusivities are given in Tables 4.40 – 4.42. The measured temperature profiles of air and solids at bed top and the corresponding estimated heat transfer coefficients are shown in Figures 4.36 – 4.38. A comparison of drying rates are given in figures 4.11 to 4.16.

SPDTSB 1 had column cross sectional area(CSA) and fluid inlet area equivalent to that of MPDTSB, but the CSA of DT in SPDTSB 1 was three times less compared to MPDTSB. So, the air jet velocities in Systems MPDTSB and SPDTSB 1 were same, but the air superficial velocity in DT in SPDTSB 1 was three times higher than that in MPDTSB. The SPDTSB 2 had three times less column CSA, fluid inlet area and CSA of DT compared to MPDTSB. So, the air jet velocities as well as air superficial velocities in DT of SPDTSB 2 were three times more compared to MPDTSB. The static bed depths for a given bed mass of all the grains are approximately same for Systems MPDTSB and SPDTSB 1, whereas about three times more for SPDTSB 2. The results obtained indicated that MPDTSB performed better as grain dryer when compared to other two and the reasons were as follows.

The moisture diffusion through grains controlled the overall process here and the rate of diffusion would depend on the temperature of grains. The grains would enter the bottom of each DT during each cycle and get heated up during their travel through DT; the extent of this heating would depend on gas-solid contact time within DT. Since the air velocity through DT in SPDTSB 1 was higher, the grains would travel at higher velocities compared to MPDTSB; though the lengths of travel of grains were almost same in both cases, the gas-solid contact times were lower in SPDTSB 1. So, the solids heating might be slower in SPDTSB 1 compared to MPDTSB resulting in longer drying times in SPDTSB 1. In addition, there were three DT and fountain regions in MPDTSB compared to SPDTSB 1, which helped in achieving faster moisture removal leading to lower drying times in MPDTSB. Between MPDTSB and SPDTSB 2, the air velocities in SPDTSB 2 were three times higher, but the grains had to travel through longer distances in DT because the bed depths were three times more. As a result, the extent of grains heating in DTs might approximately be same in MPDTSB and SPDTSB 2. However, the hot grains from DT had to travel through a much deeper annulus in SPDTSB 2 resulting in loss of considerable heat and much cooler grains might re-enter DT for further heating in the following cycle. So, the overall transfer process became slower resulting in longer drying times in SPDTSB 2.

The required final temperatures of air and solids corresponding to a given final moisture of solids would be fixed; these two temperatures could be attained much faster in MPDTSB as shown in the Figures 4.39 and 4.44. Hence, the estimated values of diffusivities, heat transfer coefficients and thermal efficiencies of MPDTSB were found to be better when compared to SPDTSBs. In addition, it was observed in the experiments that the presence of DTs in the bed led to the formation of much deeper fountains when operated well above MSBD. Since the hot solid content of these multiple fountains would be considerable and these solids would be exposed to outgoing hot air, moisture removal could possibly be occurring to some extent in the fountain regions also. So, the presence of multiple DTs helped in enhancing heat transfer; though bulk of the drying occurring in annuli, multiple fountains might also contribute to moisture removal.

4.8 Scope for scale up of the proposed design

Large scale commercial operations would require handling of larger bed masses and deeper beds, and a conventional single spouted bed would not be suitable as discussed earlier (Chapter 1). Hence, a MPDTSB was used in this work to explore the possibilities for scale up to deeper beds.

The experimental results related to scale up studies presented in Tables 4.43 to 4.45 indicated the following.

- It was possible to overcome the limitation of MSBD in a MPDTSB so that deeper beds of solids could be handled in the dryer. A maximum bed depth of 65cm (bed mass = 8 kg) for ragi, 61 cm (bed mass =8kg) for barley and 31 cm (bed mass = 4kg) for wheat could be used (Case 5) in the study. These bed depths were far beyond the MSBD (Case 1) for each material, but much deeper beds could not be used because of air supply limitations.

- It is to be noted here that all the experiments related to scale up were conducted at the same air flow rate of 36 m^3/h. The air supplied to the bed was expected to perform the following roles.
    - To keep the bed in a spouted state with a required recirculation of solids.
    - To supply the required heat to the bed of grains.
    - To take away the moisture from the bed.

  At a given constant air rate the solids recirculation rates would decrease as the bed mass increased (as prevailed from Case 2 to Case 5). The results indicated that as the bed mass increased the batch drying time and air supply per kg solids decreased and thermal efficiency increased. So, we could conclude that there was effective utilization of hot air as the bed mass increased for a given air flow rate. Hence, it would be desirable to operate deeper beds just above minimum spouting velocities so that the drying operation would be efficient and economical. Suppose a deeper bed when operated well above minimum spouting velocity would give higher solids recirculation, but it would not be economical and thermally efficient.
- For a given grain size and bed mass, an appropriate choice of DT diameter, hole size and fluid inlet size would become necessary to achieve spouting and operate the bed above the minimum spouting velocity. The choice should be such that the process as a whole would be efficient, economical and there would not be any grain damage.
- Porous draft tubes would help in reducing the batch drying times when compared to non-porous draft tubes under identical conditions.

Considering the points mentioned above we could say that the proposed design would be more efficient for an operation like solids drying and hence could be considered as a potential candidate for scale up to large scale operations.

4.9 Empirical correlation for batch drying time in MPDTSB

The influence of operating variables and design parameters of the dryer on batch drying times was discussed in Section 4.1 and 4.2. The following conclusions were drawn based on those results.

- The drying occurred under falling rate period under all conditions employed for all the three solid materials used.
- An increase in air inlet temperature resulted in increasing drying rates and reduction in batch drying times.
- The drying rates and batch drying times increased with an increase in initial moisture contents of grains.
- An increase in bed masses resulted in reduction of drying rates and longer batch drying times.
- The drying rates increased and the batch drying times decreased as the inlet airflow rates were increased, but the influences were not very significant.
- The batch drying times were less with porous draft tubes when compared to non-porous draft tubes.
- An increase in draft tube diameter and diameter of holes on draft tubes would lead to reduction in batch drying time. However, a proper choice of these two design parameters would be necessary to achieve proper spouting.
- Smaller diameter fluid inlets would help to reduce batch-drying times, but could lead to grain damage.

The following empirical equation involving dimensionless groups was formulated keeping the above-mentioned results in mind.

$$\Theta_t = k.\ \pi_1^{n1}.\ \pi_2^{n2}.\ \pi_3^{n3}.\ \pi_4^{n4}.\ \pi_5^{n5} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4.5)$$

Here, Θ_t is batch drying time in minutes, k is a constant having the units of minutes, π_1, π_2, π_3, π_4, π_5 are dimensionless groups, and n_1, n_2, n_3, n_4 and n_5 are powers.

The dimensionless groups are formulated keeping the following points in mind.

- The moisture removal from the grains is essentially diffusion controlled.

- The moisture diffusivities in grains and the batch drying times are influenced by operating and design variables considered, as well as properties of grains used in the study.

The physical significances of these dimensionless groups are as follows.

$\pi_1 = \lambda_d / RT_a$ – This group accounts for the latent heat to be supplied to evaporate grain moisture at a given air inlet temperature.

$\pi_2 = (X_0 - X_f) / (X_0 - X_e)$ – This group accounts for the amount of moisture to be removed from grains.

$\pi_3 = H/d_h$ – This group accounts for the extent of hot air supplied to annulus regions from draft tubes. The DT hole area available will increase when the hole diameter increases for a given DT length, or when the DT length is increased for a given hole area. The hot air supply to annuli will increase in both the cases.

$\pi_4 = d_i/d_t$ – This group accounts for the superficial velocity of air in draft tubes and gas-solid contact time in DTs.

$\pi_5 = a_v^2 D_e \tau$ – This group accounts for moisture diffusion in grains for a given bed mass and air flow rate.

The following equation was obtained through non-linear regression analysis using 180 experimental data.

$$\Theta t = 0.0056 \left(\frac{\lambda_d}{RT_a}\right)^{3.46} \left(\frac{(X_0 - X_f)}{(X_0 - X_e)}\right)^{2.05} \left(\frac{H}{d_h}\right)^{0.48} \left(\frac{d_i}{d_t}\right)^{0.25} (a_v{}^2 D_e \tau)^{0.11} \quad \text{………………….} (4.6)$$

For ranges

π_1: 15.334 to 17.3666

π_2: 0.45704 To 0.95944

$\pi_{3:}$ 10.25 to 325

$\pi_{4:}$ 0.20513 to 1

$\pi_{5:}$ 1.93E-07 to 3.35E-05

Using equation 4.6 the batch drying times were calculated and compared with the corresponding experimental values. The comparison is given Fig.4.45.

The results indicated that the proposed correlation predicted the experimental drying times reasonably well with a RMSE = 0.08458 and R^2 = 0.8834. The correlation would be applicable for the range of dimensionless groups used in this study. However, with a large number of experimental data under a wide range of operating and design conditions it would be possible to propose a general correlation involving the dimensionless groups used here. Such a correlation would be useful for scale up and design of a multiple porous draft tube dryer.

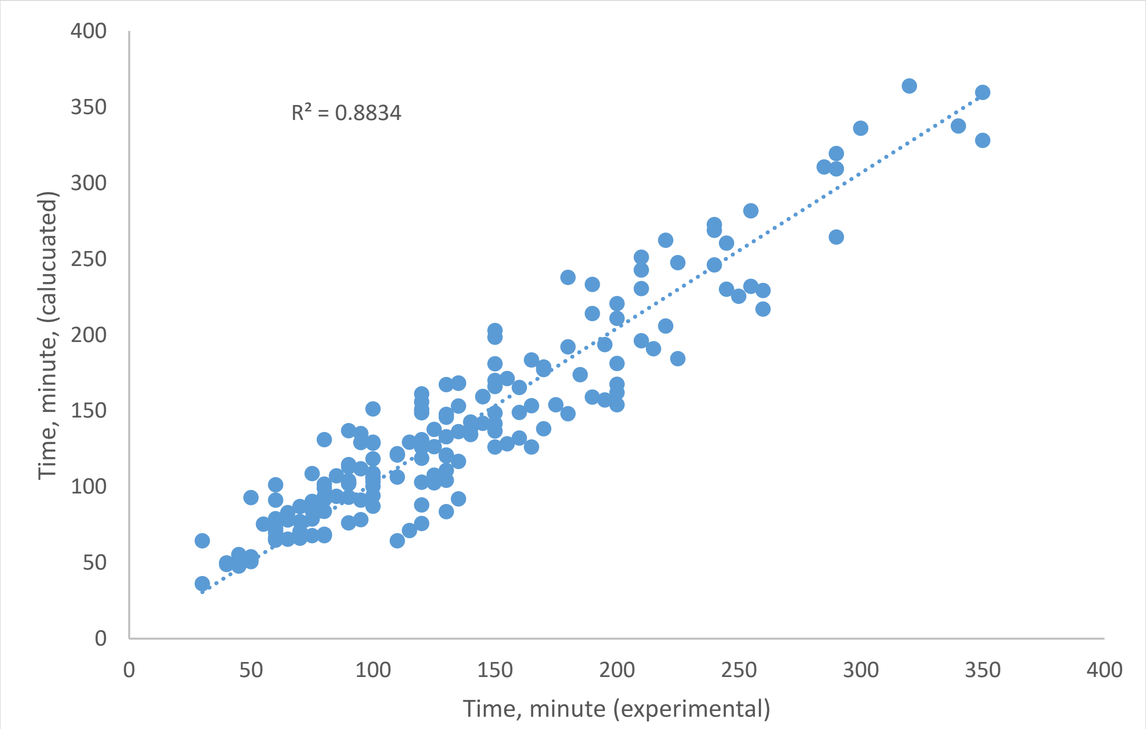


Figure 4.45 Comparison of batch drying times calculated with the corresponding experimental values.

Table 4.1.1 Influence of operating and design parameters on batch drying time for ragi.

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^{0}C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
1	35	0.15	30	2.5	26	21	0	155
2	35	0.2	30	2.5	26	21	0	180
3	35	0.25	30	2.5	26	21	0	210
4	35	0.3	30	2.5	26	21	0	240
5	35	0.35	30	2.5	26	21	0	260
6	40	0.15	30	2.5	26	21	0	100
7	40	0.2	30	2.5	26	21	0	160
8	40	0.25	30	2.5	26	21	0	180
9	40	0.3	30	2.5	26	21	0	220
10	40	0.35	30	2.5	26	21	0	240
11	45	0.15	30	2.5	26	21	0	90
12	45	0.2	30	2.5	26	21	0	150
13	45	0.25	30	2.5	26	21	0	160
14	45	0.3	30	2.5	26	21	0	200
15	45	0.35	30	2.5	26	21	0	230
16	50	0.15	30	2.5	26	21	0	90
17	50	0.2	30	2.5	26	21	0	130
18	50	0.25	30	2.5	26	21	0	150
19	50	0.3	30	2.5	26	21	0	190
20	50	0.35	30	2.5	26	21	0	200
21	55	0.15	30	2.5	26	21	0	80
22	55	0.2	30	2.5	26	21	0	110
23	55	0.25	30	2.5	26	21	0	140
24	55	0.3	30	2.5	26	21	0	170
25	55	0.35	30	2.5	26	21	0	190
26	35	0.15	33	2.5	26	21	0	150

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
27	35	0.2	33	2.5	26	21	0	180
28	35	0.25	33	2.5	26	21	0	210
29	35	0.3	33	2.5	26	21	0	220
30	35	0.35	33	2.5	26	21	0	240
31	40	0.15	33	2.5	26	21	0	100
32	40	0.2	33	2.5	26	21	0	160
33	40	0.25	33	2.5	26	21	0	180
34	40	0.3	33	2.5	26	21	0	210
35	40	0.35	33	2.5	26	21	0	235
36	45	0.15	33	2.5	26	21	0	90
37	45	0.2	33	2.5	26	21	0	140
38	45	0.25	33	2.5	26	21	0	160
39	45	0.3	33	2.5	26	21	0	200
40	45	0.35	33	2.5	26	21	0	220
41	50	0.15	33	2.5	26	21	0	80
42	50	0.2	33	2.5	26	21	0	120
43	50	0.25	33	2.5	26	21	0	150
44	50	0.3	33	2.5	26	21	0	180
45	50	0.35	33	2.5	26	21	0	190
46	55	0.15	33	2.5	26	21	0	60
47	55	0.2	33	2.5	26	21	0	110
48	55	0.25	33	2.5	26	21	0	130
49	55	0.3	33	2.5	26	21	0	160
50	55	0.35	33	2.5	26	21	0	180
51	35	0.15	36	2.5	26	21	0	130
52	35	0.2	36	2.5	26	21	0	165
53	35	0.25	36	2.5	26	21	0	200
54	35	0.3	36	2.5	26	21	0	220

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
55	35	0.35	36	2.5	26	21	0	240
56	40	0.15	36	2.5	26	21	0	100
57	40	0.2	36	2.5	26	21	0	160
58	40	0.25	36	2.5	26	21	0	180
59	40	0.3	36	2.5	26	21	0	185
60	40	0.35	36	2.5	26	21	0	230
61	45	0.15	36	2.5	26	21	0	90
62	45	0.2	36	2.5	26	21	0	130
63	45	0.25	36	2.5	26	21	0	150
64	45	0.3	36	2.5	26	21	0	160
65	45	0.35	36	2.5	26	21	0	170
66	50	0.15	36	2.5	26	21	0	80
67	50	0.2	36	2.5	26	21	0	120
68	50	0.25	36	2.5	26	21	0	140
69	50	0.3	36	2.5	26	21	0	140
70	50	0.35	36	2.5	26	21	0	160
71	55	0.15	36	2.5	26	21	0	70
72	55	0.2	36	2.5	26	21	0	90
73	55	0.25	36	2.5	26	21	0	120
74	55	0.3	36	2.5	26	21	0	120
75	55	0.35	36	2.5	26	21	0	140
76	35	0.15	30	2	26	21	0	120
77	35	0.25	30	2	26	21	0	180
78	35	0.35	30	2	26	21	0	210
79	45	0.15	30	2	26	21	0	70
80	45	0.25	30	2	26	21	0	140
81	45	0.35	30	2	26	21	0	150
82	55	0.15	30	2	26	21	0	50

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
83	55	0.25	30	2	26	21	0	105
84	55	0.35	30	2	26	21	0	130
85	35	0.15	36	2	26	21	0	100
86	35	0.25	36	2	26	21	0	170
87	35	0.35	36	2	26	21	0	180
88	45	0.15	36	2	26	21	0	60
89	45	0.25	36	2	26	21	0	120
90	45	0.35	36	2	26	21	0	140
91	55	0.15	36	2	26	21	0	40
92	55	0.25	36	2	26	21	0	85
93	55	0.35	36	2	26	21	0	110
94	35	0.15	30	3	26	21	0	150
95	35	0.25	30	3	26	21	0	240
96	35	0.35	30	3	26	21	0	290
97	45	0.15	30	3	26	21	0	110
98	45	0.25	30	3	26	21	0	180
99	45	0.35	30	3	26	21	0	260
100	55	0.15	30	3	26	21	0	80
101	55	0.25	30	3	26	21	0	150
102	55	0.35	30	3	26	21	0	200
103	35	0.15	36	3	26	21	0	130
104	35	0.25	36	3	26	21	0	230
105	35	0.35	36	3	26	21	0	280
106	45	0.15	36	3	26	21	0	100
107	45	0.25	36	3	26	21	0	160
108	45	0.35	36	3	26	21	0	200
109	55	0.15	36	3	26	21	0	80
110	55	0.25	36	3	26	21	0	140

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
111	55	0.35	36	3	26	21	0	160
112	40	0.2	30	2.5	w/o DT	21	NA	80
113	40	0.3	30	2.5	w/o DT	21	NA	120
114	50	0.2	30	2.5	w/o DT	21	NA	60
115	50	0.3	30	2.5	w/o DT	21	NA	100
116	40	0.2	30	2.5	26	21	0	170
117	40	0.3	30	2.5	26	21	0	210
118	50	0.2	30	2.5	26	21	0	140
119	50	0.3	30	2.5	26	21	0	160
120	40	0.2	30	2.5	26	21	2	160
121	40	0.3	30	2.5	26	21	2	200
122	50	0.2	30	2.5	26	21	2	110
123	50	0.3	30	2.5	26	21	2	150
124	40	0.2	30	2	w/o DT	21	NA	65
125	40	0.3	30	2	w/o DT	21	NA	105
126	50	0.2	30	2	w/o DT	21	NA	55
127	50	0.3	30	2	w/o DT	21	NA	60
128	40	0.2	30	2	21	21	0	140
129	40	0.3	30	2	21	21	0	160
130	50	0.2	30	2	21	21	0	105
131	50	0.3	30	2	21	21	0	150
132	40	0.2	30	2	21	21	2	130
133	40	0.3	30	2	21	21	2	150
134	50	0.2	30	2	21	21	2	80
135	50	0.3	30	2	21	21	2	135
136	40	0.2	30	2	21	21	4	65
137	40	0.3	30	2	21	21	4	90
138	50	0.2	30	2	21	21	4	50

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
139	50	0.3	30	2	21	21	4	80
140	40	0.2	36	2	w/o DT	21	NA	50
141	40	0.3	36	2	w/o DT	21	NA	70
142	50	0.2	36	2	w/o DT	21	NA	40
143	50	0.3	36	2	w/o DT	21	NA	45
144	40	0.2	36	2	21	21	0	120
145	40	0.3	36	2	21	21	0	135
146	50	0.2	36	2	21	21	0	105
147	50	0.3	36	2	21	21	0	120
148	40	0.2	36	2	21	21	2	100
149	40	0.3	36	2	21	21	2	120
150	50	0.2	36	2	21	21	2	80
151	50	0.3	36	2	21	21	2	100
152	40	0.2	36	2	21	21	4	60
153	40	0.3	36	2	21	21	4	85
154	50	0.2	36	2	21	21	4	45
155	50	0.3	36	2	21	21	4	75
156	40	0.2	30	2	w/o DT	21	NA	65
157	40	0.3	30	2	w/o DT	21	NA	105
158	50	0.2	30	2	w/o DT	21	NA	55
159	50	0.3	30	2	w/o DT	21	NA	60
160	40	0.2	30	2	26	21	0	130
161	40	0.3	30	2	26	21	0	155
162	50	0.2	30	2	26	21	0	100
163	50	0.3	30	2	26	21	0	140
164	40	0.2	30	2	26	21	2	90
165	40	0.3	30	2	26	21	2	130
166	50	0.2	30	2	26	21	2	70

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
167	50	0.3	30	2	26	21	2	120
168	40	0.2	30	2	26	21	4	60
169	40	0.3	30	2	26	21	4	80
170	50	0.2	30	2	26	21	4	40
171	50	0.3	30	2	26	21	4	70
172	40	0.2	36	2	w/o DT	21	NA	50
173	40	0.3	36	2	w/o DT	21	NA	70
174	50	0.2	36	2	w/o DT	21	NA	40
175	50	0.3	36	2	w/o DT	21	NA	50
176	40	0.2	36	2	26	21	0	110
177	40	0.3	36	2	26	21	0	130
178	50	0.2	36	2	26	21	0	90
179	50	0.3	36	2	26	21	0	110
180	40	0.2	36	2	26	21	2	80
181	40	0.3	36	2	26	21	2	110
182	50	0.2	36	2	26	21	2	60
183	50	0.3	36	2	26	21	2	90
184	40	0.2	36	2	26	21	4	55
185	40	0.3	36	2	26	21	4	75
186	50	0.2	36	2	26	21	4	40
187	50	0.3	36	2	26	21	4	60
188	40	0.2	36	2	w/o DT	21	NA	65
189	40	0.3	36	2	w/o DT	21	NA	105
190	50	0.2	36	2	w/o DT	21	NA	55
191	50	0.3	36	2	w/o DT	21	NA	60
192	40	0.2	36	2	39	21	0	80
193	40	0.3	36	2	39	21	0	120
194	50	0.2	36	2	39	21	0	60

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	m_b, kg	d_t, mm	d_i, mm	d_h, mm	
195	50	0.3	36	2	39	21	0	75
196	40	0.2	36	2	39	21	2	60
197	40	0.3	36	2	39	21	2	90
198	50	0.2	36	2	39	21	2	50
199	50	0.3	36	2	39	21	2	70
200	50	0.2	36	2	21	21	4	40
201	50	0.2	36	2	21	15	4	35
202	50	0.2	36	2	21	8	4	35
203	50	0.2	36	2	21	21	4	40
204	50	0.2	36	2	21	15	4	35
205	50	0.2	36	2	21	8	4	35
206	50	0.2	36	4	21	21	4	75
207	50	0.2	36	4	21	15	4	70
208	50	0.2	36	4	21	8	4	60
209	50	0.2	36	6	21	21	4	100
210	50	0.2	36	6	21	15	4	95
211	50	0.2	36	6	21	8	4	80
212	50	0.2	36	8	21	21	4	130
213	50	0.2	36	8	21	15	4	120
214	50	0.2	36	8	21	8	4	100

Table 4.1.2 Influence of operating and design parameters on batch drying time for barley.

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
215	40	0.15	36	1	26	15	0	70
216	50	0.15	36	1	26	15	0	50
217	60	0.15	36	1	26	15	0	35
218	40	0.2	36	1	26	15	0	85
219	50	0.2	36	1	26	15	0	70
220	60	0.2	36	1	26	15	0	50
221	40	0.25	36	1	26	15	0	105
222	50	0.25	36	1	26	15	0	85
223	60	0.25	36	1	26	15	0	70
224	40	0.15	36	2	26	15	0	110
225	50	0.15	36	2	26	15	0	80
226	60	0.15	36	2	26	15	0	60
227	40	0.2	36	2	26	15	0	135
228	50	0.2	36	2	26	15	0	105
229	60	0.2	36	2	26	15	0	75
230	40	0.25	36	2	26	15	0	165
231	50	0.25	36	2	26	15	0	125
232	60	0.25	36	2	26	15	0	90
233	40	0.15	36	3	26	15	0	140
234	50	0.15	36	3	26	15	0	115
235	60	0.15	36	3	26	15	0	75
236	40	0.2	36	3	26	15	0	165
237	50	0.2	36	3	26	15	0	130
238	60	0.2	36	3	26	15	0	100
239	40	0.25	36	3	26	15	0	220
240	50	0.25	36	3	26	15	0	165

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
241	60	0.25	36	3	26	15	0	120
242	40	0.15	36	4	26	15	0	160
243	50	0.15	36	4	26	15	0	130
244	60	0.15	36	4	26	15	0	100
245	40	0.2	36	4	26	15	0	195
246	50	0.2	36	4	26	15	0	150
247	60	0.2	36	4	26	15	0	130
248	40	0.25	36	4	26	15	0	265
249	50	0.25	36	4	26	15	0	200
250	60	0.25	36	4	26	15	0	160
251	40	0.15	36	1	26	15	2	60
252	50	0.15	36	1	26	15	2	45
253	60	0.15	36	1	26	15	2	30
254	40	0.2	36	1	26	15	2	75
255	50	0.2	36	1	26	15	2	60
256	60	0.2	36	1	26	15	2	45
257	40	0.25	36	1	26	15	2	90
258	50	0.25	36	1	26	15	2	75
259	60	0.25	36	1	26	15	2	60
260	40	0.15	36	2	26	15	2	95
261	50	0.15	36	2	26	15	2	70
262	60	0.15	36	2	26	15	2	50
263	40	0.2	36	2	26	15	2	120
264	50	0.2	36	2	26	15	2	90
265	60	0.2	36	2	26	15	2	65
266	40	0.25	36	2	26	15	2	150
267	50	0.25	36	2	26	15	2	110
268	60	0.25	36	2	26	15	2	80

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
269	40	0.15	36	3	26	15	2	130
270	50	0.15	36	3	26	15	2	100
271	60	0.15	36	3	26	15	2	65
272	40	0.2	36	3	26	15	2	150
273	50	0.2	36	3	26	15	2	115
274	60	0.2	36	3	26	15	2	90
275	40	0.25	36	3	26	15	2	200
276	50	0.25	36	3	26	15	2	150
277	60	0.25	36	3	26	15	2	110
278	40	0.15	36	4	26	15	2	150
279	50	0.15	36	4	26	15	2	120
280	60	0.15	36	4	26	15	2	90
281	40	0.2	36	4	26	15	2	180
282	50	0.2	36	4	26	15	2	135
283	60	0.2	36	4	26	15	2	120
284	40	0.25	36	4	26	15	2	240
285	50	0.25	36	4	26	15	2	185
286	60	0.25	36	4	26	15	2	145
287	40	0.2	36	2	26	21	2	135
288	50	0.2	36	2	26	21	2	90
289	60	0.2	36	2	26	21	2	75
290	40	0.25	36	2	26	21	2	165
291	50	0.25	36	2	26	21	2	120
292	60	0.25	36	2	26	21	2	85
293	40	0.2	36	4	26	21	2	200
294	50	0.2	36	4	26	21	2	150
295	60	0.2	36	4	26	21	2	130
296	40	0.25	36	4	26	21	2	260

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
297	50	0.25	36	4	26	21	2	200
298	60	0.25	36	4	26	21	2	160
299	40	0.2	36	2	21	15	2	135
300	50	0.2	36	2	21	15	2	100
301	60	0.2	36	2	21	15	2	70
302	40	0.25	36	2	21	15	2	170
303	50	0.25	36	2	21	15	2	125
304	60	0.25	36	2	21	15	2	90
305	40	0.2	36	4	21	15	2	190
306	50	0.2	36	4	21	15	2	140
307	60	0.2	36	4	21	15	2	125
308	40	0.25	36	4	21	15	2	255
309	50	0.25	36	4	21	15	2	195
310	60	0.25	36	4	21	15	2	155
311	40	0.2	36	2	21	21	2	150
312	50	0.2	36	2	21	21	2	100
313	60	0.2	36	2	21	21	2	80
314	40	0.25	36	2	21	21	2	180
315	50	0.25	36	2	21	21	2	135
316	60	0.25	36	2	21	21	2	95
317	40	0.2	36	4	21	21	2	210
318	50	0.2	36	4	21	21	2	160
319	60	0.2	36	4	21	21	2	135
320	40	0.25	36	4	21	21	2	275
321	50	0.25	36	4	21	21	2	210
322	60	0.25	36	4	21	21	2	170
323	40	0.2	36	4	26	8	4	120
324	60	0.2	36	4	26	8	4	70

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
325	40	0.25	36	4	26	8	4	145
326	60	0.25	36	4	26	8	4	95
327	60	0.2	36	2	21	8	2	60
328	60	0.2	36	4	21	8	2	100
329	60	0.2	36	6	21	8	2	165
330	60	0.2	36	8	21	8	2	220

Table 4.1.3 Influence of operating and design parameters on batch drying time for wheat (MPDTSB).

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
331	40	0.15	36	1	26	15	0	95
332	50	0.15	36	1	26	15	0	70
333	60	0.15	36	1	26	15	0	55
334	40	0.2	36	1	26	15	0	135
335	50	0.2	36	1	26	15	0	110
336	60	0.2	36	1	26	15	0	80
337	40	0.25	36	1	26	15	0	170
338	50	0.25	36	1	26	15	0	140
339	60	0.25	36	1	26	15	0	110
340	40	0.15	36	2	26	15	0	140
341	50	0.15	36	2	26	15	0	120
342	60	0.15	36	2	26	15	0	100
343	40	0.2	36	2	26	15	0	210
344	50	0.2	36	2	26	15	0	155
345	60	0.2	36	2	26	15	0	130
346	40	0.25	36	2	26	15	0	240
347	50	0.25	36	2	26	15	0	210
348	60	0.25	36	2	26	15	0	185
349	40	0.15	36	3	26	15	0	190
350	50	0.15	36	3	26	15	0	160
351	60	0.15	36	3	26	15	0	130
352	40	0.2	36	3	26	15	0	240
353	50	0.2	36	3	26	15	0	210
354	60	0.2	36	3	26	15	0	190
355	40	0.25	36	3	26	15	0	305
356	50	0.25	36	3	26	15	0	265

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
357	60	0.25	36	3	26	15	0	235
358	40	0.15	36	4	26	15	0	255
359	50	0.15	36	4	26	15	0	220
360	60	0.15	36	4	26	15	0	185
361	40	0.2	36	4	26	15	0	295
362	50	0.2	36	4	26	15	0	260
363	60	0.2	36	4	26	15	0	235
364	40	0.25	36	4	26	15	0	245
365	50	0.25	36	4	26	15	0	310
366	60	0.25	36	4	26	15	0	275
367	40	0.15	36	1	26	15	2	80
368	50	0.15	36	1	26	15	2	60
369	60	0.15	36	1	26	15	2	50
370	40	0.2	36	1	26	15	2	120
371	50	0.2	36	1	26	15	2	100
372	60	0.2	36	1	26	15	2	75
373	40	0.25	36	1	26	15	2	150
374	50	0.25	36	1	26	15	2	130
375	60	0.25	36	1	26	15	2	100
376	40	0.15	36	2	26	15	2	130
377	50	0.15	36	2	26	15	2	110
378	60	0.15	36	2	26	15	2	95
379	40	0.2	36	2	26	15	2	190
380	50	0.2	36	2	26	15	2	145
381	60	0.2	36	2	26	15	2	120
382	40	0.25	36	2	26	15	2	225
383	50	0.25	36	2	26	15	2	200
384	60	0.25	36	2	26	15	2	180

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
385	40	0.15	36	3	26	15	2	180
386	50	0.15	36	3	26	15	2	150
387	60	0.15	36	3	26	15	2	125
388	40	0.2	36	3	26	15	2	220
389	50	0.2	36	3	26	15	2	195
390	60	0.2	36	3	26	15	2	175
391	40	0.25	36	3	26	15	2	285
392	50	0.25	36	3	26	15	2	250
393	60	0.25	36	3	26	15	2	230
394	40	0.15	36	4	26	15	2	240
395	50	0.15	36	4	26	15	2	210
396	60	0.15	36	4	26	15	2	175
397	40	0.2	36	4	26	15	2	275
398	50	0.2	36	4	26	15	2	245
399	60	0.2	36	4	26	15	2	225
400	40	0.25	36	4	26	15	2	320
401	50	0.25	36	4	26	15	2	290
402	60	0.25	36	4	26	15	2	260
403	40	0.2	36	2	26	21	2	210
404	50	0.2	36	2	26	21	2	155
405	60	0.2	36	2	26	21	2	125
406	40	0.25	36	2	26	21	2	240
407	50	0.25	36	2	26	21	2	210
408	60	0.25	36	2	26	21	2	190
409	40	0.2	36	4	26	21	2	290
410	50	0.2	36	4	26	21	2	255
411	60	0.2	36	4	26	21	2	230
412	40	0.25	36	4	26	21	2	340

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
413	50	0.25	36	4	26	21	2	300
414	60	0.25	36	4	26	21	2	250
415	40	0.2	36	2	21	15	2	210
416	50	0.2	36	2	21	15	2	160
417	60	0.2	36	2	21	15	2	130
418	40	0.25	36	2	21	15	2	245
419	50	0.25	36	2	21	15	2	215
420	60	0.25	36	2	21	15	2	200
421	40	0.2	36	4	21	15	2	290
422	50	0.2	36	4	21	15	2	260
423	60	0.2	36	4	21	15	2	230
424	40	0.25	36	4	21	15	2	350
425	50	0.25	36	4	21	15	2	310
426	60	0.25	36	4	21	15	2	260
427	40	0.2	36	2	21	21	2	220
428	50	0.2	36	2	21	21	2	170
429	60	0.2	36	2	21	21	2	140
430	40	0.25	36	2	21	21	2	255
431	50	0.25	36	2	21	21	2	220
432	60	0.25	36	2	21	21	2	200
433	40	0.2	36	4	21	21	2	300
434	50	0.2	36	4	21	21	2	270
435	60	0.2	36	4	21	21	2	240
436	40	0.25	36	4	21	21	2	350
437	50	0.25	36	4	21	21	2	315
438	60	0.25	36	4	21	21	2	270
439	50	0.2	36	3	21	8	2	220
440	50	0.2	36	3	21	8	4	190

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
441	50	0.2	36	3	26	8	2	200
442	50	0.2	36	3	26	8	4	180
443	50	0.2	36	1	26	15	2	130
444	50	0.2	36	4	26	15	2	250
445	50	0.2	36	1	26	15	2	120
446	50	0.2	36	4	26	15	2	240
447	50	0.2	36	1	26	15	2	115
448	50	0.2	36	4	26	15	2	210

Table 4.1.4 Influence of operating and design parameters on batch drying time for ragi considering variable hole area (MPDTSB).

Sl no	Operating variables				Design variables					Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	P_h, mmxmm	A_h, mm^2	
1	40	0.2	30	2.5	26	21	4	45 X 17	527.52	120
2	40	0.3	30	2.5	26	21	4	45 X 17	527.52	150
3	50	0.2	30	2.5	26	21	4	45 X 17	527.52	80
4	50	0.3	30	2.5	26	21	4	45 X 17	527.52	120
5	40	0.2	30	2.5	26	21	4	30 X17	715.92	100
6	40	0.3	30	2.5	26	21	4	30 X17	715.92	140
7	50	0.2	30	2.5	26	21	4	30 X17	715.92	75
8	50	0.3	30	2.5	26	21	4	30 X17	715.92	110
9	40	0.2	30	2	21	21	4	45 X 14	527.52	105
10	40	0.3	30	2	21	21	4	45 X 14	527.52	120
11	50	0.2	30	2	21	21	4	45 X 14	527.52	70
12	50	0.3	30	2	21	21	4	45 X 14	527.52	100
13	40	0.2	30	2	21	21	4	30 X14	715.92	90
14	40	0.3	30	2	21	21	4	30 X14	715.92	105
15	50	0.2	30	2	21	21	4	30 X14	715.92	60
16	50	0.3	30	2	21	21	4	30 X14	715.92	90
17	40	0.2	36	2	21	21	4	45 X 14	527.52	90
18	40	0.3	36	2	21	21	4	45 X 14	527.52	100
19	50	0.2	36	2	21	21	4	45 X 14	527.52	65
20	50	0.3	36	2	21	21	4	45 X 14	527.52	90
21	40	0.2	36	2	21	21	4	30 X14	715.92	80
22	40	0.3	36	2	21	21	4	30 X14	715.92	90
23	50	0.2	36	2	21	21	4	30 X14	715.92	55
24	50	0.3	36	2	21	21	4	30 X14	715.92	80
25	40	0.2	30	2	26	21	4	45 X 17	527.52	90
26	40	0.3	30	2	26	21	4	45 X 17	527.52	100

Sl no	Operating variables				Design variables					Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	P_h, mmxmm	A_h, mm^2	
27	50	0.2	30	2	26	21	4	45 X 17	527.52	50
28	50	0.3	30	2	26	21	4	45 X 17	527.52	80
29	40	0.2	30	2	26	21	4	30 X17	715.92	65
30	40	0.3	30	2	26	21	4	30 X17	715.92	90
31	50	0.2	30	2	26	21	4	30 X17	715.92	50
32	50	0.3	30	2	26	21	4	30 X17	715.92	80
33	40	0.2	36	2	26	21	4	45 X 17	527.52	80
34	40	0.3	36	2	26	21	4	45 X 17	527.52	95
35	50	0.2	36	2	26	21	4	45 X 17	527.52	50
36	50	0.3	36	2	26	21	4	45 X 17	527.52	80
37	40	0.2	36	2	26	21	4	30 X17	715.92	60
38	40	0.3	36	2	26	21	4	30 X17	715.92	90
39	50	0.2	36	2	26	21	4	30 X17	715.92	50
40	50	0.3	36	2	26	21	4	30 X17	715.92	70

4.1.5 Influence of operating and design parameters on batch drying time (SPDTSB1).

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
Material: Ragi								
1	40	0.2	36	2	26	26	2	140
2	60	0.2	36	2	26	26	2	45
3	40	0.25	36	2	26	26	2	155
4	60	0.25	36	2	26	26	2	75
5	40	0.2	36	4	26	26	2	180
6	60	0.2	36	4	26	26	2	80
7	40	0.25	36	4	26	26	2	200
8	60	0.25	36	4	26	26	2	105
9	40	0.2	36	2	26	26	2	120
10	60	0.2	36	2	26	26	2	40
11	40	0.25	36	2	26	26	2	150
12	60	0.25	36	2	26	26	2	75
13	40	0.2	36	4	26	26	2	160
14	60	0.2	36	4	26	26	2	70
15	40	0.25	36	4	26	26	2	180
16	60	0.25	36	4	26	26	2	90
Material: Barley								
17	40	0.2	36	2	26	26	2	165
18	60	0.2	36	2	26	26	2	85
19	40	0.25	36	2	26	26	2	180
20	60	0.25	36	2	26	26	2	100
21	40	0.2	36	4	26	26	2	215
22	60	0.2	36	4	26	26	2	130
23	40	0.25	36	4	26	26	2	270
24	60	0.25	36	4	26	26	2	160

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
25	40	0.2	36	2	26	26	2	140
26	60	0.2	36	2	26	26	2	80
27	40	0.25	36	2	26	26	2	160
28	60	0.25	36	2	26	26	2	85
29	40	0.2	36	4	26	26	2	180
30	60	0.2	36	4	26	26	2	110
31	40	0.25	36	4	26	26	2	260
32	60	0.25	36	4	26	26	2	150
Material: Wheat								
33	40	0.2	36	2	26	26	2	240
34	60	0.2	36	2	26	26	2	175
35	40	0.25	36	2	26	26	2	280
36	60	0.25	36	2	26	26	2	220
37	40	0.2	36	4	26	26	2	320
38	60	0.2	36	4	26	26	2	260
39	40	0.25	36	4	26	26	2	360
40	60	0.25	36	4	26	26	2	290
41	40	0.2	36	2	26	26	2	210
42	60	0.2	36	2	26	26	2	130
43	40	0.25	36	2	26	26	2	250
44	60	0.25	36	2	26	26	2	200
45	40	0.2	36	4	26	26	2	300
46	60	0.2	36	4	26	26	2	245
47	40	0.25	36	4	26	26	2	340
48	60	0.25	36	4	26	26	2	280

4.1.6 Influence of operating and design parameters on batch drying time (SPDTSB2).

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^{0}C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
Material: Ragi								
1	40	0.2	36	2	26	15	2	160
2	60	0.2	36	2	26	15	2	55
3	40	0.25	36	2	26	15	2	190
4	60	0.25	36	2	26	15	2	100
5	40	0.2	36	4	26	15	2	220
6	60	0.2	36	4	26	15	2	110
7	40	0.25	36	4	26	15	2	250
8	60	0.25	36	4	26	15	2	120
9	40	0.2	36	2	26	15	2	140
10	60	0.2	36	2	26	15	2	50
11	40	0.25	36	2	26	15	2	180
12	60	0.25	36	2	26	15	2	90
13	40	0.2	36	4	26	15	2	185
14	60	0.2	36	4	26	15	2	80
15	40	0.25	36	4	26	15	2	215
16	60	0.25	36	4	26	15	2	105
Material: Barley								
17	40	0.2	36	2	26	15	2	200
18	60	0.2	36	2	26	15	2	105
19	40	0.25	36	2	26	15	2	230
20	60	0.25	36	2	26	15	2	150
21	40	0.2	36	4	26	15	2	250
22	60	0.2	36	4	26	15	2	170
23	40	0.25	36	4	26	15	2	340
24	60	0.25	36	4	26	15	2	200

Sl no	Operating variables				Design variables			Θ_t, minute
	T_a, ^0C	X_0, kg/kg	v_o, m^3/h	M_b, kg	d_t, mm	d_i, mm	d_h, mm	
25	40	0.2	36	2	26	15	2	170
26	60	0.2	36	2	26	15	2	95
27	40	0.25	36	2	26	15	2	210
28	60	0.25	36	2	26	15	2	110
29	40	0.2	36	4	26	15	2	240
30	60	0.2	36	4	26	15	2	135
31	40	0.25	36	4	26	15	2	310
32	60	0.25	36	4	26	15	2	200
Material: Wheat								
33	40	0.2	36	2	26	15	2	280
34	60	0.2	36	2	26	15	2	210
35	40	0.25	36	2	26	15	2	320
36	60	0.25	36	2	26	15	2	260
37	40	0.2	36	4	26	15	2	350
38	60	0.2	36	4	26	15	2	300
39	40	0.25	36	4	26	15	2	400
40	60	0.25	36	4	26	15	2	360
41	40	0.2	36	2	26	15	2	250
42	60	0.2	36	2	26	15	2	160
43	40	0.25	36	2	26	15	2	290
44	60	0.25	36	2	26	15	2	240
45	40	0.2	36	4	26	15	2	340
46	60	0.2	36	4	26	15	2	280
47	40	0.25	36	4	26	15	2	390
48	60	0.25	36	4	26	15	2	330

Influence of DT holes on batch drying time

Table 4.2 Comparison between porous and non-porous draft tube for ragi.

(v_0 = 36m^3/hr, m_b = 2kg, d_t = 26mm, d_i = 21mm)

Sl.no	X_0, kg/kg	T_a, ^0C	NPDT	2 mm hole
			Time, minute	
1	0.2	40	110	80
2		50	90	60
3	0.3	40	130	110
4		50	100	90

Table 4.3 Comparison between porous and non-porous draft tube for barley.

(v_0 = 36m^3/hr, m_b = 2kg, d_t = 26mm, d_i = 15mm)

Sl.no	X_0, kg/kg	T_a, ^0C	NPDT	2 mm hole
			Time, minute	
1	0.2	40	135	120
2		60	75	65
3	0.25	40	165	150
4		60	90	80

Table 4.4. Comparison between porous and non-porous draft tube for wheat.

(v_0 = 36m^3/hr, m_b = 2kg, d_t = 26mm, d_i = 15mm)

Sl.no	X_0, kg/kg	T_a, ^0C	NPDT	2 mm hole
			Time, minute	
1	0.2	40	210	190
2		60	130	120
3	0.25	40	250	225
4		60	195	180

Influence of DT diameter on batch drying time

Table 4.5 Influence of DT diameter on batch drying time for ragi.

(v_0 = 36m^3/hr, m_b = 2kg, d_i = 21mm, d_h= 2mm)

Sl.no	X_0, kg/kg	T_a, ^{0}C	d_t =21mm	d_t =26mm	d_t =39 mm
			Time, minute		
1	0.2	40	100	80	60
2		50	80	60	50
3	0.3	40	120	110	90
4		50	100	90	70

Table 4.6 Influence of DT diameter on batch drying time for barley.

(v_0 = 36m^3/hr, m_b = 2kg, d_i = 15mm, d_h= 2mm)

Sl.no	X_0, kg/kg	T_a, ^{0}C	d_t =21mm	d_t =26mm
			Time, minute	
1	0.2	40	135	120
2		60	70	65
3	0.25	40	170	150
4		60	90	80

Table 4.7 Influence of DT diameter on batch drying time for wheat.

(v_0 = 36m^3/hr, m_b = 2kg, d_i = 15mm, d_h= 2mm)

Sl.no	X_0, kg/kg	T_a, ^{0}C	d_t =21mm	d_t =26mm
			Time, minute	
1	0.2	40	210	190
2		60	130	120
3	0.25	40	245	225
4		60	200	180

Influence of hole size on batch drying time.

Table 4.8 Influence of hole size on batch drying time for ragi.

(v_0 = 36m^3/hr, m_b = 2kg, d_t= 21 mm, d_i =21mm)

Sl.no	X_0, kg/kg	T_a, ^0C	NPDT	d_h= 2mm	d_h= 4 mm
			Time, minute		
1	0.2	40	120	95	60
2		50	105	70	40
3	0.30	40	135	120	85
4		50	120	100	75

Table 4.9 Influence of hole size on batch drying time for barley.

(v_0 = 36m^3/hr, m_b = 4kg, d_t= 21 mm, d_i =15 mm)

Sl.no	X_0, kg/kg	T_a, ^0C	NPDT	d_h= 2mm	d_h= 4 mm
			Time, minute		
1	0.2	50	180	145	125
2		60	150	120	110
3	0.25	50	105	165	150
4		60	180	145	130

Table 4.10 Influence of hole size on batch drying time for wheat.

(v_0 = 36m^3/hr, m_b = 3 kg, d_t= 21 mm, d_i =15 mm)

Sl.no	X_0, kg/kg	T_a, ^0C	NPDT	d_h= 2mm	d_h= 4 mm
			Time, minute		
1	0.2	50	250	220	200
2		60	210	190	170
3	0.25	50	290	250	220
4		60	245	210	190

Table 4.11 Influence of DT hole area on batch drying time for ragi.

(v_0 = 30m^3/h, m_b = 2kg, d_t= 21mm, d_i =21mm)

Sl no	D_h mm	P_h	N_h	A_h, mm^2	X_0=0.2 kg/kg		X_0=0.3 kg/kg	
					T_a=40	T_a=50	T_a=40	T_a=50
1	2	15 X 14	114	357.96	130	80	150	135
2	4	45 X 14	42	527.52	105	70	120	100
3	4	30 X14	57	715.92	90	60	105	90
4	4	15 X 14	114	1431.84	65	50	90	80

Influence of fluid inlet diameter on batch drying time

Table 4.12 Influence of fluid inlet diameter on batch drying time for ragi.

(T_a= 50^{0}C, X_0= 0.2kg/kg, v_0 = 36m^3/h, d_t= 21mm, d_h= 4mm)

d_i, mm	Batch drying time, min			
	m_b = 2 kg	m_b = 4 kg	m_b = 6 kg	m_b = 8 kg
21	40	75	100	130
15	35	70	90	120
08	35	60	80	100

Table 4.13 Influence of fluid inlet diameter on batch drying time for barley.

(T_a= 60^{0}C, X_0= 0.2kg/kg, v_0 = 36m^3/h, d_t= 21mm, d_h= 2mm)

d_i, mm	Batch drying time, min	
	m_b = 2 kg	m_b = 4 kg
21	75	135
15	65	120
08	60	110

Table 4.14 Influence of fluid inlet diameter on batch drying time for wheat.

(T_a= 50^0C, X_0= 0.2kg/kg, v_0 = 36m^3/h, d_t= 26mm, d_h= 2mm)

d_i, mm	Batch drying time, min	
	m_b = 2 kg	m_b = 4 kg
21	130	250
15	120	240
08	115	210

Table 4.15 Comparison of Drying time; Thermal efficiency; EDC for drying ragi, barley and wheat in MPDTSB.

(v_0 = 36m^3/h, d_h= 2mm)

Sl. No	Parameters			Ragi			Barley			Wheat		
	m_b, kg	X_0, kg/kg	T_a, ^{0}C	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s
1	2	0.20	40	100	61.00	2.77	120	56.61	12.31	190	44.65	14.51
2			60	30	82.11	6.87	70	78.63	17.01	120	62.18	18.43
3		0.25	40	130	61.04	2.32	150	56.45	10.53	225	47.47	12.81
4			60	65	83.04	3.74	80	80.65	16.22	180	64.59	14.54
5	4	0.20	40	140	68.12	1.98	180	63.51	8.84	275	50.11	10.15
6			60	60	84.16	3.69	100	81.61	11.91	225	66.20	10.23
7		0.25	40	165	71.34	1.88	240	64.03	7.01	320	54.24	9.19
8			60	80	85.50	3.17	145	82.44	9.72	260	68.62	10.21

Table 4.16 Comparison of Drying time; Thermal efficiency; EDC for drying ragi, barley and wheat in SPDTSB 1.

(v_0 = 36m^3/h, d_h= 2mm)

Sl. No	Parameters			Ragi			Barley			Wheat		
	m_b, kg	X_0, kg/kg	T_a, ^{0}C	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s
1	2	0.20	40	120	51.94	2.27	140	46.59	10.91	210	42.84	14.31
2			60	40	71.64	5.15	80	70.15	14.83	130	57.40	17.22
3		0.25	40	150	56.06	2.04	160	54.25	10.24	250	44.43	11.84
4			60	75	76.87	3.34	85	76.13	13.93	200	59.14	13.55
5	4	0.20	40	160	65.03	1.84	180	63.26	8.84	300	45.94	9.09
6			60	70	81.71	3.15	110	79.35	11.10	245	62.40	9.67
7		0.25	40	180	68.33	1.82	260	61.38	6.61	340	49.50	8.85
8			60	90	83.04	2.68	150	79.70	9.61	280	64.78	9.52

Table 4.17 Comparison of Drying time; Thermal efficiency; EDC for drying ragi, barley and wheat in SPDTSB 2 (v_0 = 36m^3/h, d_h= 2mm)

Sl. No	Parameters			Ragi			Barley			Wheat		
	m_b, kg	X_0, kg/kg	T_a, ^{0}C	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s	θ_t minutes	E_f, %	D_{eff} x 10^{12} m^2/s
1	2	0.20	40	140	44.52	2.17	170	41.91	8.99	250	39.27	11.91
2			60	50	65.31	4.24	95	64.10	12.51	160	53.30	13.82
3		0.25	40	180	49.76	1.84	210	47.04	7.40	290	41.14	10.75
4			60	90	68.99	2.88	110	67.18	11.63	240	54.41	11.42
5	4	0.20	40	185	59.85	1.66	240	54.96	6.34	340	41.15	8.69
6			60	80	77.85	2.89	135	76.94	9.34	280	57.83	8.70
7		0.25	40	215	62.83	1.54	310	57.07	5.49	390	42.99	7.82
8			60	105	79.25	2.60	200	78.16	7.27	330	58.89	8.65

Estimation of moisture diffusivities in grains

Estimation of moisture diffusivities in ragi

Table 4.18 Influence of flow rate and temperature on moisture diffusivities of ragi.

(X_0= 0.3 kg/kg, m_b = 2.5kg, d_t=26 mm, d_i = 21mm, NPDT)

T_a, ^{0}C	$v_0 = 30m^3/h$	$v_0 = 33m^3/h$	$v_0 = 36m^3/h$
	D_{eff} x 10^{12} m^2/s		
35	1.43	1.52	1.73
40	1.49	1.56	1.78
45	1.52	1.62	1.89
50	1.57	1.72	2.12
55	1.72	1.93	2.42

Table 4.19 Influence of bed mass and temperature on moisture diffusivities of barley.

(v_0 = 36 m^3/hr, d_t= 26mm, d_i = 15mm, d_h= 2mm)

T_a ^{0}C	m_b = 2kg	m_b = 3kg	m_b = 4kg
	D_{eff} x 10^{12} m^2/s		
40	643	502	391
50	814	567	453
60	1030	748	565

Table 4.20 Influence of bed mass and temperature on moisture diffusivities of wheat.

(X_0= 0.25, v_0 =36 m^3/hr, d_t= 26, d_i = 15mm, d_h= 2mm)

T_a ^{0}C	m_b =2kg	m_b = 3kg	m_b = 4kg
	D_{eff} x 10^{12} m^2/s		
40	738	642	517
50	814	696	536
60	912	747	618

Table 4.21 Influence of bed mass on moisture diffusivities of ragi.

(X_0= 0.25 kg/kg, m_b = 2.5kg, d_t=26 mm, d_i = 21mm, NPDT)

T_a ^0C	m_b =2 kg	m_b =3 kg
	D_{eff} x 10^{12} m^2/s	
35	2.15	1.59
45	2.53	1.87
55	3.08	2.21

Table 4.22 Influence of DT and hole diameter on moisture diffusivities of ragi.

(v_0 = 36 m^3/h, m_b = 2 kg, d_i = 21mm)

d_h, mm	X_0 kg/kg	T_a ^0C	d_t =21mm	d_t = 39 mm
			D_{eff} x 10^{12} m^2/s	
NPDT	0.2	40	2.53	4.10
		50	2.59	4.44
	0.3	40	2.47	3.87
		50	2.52	4.09
2 mm	0.2	40	4.01	29.41
		50	4.28	30.42
	0.3	40	3.16	24.42
		50	3.23	26.30

Table 4.23 Influence of DT and hole diameter on moisture diffusivities of barley.

(v_0 = 36 m^3/h, m_b = 2kg, d_t= 21mm, d_i = 21mm)

X_0 kg/kg	T_a ^0C	NPDT	d_h = 2mm	d_h = 4mm
		D_{eff} x 10^{12} m^2/s		
0.2	40	2.53	4.01	4.56
	50	2.59	4.28	5.67
0.3	40	2.47	3.16	3.98
	50	2.63	3.23	4.04

Table 4.24 Influence of hole diameter on moisture diffusivities of barley.

(X_0= 0.2 kg/kg, v_0 = 36 m^3/hr, m_b = 4kg, d_t= 21, d_i = 8mm, d_h= 2mm)

T_a ^{0}C	D_h=2mm	D_h=4mm
	D_{eff} x 10^{12} m^2/s	
50	662	956
60	703	1020

Table 4.25 Influence of hole diameter on moisture diffusivities of wheat.

(T_a= 50^0 C, X_0= 0.2 kg/kg, v_0 = 36 m^3/hr, m_b = 3kg, d_i = 8mm)

d_h, mm	d_t= 21mm	d_t= 26 mm
	D_{eff} x 10^{12} m^2/s	
2	647	766
4	777	872

Table 4.26 Influence of fluid inlet diameter and bed mass on moisture diffusivities of ragi. (T_a= 50^0C, X_0=0.2 kg/kg, v_0 = 36m^3/h, d_t= 21, d_h= 4mm)

m_b, kg	d_i = 8mm	d_i = 15mm	d_i = 21mm
	D_{eff} x 10^{12} m^2/s		
4	3.92	3.15	3.01
6	3.28	2.86	2.78
8	2.69	2.27	2.14

Table 4.27 Influence of fluid inlet diameter and temperature on moisture diffusivities of barley. (X_0=0.2 kg/kg, v_0 =36m^3/h , m_b = 2kg, d_t=26, d_h= 2mm)

T_a^{0}C	d_i = 8mm	d_i=15mm	d_i=21mm
	D_{eff} x 10^{12} m^2/s		
40	933	721	492
50	1011	802	601
60	1326	1100	1000

Table 4.28 Influence of fluid inlet diameter and bed mass on moisture diffusivities of wheat.

(T_a= 50^0 C, X_0= 0.2 kg/kg, v_0 = 36 m^3/hr, d_t= 21mm, d_h= 2mm)

$m_{b,\ kg}$	d_i =8 mm	d_i =15 mm	d_i =21 mm
	D_{eff} x 10^{12} m^2/s		
1	4222	2542	1644
4	3550	1934	1060

Table 4.29 Activation energy for drying of various agricultural products.

Vegetables	**Ea (kJ/mol)**	**References**
Barley	34.84	Present work
Barley	37.90	Markowski (2010)
Ragi	28.42	Present work
Ragi	30.50	Srinivasa Kannan et.al., (2012)
Wheat	32.6	Present work
Wheat	27.2	Gely and Giner (2007)
Soya bean	28.8	Gely and Giner (2007)
Carrot	28.4	Doymaz (2004)
Beans	35.4	Doymaz (2005)
Pepper	33.8	Di Scala and Crapiste,

Influence of operating and design variable on thermal efficiency

Table 4.30 Influence of flow rate and temperature on thermal efficiency of drying ragi.

(X_0= 0.25kg/kg, m_b = 2 kg, d_t= 26mm, d_i = 21mm, NPDT)

T_a ^{0}C	v_0 =30m^3/h	v_0 =36m^3/h
	E_f, %	
35	57.06	60.41
45	63.54	67.77
55	70.61	75.33

Table 4.31 Influence of bed mass and temperature on thermal efficiency of drying barley, (T_a= X_0= 0.2 kg/kg, v_0 =36 m^3/hr, d_t= 26mm, d_i = 15mm, d_h= 2mm)

T_a, ^{0}C	m_b =2kg	m_b =3kg	m_b =4kg
	E_f, %		
40	51.14	53.00	58.89
50	61.53	66.03	72.46
60	71.41	74.39	80.69

Table 4.32 Influence of bed mass and temperature on thermal efficiency of drying wheat, (X_0=0.2 kg/kg, v_0 = 36 m^3/hr, m_b = 2kg ,d_t= 26,d_i =15mm, d_h= 2mm)

T_a ^{0}C	m_b =2kg	m_b =3kg	m_b =4kg
	E_f, %		
40	36.58	42.99	46.85
50	48.25	53.73	59.87
60	53.20	60.72	67.94

Table 4.33 Influence of bed mass on thermal efficiency of drying ragi (X_0= 0.25 kg/kg, v_0 = 36m^3/h, d_t= 26mm, d_i = 21mm, NPDT)

T_a , ^{0}C	m_b =2kg	m_b =3kg
	E_f, %	
35	60.41	64.30
45	67.77	71.16
55	75.33	78.32

Table 4.34 Influence of hole diameter on thermal efficiency of drying ragi.

(v_0 = 36m^3/h, m_b = 2kg, d_t= 21mm, d_i = 21mm)

X_0, kg/kg	T_a, ^0C	NPDT	d_h=2mm	d_h=4mm
		E_f, %		
0.2	40	51.83	57.22	61.93
	50	73.06	75.48	79.83
0.3	40	58.87	61.14	66.00
	50	78.84	81.09	84.10

Table 4.35 Influence of hole diameter on thermal efficiency of drying barley.

(X_0=0.2 kg/kg, v_0 = 36 m^3/hr, m_b = 2kg, d_t= 21, d_i = 8 mm)

T_a ^0C	NPDT	d_h=2mm	d_h=4mm
	E_f, %		
50	65.10	70.73	74.95
60	73.29	80.01	85.01

Table 4.36 Influence of draft tube ID on thermal efficiency of drying ragi.

(v_0 =36m^3/h, m_b = 2 kg, d_i = 21 mm, NPDT)

X_0, kg/kg	T_a, ^0C	d_t= 21mm	d_t= 26 mm	d_t= 39mm
	E_f, %			
0.2	40	49.67	54.19	57.69
	50	71.13	74.70	76.30
0.3	40	55.77	60.24	62.75
	50	76.30	77.13	80.52

Table 4.37 Influence of fluid inlet diameter on thermal efficiency of drying ragi.

(T_a= 50^{0}C, X_0= 0.2 kg/kg, v_0 = 36m^3/h, d_t= 21, d_h= 4mm)

m_b, kg	d_i=8mm	d_i=15mm	d_i=21mm
	E_f, %		
4	74.20	70.50	68.75
6	80.63	76.60	70.96
8	84.10	78.84	72.78

Table 4.38 Influence of fluid inlet diameter on thermal efficiency of drying barley.

(X_0=0.2 kg/kg, v_0 = 36 m^3/hr, m_b = 2kg, d_t= 26)

T_a ^{0}C	15 mm	21 mm
	E_f, %	
40	53.98	49.08
50	65.43	60.50
60	74.48	69.25

Table 4.39 Influence of fluid inlet diameter on thermal efficiency of drying wheat.

(T_a= 50^{0}C, X_0= 0.2kg/kg, v_0 = 36m^3/h, d_t= 26, d_h= 2mm)

m_b, kg	d_i =8 mm	d_i =15 mm	d_i =21 mm
	E_f, %		
1	57.98	55.56	51.29
4	64.97	59.63	54.58

Table 4.40 Comparison of Drying time; Thermal efficiency; EDC for drying ragi in different porous daft tube spouted bed. (v_0 = 36m^3/h, d_h= 2mm)

Sl. No	Parameters			Drying Time, minutes			Thermal efficiency, %			D_{eff} x 10^{12} m^2/s		
	m_b, kg	X_0, kg/kg	T_a, ^0C	MPDTSB	SPDTSB1	SPDTSB2	MPDTSB	SPDTSB1	SPDTSB2	MPDTSB	SPDTSB1	SPDTSB2
1	2	0.20	40	100	120	140	61.00	51.94	44.52	2.77	2.27	2.17
2			60	30	40	50	82.11	71.64	65.31	6.87	5.15	4.24
3		0.25	40	130	150	180	61.04	56.06	49.76	2.32	2.04	1.84
4			60	65	75	90	83.04	76.87	68.99	3.74	3.34	2.88
5	4	0.20	40	140	160	185	68.12	65.03	59.85	1.98	1.84	1.66
6			60	60	70	80	84.16	81.71	77.85	3.69	3.15	2.89
7		0.25	40	165	180	215	71.34	68.33	62.83	1.88	1.82	1.54
8			60	80	90	105	85.50	83.04	79.25	3.17	2.68	2.60

Table 4.41 Comparison of Drying time; Thermal efficiency; EDC for drying barley in different Porous draft tube spouted bed. (v_0 = 36m^3/h, d_h= 2mm)

Sl. No	Parameters			Drying Time, minutes			Thermal efficiency, %			D_{eff} x 10^{12} m^2/s		
	m_b, kg	X_0, kg/kg	T_a, ^{0}C	MPDTSB	SPDTSB1	SPDTSB2	MPDTSB	SPDTSB1	SPDTSB2	MPDTSB	SPDTSB1	SPDTSB2
1	2	0.20	40	120	140	170	56.61	46.59	41.91	12.3	10.9	8.99
2			60	70	80	95	78.63	70.15	64.10	17.0	14.8	12.5
3		0.25	40	150	160	210	56.45	54.25	47.04	10.5	10.2	7.40
4			60	80	85	110	80.65	76.13	67.18	16.2	13.9	11.6
5	4	0.20	40	180	180	240	63.51	63.26	54.96	8.84	8.84	6.34
6			60	100	110	135	81.61	79.35	76.94	11.9	11.1	9.34
7		0.25	40	240	260	310	64.03	61.37	57.07	7.01	6.61	5.49
8			60	145	150	200	82.45	79.70	78.16	9.72	9.61	7.27

Table 4.42 Comparison of Drying time; Thermal efficiency; EDC for drying wheat in different porous draft tube spouted bed. (v_0 = 36m^3/h, d_h= 2mm)

Sl. No	Parameters			Drying Time, minutes			Thermal efficiency, %			D_{eff} x 10^{12} m^2/s		
	m_b, kg	X_0, kg/kg	T_a, ^0C	MPDTSB	SPDTSB1	SPDTSB2	MPDTSB	SPDTSB1	SPDTSB2	MPDTSB	SPDTSB1	SPDTSB2
1	2	0.20	40	190	210	250	44.65	42.84	39.27	14.51	14.32	11.92
2			60	120	130	160	62.18	57.40	53.30	18.43	17.21	13.88
3		0.25	40	225	250	290	47.47	44.43	41.14	12.81	11.85	10.70
4			60	180	200	240	64.59	59.14	54.41	14.56	13.54	11.46
5	4	0.20	40	275	300	340	50.11	45.94	41.15	10.12	9.09	8.69
6			60	225	245	280	66.19	62.39	57.83	1.02	9.67	8.70
7		0.25	40	320	340	390	54.24	49.50	42.99	9.19	8.85	7.82
8			60	260	280	330	68.62	64.78	58.89	10.21	9.52	8.65

Table 4.43 Comparison of performance between MSB without & with draft tubes – ragi.

(T_a= 50^0C, X_0= 0.2kg/kg, v_0 = 36 m^3/h, d_t= 21mm, d_i =21, d_h= 4mm)

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5
Static bed depth, cm	15.00	15.50	33.00	49.00	65.00
Bed mass, kg	2.00	2.00	4.00	6.00	8.00
Bed pressure drop. Pa	656.70	187.60	234.51	281.43	359.62
Batch drying time, min	40.00	40.00	75.00	100.00	130
Thermal efficiency, %	68.89	68.23	74.21	78.83	80.86
Batch drying time per kg, min	20	20	18.75	16.67	16.25
Air requirement per kg, m^3	12.00	12.00	11.25	10.00	9.75

Table 4.44 Comparison of performance between MSB without & with draft tubes– barley.

(T_a= 50^0C, X_0= 0.2kg/kg, v_0 = 36 m^3/h, d_t= 21mm, d_i =15, d_h= 2mm)

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5
Static bed depth, cm	5.50	15.20	31.50	47.70	61.00
Bed mass, kg	1.00	2.00	4.00	6.00	8.00
Bed pressure drop. Pa	672.3	218.9	265.8	328.3	390.9
Batch drying time, min	35.00	75.00	125.00	180.00	230.00
Thermal efficiency, %	57.39	61.21	66.11	68.86	71.85
Batch drying time per kg, min	35.00	35.00	31.25	30.00	28.75
Air requirement per kg, m^3	21.00	21.00	18.75	18.00	17.25

Table 4.45 Comparison of performance between MSB without & with draft tubes – wheat. (T_a= 50^0C, X_0= 0.2kg/kg, v_0 = 36 m^3/h, d_t= 21mm, d_i =15, d_h= 2mm)

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5
Static bed depth, cm	6.00	6.50	15.00	23.00	31.00
Bed mass, kg	1.00	1.00	2.00	3.00	4.00
Bed pressure drop. Pa	703.60	203.30	250.20	297.10	344.00
Batch drying time, min	105.00	115.00	170.00	190.00	210.00
Thermal efficiency, %	48.28	47.35	50.87	51.58	52.84
Batch drying time per kg, min	105.00	115.00	85.00	63.33	52.50
Air requirement per kg, m^3	63.00	69.00	51.00	37.98	31.50

CHAPTER 5

SUMMARY AND CONCLUSIONS

A multiple porous draft tube spouted bed was used to carry out drying of Ragi (*Eleusine coracana)*, Barley and Wheat grains. Batch experiments were conducted under the following conditions:

Conditions	**Values**
Column cross section (mm X mm):	MPDTSB = 75 X 225. SPDTSB1 = 129.9 X 129.9. SPDTSB2 = 75 X 75.
Number of spout cells:	Three cells in MPDTSB. One cell in SPDTSBs.
Inlet air temperatures (T_a, ^0C):	35, 40, 45, 50, 55, 60.
Initial moisture contents of grains (X_0, Kg moisture/Kg dry solids):	Ragi = 0.15, 0.2, 0.25, 0.3, 0.35. Barley = 0.15, 0.2, 0.25. Wheat = 0.15, 0.2, 0.25.
Inlet air flow rates (v_0, m^3/h):	30, 33, 36.
Bed masses (m_b, Kg):	2, 2.5, 3,4, 6 and 8.
Draft tube diameters (d_t, mm):	21,26, 39.
DT hole diameters (d_h, mm):	0, 2, 4.
Fluid inlet diameters (d_i, mm):	8, 15, 21.

Batch drying times, moisture diffusivities in grains, thermal efficiencies and gas-solid heat transfer coefficients were found using the experimental data. Also, the performance of MPDTSB dryer was compared with the performance of two SPDTSB dryers. Using the experimental data an empirical equation was proposed to predict batch drying times in MPDTSB.

The following conclusions were drawn based on the results obtained in this study.

1. It was possible to overcome the limitation of maximum spoutable bed depth in a multiple draft tube spouted bed so that deeper beds of solids could be handled in the dryer. A maximum bed depth of 65cm (bed mass = 8 kg) for ragi, 61 cm (bed

mass =8kg) for barley and 31 cm (bed mass = 4kg) for wheat could be used in the study. These bed depths were far beyond the MSBD for each case; however much deeper beds could not be used because of air supply limitations.

2. The operating parameters influenced the batch drying time. A higher air inlet temperature and air rate resulted in lower batch drying times, but such conditions would increase the operating costs. In addition, a higher operating temperature could lead to thermal damage of grains.
3. The drying rate decreased and batch drying time increased as the initial moisture content of grains increased.
4. The drying of grains occurred under falling rate period and the overall process was diffusion controlled.
5. Porous draft tubes helped in reducing the batch drying times when compared to non-porous draft tubes under identical conditions.
6. The results indicated that the batch drying time decreased as the DT hole diameter in porous DTs increased.
7. The results indicated that the batch drying times decreased as the DT hole areas increased.
8. Since the DT holes would help in hot air supply into annuli an appropriate choice of hole diameter and hole pitch for a given DT length would become necessary. However, for a given air flow rate a large diversion of air through holes into annuli could lead a situation where the vertical velocity component of air in DT would not be sufficient for proper spouting to occur unless the air flow rate would be increased.
9. The batch drying times decreased with increase in draft tube diameter and hole size. So, in the context of design when relatively smaller sized grains are to be handled, DTs having smaller id and larger holes may be used. However, for larger sized solids DTs having larger id and larger holes may be preferred to avoid chocking of DTs.
10. Batch drying times decreased as the fluid inlet size decreased for a given bed mass. However, it is to be noted here that an upper limit for fluid inlet diameter could exist for a given particle size and the requirement could be that the ratio of fluid inlet

diameter to particle size should not exceed about 25 to 30, irrespective of particle density (Epstein,2011). This condition was satisfied for all cases used in this study.

11. Smaller diameter fluid inlets lead to grain damage. So, a proper choice of fluid inlet size would become important wherever grain damage would be undesirable. However, in situations where the grains were to be ground to make powder and size reduction during drying could be tolerable, one could take advantage of lower drying times with smaller fluid inlets.
12. The properties of grains influenced drying times. Ragi grains required lesser drying times when compared to barley and wheat under identical conditions.
13. The grain temperature fixes the moisture diffusion rate through grains. So, the operating and design variables are to be chosen in such a way that the required final temperature of grains can be achieved faster.
14. The thermal efficiencies for ragi were found to be higher when compared to wheat, with barley in between.
15. The moisture diffusivities were found to be dependent on both operating and design variables of the dryer.
16. The thermal efficiencies for MPDTSB were found to be higher when compared to those for SPDTSBs.
17. The gas-solid convective heat transfer coefficients were found to be higher in MPDTSB when compared to those in SPDTSBs.
18. It would be desirable to operate deeper beds just above minimum spouting velocities so that the drying operation would be efficient and economical.
19. For a given grain size and bed mass, an appropriate choice of DT diameter, hole size and fluid inlet size would become necessary to achieve spouting and operate the bed above the minimum spouting velocity. The choice should be such that the process as a whole would be efficient, economical and there would not be any grain damage.
20. Presence of multiple porous DTs in the bed helped in achieving lower drying times when compared to single spout beds under identical conditions. So, in the context of scale up to large scale drying operation a MPDTSB having more number of spout cells provided with porous draft tubes should be beneficial, where enhanced heat and mass transfer rates can be achieved.

21. Bulk of the drying could be occurring in annuli and the multiple fountains formed in the bed could also be contributing to moisture removal.
22. The proposed empirical correlation predicts experimental drying times reasonably well with a RMSE of 0.08458 and $R^2 = 0.8834$. It is applicable for the range of dimensionless groups used in this study.
23. It could be noted that in the context of drying thermally sensitive materials the contact times between hot air and solids would be critical. So, in such cases a MPDTSB having more number of spout cells as well as larger cell sizes might be considered for design; this would help in having relatively shallow bed and lower gas-solid contact times.
24. It was felt that in the case of large scale drying of agricultural grains, having a very deep bed in a MPDTSB to be operated at high temperatures (in order to reduce batch drying times) might not be desirable, as this could lead to grain damage because of lager contact times between hot air and grains. So in such cases, a MPDTSB having more number of spout cells as well as larger cell sizes might be considered for design; this would help in having relatively shallow beds and lower gas-solid contact times.
25. Even though the suitability of this design was tested for drying of agricultural grains, it was felt that this contactor would also be useful for drying other coarse solids of industrial significance.

The overall performance of the proposed design of Multiple Porous Draft Tube Spouted Bed seemed to be good for solids drying. Scale up of this design for large scale operations should be possible.

SCOPE FOR FUTURE WORK

Based on the results obtained and conclusions drawn in this study the following suggestions are given for future work to test the suitability and enhance the scope of the proposed design of MPDTSB dryer.

1. Drying studies may be carried out using much deeper beds or larger bed masses to check the validity of this design for further scale up. This may be done by employing larger spout cell sizes, more number of spout cells or combination of both.
2. Drying studies may be carried out by employing variable air temperature – starting the batch operation with a highest permissible temperature and reducing the temperature step-wise. Such an operation may reduce the total batch drying time and may lead to an improvement in overall economics of the process, yet maintaining the required product quality.
3. A variable air flow may be used for batch drying; this may be done by employing a high flow rate (well above the minimum needed for spouting) of hot air at the start and gradually decreasing it step-wise to a flow rate just above the minimum. Such an operation may help to reduce the overall costs involved in hot air supply.
4. A combination of variable air temperature and variable air flow rate in a batch operation – high temperature and high flow rate at the start and step-wise reduction to lower conditions at the end.
5. Hot air recirculation may make the process more energy efficient.
6. A variable hole diameter and variable hole pitch along the draft tube may help in uniform hot air supply into the annulus regions.
7. Porous draft tubes having converging-diverging cross sections can help in pressure recovery in large deeper beds.
8. Drying of other coarser solids can be done to find the suitability of this contactor.

APPENDIX – I

Procedures used for measuring various properties of grains.

1. **Finding moisture content of grains (dry basis)**

   The solids sample are taken from dryer and kept in desiccator the initial mass was noted down. The samples were kept in oven for sufficiently long time to attain constant final weight (bone dry). Moisture content is found using the formula.

$$X = \frac{Wi - Wf}{Wf} \text{ X } 100$$

   Where;

   W_i = Initial mass of the sample

   W_f = Final mass of the sample

2. **Finding grain sizes.**

   100 particles are taken the sizes of the individual particles are measured using screw gauge. (Zenz and Othmer)

   The formula employed is

   Total reading = MSR + (n x LC)

   The average particle size is determined using the formula

$$Dp = \frac{\sum n.Dp}{\sum n}$$

   Where;

   Dp = Diameter of the individual particle

   n = number of sample considered for measurement

3. **Finding bulk and true density**

   A known quantity of sample is taken in a measuring cylinder the cylinder is tapped mechanically by rising the cylinder a few centimetre high and allowing it to drop under its own mass, the so obtained volume is noted down and the density is determined dividing mass of the sample by volume noted down to obtain bulk density.

To obtain the true density, the pore volume is determined by adding a non-wetting liquid, the difference of volume of sample and pore volume would provide actual volume of the sample. The true density is obtained by dividing mass of the sample by actual volume.

4. Specific grain surface.

$$\text{Specific surface area} = \frac{Surface\ area\ of\ each\ grain}{Mass\ of\ single\ grain}$$

Surface area of each grain = 4 π r^2 = 5.723 x 10^{-6} (ragi)

Np x m_p = 1 kg

$$\frac{\text{Np x } m_p}{\varrho} = \frac{\text{volume}}{kg} = Np\frac{4}{3}\,\pi r^3$$

$$\frac{m_p}{\varrho} = \frac{4}{3}\,\pi r^3$$

mp $= \frac{4}{3}\,\pi r^3 x\ \varrho =$ 1.6 x 10^{-6}

$$\text{Specific surface area} = \frac{5.723 \text{ x } 10^{-6}}{1.6 \text{ x } 10^{-6}}$$

= 3.575 m^3/kg

APPENDIX – II

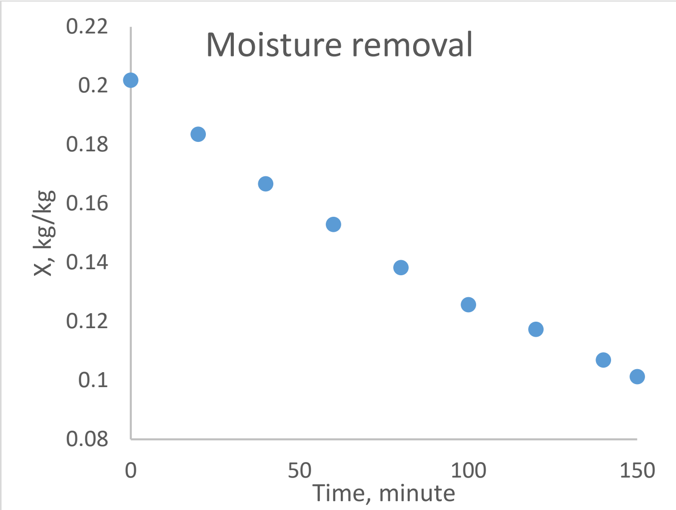
Model observation Table.

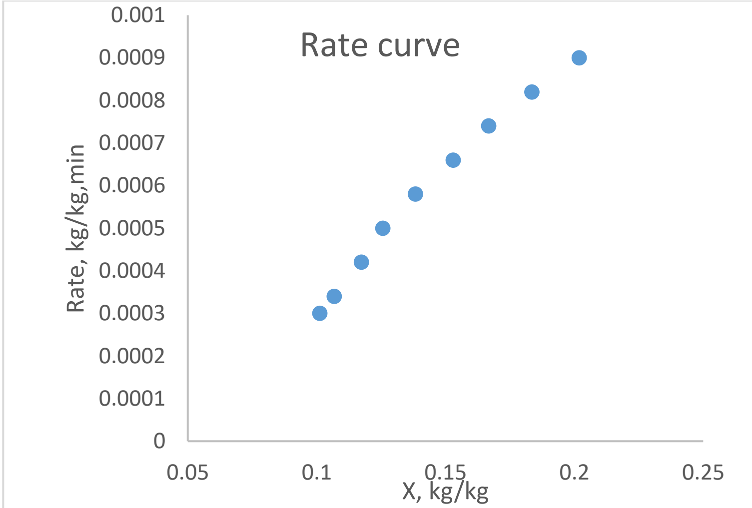
Sl.no	t, min	m_i, gm	m_f , gm	water, gm	X, kg/kg	R.H		Ta ^{0}C		Tg ^{0}C	Rate, dx/dt kg/kg, min
						In	out	In	out		
1	0	15.0021	12.4821	2.5200	0.2019	22.8	60.3	40	34	30.5	0.00090
2	20	15.2134	12.8542	2.3592	0.1835	24.5	52.4	40	34.5	31.4	0.00082
3	40	15.2134	13.0391	2.1743	0.1668	22.5	38.5	40	35.3	32.5	0.00074
4	60	15.1021	13.0982	2.0039	0.1530	21.5	31.2	40	36.3	33.6	0.00066
5	80	15.3216	13.4602	1.8614	0.1383	22.3	28.5	40	37	34.5	0.00058
6	100	15.4327	13.7092	1.7235	0.1257	21.1	26.5	40	37	35.2	0.00050
7	120	15.1212	13.5329	1.5883	0.1174	22.6	25.3	40	37	35.9	0.00042
8	140	15.3201	13.8408	1.4793	0.1069	22.4	26	40	37.2	36.5	0.00034
9	150	15.0021	13.6221	1.3800	0.1013	22.4	25.5	40	37.4	36.7	0.00030

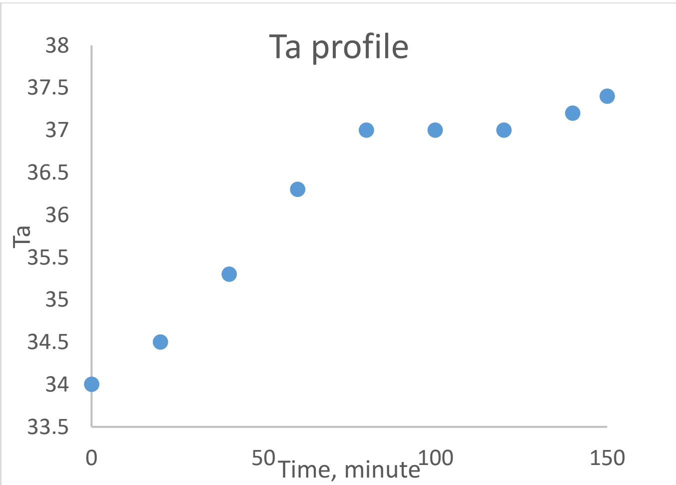
Where: t =Batch drying time; m_i and m_f initial and final mass of sample; Ta and Tg inlet air and grain temperature

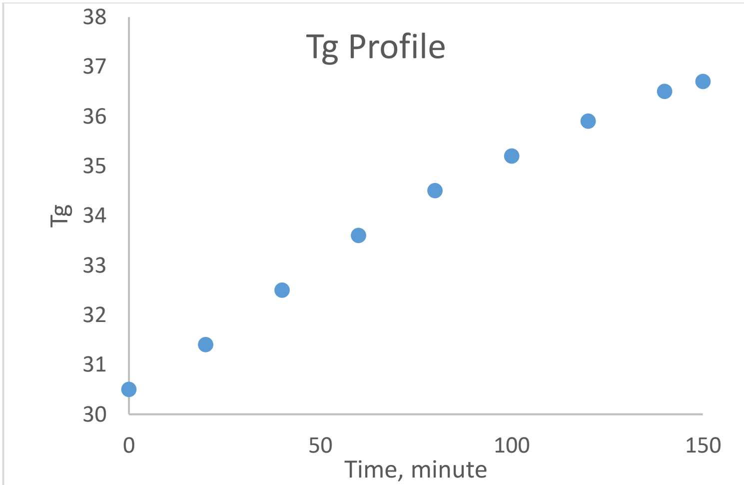
Making use of the above data following graphs are plotted

1. Time v/s Moisture
2. Rate curve
3. Time v/s Ta
4. Time v/s tg, etc. . .


Moisture removal
X, kg/kg
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0
50
100
150
Time, minute


Rate curve
Rate, kg/kg,min
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0.05
0.1
0.15
0.2
0.25
X, kg/kg


Ta profile
Ta
38
37.5
37
36.5
36
35.5
35
34.5
34
33.5
0
50
100
150
Time, minute


Tg Profile
Tg
38
37
36
35
34
33
32
31
30
0
50
100
150
Time, minute

APPENDIX – III

Estimation of moisture diffusivities in grain.

$$\bar{M} = \frac{\bar{X}-X_e}{X_0-X_e} = 1-\frac{2}{\sqrt{\pi}}X + \frac{f''(0)}{2}X^2$$

Where $X = a_v\sqrt{D_{eff}t}$ and $f''(0) = 0.588$ for wheat and 0.661 for spherical particles.

$$\bar{M} = \frac{\bar{X}-X_e}{X_0-X_e} = 1 - \frac{2}{\sqrt{\pi}}a_v\sqrt{D_{eff}t} + 0.331a_v^2D_{eff}t$$

Specific surface area per unit volume,

$$a_v = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

For Barley, $a_v = 2013.4\ m^2/m^3$

Now,

Here, Dimensionless moisture content.

Let $q = \frac{2}{\sqrt{\pi}}a_v\sqrt{t}$ $\quad r = 0.331a_v^2t$

Thus, the above equation can be simplified as,

$$\bar{M} = 1 - q\sqrt{D_{eff}} + D_{eff}r$$

Let $D_{eff} = x^2$

$$p = 1 - q * x + r * x^2$$

Or,

$$r * x^2 - q * x + (1 - p) = 0$$

$$\bar{M} = \frac{0.1792 - 0.02}{0.1940 - 0.02} = 0.91506$$

$$q = \frac{2}{\sqrt{\pi}}a_v\sqrt{t} = \frac{2}{\sqrt{\pi}} * 2013.4 * \sqrt{5 * 60} = 39342.175$$

$$r = 0.331a_v^2t = 0.331 * 2013.4^2 * 5 * 60 = 402540310$$

Set of values generated for $\bar{M}$ V/s t, the equation is solved by nonlinear least square method using POLYMATH© 5.1 and diffusivity is obtained

$$D_{eff} = 4.879 * 10^{-12} m^2/s$$

Values of equilibrium moisture content for various at different temperature

T_a, ^0C	EMC, kg moisture/kg dry solids		
	Ragi	Barley	Wheat
30	0.1095	0.1076	0.1098
35	0.0930	0.0934	0.1022
40	0.0737	0.0822	0.0873
45	0.0627	0.0697	0.0815
50	0.0557	0.0632	0.0721
55	0.0479	0.0599	0.0683
60	0.0425	0.0551	0.0654

APPENDIX – IV

Estimation of thermal efficiency

$$\text{Thermal efficiancy} = \frac{\text{Latent heat required to evaporate the moisture in grains}}{\text{Heat supplied to grains by hot air}}$$

It can be written as the following equation

$$E_f = \frac{W_s(X_0 - X_f)\lambda_g}{W_a C_H (T_{a1} - T_{av}) t_d}$$

Where, λ_g is latent heat of desorption (kJ/kg)

$W_s = $ Mass of solids, kg

$W_a = $ Mass flow rate of inlet dry air, kg/h

$C_H = $ Humid heat $\frac{\text{kJ}}{\text{kg dry air K}}$

$T_{av} = $ Exit air temperature, °C

$t_d = $ total drying time, min

$$W_s = W_m - W_s X_0$$

Mass of solids, $W_s = \frac{W_m}{1 + X_0}$ kg

And,

Mass of dry air entering, $W_a = \frac{v_a}{V_H}$ kg/h

Humid Volume of air, $V_H = \frac{RT}{P_w M_w}$ m^3/kg

Vapour Pressure of air, $P_w = P_w^{sat} * RH$

$$V_H = \left(\frac{H}{M_A} + \frac{1}{M_B}\right) * 22.414 * \left(\frac{T}{273}\right) * \left(\frac{101.325}{P_T}\right)\ m^3/kg$$

Hence,

Volumetric flowrate of air at NTP, $v_a = \left(\frac{V_0}{T_0}\right) T_a$

Saturated vapour pressure of air at 100°C, $P_w^{sat} = 1.77$ kPa

Oulet air humidity, $RH = \frac{24}{100} = 0.24$

Vapour pressure of air , $P_w = P_w^{sat} * RH = 7.375\ \ X\ 0.24 = 1.77$ kPa

Absolute molal humidity, $H_m = \frac{P_w}{P_T - P_w} = \frac{1.77}{101.3 - 1.77} = 0.018\ \frac{\text{kmol water}}{\text{kmol dry air}}$

Mass humidity, $H = 0.622 * H_m = 0.622 * 0.018 = 0.011 \frac{\text{kg water}}{\text{kg dry air}}$

Substituting all the values in the above equation we get,

$$V_H = \left(\frac{0.011}{18} + \frac{1}{29}\right) * 22.414 * \left(\frac{40 + 273}{273}\right) * \left(\frac{101.325}{202.65}\right) = 0.4536\ m^3/kg$$

$$v_a = \left(\frac{V_0}{T_0}\right) T_a = \left(\frac{36}{30 + 273}\right) * (40 + 273) = 37.188\ m^3/h$$

$$W_a = \frac{v_a}{V_H} = \frac{37.188}{0.4536} = 81.984\ kg/h$$

$$C_H = 1.006 + 1.84 * H = 1.006 + 1.84 * 0.011 = 1.02624 \frac{kJ}{\text{kg dry air K}}$$

$$W_s = \frac{W_m}{1 + X_0} = \frac{2}{1 + 0.2} = 1.667\ kg$$

Substituting all the above values in the equation for thermal efficiency we get the value thermal efficiency as,

$$E_f = 42.48\ \%$$

APPENDIX – V

Estimation of gas – solid heat transfer coefficient

Heat Balance

The heat absorbed by barley grains from hot air is used for the vaporisation of moisture from grains.

$$W_s C_{ps} \frac{\partial Ts}{\partial t} = h_T (W_s a_s)(T_a - T_s) - W_s \left(-\frac{dX}{dt}\right) \lambda_g$$

On rearrangement

$$\mathrm{h_T} = \frac{\mathrm{C_{Ps}} * \left(\frac{\mathrm{dT_s}}{\mathrm{dt}}\right) + \left(\frac{-\mathrm{dX}}{\mathrm{dt}}\right) * \lambda_\mathrm{g}}{\mathrm{a_s} * (\mathrm{T_a} - \mathrm{T_s})}$$

Where, $\mathrm{h_T}$ is heat transfer coefficient in $\mathrm{W/m^2K}$

$\mathrm{C_{Ps}}$ is specific heat capacity of solids (barley)

$$\mathrm{C_{Ps}} = 1.651 + 0.04116 * \mathrm{M}$$

M is the moisture content of the solid

$$\mathrm{C_{Ps}} = 1.651 + 0.04116 * 0.1940 = 1.6589\ \mathrm{kJ/kgK}$$

$\mathrm{a_s}$ is specific surface area of barley grain

$$\mathrm{a_s} = 1.4992\ \mathrm{m^2/kg}$$

$\frac{-\mathrm{dX}}{\mathrm{dt}}$ is slope of the drying curve

$\frac{\mathrm{dT_s}}{\mathrm{dt}}$ is slope of the bed temperature profile

$\mathrm{T_a}$ is hot air inlet temperature (°C)

$\mathrm{T_s}$ is bed temperature of solids (°C)

λ_g is the latent heat od desorption of water molecule from solids (barley)

$$\lambda_\mathrm{g} = \mathrm{L_r} + \mathrm{Cexp}(-\mathrm{B} * \mathrm{M})$$

$\mathrm{L_r}$ is latent heat of vapourisation (steam table)

For Barley, C = 2391.31, B = 19.83, M = Moisture (X%)

$$\lambda_\mathrm{g} = 2257.92 + 2391.31\mathrm{exp}(-19.83 * 0.1940) = 2308.899\ \mathrm{kJ/kg}$$

The values of h($\mathrm{W/m^2,{}^0C}$) is generated as a function of time (minute) and the graph is plotted.

APPENDIX – VI

Empirical correlation for batch drying time in MPDTSB

$$\Theta t = k.\left(\frac{\lambda_d}{R\tau_a}\right)^{n1}\left(\frac{(X_0 - X_f)}{(X_0 - X_e)}\right)^{n2}\left(\frac{H}{d_h}\right)^{n3}\left(\frac{d_i}{d_t}\right)^{n4}\left({a_v}^2 D_e \tau\right)^{n5}$$

$$\left(\frac{\lambda_d}{R\tau_a}\right) = \frac{43320.6}{8.314\ X\ 313} = 16.6472$$

$$\left(\frac{(X_0 - X_f)}{(X_0 - X_e)}\right) = \frac{(0.2 - 0.1)}{(0.2 - 0.076)} = 0.80451$$

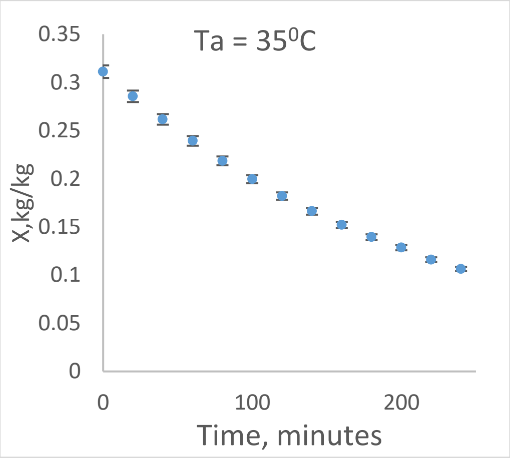
$$\left(\frac{H}{d_h}\right) = \frac{330}{2} = 165$$

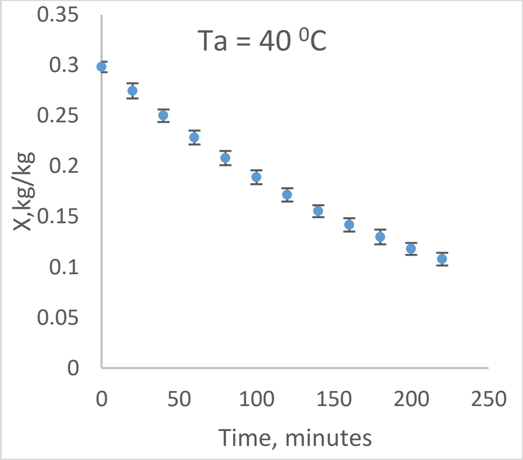
$$\left(\frac{d_i}{d_t}\right) = \frac{15}{26} = 0.5769$$

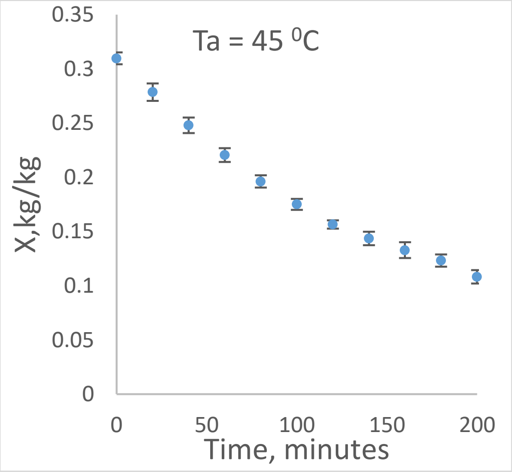
${a_v}^2 D_e \tau = (4444.5)^2 \text{ X } 2.77\text{X}10^{-12} \text{ X } 0.0042 = 2.30 \text{ X } 10^{-7}$

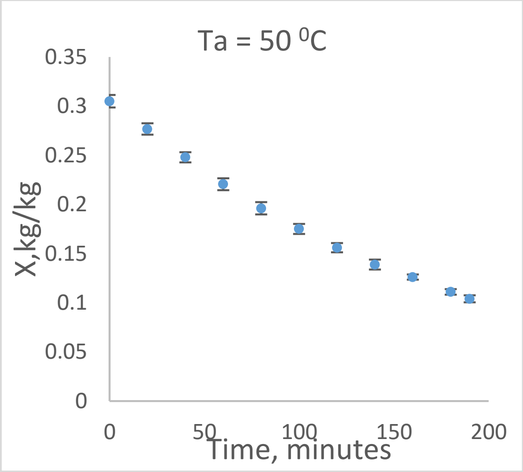
These values are obtained for various data set in similar way and equation so obtained is solved using non – linear regression analysis to evaluate the values of k and $n_1 - n_5$.

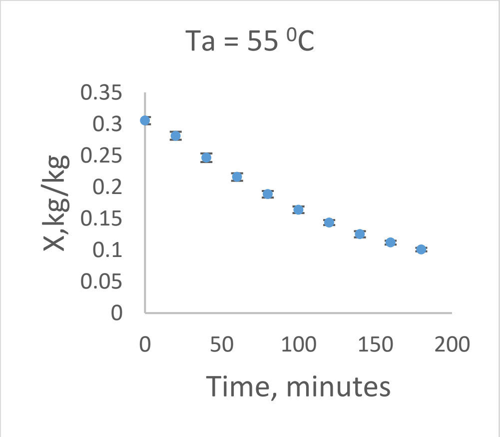
APPENDIX – VII











Typical error graphs generated for Ragi considering two data sets

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PAPERS BASED ON THIS RESERCH WORK

PAPERS IN PEER REVIEWDED INTERNATIONAL JOURNALS

1. S, Rajashekhara., D V R, Murthy. (2017) “Drying of agricultural grains in a multiple porous draft tube spouted bed**”**, *Chemical engineering communications*, DOI: 10.1080/00986445.2017.1328412

Publications (submitted/under review)

1. S, Rajashekhara., D V R, Murthy Estimation of gas-solid heat transfer coefficient and thermal efficiencies in spouted bed dryer (Under review)
2. S, Rajashekhara., D V R, Murthy. A correlation for predicting batch – drying time in a multiple spouted bed dryer (under review)
3. S, Rajashekhara., D V R, Murthy. Evaluation of moisture diffusivity in spouted bed dryer (Submitted)

BOOK CHAPTERS

1. Rajashekhara S., Murthy D.V.R. (2016) “Batch drying of wheat in a multiple porous draft tube spouted bed.” In: Regupathi I., Shetty K V., Thanabalan M. (eds) *Recent Advances in Chemical Engineering*. Springer, Singapore

RESEARCH PAPERS IN INTERNATIONAL CONFERNCES

1. S, Rajashekhara., D V R, Murthy.,(2015) “Grain Drying in a Multiple Draft Tube Spouted Bed- A Preliminary Study”, *Proceedings of the 8th Asia-Pacific Drying Conference*, Kuala Lumpur, Malaysia, .80-84.
2. S, Rajashekhara., D V R, Murthy., (2015) “Influence of fluid inlet diameter on drying time in multiple draft tube spouted bed”, 68th *Annual Session of Indian Institute of Chemical Engineers, (CHEMCON – 2015)* Guwahati, India.
3. D V R, Murthy., S, Rajashekhara., and Kevin Varghese Abraham., (2016) **“**Solid drying studies in a multiple draft tube spouted bed dryer**”,** 5th *International Engineering Symposium – IES 2016,* Kumamoto university, Japan. Pp K2-2-1 – K-2-2-3

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S Rajashekhara and D V R Murthy, (2016). "Spouted beds as fluid solid contacting devices – a review." *National conference on advances in synthesis and separation in chemical and biological processes,* Dayanada Sagar College of Engineering, Bangalore, India

PATENT FILED

D V R Murthy and Rajashekhara S. "Multiple porous draft tubes spouted bed contactor". The application Number is 2940/CHE/2015 and dated June 11, 2015.

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- ✓ Heat transfer.
- ✓ Equipment Design.
- ✓ Biochemical Engineering.

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Place : Department of Food Engineering. Central Food Technological Research Institute, (CFTRI) Mysore.,

- **B.E**

Title : Heat of vaporization data for
1,1,1-Trichloroethane - 1,2-Dichloroetahne
1,1,1-Trichloroethane - 1,1,2,2 -Tetrachloroethane
1,1,2,2-Tetrachloroethane - 1, 1,1 – Trichloroethane
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