

**DEVELOPMENT AND PERFORMANCE  
EVALUATION OF A NATURAL CONVECTION  
GRAIN DRYER**

*A Thesis Submitted in  
Partial Fulfilment of the Requirements  
for the Degree of*

**Doctor of Philosophy**

by

**Siba Shankar Mohapatra**



**Centre for Energy  
Indian Institute of Technology Guwahati  
August 2012**

# DECLARATION

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I hereby certified that the work contained in the thesis entitled 'Development and Performance Evaluation of a Natural Convection Grain Dryer' has been done by me, a research scholar in the Centre for Energy, Indian Institute of Technology Guwahati, India, under the guidance of Prof. Pinakeswar Mahanta for the award of the degree of the Doctor of Philosophy and that this work has not been submitted elsewhere for a degree.

Date

Siba Shankar Mohapatra  
Research Scholar  
Centre for Energy  
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August 2012

# CERTIFICATE

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It is certified that the work contained in the thesis entitled 'Development and Performance Evaluation of a Natural Convection Grain Dryer' by Siba Shankar Mohapatra, a research scholar in the Centre for Energy, Indian Institute of Technology Guwahati, India, for the award of the degree of the Doctor of Philosophy has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

Date:

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# Abbreviations

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SHSM	Sensible Heat Storage Material
PCM	Phase Change Material
MC	Moisture Content
IMC	Initial Moisture Content
FMC	Final Moisture Content
BBP	Biomass Burning Plate
BFP	Biomass Feeding Pipe
EUR	Energy Utilisation Ratio
BD	Batch Wise Drying
CD	Continuous Drying
DAS	Data Acquisition System
RH	Relative Humidity
EMC	Equilibrium Moisture Content
HRY	Head Rice Yield
DSC	Differential Scanning Calorimeter
CENG	Compressed Expanse Natural Graphite
w.b	Weight Basis
d.b	Dry Basis

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**Siba Shankar Mohapatra**



## APPENDIX – I

### Calibration of K- type Thermocouple

The Chromel-Alumula (K-Type) thermocouples were used for the measurement of drying air temperature during experiment. The thermocouples were calibrated before use in the dryer for experiment. The calibration of thermocouple was done using the oil heater calibration machine. One junction of the thermocouple is kept in ambient while the other end is subjected to changing oil temperature. The oil is heated up to a temperature of 100 °C and then cooled back to room temperature. Voltage is read through ammeter during both heating and cooling. Following data has been obtained.

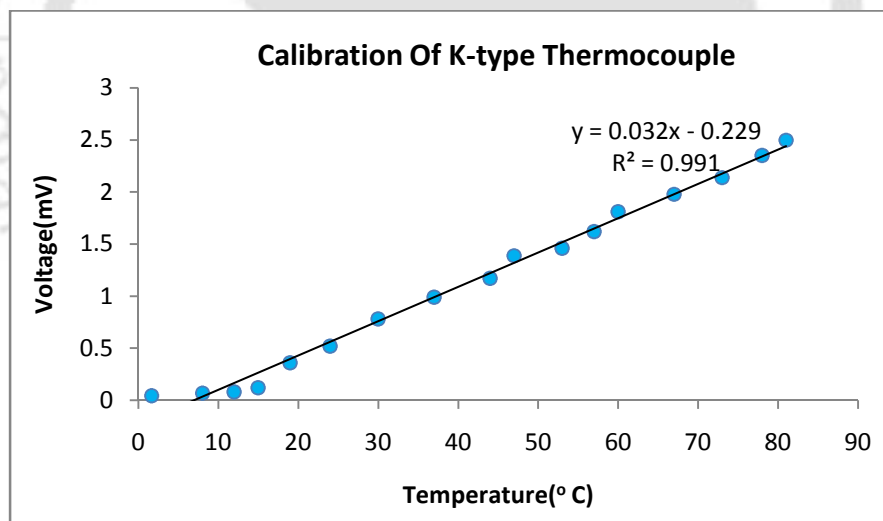


Figure I.1 Calibration of Thermo Couple

Appendix

Table : I.1 (Variation of voltage and temperature)

Sl.No.	Voltage in mV ( $Y_1$ )	Oil Temperature, °C	Reference Temperature, °C	Temperature Difference ( $X_1$ )
1	0.042	20.64	19	1.64
2	0.067	27	19	8
3	0.08	31	19	12
4	0.12	34	19	15
5	0.36	38	19	19
6	0.52	43	19	24
7	0.78	49	19	30
8	0.99	56	19	37
9	1.17	63	19	44
10	1.39	66	19	47
11	1.46	72	19	53
12	1.62	76	19	57
13	1.81	79	19	60
14	1.98	86	19	67
15	2.14	92	19	73
16	2.35	97	19	78
17	2.5	100	19	81
	$\Sigma Y_1 = 19.39$			$\Sigma X_1 = 706.64$

## APPENDIX-II

### Sample Calculations on Operating Parameters, Heat Transfer Coefficient:

#### ❖ Calculations of Dryer Efficiency

2.25 kg of biomass is required for the removal of 5.6kg of water from 3 (three) batches, each 10 kg of paddy (Total 30kg) when both SHSM and PCM are used. The efficiency for the dryer is calculated as

$$\eta = \frac{WL}{MC}$$
$$= \frac{5.6 \times 2.27}{2.25 \times 17.6} = 32.1 \%$$

Where,  $W$  is the weight of water evaporated (kg),  $L$  is the latent heat of evaporation of water (MJ/kg),  $M$  is the Mass of biomass fuel used in the furnace (Kg),  $C$  is the calorific value of biomass fuel (MJ/kg).

#### ❖ Thermal bouncy ( $\Delta P$ ) due to density difference

$$\Delta p = \beta \rho_a g H (\Delta T)$$
$$= \frac{1}{288} \times 1.20 \times 9.81 \times 93 \times 58.5 = 1.653 \text{ N / m}^2$$

$$\Delta T = (58.5 - 15) = 43.5^\circ \text{ C}$$

$\Delta T$  is the temperature difference between ambient and drying air temperature (K),  $\beta$  is the coefficient of thermal expansion ( $\text{K}^{-1}$ ),  $\rho_a$  is the density of ambient air ( $\text{kg/m}^3$ ),  $g$  is the acceleration due to gravity, and  $H$  is the vertical height (m).

- ❖ Determination Of Convective Heat Transfer Coefficient And Amount Of Heat Transfer

$$Q_c = h_c A (T_s - T_a)$$

$$Nu = \frac{h_c X}{k_v} = C (Gr \cdot Pr)^n$$

Where  $h_c$  is the heat transfer coefficient ( $W/m^2K$ ),  $A$  is the total surface area of biomass burner,  $T_s$  is the burner surface temperature and  $T_a$  is the surrounding fluid temperature. 'Gr' is the Grashof number ( $\beta g X^3 \rho^2 \Delta T / \mu_v$ ), Pr is the Prandtl number ( $\mu_v C_v / K_v$ ) and 'Nu' is the Nusselt number ( $h_c X / K_v$ ).

$$Nu = \frac{h_c \times 45}{0.0524}$$

$$Nu = C (Gr \cdot Pr)^n = 0.54 \times (R_a)^{1/4} = 0.58 \times (4.38 \times 10^6)^{1/5} = 12.35$$

The value of  $R_a = 4.38 \times 10^6$ . So the flow is laminar and for natural convection. The value of  $h_c$  is calculated as 1.43 kJ/kg K

By putting all these values  $Q_c$  is calculated as 1051 J/sec.

- ❖ Pressure Drop Through The Biomass Burner

$$\Delta p_D = gH(\Delta p) = gH(T_a^{-1} - T_o^{-1}) \frac{p_a}{R}$$

$\rho_a$  is the density of ambient air ( $kg/m^3$ ),  $\rho^*$  is the average air density inside the dryer ( $kg/m^3$ ),  $T_a$  is the ambient air temperature (K),  $T_o$  is the temperature of drying air above

## Appendix

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the biomass burner (K).  $P_a$  Atmospheric pressure and the value is  $1.01 \times 10^5$  pa,  $R = 2.9 \times 10^2$  J kg<sup>-1</sup>K<sup>-1</sup>.

$$\Delta p_D = gH(\Delta\rho) = 9.81 \times 0.6 \times \left( \frac{1.01 \times 10^5}{2.9 \times 10^2} \right) \times (0.06 - 0.005) = 125.9 \text{ pa}$$



## APPENDIX-III

### Uncertainty Analysis

Percent uncertainty in the heat transfer coefficient can be determined by using Kline and Mc Clintok method (Kline and Mc Clintok, 1953).

The local heat transfer coefficient along the riser column is defined as,

$$h = \frac{q}{[A_s \times (T_s - T_b)]} \text{ W / m}^2 \text{ K}$$

where

q: heat supplied ,W

H: height of heated section ,m

B: width of heated section, m

$T_b$  : bed temperature,  $^{\circ}\text{C}$

$T_s$  : surface temperature,  $^{\circ}\text{C}$

Now

$$h = f(q, H, B, T_s, T_b)$$

Therefore % of uncertainty =  $\frac{\text{Error}}{h} \times 100\%$

$$= \pm 100 \times \sqrt{\left[\left(\frac{W_2}{q}\right)^2 + \left(\frac{-W_2}{B}\right)^2 + \left(\frac{W_3}{H}\right)^2 + \left(\frac{-W_4}{T_s - T_b}\right)^2 + \left(\frac{-W_5}{T_s - T_b}\right)^2\right]}$$

Thus % of Uncertainty

## Appendix

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$$= \pm 100 \times \sqrt{\left[\left(\frac{7}{421}\right)^2 + \left(\frac{-0.001}{0.4}\right)^2 + \left(\frac{0.001}{0.4}\right)^2 + \left(\frac{-0.7}{54.48 - 39.46}\right)^2 + \left(\frac{0.8}{54.48 - 39.46}\right)^2\right]}$$
$$= \pm 4.75\%$$



## APPENDIX-IV

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This part represents the pictorial view of the dryer, paraffin wax during melting, paraffin wax during solidification, and drying of paddy.



Fig: 4.6(a) Pictorial views of dryer after re-



Fig: 4.6(b) Pictorial views of paraffin wax during melting on the tray inside the dryer



Fig: 4.6(c) Pictorial views after solidification of paraffin wax in the tray inside the dryer



Fig: 4.6(d) Pictorial views of drying tray with paddy in the dryer



Fig: 4.6(e) Pictorial views of dryer with all measurement system



# CHAPTER 1

## INTRODUCTION

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### 1.1 Motivation

Rice (*Oryza Sativa*) is not only a staple food in many countries in world; it is a way of life. It is the most important cereal crop in the developing world and is the staple food of over one half the world's populations (Juliano, 1993). It is the main staple food for about 60% of world's population. About 90% of world's rice is produced and consumed in Asia (Marshall and wadsworth, 1994). It is generally considered as the main source of carbohydrate to supply food energy in the diet (Riahi and Ramaswamy, 2003).

Rice is the major source of dietetic energy and protein (Juliano, 1993). The major nutrient of milled rice is starch (90% of dry matter) followed by protein (8% of dry matter) (Juliano, 1985).

Latest current world population, for mid-year 2010, is estimated at 6,852,472,823. Yet 925 million people in the world today are under starvation. Many children under the age of five suffer from chronic or a cute protein and energy deficiencies in the developing and under developed countries. One person in seven does not have access to sufficient food energy to lead a healthy, active life. Poor nutrition plays a role in at least half of the 10.9 million child deaths each year--five million deaths (FAO, Economic and Social Development Department, Sept. 2010.). Figure 1.1 (a) presents the number of hungry people in millions from 1969-2010. Figure 1.1 (b) shows the total number of hungry people in different countries in 2010.

India produces about 150 million tonnes of food grains per year. The major components of production are 47 million tonnes of wheat, 64 million tonnes of rice, and

13 million tonnes of pulses (Anon, 1987). Due to technological advances in agriculture and the introduction of high-yielding varieties, this may increase. From this production, an average 10% is lost during postharvest operations between the fields and consume. This means that about 15 million tonnes of food grain, valued at about \$A240 million (Indian Rupees 2400 million) goes to waste. Among the various causes of losses, the most important one is improper drying before storage.

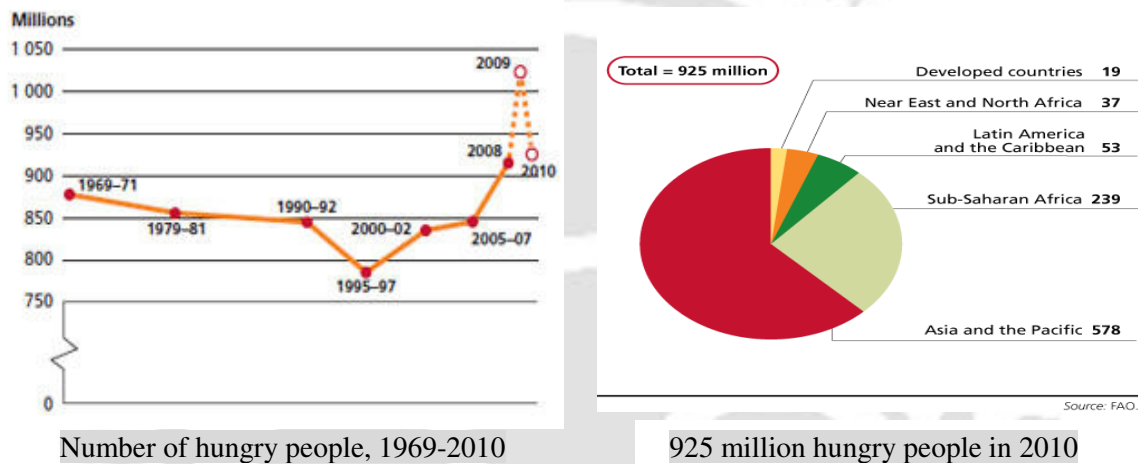


Figure 1.1. Variation of number of hungry people (FAO, 2010)

About 70% of total grain production in India is retained at farmer level: only 30% is sold on the open market. This means that about 105 million tonnes is kept by farmers. The losses here, though perhaps not felt by individuals, on a collective basis have a substantial impact on the country. It is therefore essential to supply a right drying technology to the end users which is the major custodian of the nation's grain, so that some percentage of food losses will decrease, indirectly decrease the number of hungry people in the world .

It is well-known that deterioration in quality caused by improper drying cannot be eliminated until improved drying systems based on mechanical dryers have been adopted. However, for many reasons, these systems have not been adopted in farmer's level. An

important reason for not using dryers is their high initial costs, complicated structure, non availability or high requirement of electricity and petroleum fuels. Most of the commercially available dryers are designed to suit the needs of the processing industry and their output capacity is therefore far above the needs of individuals, or even of farmer groups.

So far, extension agencies have concentrated on increasing production. The time has now come to see that grain saved is equivalent to grain produced. High technology has led to production targets being achieved, but much less attention has been given to minimizing losses which have remained constant since the beginning of the 'Green Revolution'.

Due to changes in ecological balance and keeping in mind of untimely rains an introduction of a simple, low cost mechanical dryer for the farmers is necessary and highly required.

Present research work involves an innovative design and development of a simple (in construction and operation) and low cost natural convection grain dryer for farmers of the world to minimize the losses.

## **1.2 Principle of Drying**

Drying is a process in which moisture content from a wet solid grain is removed with the help of heated air. In this process heated air evaporates the moisture and carries it away from the grain surface. The physical phenomenon that occurs during drying of grains includes removal of moisture from the interior of the grains and the loss of water vapor from the grain surface. The removal of surface moisture depends on the difference between the vapor pressure of the air and the vapor pressure of the water in the grain. When these vapor pressures are equal, there is no moisture transfer from the grain and it remains constant at a value called the equilibrium moisture content (EMC) (Arora, 2001).

In the drying process heated air is passed through the product which sufficiently increases the vapor pressure of the moisture held within the product results to increase the moisture migration from within the product and significantly decreasing the relative humidity of the drying air to enhance its moisture carrying capability.

So as to maintain the quality of paddy, it should not be dried too fast and the drying process should be slow and uniform. The surface moisture of paddy is removed easily and quickly, but the moisture inside the grain last longer. Fast drying causes internal grain stress, which leads to cracking and subsequent breakage during milling operation. If surface moisture is removed too quickly, the outer layers contract and the high temperature used for moisture removal causes expansions that result in more internal stress. If the temperature of the drying air is raised by only a few degrees, the relative humidity of air is lowered enough to make it effective for paddy drying.

The drying rate is determined by the initial moisture content, temperature and variety of the grain. The rate of moisture removal is also affected by drying air temperature, relative humidity and the volume of air passing through the grain. The drying method, type of dryers, and efficiency of the equipment also affect the moisture removal rate of the grain. The higher the initial moisture content of the grain, more time it will take for the moisture removal. In general, the higher the drying air temperature, the faster the moisture removal rate. However, too high an air temperature may cause breaking during milling operation. Moisture removal rate decreases if the air having more relative humidity. Air with low relative humidity has the capacity to absorb more moisture and dries the paddy grain faster.

A drying curve, as illustrated in the figure 1.2 below, shows how the grain moisture content changes over time and how grain temperature changes. It can be seen in the figure; the drying rate is not constant but changes over time. The temperature of the grain equally changes over time.

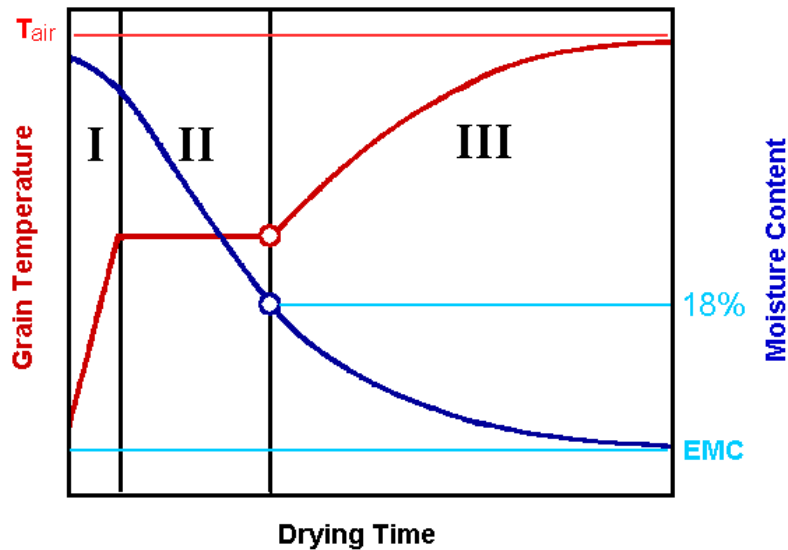


Figure 1.2: Theoretical drying curves (grain temperature red and moisture content blue) with different drying periods (IRRI 2005)

There are three different periods which will occur consecutively in time:

- I. Preheating period (drying rate is slowly increasing): When wet grain is exposed to hot air, initially only a very slight change in MC is observed because heat provided to the drying air is used to heat up the grain.
- II. Constant-rate period (drying rate is constant in time): Once the grain is at the drying temperature, water starts to evaporate from the surface of the grain. During this period, all the heat from the drying air is used to evaporate surface moisture and the amount of moisture removed from the grain is constant in time. It is therefore called the constant-rate period. During this period, grain temperature is constant as well. The primary resistance to heat and mass transfer is at the surface. When the surface appears to develop dry patches, the rate of drying begins to decrease.
- III. Falling-rate period (drying rate declines over time): As time passes, it takes more time for internal moisture to appear at the surface, and evaporation of water is no

longer constant in time. As a result, drying rate will decline. Some of the heat from the drying air will heat up the grain. For paddy grain, the falling-rate period typically occurs at around 18% grain moisture content. During this period, the rate of drying is controlled by the rate of migration of water.

There are different mechanisms of moisture transfer from the interior of the paddy grain. Some of them are given as follows:

- ❖ Liquid movement due to capillary forces.
- ❖ Diffusion of liquid due to concentration difference.
- ❖ Water-vapor diffusion by partial-pressure difference.

### 1.3 Different drying processes

There are different drying methods used for drying rice. There is no ideal dryer for drying rice since each drying method has its own inherent advantages and disadvantages. Various types of drying methods are discussed in the following subsections.

#### 1.3.1. Field Drying

In many traditional harvesting systems farmers leave their harvested rice in the field for extended time because they want to pre-dry the paddy. In this practice, leads to massive heat build up inside the stacks. As a result molds grow quickly and infest the grains and discoloration usually develops within the first day of field drying. There are some losses of paddy due to bird and rodents when spread in field. Another unwanted effect is that the relatively dry grains often absorb water from the wetter straw, which leads to fissuring of the dryer grains and thus reduces the potential head rice recovery. It can reduce 1% moisture content per day. Figure 1.3 presents the figure of field drying. It is impossible to produce good quality grains with field drying practices and field drying should therefore be avoided.



Figure 1.3. Field Drying (Vill. Mandakata, Dist. Kamrup, Assam) (Dandotiya, 2009)

### 1.3.2. Sun Drying

Sun drying (Figure 1.4) is the traditional method for reducing the moisture content (MC) of paddy by spreading the grains in the sun. The sun heats up the grains and also the surrounding air. This causes the water to evaporate from the grains. Sun drying is still preferred in Asia because it is cheap compared to mechanical drying. Since it uses the sun as heat source it is friendly to the environment.

The limitations of sun drying are

- ❖ It is not possible during rain and at night.
- ❖ Any delay leads to excess respiration and fungal growth causing losses and yellowing.
- ❖ It is labor intensive and has limited capacity.

Temperature control is difficult. Overheating or re-wetting of grains can result in low milling quality as a result of cracks developing in the kernels.

**Mat drying:** It is one of the most disinfected methods of sun drying where less contamination occurs with sand and other particle. In this method paddy grains can be placed in carpet or plastic sheet open to the sun light. Drawback of this method is that bottom grains may absorb moisture from the soil (Dandotyia, 2009).



Figure 1.4. Sun drying on woven mat (IRRI 2005)

**Panicle drying:** This is one of the oldest methods of sun drying where there is almost no contamination but the disadvantage of this method is that the drying inside the panicle is very slow and this method is effective for small quantity of paddy drying.



Panicle drying on field

(a)



Panicle drying on road

(b)

Figure 1.5 (a) (b) Panicle drying (Vill. Mandakata, Dist. Kamrup, (Dandotya, 2009))

**Pavement drying:** It is one of the direct methods of open sun drying used by farmers. In this method pavement is constructed for drying the grain particles (figure 1.6). Large amount of grains can be dried by using this method and the system can be partially mechanized but the drawback is because of contamination with dirt and due to capital cost.



Figure 1.6 Pavement drying (Paddy Drying IRRI, 2005)

## 1.4 Different Types of Dryers

Dryers are categorized on the basis of operation and type of fuel used. On the basis of operation solar dryers are classified in two types one is natural convection type and other one is forced convection type. On the basis of fuel used either solar energy or the energy of biomass are used as heating medium for the drying of any product.

### 1.4.1. Solar Dryers

Solar dryers can be divided into three categories such as

**Natural circulation type:** In natural circulation type no external agency is required to supply the heat for moisture transfer from the product. Natural circulation type may be direct solar dryer, indirect solar dryer or mixed mode type solar dryer.

**Direct solar dryer:** In direct natural convection type dryers, the air is heated in drying chamber which acts as both the solar collector and the dryer. The sun rays which passes through the transparent roof of dryer and heats the air inside the drying chamber ideally painted black to absorb the maximum amount of heat. The solar radiations are directly absorbed by the product itself. The food product is heated up and the moisture from the product evaporates and goes out by natural convection due to the vapor pressure difference. It is having disadvantages of low capacity and no control on temperatures.

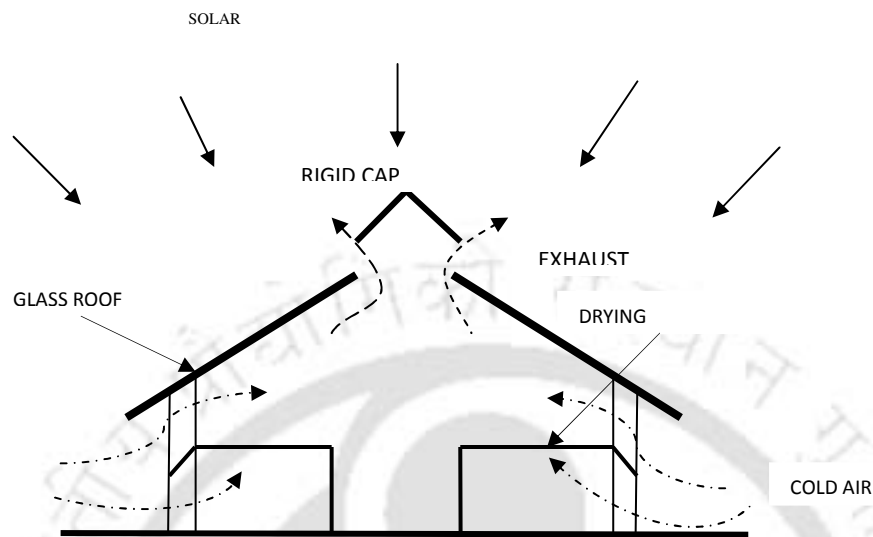


Figure 1.7. Direct type solar dryer

**Indirect solar dryer:** An indirect solar dryer consists of two parts: one is a solar collector and the other is drying chamber. Heat received by solar collector due to sun's radiation heated the air and due to density difference it moves to the drying chamber containing grain.

Solar dryers suffer from major limitations. They cannot be used at night, and their efficiency declines in cloudy or rainy weather. To overcome these problems mixed dryers have been proposed.

**Mixed dryers:** Mixed dryers use burning fuel as back-up sources of thermal energy when ever required. These dryers are independent from weather conditions and a wider range of agricultural products may be dried. These dryers are better than solar dryer with a better capacity.

**Forced circulation type dryers:** In these dryers, hot air is continuously blown over the food product. The food products itself is loaded or unload continuously or periodically. These kinds of dryers are comparatively thermodynamically efficient, faster and can be

used for drying large variety of agricultural product. These dryers cannot use the places where there is no electricity and is difficult to use in the farmers level.

### 1.4.2. Mechanical Dryer

Due to controlled drying, mechanical dryers becomes more important. Mechanical dryers are gaining importance from the view of controlled drying. Drying temperature, moisture, etc can be controlled in this type of dryers. Based on the capacity and methods of drying, these dryers are classified into the following categories.

**Batch dryer:** The capacity of the drier is 1-3 tons of grain per day and 6-12 hours are required for moisture removal. The inlet air temperature is maintained; depend upon the product to be dried. Kerosene or rice husk can be used as fuel in batch dryer. This type of dryer is expensive and labor intensive (Wimberly, 1983).

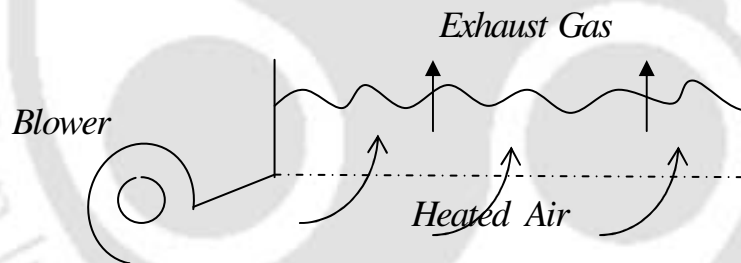


Figure 1.8 Cross section of 1 ton batch-bin type dryer

**Re-circulating batch dryer:** This is a kind of batch dryer with a capacity of 4-12 tonnes/day and 8 hours is required for the moisture removal. For paddy drying the air temperature is maintained around 50-60 °C. It is an effective fast drying process because of the continuous movement of the paddy during the short period of drying. (Wimberly 1983, Dandotiya, 2009).

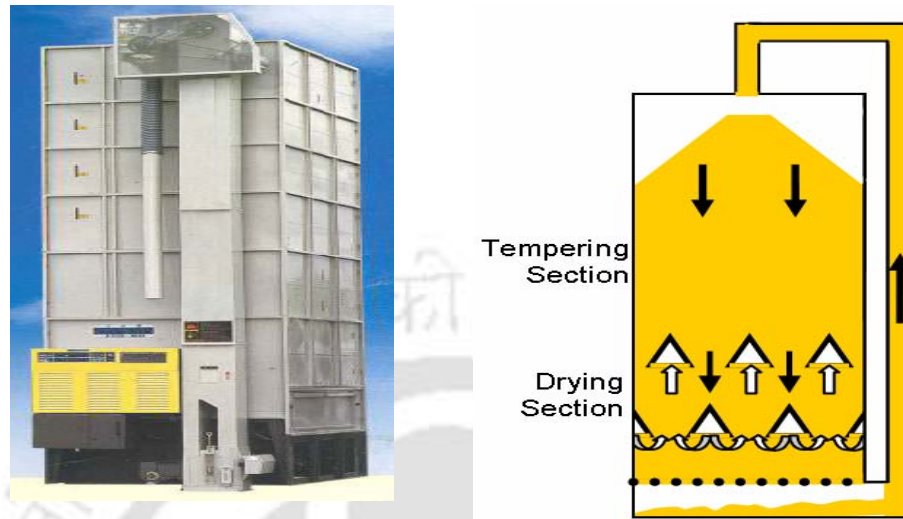


Figure 1.9. Large capacity re-circulating batch dryer (IRRI 2005)

**Continuous-flow drying:** In this kind of dryer, during moisture removal process, wet paddy enters at the top and flows continuously through the dryer. Hot air passes through the paddy, for the moisture removal. During the drying period of 15 to 30 minutes, there is a reduction of 1 to 3% of moisture from the product (Wimberly, 1983). Investment cost of the dryer is high. Figure 1.10 (a) (b) presents such kind of system at North Guwahati, Assam.



Figure 1.10. (a) LSU Type dryer (near IIT Guwahati)



Figure 1.10.(b) Continuous drying

### 1.5 Factors affecting drying quality

Quality of paddy is very important since it is used as staple food in most of the world and to get the demand in the international market. Different factors which affect both nutritional value and milling quality of paddy is discussed below.

**Moisture Content:** It is essential that the grain after drying is at moisture content suitable for storage. Moisture content will depend on the type of grain, duration of storage, and the storage conditions available. It is also important that the drying operation is carried out to minimize the range of moisture levels in a batch of dried grain.

**Stress Cracking and Broken Grain:** Drying with heated air or excessive exposure to sun can raise the internal kernel temperature to such a level that the endosperm cracks. The extent of stress cracking is related to the rate of drying. Rapid cooling of grain can also contribute to stress crack development.



Figure. 1 .11 Picture of broken rice

**Nutritive Value:** Grain constituents such as proteins, starch and gluten may be negatively affected when the grain attains excessive temperatures. The feeding value of grains can be lowered if inadequately dried.

**Grain Viability:** Seed grain requires a high proportion of individual grains with germination properties. The viability of grain is directly linked to the temperature attained by grains during drying (Kreyger, 1972).

**Mould Growth:** Many changes in grain quality are linked to the growth of moulds and other microorganisms. The rate of development of microorganism is dependent on the grain moisture content, grain temperature, and the degree of physical damage to individual grains. Mould growth causes damage to individual grains resulting in a reduction in value. Under certain circumstances mycotoxin development can be a particular hazard. Figure 1.12 shows the damaged and discolored grain.



Figure 1.12. (a) Damaged grain (b) Discolored grain

The desirable properties of high-quality grains include:

- ❖ low and uniform moisture content
- ❖ minimal proportion of broken and damaged grains
- ❖ low susceptibility to subsequent breakage
- ❖ high viability
- ❖ low mould counts
- ❖ high nutritive value

## 1.6 Research Goal and Objectives

Since a large amount of losses and degradation of quality of agricultural products takes place due to improper drying, it is necessary to supply right technology to the farmers for the reduction of losses and to maintain the quality of the products. Conventional paddy

dryers developed so far utilizes thermostatic temperature controller to maintain the temperature of drying air (Obregon, 2012, Srzednicki, 2006). Such systems require synchronization of temperature controller and moisture meters rendering the process complicated. Further, cost of equipment and maintenance become high. Drying air being heated up sensibly, maintenance of the temperature for quality drying is quite difficult. Apart from the above, the availability of conventional electricity supply in rural areas is poor and expensive. Use of solar energy for drying of agricultural crops is an alternative option as addressed by many researchers but its initial cost is high. Thus there is a need for the development of a simple and economic dryer for quality drying of paddy which can cater the need of rural areas.

The main objectives of the present investigations reported in the thesis using biomass as fuel in a Natural convection grain dryer are as follows:

- ❖ To develop an efficient and economic natural convection grain dryer suiting to the need of the end users.
- ❖ Performance evaluation of the developed natural convection dryer to study the effect of various drying parameters on quality drying of paddy.
- ❖ Performance evaluation of the grain dryer by using sensible heat storage materials (SHSM) and phase change materials (PCM) individually as well as combination of both.
- ❖ Performance evaluation of the grain dryer for quality drying by using phase change material (PCM)
- ❖ Complete thermo economic analysis of the dryer for improvement.

## 1.7 Organization of the Thesis

Chapter 2 covers an exhaustive literature review on drying and pertaining areas. It

includes the studies related to paddy, the concept drying, laboratory and field level dryers, energy exergy studies, study of the thermal energy storage materials, and moisture determination. This is followed by a thorough review of experimental investigations reported in open literature. The key issues and findings have been discussed, compared and summarized. All the related information has been summarized and the existing gaps in the fields of paddy drying have been identified.

Chapter 3 discusses the drying mechanism, drying kinetics and moisture transfer in drying are discussed. Theories related to heat and moisture transfer rate, heat gain by drying air, different thin layer drying equations and the design principles for biomass burner and drying chamber are presented. Finally the formulations related to the thermodynamic equations of the dryer based on energy and exergy are reported.

Chapter 4 presents the detail descriptions of the experimental setup with different components. This is followed by the description of the experimental procedure. Tools and techniques used for measurements of various parameters are discussed.

Chapter 5 deals with parametric study on paddy drying in a natural convection dryer without any thermal energy storage materials was conducted under Phase-I and discussed in chapter 5. Effect of drying time, thickness of paddy layers, humidity of environment, fuel requirement, etc on the moisture removal rate of paddy grain are presented.

The performance of the dryer was evaluated by varying different drying parameters. The moisture transfer characteristic of paddy was studied by varying the thickness of paddy layer at same relative humidity (65%) of the atmosphere and found that moisture transfer rate decreases with increasing thickness of paddy. Again a moisture transfer characteristic of same amount of paddy was studied at different humidity conditions of the atmosphere. The capacity and efficiency of the dryer is calculated in batch wise and continuous process.

Chapter 6 presents parametric studies on paddy drying in the developed natural convection dryer containing thermal energy storage materials are conducted and presented. Both the sensible heat storage material (SHSM) and phase change material (PCM) are incorporated in the dryer and experiments are performed in 3(three) different phases. Experiments with SHSM and PCM are conducted individually as well as in combination of both. Pebbles are used as SHSM in Phase –II and PCM is used in Phase –III. Combination of both SHSM and PCM is conducted in Phase-IV. The efficiency in phase II-IV for the drying of three batches each of 10kg and two batches each of 15kg of paddy is found to be 26.2%, 24.0% and 32.1%, respectively in continuous process. Finally the comparison of drying time, biomass requirement, moisture removal rate, efficiency, nutritional value and milling value for all four phases are compared.

Chapter 7 discusses detail energy and exergy analysis of the developed dryer is done. Energy analysis with and without thermal energy storage materials and phase change materials and combination of both for different amount of paddy are presented. In energy analysis part, heat gain by drying air, heat used during dehumidification of paddy grain, energy utilization ratio and the comparison of the results for the 4 (four) phases are discussed. This is followed by the detail exergy analysis of all the 4 (four) phases of the experiment with different amount of paddy. Exergy variation in different sections of the dryer, flue gas and drying air below the paddy tray, etc are presented. Finally the comparison of experimental results with and without thermal energy storage materials is analyzed. The maximum exergetic efficiency during the drying period of 30 minutes for 10kg of paddy is found to be 51.6 %, 32.1 %, 32.8 % and 37.3% for phase-I, phase-II, phase-III, and phase-IV, respectively. However, the exergetic efficiency was decreasing with time. Finally economic analysis of the dryer is presented.

Chapter 8 summarizes the major conclusions drawn on the work are presented. Scopes for future work are highlighted.

## CHAPTER 2

# LITERATURE REVIEW

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### 2.1 Introduction

Drying is one of an important post handling process of agricultural produce. It can extend shelf life of the harvested products, improve quality, reduces post harvest losses and lower transportation costs since most of the water are taken out from the product during the drying process. The literature which is discussed in this chapter is related to my research work.

### 2.2 Literature on structure and constituents of paddy

The structure of paddy grain consists of the endosperm, bran and hull (FAO 1995, Lague and Jenkins 1991) as shown in Fig. 2.1. The endosperm constitutes the nutritional reserves for the embryo containing carbohydrate (starch), aleurone and protein (Juliano and Bechtel 1985 and Riahi and Ramaswamy 2003). Starch content is 74-78% of the kernel weight whereas aleurone content is significantly small (Brooker et al. 1992). The structure of the starch granule in paddy is either crystalline or a combination of alternate crystalline and non-crystalline layers (Wilkinson 2000).

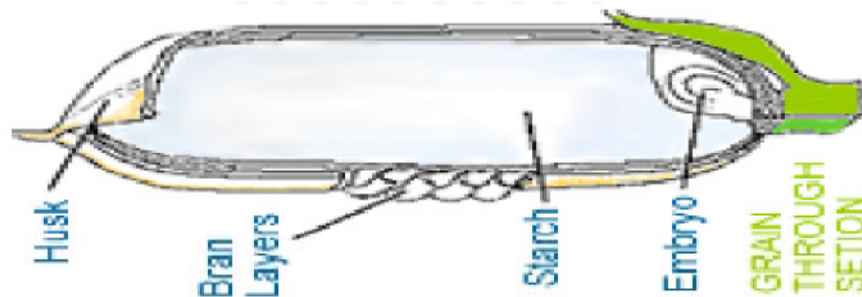


Figure 2.1. Complete structure of paddy

Protein is the second most important component of rice after carbohydrate. It acts as a bio-adhesive binding the discrete cell structures and starch granules together (Zhang *et al.*, 2003a). But protein is not uniformly distributed throughout. It remains intact upon cooking (Juliano and Bechtel, 1985). The quality of rice is influenced by the chemical interactions between both the starch and protein. Rice is obtained by removal of the hull by milling process.

### **2.3 Literature on quality maintenance of paddy**

Different rice grains are demanded by different customers, depending on their preferences (Brooker *et al.*, 1992). Most consumers prefer the best quality they can afford (Bakker-Arkema and Salleh, 1985). Long-grain (higher-quality) rice is sold mostly in Europe, medium- quality long-grain rice in the countries of Asia, the short grain rice in various special-demand areas, high quality parboiled rice in the Near East and Africa, and the lower-quality parboiled rice in special markets in Asia and Africa (Juliano, 1993). Grain quality refers to dry grain for consumption, with minimum moisture, microbial deterioration and spoilage (IRRI 2002d). There are few literatures in quality measuring methods for rice. Some methods are now adopted by food industries (Kohlwey 1994).

Quality of paddy grain can be judged by subjective as well as objective methods (IRRI 2002). Subjective characteristics are based on individual preference such as taste, smell and appearance of the product while objective characteristics are physical and chemical in nature. Physical characteristics refer to the texture whereas chemical characteristics refer to the nutritional value of the product. Bakker-Arkema and Salleh (1985) and IRRI (2002c) estimated six physical characteristics, such as moisture content, maturity, varietal purity, dockage, discoloration and cracks for determining the quality of paddy grain. Head rice yield (HRY), colour, and subsequent cooking qualities are some of the characteristics of rice quality (Zhang *et al.*, 2003a).

According to Bakker-Arkema and Salleh (1985) and IRRI (2002c), water, insects and heat exposure can cause the grain to deteriorate the quality through biochemical

changes in the grain resulting in the development of odour and changes in physical appearance.

Dong and Zhihuai (2003) reported that, overexposure of grain to fluctuating temperature and mechanical impact may possibly lead to the development of cracks in individual kernels. Cracks may lead to the growth of mould and insects. Because of the cracks in the endosperm tissue, the nourishment that the embryo can obtain is reduced so as to reduce the vitality of the seeds. Overexposure of the mature grain to variable temperature and moisture conditions in the field results in adsorption and desorption of moisture creating fissuring of rice kernel (Chau and Kunze 1982, Velupillai and Pandey 1990, and Kunze 2001).

Wratten et al., 1969 and Sablani and Ramaswamy, 2003, had reported that the thermal conductivity, specific heat capacity, moisture diffusivity, thermal diffusivity and latent heat of vaporization to be significant parameters for maintaining the quality of paddy through drying process.

Brooker et al. (1974) reported the shrinking of the grain coat due to rapid drying rate leading to the reduction in moisture movement within the grain. Such condition, known as case-hardening, can prevent further drying producing dormant seeds (Brooker et al., 1974).

Wongpornchai et al, (2004) reported the effect of drying rate on moisture removal from the grain at high temperature. They reported reduction in the concentration of the key aroma constituent (2- acetyl-1- pyrroline) of the paddy at high temperature drying incurring loss in quality.

## **2.4 Parametric study on quality paddy drying**

Both heat and mass transfer takes place simultaneously during the grain drying process. Heat is transferred from the drying air to the surface of the grain and subsequently to the interior of the grain. Moisture from the surface of the grain is transferred to atmosphere

by the process of evaporation whereas moisture from the interior of the grain is transferred because of concentration gradient. Capillary effect inside the grain helps in transferring the moisture from the interior of the grain where concentration of the moisture is higher than that of the grain surface (Noomhorm Verma, 1986). In principle, partial pressure difference created between the grain surface and atmosphere due to the flow of hot air causes the surface moisture transfer. Moisture transfer from the core of the grain to the surface is due to mass diffusion (Trim and Robinson, 1994). In ideal and efficient drying situations, paddy grain should be dried uniformly (Teter 1987) and quickly, but its quality for the end use should not be badly affected (Patindol et al. 2003).

Grain drying can be achieved by circulating heated air at certain temperature over a stack of grains (Lucia and Assennato, 1994). Movement of hot air imparts heat to the grain facilitating the absorption of moisture from the outermost layer. This process neither takes place uniformly inside the drying chamber nor among individual grains. Indeed, the water present in the outer layers of the grain evaporates much faster and more easily than that of the internal layer (endosperm). It is well established that the reduction of grain moisture from the surface (hull) takes place quickly than that from the endosperm in case of cereal grains (Chakraborty 1994, Majumder 2006, Keey 2002). Lucia and Assennato, 1994 had reported that the removal of moisture of paddy grain from 35-25% takes place at a faster rate when compared to the same for the range of moisture removal from 25% to 15%.

Air temperature, air flow rate, relative humidity of atmosphere, exposure time, initial moisture content, depth of the grain bed and geometry of the grains were reported to be important parameters in drying of cereal grain (Chakraverty, 1994).

#### **2.4.1 Effect of drying air temperature**

Wasserman et al. (1956) and Thompson et al. (1955) studied the effect of drying air temperature in the range of 24-60°C on the drying characteristics of short grain paddy and observed that both drying time and HRY decreased with increase of drying air

temperature. They had compared the drying time at different temperatures and estimated that the drying time was reducing with increase in air temperature. There were increase of drying time of 50% at 32°C as compared to 10-15% in the range of 43-60°C.

Simmonds et al. (1953a) reported that the removal of moisture from wheat was mainly depended on temperature of drying air (21°C-77 °C) and rate of moisture removal was increasing with the rise of air temperature.

Ojha and Chakraverty (1975), studied the effects of drying air temperature in the range of 45-85°C by exposing the paddy for 5, 10, 15, 20 minutes, respectively. Final moisture content of paddy grain were observed to be 13.5%, 12.5%, 11.5% and 10.5%, respectively. They also observed that HRY decreases with the increase of drying air temperature or exposure time or both. They reported a sharp decrease of HRY at 65°C.

Chungu (1985) compared the drying of paddy under a shade as well as in a natural convection grain dryer and reported that there is no significant difference in HRY of paddy under both the systems up to 60°C. However, HRY percentage was decreasing above 60°C increasing in more amount of broken rice after milling operation.

Tabassum and Jindal (1992) reported the effect of temperature of drying air on the paddy drying. They found that difference in moisture removal rate at drying air temperature of 45° and 49°C is insignificant but moisture removal rate is quite low at drying air temperature of 40°C.

Yadollahinia et. al(2008) studied the effect of drying air temperature ranges from 30°C to 70°C on paddy and observed that removal of moisture from the paddy increased with increase of air temperature.

Luangmalawat et al. (2007) reported that hot air drying is the most common method used for food dehydration and the quality of food product is sensitive to the drying air temperature. Aguilera (2005), Bello *et al.* (2006), Silva and Avila (1999),

reported that temperature may cause the degradation of food qualities such as colour shrinkage, nutritional substances and removal of moisture.

Abe et al. (1992) reported about drying of high moisture content paddy with heated air. They found that drying of paddy starts from the surface of the kernel and then progress inwards. Rapid drying causes case hardening and happen when the surface of the grain dries out rapidly sealing the moisture within the inner layers. The internal pressure thus developed causes cracks on the grain.

Fan et al. (2000b) claimed that high temperature can be used to accelerate the drying process when the grain moisture content (MC) is over a critical point of about 15%. Only below this point can the grain quality be badly affected. Dounporn et al. (2012) reported the effect of paddy drying with different temperature and reported that the drying rate increases with increase in drying temperature.

According to Chakraverty (1994) the optimum temperature of drying air for drying of raw paddy is 60°C. He also reported that up to temperature 60°C, the quality of starch does not change and at temperature above 70°C with the presence of high moisture content in the grain, gelatinization and partial conversion of starch to dextrin take place.

#### **2.4.2 Effect of humidity of air**

Thompson et.al (1955) and wasserman et al. (1956) reported the effect of humidity on the paddy drying. They found that there is no significant influence on the HRY in the specific humidity range from 0.003 to 0.01g/g but has prominent effect on drying time.

Henderson (1957) studied the effect of relative humidity (8%-65%) and observed that the HRY of total yield decreased with decreasing relative humidity and is increased with increasing air temperature. Kunze and Prasad (1978) studied the effect of humidity

on the harvested paddy and observed that low moisture paddy grain fissures more when subjected to high relative humidity.

Tabassum and Jindal (1992) reported that the moisture removal rate was faster at low relative humidity and same was decreased at higher relative humidity. The effect of relative humidity is less than the effect of temperature and initial moisture content. Fig 2.2 shows the effect of moisture removal at the different humidity.

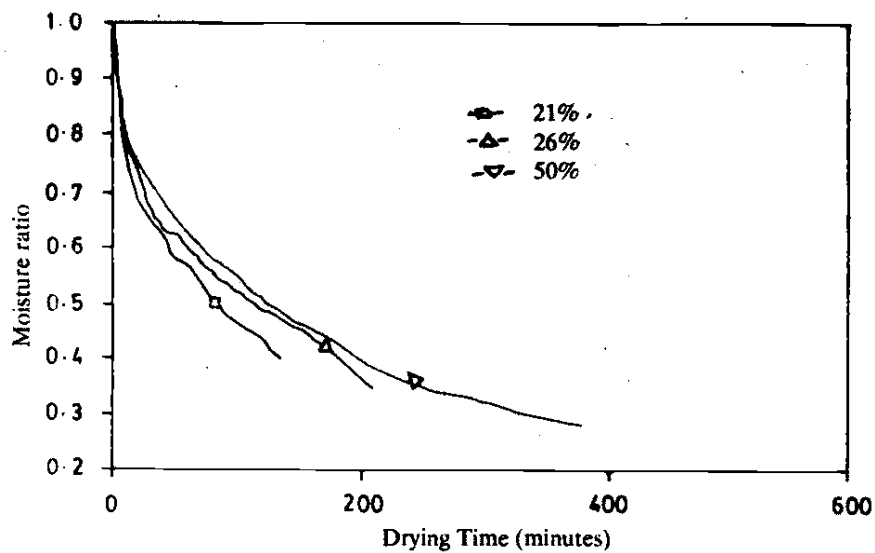


Figure. 2.2 Effect of relative humidity on moisture removal rate (IMC= 20%, AFR= 0.2 m<sup>3</sup>/sec-m<sup>2</sup>) (Tabassum and Jindal, 1992)

Chakraverty (1994) reported that with increase in air humidity rate of moisture removal decreases slightly. The effect however, is much smaller in comparison to the effect of temperature changes.

Ng *et al.* (2005) reported that, low humidity and high temperature surrounding the kernel caused rapid evaporating capacity and increased the moisture gradient in the kernel. Bonazzi *et al.* (1997) suggested that using of high relative humidity and heated air in moisture removal from the kernel produced low cracking and more head yield and also halved the operation time.

Hustrulid (1962, 1963), found out that air temperature was found to have the greatest effect on drying rate followed by air velocity and initial moisture content on the drying of wheat. Relative humidity had the least effect of all.

#### **2.4.3 Effect of moisture content on quality of paddy grain**

Calderwood (1977) studied the mixing of two batches of paddy having different MC. He found that breaking of rice increases after mixing of two batches of paddy of different MC than the individual batch of paddy.

Halos (1985) reported the effect of IMC of rewetted paddy to be significant for increasing HRY. Chakraverty (1994) reported that moisture removal rate increases with increase in moisture content of grain.

Zheng and Lan (2007) had reported better taste of rice with the increase of IMC with constant drying air temperature. However, taste degrades with low drying air temperature for high IMC paddy. Lihare and Bawane (2012) studied the quality of paddy with varying the drying time and observed that drying duration is more when relative humidity is more. The moisture content of the paddy decreases with increase in drying time but the rate of reduction in moisture contents becomes less as the drying time progressing.

Kunze (1979) had reported the main cause of cracking of paddy grain to be the rapid adsorption and desorption of moisture. According to Ng et al. (2005), combined effect of moisture and temperature gradient leads to high stresses causing the cracking of grain kernels.

Hellevang (2004) reported that the mixing of dry grain with wet grain to be the main cause of fissuring and HRY reductions. He suggested that care to be taken to avoid mixing of dry grain (MC less than 15%) with moist grain (MC greater than 18%). Siebenmorgen and Jindal (1986) reported in their studies that the MC of around 15% is the critical level above which internal moisture migration does not readily induce

cracking in the grain. Long term exposure of paddy in field under varying atmospheric conditions results in absorptions and desorption of moisture by the grains leading to fissuring (Chau and Kunze (1982), Velupillai and Pandey (1990), Lu *et al.* (1994) and Kunze (2001)).

Li *et al.* (1999) reported that the moisture and temperature gradient within the grain kernel during drying will result in volumetric changes. This non-uniform expansion and contraction result in failure when the induced stresses exceed the failure strength of the grain material.

#### **2.4.4 Effect of air velocity on thin layer drying**

Yadollahinia *et al.* (2008), studied the effect of air velocity on the drying period of paddy and reported that the effect of air velocity with moisture removal rate is insignificant. He reported that with increase of air velocity from 0.25 to 1  $\text{ms}^{-1}$ , very little effect on the drying rate. Similar results were observed by Akpinar *et al.* (2003) while studying on drying of red pepper.

Chinenye (2009) reported that drying rate of cocoa bean increased with increase air velocity and air temperature but decreased with time. The dryer can remove an average of 4.66 kg of water per day at 55-81 °C at air velocity of 1.3 m/s while at 2.51 m/s it can remove an average of 5.3 kg of water per day under the same drying conditions.

Henderson and Pabis (1961) found out that air flow rate had no observable effect on thin layer drying of wheat when air flow was turbulent. According to them, air flow rate varying from  $10\text{cm}^3/\text{sec}/\text{cm}^2$  to  $68\text{cm}^3/\text{sec}/\text{cm}^2$  had no significant effect on the drying rate of wheat but in case of paddy and corn, air flow rate has some effect on drying rate. Similar observation was also made by Hustrulid (1962, 1963); he found out that drying air temperature was found to have the highest effect on drying rate followed

by air velocity and initial moisture content, respectively. However, effect of relative humidity was not reported in the study.

Tabassum and Jindal (1992) reported about the effect of air flow rate on the moisture removal rate of paddy and found that air flow rate produced insignificant effect on the moisture removal rate (Fig. 2.3).

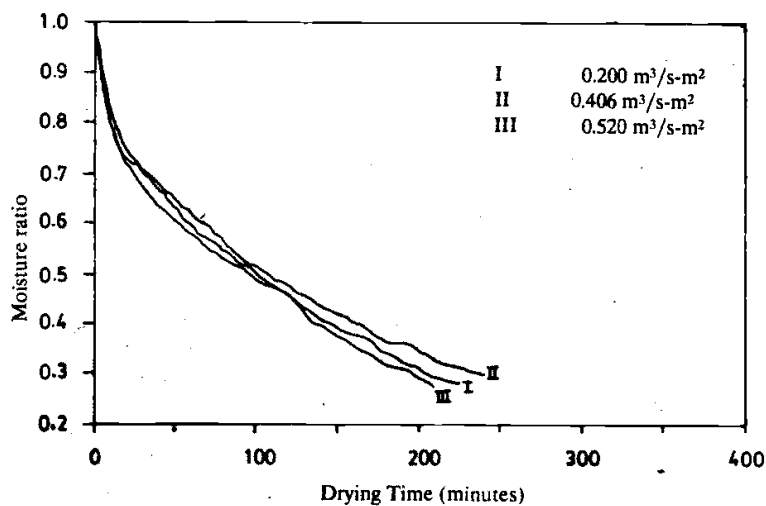


Figure.2.3 Effect of air flow rate on moisture removal rate (IMC= 20%, AFR= 0.2 m<sup>3</sup>/sec-m<sup>2</sup>) (Tabassum and Jindal, 1992)

## 2.5 Traditional paddy drying

Sun drying has been used since the starting of the human life to dry grains and other agricultural products. It is the most common practice in Asia and other tropical and subtropical countries (Togrul and Pehlivan, 2002).

Garg and Kumar (1999) reported that, in open sun-drying method, rice grain is usually spread in a thin layer on a ground and exposed directly to the sun, wind and other atmospheric conditions. Heat is transferred to the air by the solar radiation and subsequently heated air acts over the exposed surface of the grain bed. Some part of this heat is transferred to the bed interior to raise the temperature of kernels and the remaining

heat is utilized to evaporate the surface moisture to the surrounding air. Some of the heat can also be lost by conduction to the ground below the grain bed.

In order to ensure good and uniform drying, the grain thickness should not exceed 8 cm and the grain should be turned over from time to time (Teter, 1987). To increase the drying rate and good grain quality, stirring or mixing of the grain is required (Nindo *et al.* (1995). The most common method for stirring is to use hands. Some simple hand tools are also used for stirring.

Mahamed (1990) and Venkataraman *et al.* (2012) stated that the intensity of solar energy decreases with greater distance from the sun. The energy available on the earth depends on the time of day, the time of year, the weather, the latitude of the site and the site's tilted angle.

Due to uncontrolled solar intensity and wide variability of atmospheric conditions (relative humidity, air flow velocity, rain, frost, etc.), open sun drying is time consuming and difficult to maintain the quality of drying product (Mulet *et al.* 1993). Imoudu and olufayo (2000) claimed that the method is very simple and very economical but requires more labour to produces paddy with lower quality than other methods of drying.

Depending on various factors such as, solar intensity, ambient air temperature and RH, wind velocity, the grain initial MC, variety and depth of grain, the type of drying pad used and the intensity of stirring; the grain is usually dried for 1 to 3 days after threshing. If the weather is cloudy and rainy, more days may be required for drying. (Zaman and Bala, 1989). Basunia and Abe (2001) and Togrul (2004) reported that this method is not suitable for large scale drying due to the lack of facility to control the process properly.

## **2.6 Experimental investigation on drying with different dryers**

As mentioned in subsection 2.5, open air drying is not suitable for quality drying of paddy grain. This has motivated the researchers to develop new paddy dryers throughout

the world. It has been reported in literature that there is a large range of laboratory as well as pilot scale dryers ( Esper and Mühlbauer (1999)), Wahidi and Rohani (2001), Oztekin *et al.* (2002), Bansal (2004) and Sharma *et al.*(2009) ). It is observed that most of the dryers reported in the literature so far are either of forced convection or free convection type with solar, mechanical or chemical energy as input. Effects of different parameters on drying were investigated experimentally by various researchers.

### 2.6.1 Forced convection type dryer

Heated air is forced through the product to be dried in case of forced convection dryer. These types of dryers usually consist of an electric motor coupled to blower to force the air through the product. In indirect-mode forced convection dryer operates in the similar process but air is heated in a separate loop preventing the combustion products/flue gas to reach the drying product (Fudholi, 2010).

Ozbalta and Dincer (1994), Gwinner *et al* (1996) and Pangavhane *et al.* (2002) had discussed the advantages of forced convection dryer and reported significant decrease in drying time and low running cost are such dryers. Moreover, they observed better control of drying temperature in these dryers.

Lutz *et al* (1987) developed a multipurpose solar crop dryer for drying various agricultural products. The newly developed system consists of a solar air heater, a small fan and a tunnel dryer. This dryer can be easily constructed by unskilled labourer using cheap and locally available materials. Due to the low investment required, the solar dryer is predestined for application on small farms in developing countries. Depending on the size of the dryer 100-1000 kg of fresh material can be dried within 1-7 days to safe storage condition. During drying, the crop is protected completely from rain, dust, insects and animals.

Tiris *et al.* (1996) developed a solar dryer consisting of a solar air heater and a drying chamber for drying agricultural products. It was demonstrated that the use of this

type of solar dryer reduced the drying time significantly with improved product quality. They reported the thermal efficiencies in the range of 30-80% for varied flow rate of air. It was concluded that the performance of the dryer was better with high flow rate of drying air. Banout et al. (2011) reported the performance of the double-pass solar dryer and was found to be better than cabinet dryer and open sun drying and also technically suitable and economically viable for drying of red chillies.

Mumba (1996) designed and developed a solar grain dryer with photovoltaic powered air circulation and the same was tested in the field. The important feature in this grain dryer was the use of photovoltaic solar cells incorporated in the solar air heater section to power a d.c. fan. This photovoltaic powered air circulation induces passive control over the drying air temperature. The controlled drying air temperature has an upper limit of  $60 \pm 3^{\circ}\text{C}$  to prevent grain overheating and cracking. The dryer has been found to be cost-effective. Compared with the traditional sun drying method, this system was found to be a viable option with many benefits, such as a protected drying environment, improved dried product quality.

Sreekumar et al. (2008) developed and tested an efficient solar dryer. The solar dryer has two compartments: one for collecting solar radiation and producing thermal energy and the other for spreading the product to be dried. This arrangement was made to absorb maximum solar radiation by the absorber plate. Two axial flow fans, provided in the air inlet, can accelerate the drying rate. The maximum air temperature in the dryer was  $78.1^{\circ}\text{C}$ . The dryer was loaded with 4 kg of bitter melon having an initial moisture content of 95%, and the final desired moisture content of 5% was achieved within 6 hours without losing the product colour, while it was 11 h for open sun drying.

Arata and Sharma (1991) developed a simple design using simple tools and relatively cheap and locally available materials by small scale industries using solar air heater. Author also discussed with farmers themselves, using cheap and locally available

materials by small-scale industries. They also concluded that, the simple design mechanism can be very fruitful for the farmers.

Pawar et al. (1995) designed and fabricated a large-scale forced convection solar drying system. Drying system comprising an array of forty solar collectors and three drying cabinets with a blower. It was shown that use of this type system was feasible and had an ability to save large amounts of fuel. It keeps the product clean and it was dried in a shorter period than in open sun drying. It was found that forced convection solar drying systems were suitable in food and chemical industries where large scale drying is required.

Zomorodian et al. (2007) introduced a new approach for employing solar radiation as the main source of energy for paddy drying. The drying test rig was designed, fabricated and evaluated. The rough rice solar dryer was a cross-flow and an active mixed mode type with a new and an efficient timer assisted semi continuous discharging system. The rig consists of six ordinary solar air heaters, an auxiliary electric heating channel, a drying chamber with an electrically rotary discharging valve and an air distributing system. To evaluate the drying system, a local variety of medium size kernel of rough rice was selected to be dried by the dryer. The maximum overall efficiency of drying system was 21.24% (with average drying air temperature of 55 °C). The maximum capacity of the dryer was about 132 kg of rough rice with initially 27% d.b. down to 13% d.b. final moisture content in 3 h of drying period.

A forced convection solar dryer was constructed and tested to dry paddy at a farmer's house in Thailand as reported by (Soponronnarit, 1995). The system consists of the collector, drying bin and blower. This dryer was 4.48 m long, 3.74 m wide, solar air heater and a vertical fixed bed drying-bin having a capacity of 12 tonnes of paddy. Drying tests indicated that one tonne of paddy could be dried from a moisture content about 17% to 14% in 1–4 days depending on weather conditions. Average electrical energy consumption for a blower was estimated to be 7 KWh per drying batch.

Soponronnarit (1995) reported a forced convection hybrid solar dryer to dry paddy in Thailand. When an engine was used to drive the fan, it required, on average, 16 l of diesel oil per tonne of paddy per one percent wet-basis of moisture removed. The corresponding drying rate was 0.5 percent wet-basis per tonne of dry paddy per hour. The maximum storage capacity was 10 tonnes. Economic analysis, assuming that benefits were derived from reduction of loss and better price of paddy, showed that this drying was economical only for a paddy field where two crops were cultivated every year. The payback period was estimated to be 2.3–14.8 years.

### **2.6.1.1 Solar drying system with heat pump**

Several solar-assisted heat pump dryer have been design, fabricated and tested. Hawlader et al. (2008) studied the performance of the evaporator-collector and the air collector when operated under the meteorological conditions of Singapore. They showed that “the evaporator- collector efficiency increases with increasing refrigerant mass flow rate. It was also revealed that the efficiency of the evaporator-collector is higher than that of the air collector”. The maximum efficiencies of the evaporator-collector and the air collector were reported to be 86% and 75% , respectively.

A solar-assisted heat pump dryer was used to dry poplar and pine timbers in heat pump timber dryer were experimentally analyses. Energy and exergy analyses were made for both types of timber and the timber drying performance of the heat pump dryer was evaluated. Energy analysis was made to determine the energy utilization. Exergy analysis was accomplished to determine of exergy losses during the drying process (Ceylan et al. 2007). A heat pump dryer was designed, fabricated and tested to evaluate the drying characteristics of various herbs and the dryer performance under various conditions. Fatouh et al. (2006) have been reported that the heat pump assisted dryer is recommended for industrial use.

### 2.6.1.2 Solar-assisted dehumidification system

The temperature of air in drying process affects the quality, evaporation capacity as well as drying period. In addition, shorter time period is required for higher temperature drying. At higher temperature, pure water vapor pressure becomes higher; therefore, the difference between water vapor partial pressure and pure water vapor pressure becomes higher. This pressure difference is the driving force of water evaporation to the air. This driving force is directly proportional to the evaporation rate of water to air. However, drying at high temperature is not suitable for the materials which are sensitive to heat because it can cause cracks, browning which further reduces the taste of final product (Fudholi, 2010).

A solar dehumidification system for medicinal herbs was developed by Yahaya et. al 2008. The system consists of a solar collector, an energy storage tank, auxiliary heater, adsorbent, water to air heat exchanger, a water circulating pump, drying chamber, and other equipment. It is made up of essentially three processes, namely regeneration, dehumidification, and batch drying. During regeneration process, the air outside the dryer is heated with the heat exchanger and is supplied to the adsorbent. The adsorbent is heated with this hot air and water content rate is reduced, removing the water content. The water content is evaporated by the hot air and leaves the dryer. During dehumidification (adsorption) process, the air inside the dryer passes through the heat exchanger by use of the blower.

Ekechukwu (1997) reported that, many rural locations in developing countries, grid connected to electricity and supplies of other sources of energy are unavailable, unreliable for many farmers, also it is too expensive. Thus in this areas, crop drying systems that employ fans and electrical heating systems are inappropriate. So it is difficult to implement the same in the village. In addition, rainy seasons and cloudy sky make it difficult to use the solar dryer. Significantly high fixed as well as running costs of

fossil fuel powered dryers fail to popularize the forced convection dryer among the small scale farmers.

### **2.6.2 Natural convection type dryer**

Passive dryers use only the natural movement of heated air. They can be constructed easily with inexpensive, locally available materials which make them appropriate for small farms where raw construction material such as wood is readily available (Sharma, 2009).

Natural-circulation solar-energy dryers depend for their operation entirely on solar-energy. In such systems, solar-heated air is circulated through the crop by buoyancy forces or as a result of wind pressure. These dryers are often called "passive" in order to distinguish them from systems that employ fans to convey the air through the crop. The latter are termed "active" solar dryers. Natural-convection solar-energy assisted dryers appear the most attractive option for use in remote rural locations (Ekechukwu, 1997).

Sodha et al. (1985) had developed an analytical model and conducted a comparative experimental study for drying of raw mango slices (pulp) on traditional sun drying and on a cabinet type dryer. The mango slices were dried in thin layer of 1 cm with IMC of 95%. Drying experiments were conducted for 12 sunshine hours to reduce the MC to 13% (approx). The cabinet dryer was reported to be superior to traditional sun drying without deteriorating the product quality.

Ayensu (1997) designed and constructed a low-temperature, low-cost, and simple to operate solar dryer with wood, metals and glass sheets and same was tested for drying of groundnut. The food bed was constructed from a double layer of chicken wire-mesh with a fairly open structure to allow drying air to pass through the food sample, but prevent the pieces of food items from falling into the plenum chamber. The crops were dried to 14 % final MC and were preserved for a period of 1 year without deterioration. The designed system can be used to dry food crops (cassava chips, cassava leaves,

pepper, groundnuts, etc.). He also reported the reduction of drying time for the developed dryer to be half in comparison to the traditional sun drying.

Singh et al. (2004) designed a solar dryer to enable Indian farmers to add value to their produce by on farm drying. It can also be used in cottage industries in remote places. The developed solar energy assisted passive dryer had a multi-shelf design with intermediate heating facility. Intermediate heating of air in-between trays results in uniform drying in all the trays. Since the dryer at the farm is not likely to be used throughout the year, it has been made portable. A novel feature of this dryer is that the product can be dried under shade or otherwise as per requirement. Similar type of study on drying of garlic, ginger, onion and other spices was performed by Singh et al. (2006).

Shove (1977) reviewed the types of flat plate collectors employed in grain drying. The suspended plate collector in which air flows along both sides of the absorber plate is slightly more complicated but is credited to be more efficient than the bare or covered plate collectors. Sidewall collectors, integrated into the drying bin wall have received considerable attention and development (Peterson, 1977), (Johnson, 1980). However, these wall collectors are expensive and have a useful life of only two or three seasons. Keener et al. (1977) and Chau et al. (1980) presented interesting configurations of plastic film solar collectors of various shapes. Also other types of solar collectors including focusing collectors have been treated by Duffie and Beckman (1974) and Daniels (1977).

Later Ezeike (1986) designed a modular drying system consisting of three functional units, namely a triple-pass flat plate air collector, a drying cabinet, and a dehumidification chamber. Air flows below the bottom absorber during the first pass, then in the opposite direction and finally through the air spaces between the glazing and top absorber plate into a mixing chamber and a drying chamber; the top air space was divided into two compartments with baffles installed to distribute the air over the collector surface. The drying cabinet has two wall collectors located on the east–west line to provide additional heat gain and trays spaced equally on spacers. The dehumidification

chamber was a rectangular box fitted with three perforated trays containing the desiccant, silica gel. Results of the drying tests with rice paddy showed that the system dried rice paddy at a layer density of  $7.4 \text{ kg m}^{-1}$  from 25.93% (w.b., wet basis) to 5.31% (w.b.) in 10 hours.

Othieno et. al (1983) developed an indirect solar maize dryer. The dryer consisted of a single glazed passive solar air heater with a  $1 \text{ m}^2$  single flat-plate absorber and an air gap of 5 cm from the glazing. The entire dryer assembly was made from hardboard. To improve efficiency, the air heater was modified with a wider air gap (15 cm) to accommodate three layers of wire-mesh absorber between the glazing and the flat-plate absorber. The dryer was capable of drying 90 kg of wet maize from a moisture content of about 20% wet basis to 12% within 3 days on a bright day.

Das and Kumar (1989) designed a prototype, low cost and simple solar dryer coupled with a vertical flat plate collector chimney for drying 20 kg of field harvest high moisture paddy. This unit consisted of an inclined collector, a batch dryer and a vertical collector chimney all joined in series and positioned due south. The experiments were conducted during the winter months. The 20-kg field harvested paddy took 9 h to reduce the moisture content from 31 to 13% (d.b.), a saving of 7 hours compared to traditional sun drying. Authors had reported that drying system can also be successfully used for the drying of other grains, vegetables, fruits and small fishes efficiently, effectively and economically with acceptable quality of the final products.

Ekechukwu and Norton (1997) designed and developed a natural solar dryer suitable for the drying of crops. The results from the experimental facility have demonstrated the superior drying characteristics of integral type, natural-circulation solar-energy dryers over traditional sun drying.

Pangavhane et al. (2002) developed a natural convection solar dryer consisting of a solar air heater and a drying chamber. This system can be used for drying various agricultural products like fruits and vegetables. Grapes were successfully dried in the

developed solar dryer. The qualitative analysis showed that the traditional drying, i.e. shade drying and traditional sun drying, dried the grapes in 15 and 7 days, respectively, while the solar dryer took only 4 days and produced better quality raisins.

Koyuncu (2006) designed, constructed and tested two different types of natural-circulation greenhouse crop dryers. Each dryer mainly consisted of a framework constructed from black-coated metal bars, corrosion-resistant plastic mesh and a black-coated solar radiation absorber surface. The dryers were tested in the summer conditions. The results of the study show that the use of natural circulation greenhouse dryers for drying agricultural products, was 2.5 times more efficient than traditional sun drying.

Prasad et al. (2006) developed a direct type natural convection solar cum biomass fired dryer and reported its performance. The system was capable of generating an adequate and continuous flow of hot air temperature between 55 and 60 °C. Turmeric rhizomes were successfully dried in the developed system. The quantitative analysis showed that the traditional drying had taken 11 days to dry the rhizomes while solar biomass drier took only 1.5 days and produced better quality produce. The efficiency of the whole unit obtained was reported to be 28.57%.

Exell (1999) has been developed a low-cost mixed-mode natural convection solar dryer (chimney-type solar dryer) for drying paddy. This dryer is discontinuous-type solar dryer, based on natural convection. Paddy could be dried safely in 2–3 days.

A typical design of the solar rice dryer has been reported also by Ekechukwu and Norton (1999). This dryer consists of a solar air heater, a cabinet for the rice bed and a chimney which provides a tall column of warm air to increase buoyancy. The drying chamber is a shallow wooden box with a base made of bamboo mat with a fairly open structure to allow far and easy flow of the drying air. A clear plastic sheet covering the rice bed allows the direct heating of the rice by direct absorption of solar radiation while protecting the product against rain.

Forson et al. (2007) designed a mixed-mode natural convection solar dryer. The dryer consists essentially of an air heater, a drying chamber and a chimney. They proposed a methodology combining principles and rules of thumb that enable the design of a properly engineered mixed-mode natural convection solar crop dryer. The resulting empirical model can evaluate the performance with the physical properties of the raw product and ambient conditions as input data.

The design and construction of one of the most recent mixed-mode natural-circulation solar dryers was reported by Iloeje et. al (1993). The 2(two) tonne per batch capacity mixed-mode natural-circulation solar rice dryer consists of two separate drying compartments. These two compartments are arranged on both sides of a central gangway running through the entire length of the dryer. Provision is made for an incinerator which burns rice husk to provide supplemental heating during periods of low insolation and/or high humidity. Heat from the burner exhaust is transferred to the rice through heat exchangers located below the dryer trays by natural convection.

Zaman and Bala (2001) had been developed simple empirical equation for thin layer natural air flow solar drying of rough rice in mixed-mode type dryer, box-type dryer and open floor drying system. The moisture contents predicted by the equations were in good agreement with the observed values. The effect of drying air temperature on the drying rate constants was found to be insignificant. The highest drying rate was observed in case of mixed-mode dryer.

Bena and Fuller (2002) conducted an experiments on a direct-type natural convection solar dryer using a biomass burner for small scale purpose for drying fruits and vegetables in non-electrified areas of developing countries of the world. The overall drying efficiency of the was reported to be 9%.

## **2.7 Dryer with heating unit**

Drying is accomplice with addition of heat from different sources. Traditional sun drying as well as the solar dryers utilizes the solar radiation. These drying systems are

environmental friendly but are inherently slow in nature. Apart from these, fossil fuel is utilized in most of the mechanical dryers causing severe atmospheric pollution. Electric dryers are used in bulk drying processes such as drying of tea leaves and cereal grains etc. However, these dryers are expensive and dependent upon the availability of electricity. Considering the availability of cheap biomass in country side and good feature of the same in terms of less emission due to combustion has motivated many researchers to utilize the biomass as a fuel for combustion in drying devices (Bena and Fuller, 2002).

Prasad et al. (2006) developed a direct type natural convection solar drier integrated with a simple biomass burner. The biomass burner was having a dimension of 0.65 m × 0.60 m × 0.55 m rectangular shape box fitted with an iron grate at its base. At the bottom of burner, an adjustable door was provided for feeding the biomass and controlling the airflow rate for combustion. The system was capable of generating an adequate and continuous flow of hot air temperature between 55 and 60 °C.

Tarigan and Tekasakul (2005) reported on the a mixed-mode natural convection solar dryer integrated with a simple biomass burner and bricks heat storage as back-up heating system. The efficiency of the burner with heat storage in producing useful heat for drying was found to be 40%.

Madhlopa and Ngwalo (2007) developed an indirect type natural convection solar dryer with integrated collector-storage solar and biomass-backup heaters. The dryer was tested in three modes of operation (solar, biomass and solar–biomass), using 12 batches of fresh pineapples with each batch weighing about 20 kg, under different weather conditions.

Fudholi (2010) shows the experimental prototype direct forced convection hybrid solar dryer. LPG was used directly as an auxiliary heating fuel. It was found that an average fuel saving of 28 percent was possible. The average overall airing thermal efficiency was found to be 40.5 percent.

A forced convection solar grain drying system operated by diesel engine was constructed and tested by Soponronnarit (1995). Maximum loading of this dryer was found to be 10 tons of paddy.

## **2.8 Study with different heat storage materials**

Effect of heat storage materials to increase the internal energy inside the dryer and to minimize the heat loss from the system are reported by many investigators (Esper and Mühlbauer (1999), Wahidi and Rohani (2001)). Literature review related to heat storage material are divided in 2 (two) subsection, viz, (1) sensible heat storage and (2) Latent heat storage and are reported as follows:

### **2.8.1 Sensible Heat storage**

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat and thermo chemical or combination of these. In sensible heat storage, thermal energy is stored by raising the temperature of a solid or liquid material. Amount of heat stored depends on the specific heat of the medium, the change in temperature and the amount of storage material. Latent heat storage is one of the most efficient ways of storing thermal energy. Unlike the sensible heat storage method, the latent heat storage method provides much higher storage density, with a smaller temperature difference between storing and releasing heat (Sharma et. al 2007).

El-Sebali et al. (2002) designed an indirect type natural convection solar dryer with sand as thermal energy storage material. They dried different products such as, grapes, figs, apples, green peas, tomatoes and onions and compared the performance of the dryer with and without the storage material. It was reported that the quality of the dried products was better with storage materials. Maximum temperature of the drying air was reported to be about 60 °C.

Madhlopa and Ngwalo (2007) designed an indirect type natural convection solar dryer with integrated solar collector with storage materials and biomass-backup heaters.

The major components of the dryer were biomass burner, thermal storage mass and drying chamber (with a conventional solar chimney). The thermal mass was placed in the top part of the biomass burner enclosure. They found that the thermal mass was capable of storing part of the absorbed solar energy and heat from the burner.

Sopian et al. (2007) performed the experimental studies on the performance of a double-pass solar collector with porous media in the lower pass. They reported increase in outlet temperature of drying air and improvement in the performance of the system.

Tarigan and Tekasakul (2005) reported on the a mixed-mode natural convection solar dryer capable of drying 60-65 kg of wet groundnut. The device was integrated with a simple biomass burner and solid bricks as heat storage and a back-up heating system (Fig.2.4). The drying efficiency of the solar component alone was found to be 23%. The efficiency of the burner with heat storage in producing useful heat for drying was found to be 40%.

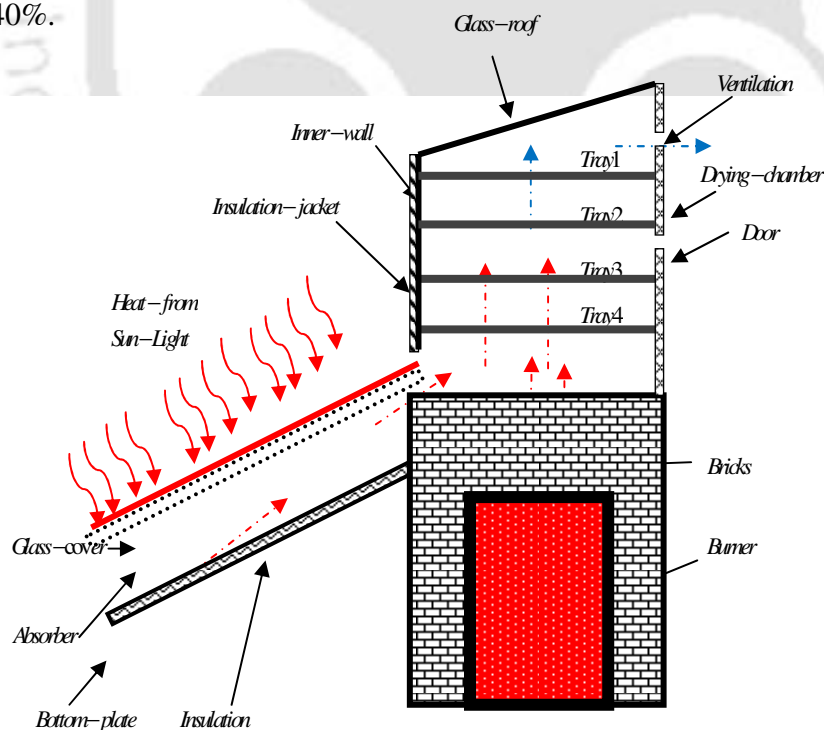


Fig:2.4-Cross-section through the dryer: side view  
(Tarigan and Tekasakul, 2005)

Sharma *et al.* 2009 had reported the properties of various solid and liquid materials for sensible heat storage. Working temperature of the storage materials were also reported as shown in Table 2.1.

Table 2.1 Properties of sensible heat storage materials. (Sharma *et al.* 2009)

Medium	Fluid type	Temp. Range (°c)	Density (kg/m <sup>3</sup> )	Sp. Heat (J/kg.k)
Rock	-	20	2500	879
Brick	-	20	1600	840
Concrete	-	20	1900-2300	880
Water	-	0-100	1000	4190
Engine oil	Oil	Up to 160	888	1880
Ethanol	Organic liquid	Up to 78	790	2400

### 2.8.2 Study related to Phase change materials

One of prospective techniques of storing thermal energy is the application of phase change materials (PCMs). Latent heat storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas and vice versa. The use of latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process. PCMs have been widely used in latent heat thermal storage system. Unlike conventional (sensible) storage materials, PCMs absorb and release heat at nearly constant temperature. They store 5-14 times more heat per unit volume than sensible storage materials such as water, masonry or rock (Sharma *et al.* 2009). Commercially available paraffin waxes are cheap with moderate thermal energy storage densities and wide range of melting temperatures. They undergo negligible sub cooling and are chemically inert and stable with no phase segregation (Farid, 2004). Esakkimuthu *et al.* (2013) studied the feasibility of using the

phase change material HS-58 in a latent heat storage unit, integrated with a solar air heater to store the excess energy.

Akgün *et al.* (2008) had done experimental study in order to study the melting and solidification processes of paraffin wax as a phase change material (PCM) in a tube in shell heat exchanger system. They had determined thermo physical properties of the paraffin wax through differential scanning calorimeter (DSC) analysis. Experiments were conducted to study the effect of increasing the inlet temperature of air and the mass flow rate of the heat transfer fluid both on the charging and discharging processes (i.e. melting and solidification) of the paraffin wax.

Sharma *et al.* (2009) had reported on the available thermal energy storage technology with PCMs with different applications. This paper incorporated the assessment of the thermal properties of various phase change materials. The heat storage applications used as a part of solar water-heating systems, solar air heating systems, solar cooking, solar green house, space heating and cooling application for buildings, off-peak electricity storage systems, waste heat recovery systems. This paper discusses about the properties of different paraffin grades as PCM for various application as shown in Table 2.2. He further discussed the melting point and latent heat of fusion of different paraffin grades based on number of carbon atoms as indicated in table 2.3

Table 2.2- Physical properties of some paraffin (Sharma, 2009)

Paraffin Grade	Freezing point/range (°c)	Heat of fusion (kJ/kg)	Group
6106	42-44	189	I
P116	45-48	210	I
5838	48-50	189	I
6035	58-60	189	I
6403	62-64	189	I
6499	66-68	189	I

Table 2.3 Melting point and latent heat of fusion of paraffin (Sharma 2009)

No.of carbon atoms	Melting point(°c)	Latent heat of fusion(kJ/kg)	Group
14	5.5	228	I
15	10	205	II
16	16.7	237.1	I
17	21.7	213	II
18	28.0	244	I
19	32.0	222	II
20	36.7	246	I
21	40.2	200	II
22	44.0	249	II
23	47.5	232	II
24	50.6	255	II
25	49.4	238	II

Farid *et al.* (2004) had reported previous work on latent heat storage material and provided an insight to current efforts to develop new classes of phase change materials (PCMs) for use in thermal energy storage. Three aspects had spotlight of this review: PCM materials, encapsulation and applications of the materials. Different parameters of phase change material were considered such as thermal conductivity, thermal energy storage density, super cooling and cost. The different applications in which the phase change method of heat storage can be functional and problems related with PCMs application were also reviewed.

Py *et al.* (2001) had reported new type of phase change material (PCM). They impregnated paraffin wax in compressed expanse natural graphite (CENG) matrix by capillary forces. High loads of paraffin wax were obtained from 65% to 95% weight depending upon the bulk graphite matrix. Thermal conductivity had been increased in new type of material. The CENG induced a reduce in overall solidification time period and a stabilization of the thermal storage power.

Enibe (2002) designed and evaluated a passive solar powered air heating system for the crop drying and poultry egg incubation consists of a single-glazed flat-plate solar collector integrated with a phase change material (PCM) heat storage system. The PCM is prepared in modules, with the modules equi-spaced across the absorber plate as shown in fig. 2.5.

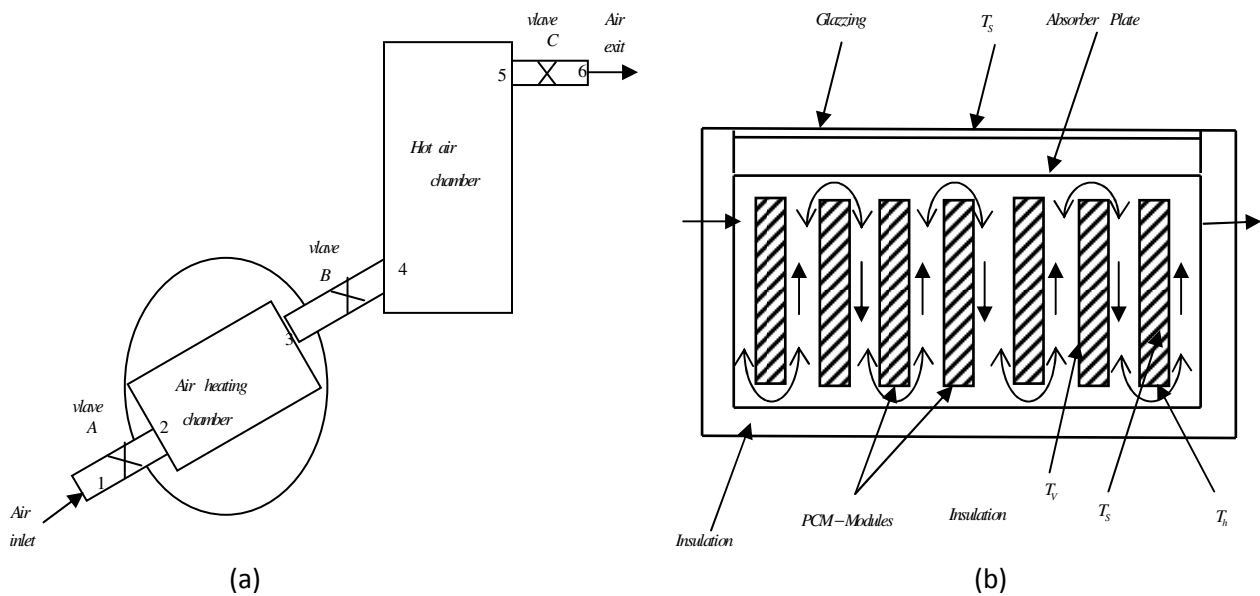


Fig. 2.5: (a) Schematic view of a natural convection solar dryer (b) Cross-section view of the solar collector (Enibe 2002)

The spaces between the module pairs serve as the air heating channels, the channels being connected to common air inlet and discharge headers. Performance improvement of the dryer was discussed by him.

Sari and Kaygusuz (2002) had determined heat transfer characteristics of lauric acid during the melting and solidification processes in a vertical double pipe energy storage system. Based on the performance analysis they determined the correlation between the heat transfer coefficient with Reynolds number and Stefan number. The results indicated that the average heat transfer coefficient and the heat flow rate were affected by the Reynolds and Stefan numbers. Variations were more important during the melting process compared to the solidification process.

Farid et al. 2004 had presented various properties of heat storage materials as shown in Table 2.4.

Table 2.4: Comparison between the different methods of heat storage. [Farid et al. 2004]

Property	Rock	Water	Organic PCM	Inorganic PCM
Density, kg/m <sup>3</sup>	2240	1000	800	1600
Specific heat, kJ/kg	1.0	4.2	2.0	2.0
Latent heat, kJ/kg	-	-	190	230
Latent heat, kJ/ m <sup>3</sup>	-	-	150	368
Storage mass for 10 <sup>6</sup> J, kg	67,000	16,000	5,300	4,350
Storage volume for 10 <sup>6</sup> J, m <sup>3</sup>	30	16	6.6	2.7
Relative storage mass	15	4	1.25	1.0
Relative Storage volume	11	6	2.5	1.0

## 2.9 Energy and Exergy analysis of the dryer

Energy and exergy analysis of drying system are important for understanding and improving the energy utilization (Akpınar et al. 2005, Bolaji 2011, Saidur et al. 2012).

Most of the dryers reported in earlier subsections were reported to be of low thermal efficiency attributing to significant losses of thermal energy of the system. A thorough understanding of energy and exergy analysis can help in overall improvement of performance of dryers. Very limited studies were reported in literature on these aspects (Midilli and Kucuk 2003).

Midilli and Kucuk (2003) analyzed the energy and exergy of the drying process of shelled and unshelled pistachios using a solar drying cabinet. Energy analysis was carried to estimate the amounts of energy gained from solar air collectors and the ratios of energy utilization. Exergy analysis was accomplished to determine the location, type, and magnitude of exergy losses during the solar drying process. They found that the exergy

losses took place mostly in the 15th shelf where the available energy was less utilized. They also found that the shelled and unshelled pistachios are sufficiently dried in the ranges between 40 and 60 °C. The highest exergetic efficiency was obtained during the solar drying of shelled pistachios. Billiris et al. (2011) reported the energy requirement in drying of paddy and found that energy requirement for parboiled paddy is significantly less than non-parboiled paddy.

Gupta and Kaushik (2008) established the optimal performance parameters for the maximum exergy delivery during the collection of solar energy in a flat-plate solar air heater. The procedure to determine optimum aspect ratio (length to width ratio of the absorber plate) and optimum duct depth (the distance between the absorber and the bottom plates) for maximum exergy delivery has been developed. The energy and exergy output rates of the solar air heater were evaluated for various values of collector aspect ratio (AR) of the collector, mass flow rate per unit area of the collector plate (G) and solar air heater duct depth (H). They found that based on the exergy output rate; there must be an optimum inlet temperature of air and a corresponding optimum G for any value of AR and H.

Celma and Cuadros (2009) analysed the energy and exergy of the drying process of olive mill waste water (OMW) by using an indirect type of natural convection solar dryer. Olive mill wastewater gets sufficiently dried at temperatures between 34<sup>o</sup> C and 52<sup>o</sup> C. Under these experimental conditions, two days were needed to reduce the moisture content to approximately one-third of the original value. Energy analysis was carried out to estimate the amounts of energy gained from solar air heater and the ratio of energy utilization of the drying chamber. Exergy analysis was developed to determine the type and magnitude of exergy losses during the solar drying process. The maximum values of the exergy inflow to the drying chamber were found to be 0.345 kJ/kg and 0.272 kJ/kg during the first and second days, respectively.

Akbulut and Durmus (2010) analysed the energy and exergy of the thin layer drying process of mulberry via forced solar dryer. The drying experiments were conducted at different five drying mass flow rate varied between 0.014 kg/s and 0.036 kg/s. The effects of inlet air velocity and drying time on both energy and exergy were studied. They found the values of energy utilization ratio are 55.2%, 32.19%, 29.2%, 21.5% and 20.5% for the five different drying mass flow rate ranged between 0.014 kg/s and 0.036 kg/s. They also found the values of exergy loss were found to be as 10.82 W, 6.41 W, 4.92 W, 4.06 W and 2.65 W with the drying mass flow rate varied between 0.014 kg/s and 0.036 kg/s. They concluded that both energy utilization ratio and exergy loss decreased with increasing drying mass flow rate while the exergetic efficiency increased.

Akinola and Fapetu (2006) evaluated the utilization of energy in a mixed-mode solar dryer. Exergetic analysis of the dryer revealed that drying in a cabinet other than direct sun drying made drying more attractive and as well conserve energy. It has an overall average exergetic efficiency of 56% and thermal efficiency of 66.95%.

Akpinar et al. (2005) concerned with the energy and exergy analyses of the single layer drying process of potato slices via a cyclone type dryer. An energy analysis was performed to estimate the ratios of energy utilization. An exergy analysis was accomplished to determine the location, type and magnitude of the exergy losses during the drying process. It was concluded that the exergy losses took place mostly in the 1st tray where the available energy was less utilized during the single layer drying process of potato slices. It is emphasized that the potato slices are sufficiently dried in the ranges between 60 and 80 °C and 20–10% relative humidity at 1 and 1.5 ms<sup>-1</sup> of drying air velocity during 10–12 h despite the exergy losses of 0–1.796 kJ s<sup>-1</sup>.

Prommas et al. (2010) investigated the energy and exergy analyses in drying process of porous media using hot air was investigated. Drying experiments were conducted to find the effects of particle size and thermodynamics conditions on energy and exergy profiles. An exergy analyses was performed to determine the exergy inlet,

exergy outlet, exergy losses and efficiency during the drying process. The results show that energy utilization ratio (EUR) and exergy efficiency depend on the particle size as well as hydrodynamic properties. Furthermore, the results of energy and exergy presented in this paper can be applied to other porous drying processes which concern effect of porosity as well as grain size.

### 2.10 Summery

The literatures presented in this paper are generally for the commercial purpose. These dryers are expensive and of complex mechanism, which is not affordable and understandable by the farmers. Maximum types of dryers are forced convection type, which required enormous amount of electrical energy. Since many rural locations in developing countries grid connected to electricity and supply of other sources of energy are unavailable so it is difficult to implement the same in the village scale.

In the present experiment a natural convection dryer is designed and developed with easily available materials which is operated without any electricity and the setup can run in any seasons throughout the year.

## CHAPTER 3

# THEORETICAL BACKGROUND AND DESIGN OF NATURAL CONVECTION GRAIN DRYER

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### 3.1 Introduction

In this chapter drying mechanism, drying kinetics and moisture transfer in drying are discussed. Various theories related to heat transfer, amount of moisture transfer, heat gain by air, energy and exergy analysis, calculation of equilibrium moisture content, different thin layer drying equation and the design principles for biomass burner and drying chamber are present.

### 3.2. Concepts of thin layer drying

Jayas et al (1991) defined a thin layer as a thickness meeting the requirement that the temperature and relative humidity of the drying air does not change when passing through the grain layer in the drying process. The drying conditions of rough rice meeting the requirement of a thin layer drying have been studied by Takahara(1988a,1988b).The experimental design of Takahara(1988b) included three thickness of rough rice (0.7,1.7,and 2.7cm)and two air flow rates(air velocity is 0.2 and 0.4 m/sec). No significant difference was found among these drying curves. It was conclude that the effect of air speed on the drying curves could be negligible when the air velocity was higher than 0.2m/sec. Generally, up to 20 cm thickness of grain bed (with a recommended air-grain ratio) is taken as thin layer (Chakraverty, 2006). All commercial flow dryers are designed on thin layer drying principles.

### 3.3 Thin layer drying mechanism

Removal of moisture from thin layer of paddy takes place in two stages as shown in Fig.3.1. These are

1. Constant-rate period
2. Falling-rate period

### 3.3.1 Drying during constant-rate period

During the constant-rate period, the surface of the paddy remains wet, the temperature and evaporation rate remain constant. Drying during this period is the same to the evaporation of moisture from a wetted surface of paddy. The heat transfer here is only by convection from the air. Here the surface remains at a constant temperature.

Mass transfer can be expressed as follows, Zaman and Bala (2001)

$$\frac{dM}{dT} = -kA(M - M_e) \quad (3.1)$$

where  $M$  is the moisture content of the paddy at any time (% w.b.),  $M_e$  is equilibrium moisture content,  $k$  is drying constant ( $\text{h}^{-1}$ ),  $T$  drying time and  $dM/dT$  represents the moisture gradient.

When the surface of the paddy appears to develop dry patches, the rate of drying begins to decline, as the internal resistance of the paddy to liquid diffusion to the surface becomes significant. When the constant-rate period ends and the falling-rate period starts, the moisture content of the paddy is called as the critical moisture content shown in figure 3.1.

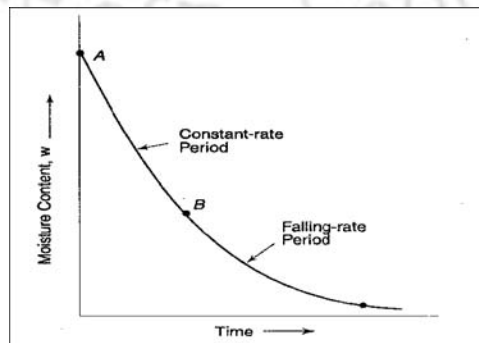


Figure. 3.1 Drying Process, (Arora, 2001)

### 3.3.2 Drying during falling rate period

Drying of paddy during the falling-rate period begins when the paddy reaches a critical moisture-content level. The rate of migration of moisture from the interior to the surface of the paddy becomes less than the rate of evaporation of moisture from the surface. Accordingly, during this stage, the rate of drying is inhibited by the rate of migration of moisture (Dandotiya 2009).

There are different mechanisms of migration of moisture from the interior of the paddy. Some of them are as follows:

1. Movement of liquid due to capillary forces.
2. Liquid diffusion due to concentration difference.
3. Surface diffusion of the liquid fascinated at the boundary of the solid.
3. Diffusion of water-vapor by partial-pressure difference.

### 3.4 Establishment of thin layer drying equation for raw paddy

Several models have been projected to explain the heat and mass transfer processes in the basic types of convective grain dryer, namely cross-flow, concurrent-flow, fixed bed and counter-flow.

Amongst the various models available, however a number of differences which are not always discussed in the literature present.

In thin layer drying experiments of paddy, air at constant temperature, humidity, and mass flow rate is passed through a thin layer of moist paddy. Thin layer drying takes place in two or more dissimilar periods. First, in very wet paddy, there is a stage during which evaporation takes place at steady rate, almost as that from a free liquid surface. This is followed by another periods in which the evaporation rate constantly decreases.

These dissimilar periods are separated by critical moisture contents. mostly there are three types of grain drying modals:

Equilibrium, non-equilibrium and logarithmic model; (Dandotiya 2009)

In fixed bed: model is classified as:

- a) Low temperature drying models which is 5°C more than the atmospheric air temperature.
- b) High temperature drying model which is 60°C greater than the atmospheric air temperature.

The Newton's model, is comparable to a one-term model that uses the first term of a general series solution of Flick's second law of diffusion, but it appears to be inadequate representation of the drying behavior of most agricultural materials particularly in high temperature drying applications. Therefore, to provide better fits to experiential data, a variety of similar one-term models connected to the thin-layer drying equations have been introduced. For example, Page modified the Newton's model by adding  $n$  (an empirical constant). Non equilibrium and logarithmic models can be applied in any type of grain drying systems. Page's equation for thin drying (Basunia and Abe, 2001)

$$R_m = \frac{M - M_e}{M_i - M_e} = \exp(-Kt^n) \quad (3.2)$$

$$N = 0.68293 + 0.01094T + 0.017036R_H \quad (3.3)$$

$$K = 0.00561 - 0.000073T - 0.00169R_H \quad (3.4)$$

where  $R_m$  is the moisture ratio,  $M$  the moisture content of grain at any time, (% d.b.),  $M_i$  initial moisture content of grain, (% d.b.),  $M_e$  the equilibrium moisture content (EMC) of grain, (% d.b.),  $t$  the drying time (h),  $K$  and  $N$  are the drying parameters are calculated by the above equation (Srivastava and Johan, 2002).  $R_H$  is the relative humidity in decimal.

$T$  is the temperature in ( $^{\circ}\text{C}$ ). Multiple regression procedure is used to find out the expression for  $N$  and  $K$ . The multiple regression analysis for  $N$  and  $K$  is function of temperature  $T$  in ( $^{\circ}\text{C}$ ) and relative humidity  $R_H$  in decimal.

A two-term solution which uses the first two terms of a general series solution of Flick's second law of diffusion, was also introduced (Pabis, 1998).

$$MR_{Two-term} = a \exp(-K_1 t) + b \exp(K_2 t) \quad (3.5)$$

Where  $k_1$  and  $k_2$  are drying constant ( $\text{min}^{-1}$ ) and  $a$  and  $b$  are empirical constants.

#### Remarks on thin layer drying equation

1. The theoretical drying equations are based on the concept that all grains in thin layer are fully exposed to the drying air under constant drying conditions (at constant drying air temperature and humidity) and dried uniformly. Therefore, there is no gradient in thin layer of grain which is not true for finite mass depths.
2. It is not possible to choose accurate boundary conditions and shape factors for drying of biological materials.
3. Drying equation developed from Newton's equation for heating or cooling does not take into account of the shape of the material.

### **3.5 Kinetics of drying**

In the drying process thermal energy is used to evaporate the moisture from the paddy and moving air to carry away the evaporated moisture. The moisture removal rate is determined by the temperature, initial moisture, and variety of the paddy. The moisture removal rate is also affected by relative humidity, and the volume of air passing through the grain. The drying method, type of dryer, and efficiency of the dryer also affect the rate of moisture removal. The higher the initial moisture content of the paddy, the longer it will take to dry. In general, the higher the drying air temperature, the faster the

moisture removal rate. However, very high drying air temperature may cause checking of the paddy grain which in turn causes breakage during milling and reduced output. Air with very high relative humidity dries slowly. Air with low relative humidity has the ability to absorb more moisture and dries the paddy faster. The process that occurs during drying of paddy grains includes the movement of water through the interior of the grain and the loss of water vapor from the surface of paddy grain. The occurrence of the latter process depends on the difference between the vapor pressure of the drying air and the vapor pressure of the water present in the paddy grain. When these vapor pressures are equal, the moisture content within the paddy grain remains constant called the equilibrium moisture content (EMC) (Arora, 2001)

Paddy should not be dried too rapid. The moisture removal process should be slow and uniform to maintain quality of paddy. Paddy gives up surface moisture content easily and rapidly, but holds moisture in the center of the kernel for longer time. Very fast drying of paddy may cause internal grain stress, which leads to checking and subsequent breakage during milling process. If surface moisture is removed too quickly, the outer layers of paddy contract and the high temperature used for drying process causes expansion that results in more internal stress. If the temperature of the drying air is raised by only a few degrees, the relative humidity of even humid air is lowered enough to make it effective for paddy drying. Most cereal grains at the time of harvesting contain moisture contents of between 20 and 30% wet basis. The safe storage moisture content is of the order of 14-15% wet basis for paddy (IRRI, 2005, Dandotiya, 2009).

### **3.6 Design methodology of dryer**

Based on preliminary investigations under controlled (or different) conditions of drying experiments, a domestic natural convection biomass dryer for agricultural applications was successfully designed, constructed, and characterized to dry paddy. The dryer is an integral and indirect type made from locally available material such as sand, bricks, cement, pebble etc.

Three main components of the dryer can be identified: an air heater (biomass burner), in which biomass is burned and burner surface is heated. The air which is in contact with the burner gets heated and moves upward to pick up the moisture; a drying chamber, in which hot air is produced due to natural convection and the paddy, is dried. The drying chamber has a rectangular drying surface area and it houses one paraffin wax tray for quality drying purpose and drying tray for the drying of paddy in batch wise; and an exhaust system through which flue gases flows to the outside so that there is no contamination of smoke in the product. Small arrangements are done for stirring of the paddy in the tray, feeding of biomass in the burner and arrangement for easy burning of biomass inside the dryer. Doors are provided for loading of biomass inside the burner. Pebbles are used inside the dryer to store the heat and paraffin wax for quality drying. Keeping the same in mind, design of different components of the dryer is done and is discussed here in the next section.

### **3.7 Design methodology of different components of dryer**

A conical shape biomass burner is designed for combustion of fire wood and loose biomass. The burner is made up by a simple and easily available material so that any persons can easily understand the burner operation system and it is very economical. It can be used for long time without any difficulty.

#### **3.7.1 Design criteria of biomass burner**

The basic design criteria of a biomass burner are based on the following requirements:

- ❖ The heating is indirect, i.e. flue gases from the chimney and the drying air could not be mixed. This protects the product from contamination by smoke, soot and ash of the flue gases.
- ❖ Sufficient air should flow to the furnace for complete burning of biomass.
- ❖ Proper combustion of biomass inside the furnace.

- ❖ Passage of flue gases through the exhaust pipe by creating sufficient draft.
- ❖ Care should taken for making holes in the biomass burning plate (BBP), so that easy removal of ash to the ash tray and no burning pieces of wood chips drop to the ash tray through the hole.
- ❖ Removal of ash to the outside should be easy.
- ❖ Biomass feeding process should be easy so that labour charge can be minimized.
- ❖ All the parts of the furnace are assembled in such a method that they can be separated at any time for maintenance and redesign of the dryer.
- ❖ The cost of the material of the furnace should be less, so that rural people can easily asses.

The basic equations to be used for design calculations and all other relevant information required are presented in this section.

The thermal power lost to atmosphere through the flue gas passes through the exhaust pipe:

$$\dot{Q}_{fg} = \dot{m}_{fg} C_{fg} (T_{fge} - T_{amb.}) \quad (3.6)$$

where  $\dot{m}_{fg}$  is the mass flow rate of flue gas,  $C_{fg}$  is the specific heat capacity of the flue gas,  $T_{fge}$  is the temperature of flue gas exit from the biomass burner (K),  $T_{amb.}$  is the ambient temperature (K).

Pressure drop through the biomass burner:

$$\Delta p = gH (\rho_a - \bar{\rho}_{fg}) \quad (3.7)$$

$$\rho_a - \bar{\rho}_{fg} = \frac{P_a}{R} (T_a - \bar{T}_{fg}) \quad (3.8)$$

where  $\Delta P$  is the draught or pressure differences produced ( $N/m^2$ ),  $H$  is the height of the chimney,  $P_a$  is the atmospheric pressure ( $1.01 \times 10^5$  pa),  $\rho_a$  is the density of atmospheric air,  $\bar{\rho}_{fg}$  is the average gas density in the chimney,  $T_a$  is the absolute ambient air temperature (K),  $\bar{T}_{fg}$  is the absolute average temperature of the flue gas inside the chimney (K).

Calculation of burner efficiency:

$$\text{Efficiency of the burner} = \frac{\text{heat transferred to air entering the drying chamber}}{\text{calorific value of wood used}} \quad (3.9)$$

### 3.7.2 Description of the biomass burner

Bio mass burner used for heating the ambient air was designed and fabricated at Workshop of IIT Guwahati. The biomass burner consisted with several parts: conical furnace, perforated biomass burning plate (BBP), biomass feeding pipe (BFP), ash tray, rectangular base over which furnace is placed, cover plate and connection of exhaust pipe on the upper end of the furnace through nipple. One end of the conical furnace was kept on the biomass burning plate which is laid on the rectangular base. Other end of the conical furnace is smaller in diameter and closed only a small opening of diameter 7cm connected to the horizontal exhaust pipe through a nipple and socket. Another vertical exhaust pipe through which flue gas exhaustion takes place connected to this horizontal pipe by a socket. Burner grate (BBP) is constructed from a perforated plate supported on the angles of the stand and ash is collected on the ash tray. Three sides of the rectangular stand over which BBP and conical furnace are kept is closed. Only front side is opened for air flow. There is a fix projection of 30 cm to the outside from the front. A movable ash tray is placed on the angles of projection for the removal of ash after burning of biomass. A handle is joined on ash tray for easy handling. A cover plate is used to cover

the projection of 30 cm. For the feeding of biomass from outside of the wall into the conical furnace, an inclined thin circular pipe whose one end of diameter 20 cm is connected to the conical furnace . The other end of diameter 13.5 cm is kept on the small opening of the wall. The inside and outside end of the biomass feeding pipe is at the height of 40cm and 70cm from the ground respectively. The length of the biomass feed pipe is 23cm. A circular thin plate of diameter 20 cm is hinged at the inside end of the biomass feeding pipe, so that when biomass will pour at the outside end it will impact so that hinged plate will open and biomass will go into the biomass burning plate. When biomass pouring is finish it will close so that flue gas and heat will not come outside through the biomass feeding pipe. Biomass feeding pipe is used for both biomass supply and air supply when required for burning of biomass. A small rectangular tray of dimension 25cm×10cm×8cm are made for drying of wood and other products (small amount) and are kept inside the biomass feed pipe (BFP). The conical furnace, rectangular stand, ash tray, cover plate, biomass burning plate and exhaust pipe are easily disassembled to different parts when required for maintenance. Thermocouples are connected to exhaust pipe and conical furnace to measure the temperature of flue gases and the temperature generated inside the furnace respectively. The specifications of different components of biomass burner are given in table 3.1. Table 3.2 presents design conditions and assumptions.

Table-3.1. Component and specification of furnace.

Component	Specifications
1.Furnace a. Shape b. Dimension c. Thickness d. Height e. Material	Conical $\varnothing_1=30\text{cm}$ , $\varnothing_2=60\text{cm}$ 5mm 68 cm Mild steel

<p>2. Biomass burning plate</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Rectangular</p> <p>59 cm × 59 cm</p> <p>5 mm</p> <p>GI Sheet</p>
<p>3. Biomass feeding pipe</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Circular pipe of varying diameter</p> <p><math>\text{Ø}_1=13.5 \text{ cm} \times 20 \text{ cm}</math></p> <p>5 mm</p> <p>Mild steel</p>
<p>4. Ash tray</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Rectangular</p> <p>60 cm × 60 cm × 2 cm</p> <p>5 mm</p> <p>Mild steel</p>
<p>5. Stand (Base)</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Rectangular</p> <p>61 cm × 61 cm × 22 cm</p> <p>10 mm</p> <p>Mild steel</p>
<p>6. Cover plate</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Rectangular</p> <p>43 cm × 62 cm × 22 cm</p> <p>5mm</p> <p>Mild steel</p>
<p>7. Exhaust pipe (Horizontal)</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Circular</p> <p>L = 200cm, <math>\text{Ø}= 6.35\text{cm}</math></p> <p>10 cm</p> <p>GI sheet</p>
<p>8. Exhaust pipe (Vertical)</p> <p>a. Shape</p> <p>b. Dimension</p> <p>c. Thickness</p> <p>d. Material</p>	<p>Circular</p> <p>L = 180 cm, <math>\text{Ø} = 6.35 \text{ cm}</math></p> <p>10 cm</p> <p>GI sheet</p>

<p>8. Nipple                  a. Shape                  b. Dimension                  c. Thickness                  d. Material</p>	<p>Circular  <math>\text{Ø} = 6.35\text{cm}</math>                  10mm                  GI sheet</p>
<p>9. Socket                  a. Thickness                  b. Material</p>	<p>10mm                  GI sheet</p>

Figure 3.2 to 3.4 shows the different component and schematic diagram of biomass burner

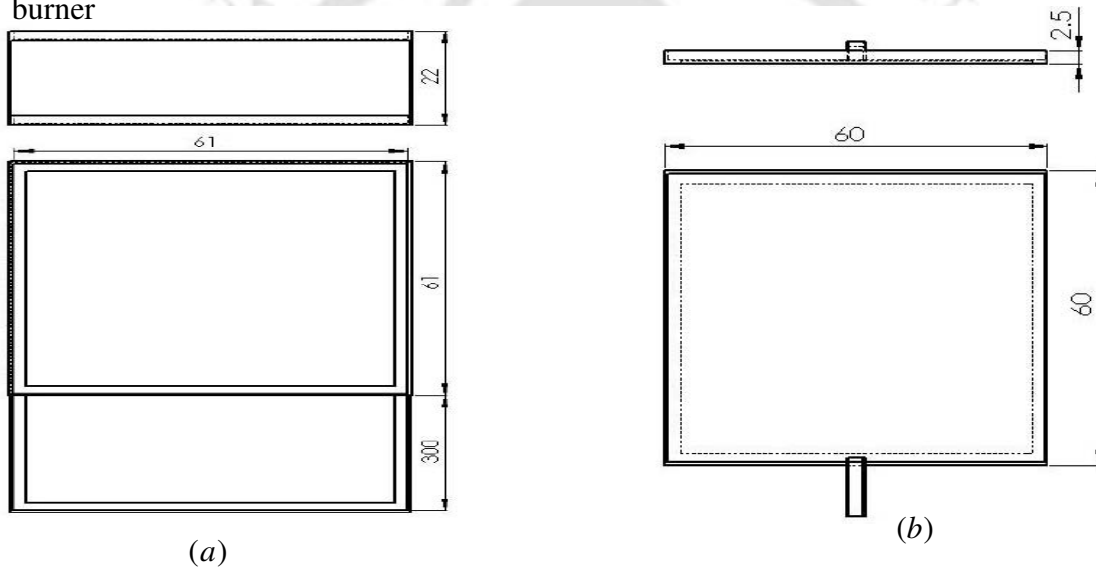


Fig.3.2: (a), (b) Schematic diagram of the base and ash tray

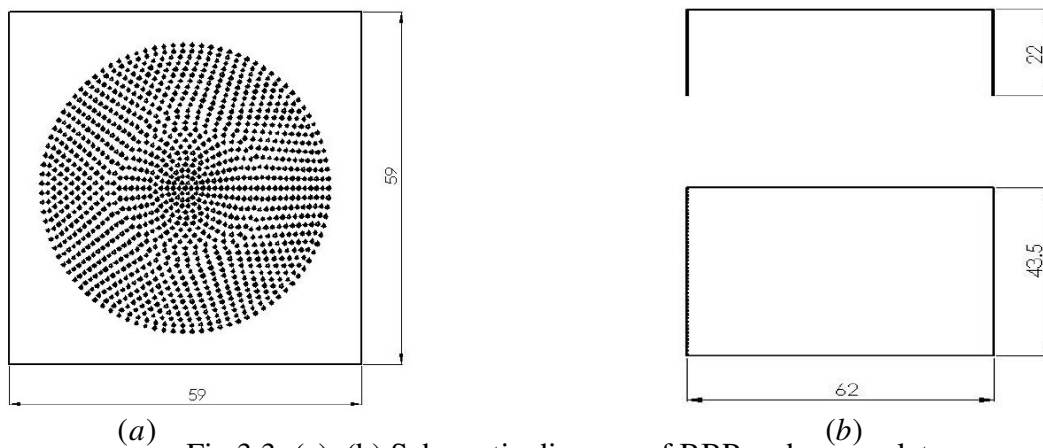


Fig.3.3: (a), (b) Schematic diagram of BBP and cover plate

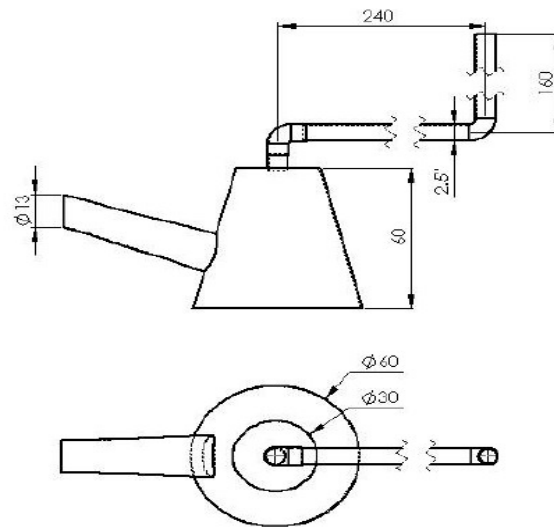


Figure 3.4: Schematic diagram of burner and exhaust pipe

**Table 3.2. Design conditions and assumptions**

Sl. no	Items	Condition or Assumption
01	Location	IIT Guwahati
02	Crop	Paddy (Rice)
04	Drying per batch	10 kg, 15 kg, 20 kg, 25 kg
05	Initial moisture content ( $X_1$ )	~ 30% (wb)
06	Final moisture content ( $X_2$ )	~ 14% (wb)
07	Ambient air temperature, ( $T_{am}$ )	~ 18 °C
08	Ambient relative humidity ( $R_{Ham}$ )	~ 65%-75%
09	Temperature of the heated air	50-65 °C

### 3.7.3 Design methodology of drying chamber

Drying chamber is the part of the natural convection dryer where the drying of paddy grain takes place. A rectangular shape drying chamber encloses the conical shape furnace

is designed and constructed. Heat supplied from the biomass burner is transferred to the drying chamber by the principle of natural convection. The drying chamber is made up by easily available materials and constructed by local artisans (Figure 3.5). The novelty of the dryer is that it can be operated by even the unskilled laborer.



Figure 3.5: Picture of dryer constructed by local artisan

#### 3.7.4 Design criteria of drying chamber without storage material

The basic design criteria of a drying chamber is based on the following requirements

- ❖ Required amount of air should flow to the drying chamber and heated for the drying of paddy.
- ❖ Placing of biomass burner inside the drying chamber so that uniform raise of ambient air temperature and also the uniform drying of paddy.
- ❖ Avoid the excessive raise of temperature inside the dryer by regulating air flow rate and feeding of biomass to the burner.
- ❖ Care should be taken to avoid losses of heat.

- ❖ The dryer is divided into different geometrical sections to know the temperature at various points for better thermodynamic analysis.
- ❖ The construction materials should be locally available and the cost of the materials should be less.

### **3.7.5 Design criteria of drying chamber with Storage materials.**

It is difficult to control the drying air temperature during drying and heat loss to the ambient when there is no storage material. So it is necessary to store the heat and use it for the drying of more number of batches of paddy for longer duration. To store the heat a sensible heat storage material (SHSM) is used. For drying of any agricultural products a constant range of temperature is required to retain the quality. By using only sensible heat storage material will not solve the problem of quality drying. To get constant range of temperature a phase change material is used.

- ❖ The specific heat capacity of sensible heat storage materials should be high.
- ❖ There should be sufficient void space between the storage materials so that air flow between the materials is possible.
- ❖ Amount of heat storage materials used depends on the amount of heat produced.
- ❖ The phase change material used should be non toxic, non reactive and non hazardous.
- ❖ The evaporation temperature and flash point of the phase change material should be high, so that there is no contamination of material with paddy and no chance of getting fire on the material.
- ❖ It should store sufficient amount of heat during phase change from solid to liquid and release heat for longer period at a constant range during the solidification.
- ❖ The cost of storage material should be less.

- ❖ The storage materials should be locally available.

The formula used for the calculation of amount of heat store as sensible heat in the pebble, amount of heat store during melting of paraffin wax, amount of drying air required for drying, amount of moisture removed from the paddy, heat required to evaporate the moisture from the paddy and the efficiency of the dryer is given.

- Thermal buoyancy ( $\Delta P$ ) produced due to density difference:

Air flow is induced by the temperature difference of air inside the drying chamber and ambient air. The thermal buoyancy ( $\Delta P$ ) produced in the drying system (Bala and woods, 2001)

$$\Delta p = \beta \rho_a g H (\Delta T) \quad (3.10)$$

$\Delta T$  is the temperature difference between ambient and drying air temperature (K),  $\beta$  is the coefficient of thermal expansion ( $K^{-1}$ ),  $\rho_a$  is the density of ambient air ( $kg/m^3$ ),  $g$  is the acceleration due to gravity, and  $H$  is the vertical height (m).

- Pressure drop through the drying bed:

Pressure drop through the dryer is due to the temperature differences or due to density differences is given by (Forson, 2005)

$$\Delta p_D = gH (\Delta \rho) = gH (T_a^{-1} - T_o^{-1}) \frac{P_a}{R} \quad (3.11)$$

$$\Delta \rho = \rho_a - \rho^*$$

$\rho_a$  is the density of ambient air ( $kg/m^3$ ),  $\rho^*$  is the average air density inside the dryer ( $kg/m^3$ ),  $T_a$  is the ambient air temperature (K),  $T_o$  is the temperature of drying air above the biomass burner (K).  $P_a$  Atmospheric pressure and the value is  $1.01 \times 10^5$  pa,  $R = 2.9 \times 10^2$  J  $kg^{-1}K^{-1}$

➤ Determination of convective heat transfer coefficient and amount of heat transfer:

Total heat transfer rate from the entire surface area of the biomass burner to the surrounding air in case of natural convection depends on the heat transfer coefficient.

$$Q_c = h_c A (T_s - T_a) \quad (3.12)$$

$h_c$  is the heat transfer coefficient ( $\text{W/m}^2\text{K}$ ),  $A$  is the total surface area of biomass burner,  $T_s$  is the burner surface temperature and  $T_a$  is the surrounding fluid temperature.

Heat transfer coefficient in case of natural convection can be determined from Grashof number and Prandtl number. [Nag, 2006]

$$Nu = \frac{h_c X}{k_v} = C (Gr \cdot Pr)^n \quad (3.13)$$

Correlationship of heat transfer with Grashoffs ( $Gr$ ) and Prandtls number ( $Pr$ ) for the present configuration (similar to a horizontal plate heated from below) is given by [Ozisik, 1985, Fujii and Imura, 1972]

$$Nu = \frac{h_c X}{k_v} = 0.58 (Gr \cdot Pr)^{\frac{1}{5}} \quad (3.14)$$

where  $Gr$  is the Grashof number ( $\beta g X^3 \rho^2 \Delta T / \mu_v$ ),  $Pr$  is the Prandtl number ( $\mu_v C_p / K_v$ ) and  $Nu$  is the Nusselt number ( $h_c X / K_v$ ). Equation 3.14 is valid for  $10^6 < Gr \cdot Pr < 10^{11}$ . This range of  $Gr \cdot Pr$  indicates the laminar natural convection. With the help of this equation Rayleigh number was calculated and found the same to be in the range of laminar natural convection. The calculation regarding same is given in Appendix II.

The rate of heat transfer on account of mass transfer to evaporate the moisture is given as [Jain and Tiwari, 2002]

$$Q_m = 0.016 h_c [P(T_c) - \gamma P(T_e)] \quad (3.15)$$

$P(T_c)$  is the partial vapor pressure at temperature  $T_c$  (crop temperature °C) (N/m<sup>2</sup>).  $P(T_e)$  is partial vapor pressure at temperature  $T_e$  (temperature just below the crop °C) (N/m<sup>2</sup>).  $\gamma$  is the relative humidity,  $\Delta T$  is the effective temperature difference (°C),  $\beta$  is the coefficient of volumetric expansion (1/°C).

➤ Amount of heat stored in the pebble:

Amount of heat stored in the sensible heat storage materials (pebble) due to the convective heat transfer from air to the pebble is given as [Atul and Sharma, 2004]

$$Q_p = \int_{T_{ip}}^{T_{fp}} m_p c_p dT_p = m_p c_{ap} (T_{fp} - T_{ip}) \quad (3.16)$$

where  $m$  is the mass of heat storage medium (kg),  $C_p$  is the specific heat (J/kg K),  $C_{ap}$  is the average specific heat between initial and final temperature of pebble J/kg K).  $T_{ip}$  is the initial temperature of the pebble (°C) and  $T_{fp}$  is the final temperature of the pebble (°C).

➤ Amount of heat stored as latent heat during melting of paraffin wax:

Quantity of heat stored in the paraffin wax is given by [Atul and Sharma, 2004]

$$Q_w = \int_{T_{iw}}^{T_{fw}} m_w c_{pw} dT + m_w a_m \Delta h_m + \int_{T_{mw}}^{T_{fw}} m_w c_{pw} dT \quad (3.17)$$

$$Q_w = m_w [C_{sw} (T_{mw} - T_{iw}) + a_m \Delta h_m + C_{lw} (T_{fw} - T_{mw})] \quad (3.18)$$

where  $m_w$  is the mass of heat storage medium i.e. paraffin wax (kg),  $T_{iw}$  initial temperature of paraffin wax (°C),  $T_{fw}$  is the final temperature of melted paraffin wax (°C),

$T_{mw}$  is the melting temperature of paraffin wax ( $^{\circ}\text{C}$ ),  $a_m$  fraction of paraffin wax melted,  $\Delta h_m$  is the heat of fusion per unit mass (J/kg),  $C_{pw}$  is the specific heat of paraffin wax (J/kg K),  $C_{sw}$  is the average specific heat between initial temperature and melting temperature of wax (kJ/kg K),  $C_{hw}$  is the average specific heat between melting and final temperature of wax (kJ/kg K).

- Amount of moisture removed from paddy:

The quantity of moisture removed ( $M_w$ ) from paddy can be found out from the following relationship [Forson, 2005]

$$M_w = \frac{W_p [M_{ip,wb} - M_{fp,wb}]}{(1 - M_{fp,wb})} \quad (3.19)$$

where  $M_w$  is the mass of water removed from wet paddy (kg),  $W_p$  is the initial mass of the paddy to be dried (kg),  $M_{ip,wb}$  is the initial moisture content of paddy on wet basis decimal,  $M_{fp,wb}$  is the final moisture content of paddy on wet basis decimal.

- Amount of drying air required for drying:

Rate of air supply in kg/min is given by the following relationship [Chakraverty, 2006]

$$G = \frac{Q_{da}}{S \cdot (t_{f,da} - t_{i,da}) \cdot \theta} \quad (3.20)$$

where,  $Q_{da}$  is the heat supplied by the drying air during drying period,  $S$  is the humid heat of ambient air,  $\theta$  is the total drying time,  $t_{i,da}$  is the initial drying air temperature and

$t_{f,da}$  is the final temperature of drying air.

$$S = 0.24 + 0.45H \quad (3.21)$$

where  $H$  is the absolute humidity of air.

- Heat required to evaporate the moisture from the paddy:

Amount of heat required to evaporate certain amount of moisture and to bring the moisture content to safe value is given by (Chakraverty, 2006). The different steps involved are as follows

Sensible heat required to raise the temperature of the of paddy ( $Q_1$ )

$Q_1 = \text{Wt. of bone dry paddy} \times \text{Sp. heat of grain (paddy)} \times \text{Temperature rise}$

$$Q_1 = W_{bdp} \times C_p \times (t_{p2} - t_{p1}) \quad (3.22)$$

$$W_{bdp} = W_{wp} \left( 1 - \frac{m_2}{100} \right) \quad (3.23)$$

Initial weight of wet paddy ( $W_{wp}$ ) =  $W_w + W_{bdp}$

$C_p$  is the Sp. heat of paddy (Kcal/kg °C) (0.42 for paddy),  $t_{p1}$  is the Initial temperature of paddy (°C),  $t_{p2}$  is the Final temperature of paddy (°C),  $W_w$  is the weight of moisture (kg),  $W_{bdp}$  is the weight of bone dried paddy (Kg),  $m_1$  is the initial moisture content in w.b and  $m_2$  is the final moisture content in w.b.

Sensible heat required to raise the temperature of moisture ( $Q_2$ )

$Q_2 = \text{Total weight of water} \times \text{Sp. Heat of water} \times \text{Temperature rise}$

$$Q_2 = W_{bdp} \times m_3 \times C_w \times (t_{p2} - t_{p1}) \quad (3.24)$$

$m_3$  is the initial moisture content in d.b

As latent heat of water vapor. ( $Q_3$ )

$Q_3 =$  Water evaporated  $\times$  Latent heat of water

$$Q_3 = W_{me} \times L_v \quad (3.25)$$

$L_v$  is the latent heat of vapourization

Total heat required (Kcal)

$$(Q) = (Q_1 + Q_2 + Q_3) \quad (3.26)$$

➤ Efficiency of the dryer:

The drying efficiency of dryer is defined as the ratio of energy used to evaporate the moisture from the paddy to the energy input to the dryer by biomass.

$$\eta = \frac{WL}{MC} \quad (3.27)$$

where,  $W$  is the weight of water evaporated (kg),  $L$  is the latent heat of evaporation of water (MJ/kg),  $M$  is the Mass of biomass fuel used in the furnace (Kg),  $C$  is the calorific value of biomass fuel (MJ/kg).

### 3.8 Formulations for energy and exergy analyses

#### Energy analysis (1<sup>st</sup> law analysis)

An energy analysis of the thin-layer drying process of paddy was performed to determine the energetic aspects as well as the behavior of the drying air throughout the natural convection type dryer using the biomass as fuel. For the energy analyses of the drying process of paddy, the following equations are generally employed to compute the relative humidity and enthalpy of drying air [Akbulut and Durmus, 2010].

➤ The useful energy or heat gain by air

$$Q_{uda} = m_{da} C_{pda} (T_{dco} - T_{dci}) \quad (3.28)$$

$Q_{uda}$  is the useful energy or heat gain by air,  $C_{pda}$  is the specific heat of drying air (J/kg °C),  $T_{dco}$  is the temperature of drying chamber outlet (°C),  $T_{dci}$  is the temperature of drying chamber inlet (°C),  $m_{da}$  is the mass flow rate of drying air (kg/sec).

- The relative humidity ( $\phi$ ) is given by

$$\phi = \frac{wp}{(0.662 + w) p_{sat,T}} \quad (3.29)$$

where  $w$  denotes the specific humidity,  $p$  is the atmospheric pressure,  $p_{sat,T}$  is the saturated vapor pressure of drying air.

- The enthalpy of drying air is given by

$$h = C_{pda} T_{da} + W h_{sat,T} \quad (3.30)$$

where,  $T_{da}$  drying air temperature and  $h_{sat,T}$  enthalpy of saturated vapor. Heat used during the dehumidification process at the paddy tray can be calculated by using psychrometric chart and the following equation: [Celma, 2007]

$$Q_{dc} = m_{da} (h_{dci,T} - h_{dco,T}) \quad (3.31)$$

$$EUF_{DC} = \frac{m_{da} (h_{dci,T} - h_{dco,T})}{m_{da} C_{pda} (T_{dco} - T_{dci})} \quad (3.32)$$

Where  $h_{dci,T}$ , enthalpy of drying air in the drying chamber inlet,  $h_{dco,T}$  is the enthalpy of drying air in the drying chamber outlet. The energy utilization factor of the drying chamber is calculated by using the following equations: [Celma, 2007].

Exergy analysis (2<sup>nd</sup> law analysis)

Exergy analysis is more suitable to incorporate the quality of useful energy output, and friction losses. The exergy concept based on the second law of thermodynamics provides an analytic framework for system performance evaluation. Exergy analysis yields useful results because it deals with irreversibility minimization or maximum exergy delivery. Exergy analysis has proven to be a powerful tool in the thermodynamic analysis of energy systems.

It should be noticed that exergy is always evaluated with respect to a reference environment. When a system is in equilibrium with the environment, the state of the system is called the dead state due to the fact that the exergy is zero. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied.

- The exergy equation of a system is given by

$$\dot{E} = \dot{m}_{da} \bar{C}_{pda} \left[ (T_{da} - T_a) - T_a \ln \frac{T_{da}}{T_a} \right] \quad (3.33)$$

$\dot{E}$  is the exergy of the system,  $\dot{m}_{da}$  is the mass of dry air,  $T_{da}$  is the temperature of drying air,  $T_a$  is the temperature of atmospheric air,  $\bar{C}_{pda}$  average specific heat of drying air.

According to the above equation, exergy inflow and outflow can be calculated depending on the inlet and outlet temperatures of the drying chamber. The equations of exergy inflow and outflow for drying chamber are given below

$$\dot{E}_{dci} = \dot{m}_{da} \bar{C}_{pda} \left[ (T_{dci} - T_a) - T_a \ln \frac{T_{dci}}{T_a} \right] \quad (3.34)$$

$$\dot{E}_{dco} = \dot{m}_{da} C_{pda} \left[ (T_{dco} - T_a) - T_a \ln \frac{T_{dco}}{T_a} \right] \quad (3.35)$$

Hence exergy loss is determined by:

$$\dot{E}_L = \dot{E}_{dci} - \dot{E}_{dco} \quad (3.36)$$

➤ Calculation of exergetic efficiency:

Exergetic efficiency for drying process can be defined as the ratio of exergy use in the drying of the product to exergy of the drying air supplied to the system [Hepbasli, 2008]

$$\eta_{ex} = \frac{\dot{E}_{xevap}}{\dot{E}_{xda}} \quad (3.37)$$

$$\dot{E}_{xevap} = \left[ \left( 1 - \frac{T_a}{T_m} \right) \dot{Q}_{evap} \right] \quad (3.38)$$

$$\dot{Q}_{evap} = \dot{m}_w h_{fg} \quad (3.39)$$

$\dot{Q}_{evap}$  is the heat transfer rate due to phase change,  $T_m$  is the exit temperature of the material,  $\dot{m}_w$  is the mass flow rate of water,  $h_{fg}$  is the vaporization of latent heat.

### 3.9 Theory related to Moisture determination

MC of grain denotes the quantity of water per unit mass of either wet or dry grain, usually expressed on a percentage basis. Grain MCs (wet and dry basis) are generally defined as (Hall, 1980; Mc Lean, 1989; Brooker et al. 1992; ASAE, 2001; ASAE, 2003c; ASAE, 2004c; ASAE, 2005c):

$$MC_{db} = \frac{\text{Weight of water}}{\text{Weight of dry matter in grain}} \times 100 \quad (3.40)$$

and

$$MC_{wb} = \frac{\text{Weight of water}}{\text{Weight of grain}} \times 100 \quad (3.41)$$

Jindal and Siebenmorgen (1987) defined the MC wet basis as the ratio of the weight of water that can be removed without changing the grain chemical structure to the initial weight of the grain.

During normal weather conditions at harvest, the grain will lose moisture during the day but gain moisture at night because of the high RH. Rain will also cause a remarkable MC increase (Siebenmorgen, 1994).

Even after drying, the variation in the MC can still exist. Hellevang (2004) stated that if grain kernels vary in moisture between 20 and 30% before drying, the variation may be between 12 and 18% after drying. There is, therefore, possible for variations of MC in stored grain.

### 3.10 Uncertainty analysis

The experimental error has been calculated in terms of percent uncertainty. The uncertainties associated with dryer performance calculations were estimated using the following two equations.

$$U_1 = \pm \frac{\sqrt{\sigma_1^2 + \sigma_2^2 + \dots + \sigma_N^2}}{N} \quad (3.42)$$

Where  $\sigma$  is the standard deviation and the equation is written as

$$\sigma = \pm \sqrt{\frac{\sum (X - \bar{X})^2}{N_o}} \quad (3.43)$$

$X - \bar{X}$  is the deviation of observation from the mean in the experiment,  $N$  and  $N_0$  are the number of sets and number of observations in each set, respectively. The percent internal uncertainty therefore has been determined using the following expressions.

$$\begin{aligned} \text{\% of internal uncertainty} \\ = \frac{U_i}{\text{Average of total number of observations}} \times 100 \end{aligned} \quad (3.48)$$

### 3.11 Summary

A natural convection dryer using biomass as fuel for the drying of paddy grain has been developed. The design and redesign of dryer used for the performance analysis during drying, with and without heat storage material to store the thermal energy and phase change material used for quality drying are described. Detail experimental procedure for performance analysis, thermodynamic analysis and measurement techniques employed during the experiment are also discussed.

## CHAPTER 5

### PARAMETRIC STUDY ON PADDY DRYING

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#### 5.1 Introduction

Parametric study on paddy drying in a natural convection dryer without any thermal energy storage materials was conducted under Phase-I and discussed in the present chapter. Effect of drying time, thickness of paddy layers, humidity of environment, fuel requirement, etc on the moisture removal rate of paddy grain are presented in the following subsections.

#### 5.2 Experimental Information

Experiments were conducted in the developed dryer without embedding any thermal energy storage medium inside it. Range of parameters considered is given in Table 5.1. Average air temperatures before reaching the paddy tray were measured in the range of  $49^{\circ}\text{C}$  -  $75^{\circ}\text{C}$  after a period of 50 minutes of combustion of biomass in the furnace. All the experiments were repeated for 3 to 4 times and average value of the parameters was reported. Experiments were conducted in series with increment of paddy of 5 kg, starting from 10 kg at the beginning for similar set of input parameters. Similarly, moisture removal rate were observed for a range of ambient relative humidity range of 65-80% with an increment of 5 %. Based on equation number 3.14 with

##### 5.2.1 Temperature profile

Figure 5.1(a)-(d) presents the variation of average value of drying air temperature with time during drying of different amount of paddy in Phase-I. When the average drying air temperature of  $50^{\circ}\text{C}$  was sensed, paddy was loaded on the drying tray.

Table 5.1 Input parameters under Phase-I

Sl No	Particulars	Ranges
1	Ambient air temperature	15 <sup>0</sup> C -18 <sup>0</sup> C
2	Relative humidity	65%-80% (increment of 5%)
3	Amount of paddy per batch	10-25 kg (increment of 5 kg)
4	Drying air temperature	49 <sup>0</sup> C -75 <sup>0</sup> C
5	Particular of dryer	Simple natural convection dryer without any thermal storage medium
6	Initial moisture content of paddy grain	30% (approx)
7	Final Moisture content of paddy grain	14-15%

Drying air temperature is controlled by controlling the feeding rate of biomass. When temperature of drying air falls nearer to 50 °C during drying process then additional amount of biomass (0.250 kg) is supplied to the furnace so as to maintain the drying air temperature near to 50 °C. It was observed from figure 5.1(b) that the drying air temperature falls below 50°C with time due to the sensible heating of the air in the drying chamber. It was observed that temperature of drying air suddenly increases above 50°C when paddy is loaded in the tray. This is because, time is required to transfer the heat to the paddy and to raise the temperature and also loss of heat to the surroundings through the drying tray is less. It is also observed that variation of temperature is less after loading of paddy below the paddy tray. It is observed that the drying air temperature in case of 25kg of paddy is more than 65°C with maximum time. This is due to the increase in thickness of the paddy layer on the tray demanding for more time to transfer the heat from the drying air to the paddy.

Drying air temperature is measured at five different points just below the drying tray, and then the average value of the five temperatures is considered. The variation of drying air

temperature below the paddy tray at five different positions at particular time is very small. The temperature variation data in every 5 minutes interval of time is given in the Appendix IV.

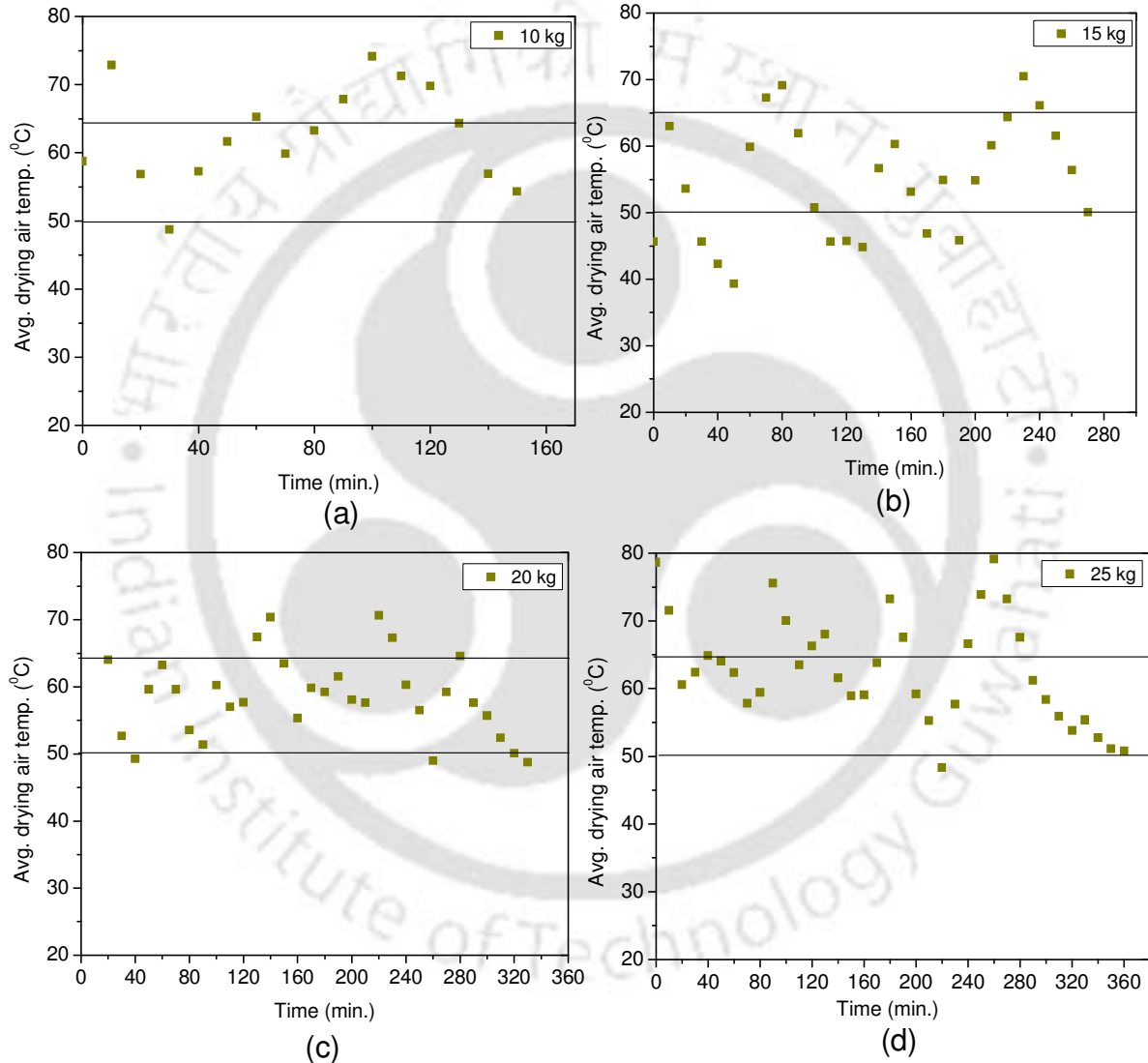
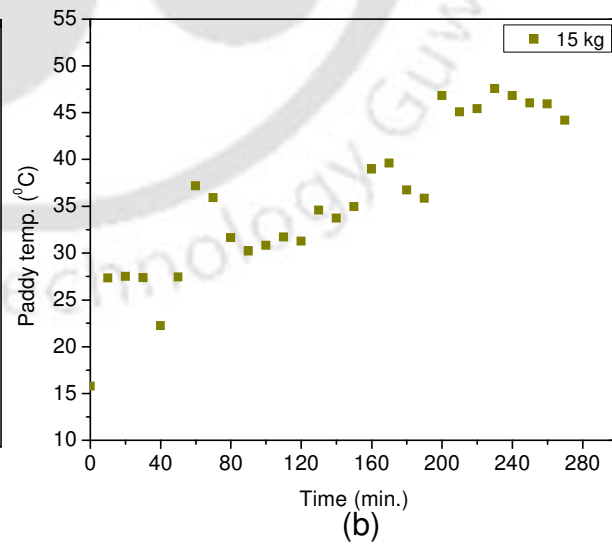
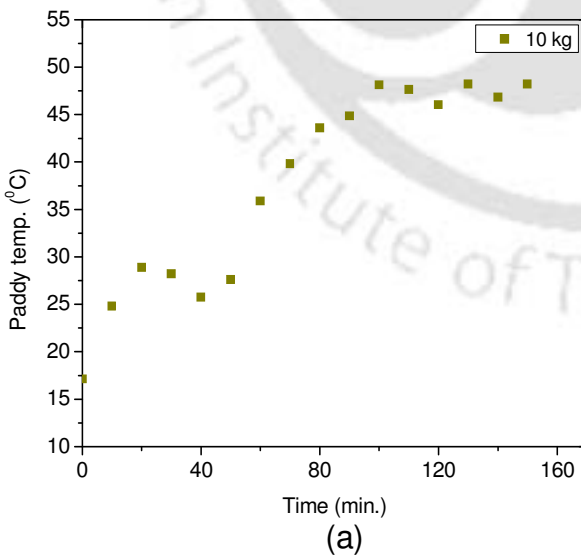


Figure 5.1. Variation of drying air temperature with time

Figure 5.2(a)-(d) presents the variation of average value of paddy grain temperature with time during the drying of different amount of paddy in Phase-I. The variation of

temperature of paddy is in the range of 25 - 49°C, 28 - 48°C, 26 - 47°C and 25 - 50°C for 10kg, 15kg, 20kg and 25kg of paddy respectively. It is observed that the initial variation of paddy temperature is very less and after some time it is slowly increases and at last it slightly decreases. But in case of 20kg and 25kg of paddy the last part of the drying the decrease of temperature is slightly more. This is because in all the cases when heat is supplied to the paddy, its temperature increases slightly since heat which is supplied to the paddy will increase the temperature of surface moisture and the vapor pressure of the moisture present inside the paddy increases which is more than the atmospheric vapor pressure and the surface moisture will transfer quickly to the critical moisture content (approximately 18%) (IRRI, 2002). When surface moisture transfer completes the heat which is supplied to the paddy will raise the temperature so that the dryness appears in the surface of the paddy. Liquid movement from the interior of the kernel is due to the liquid diffusion and capillary forces developed and due to the temperature gradient. At last when moisture is transferred to a safe moisture content level, the evaporation of heat from the paddy to the atmosphere is more and i.e. more in case of 20kg and 25kg of paddy so at the end there is decrease in temperature.



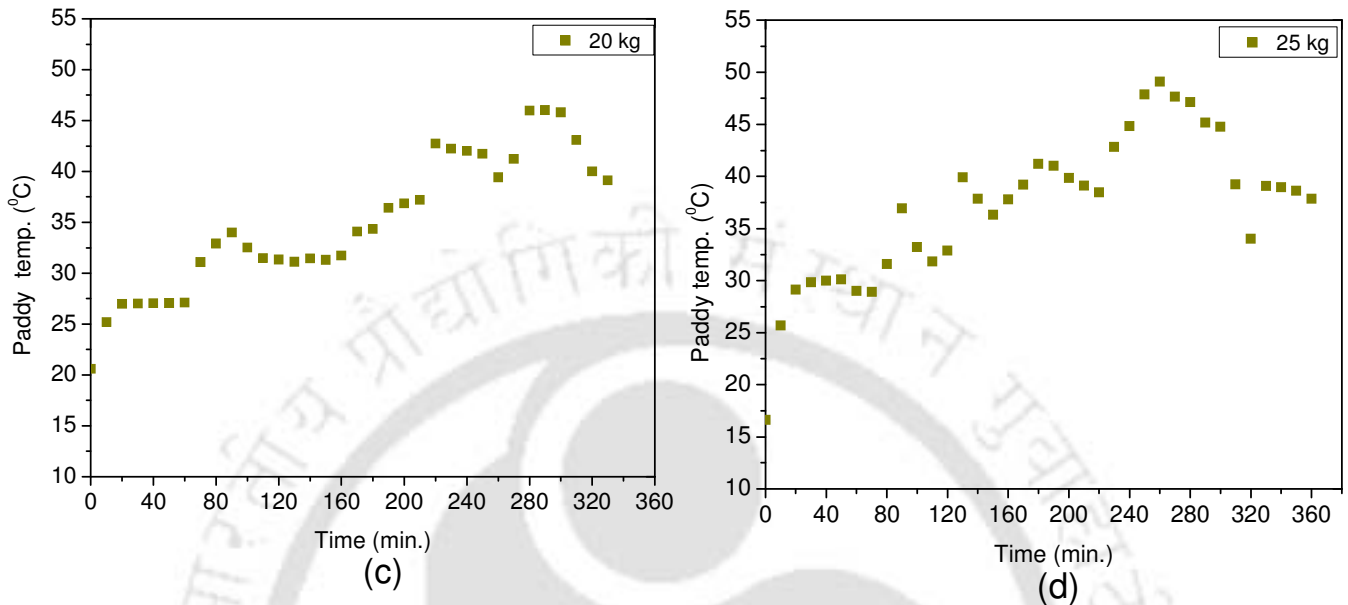


Figure 5.2. Variation of paddy temperature with time during the drying of different amount of paddy.

From the experiment it is observed that the variation of atmospheric air temperature is very less and is in between 15-18°C. So that it will not affect the moisture transfer rate.

Figure 5.3 shows the variation of drying air temperature during the burning of biomass in different section of the dryer during the drying of 10kg of paddy. Section-1, 2 and 3 are the lower, middle and upper portion of the dryer respectively. It is observed that there is very small variation of drying air temperature in section-1 and section-2, is in the range of 39-44°C and 44-51°C respectively during the drying of paddy. But in section-3 the variation is in the range of 49-75°C. It is also observed that in section-1 and section-2 the temperature of drying air will raise initially, then after some time the temperature variation is less and it falls to atmospheric temperature after drying and unloading of paddy and when biomass burning is finish. But in section-3 rise and fall of temperature is very large. This is because the draft is created due to the temperature difference between atmospheric air and the air inside the drying chamber. Hot air becomes lighter and moves

upwards. When paddy is loaded, it will not absorb heat immediately so the temperature variation takes place at section-3. When the paddy is unloaded from the tray, temperature of drying air decreases to atmospheric air temperature. The variation of drying air temperature at the upper section of the dryer just below the tray is less when storage materials are used which is discussed in chapter-6.

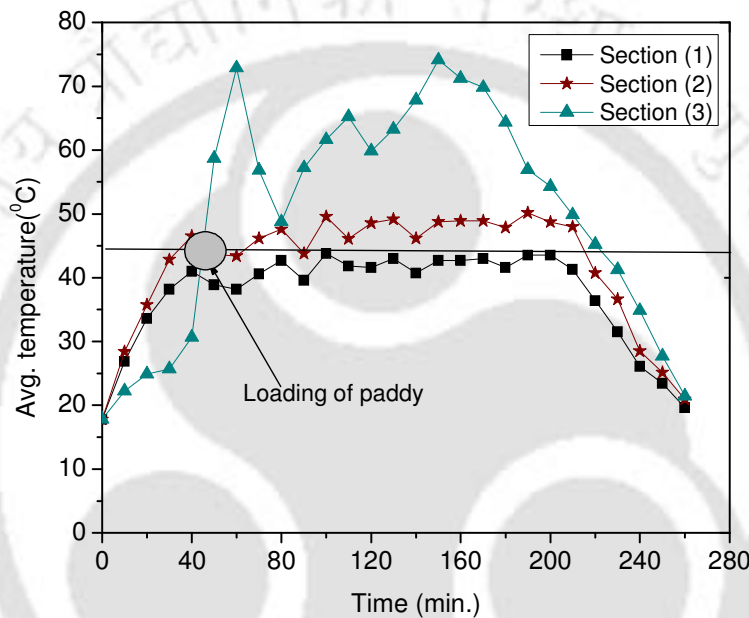


Figure 5.3. Variation of temperature in three different sections of the dryer

### 5.2.2 Moisture transfer analysis

During the drying of paddy both heat and mass transfer takes place simultaneously. Heat is transferred from the drying air to the paddy and increase the temperature of liquid water and water vapor in the grain, whereas mass is transferred out of the grain in the form of vapor (evaporated liquid) due to the vapor pressure difference between the liquid water present in the paddy and the ambient. Initially when heat is transferred, the surface moisture will evaporate. The moisture transfer from the interior of the kernel to the surface and then to the atmosphere takes place.

### 5.2.2.1 Variation of moisture with different thickness

Four batches of paddy of different amount (in weight) and having different thickness on the drying tray are dried at various times and approximately at same relative humidity (RH~65%) by using the different amount of biomass. It can be noted that the biomass is added to each batch. The heated air from the earlier batch needs less amount of heat input compared to the first batch (starting one) for drying purpose. Figure 5.4 shows the average moisture transfer of different batches of paddy with time.

It is observed that first batch contains 10 kg of paddy of thickness ~2.5 cm requires two hours and thirty minutes for the removal of moisture from 30.8 % (wb) to 14.8 % (wb). It is also observed that the initial moisture removal from the paddy in the beginning of the drying process is fast due to the removal of surface moisture. Surface moisture will readily evaporate when the grain is exposed to hot air but internal moisture evaporates slowly as it has to move away from the kernel to the outside surface due to surface forces (capillary flow). Second batch contains 15 kg of paddy of thickness ~3.5 cm and requires 4hrs 30minutes for the removal of moisture from 30.7% to 14.8%. It is observed that the initial moisture removal for 15 kg paddy is less than that of 10 kg of paddy. This is due to increase in thickness of paddy layer and more time is required to transfer the heat to the surface moisture. Third batch contains 20 kg of paddy of thickness ~4.5 cm will require 5 hrs 30 minutes for the removal of moisture from 30.7% to 14.6%. The initial moisture removal of the paddy during the beginning time is fast due to surface moisture removal but it is less as compared to 10 and 15 kg of paddy again due to increase of thickness. Fourth batch contains 25 kg of paddy of thickness ~5.5 cm will require 6hrs for the removal of moisture from 30.8% to 14.7%. The time required for drying of 25 kg of paddy is more than 20 kg, 15 kg, and 10 kg. Initial moisture transfer is more in case of 10 kg than 15 kg, 20 kg, and 25 kg.

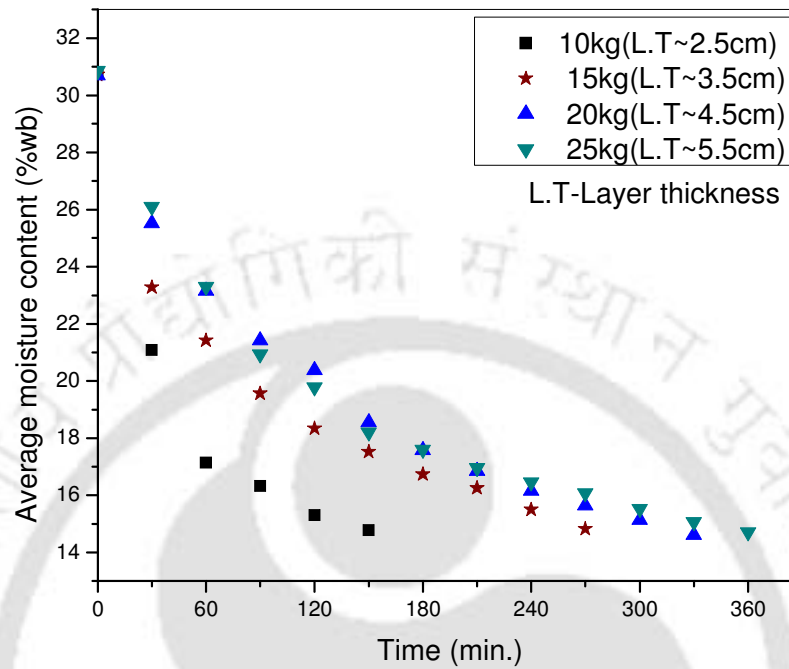


Figure 5.4. Variation of Avg. moisture content of different amount of paddy with time at RH-65%.

### 5.2.2.2 Variation of moisture with different humidity conditions

Effect of relative humidity of ambient air on the grain moisture removal rate is presented in Fig. 5.5. Significant diurnal variation of relative humidity was observed in the laboratory. Four batches of paddy of same amount (10 kg) on the drying tray are dried at various times of the different day with different relative humidity of atmospheric air.

It was observed that the moisture removal rate is slightly increased when the relative humidity of atmosphere is low. When the atmospheric relative humidity is more it requires more time to dry the product. With the increase in atmospheric humidity the moisture absorbing capacity of air decreases so that rate of moisture transfer from paddy to the atmosphere decreases.

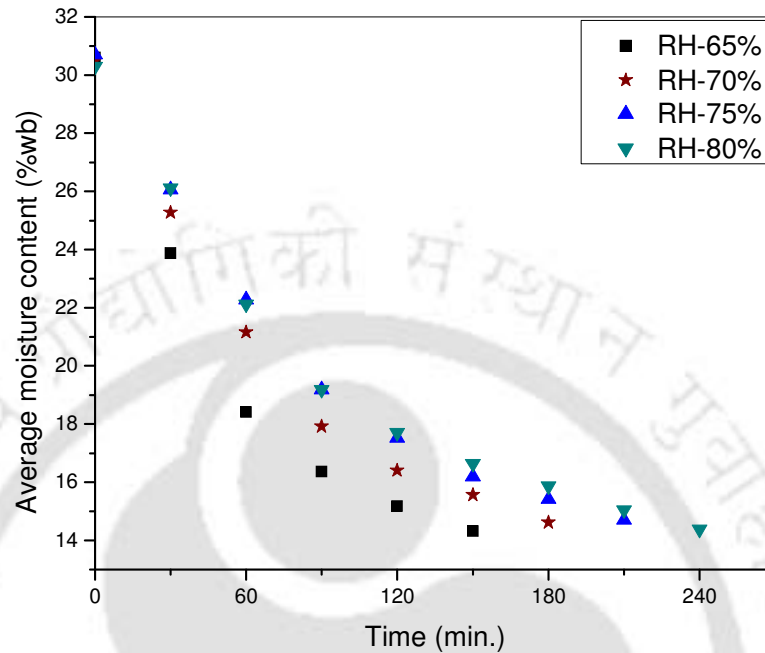


Figure 5.5. Variation of Avg. moisture content of 10kg paddy with time at relative humidity 65%, 70%, 75% and 80%.

### 5.3 Capacity and drying time

In order to test the feasibility of the dryer in terms of fuel saving and drying time, series of experiments are conducted in the present dryer in batch wise and continuous process. In continuous process the time gap between unloading and loading of paddy in the dryer is less than one minute but in batch wise process time between loading and unloading of any two batches are 24 hours.

Two batches of paddy of different amount (weight) and having different thickness on the drying tray is dried in the above two processes by using the different amount of biomass. In both the process three batches (each 10 kg) and two batches (each 15 kg) of paddy is considered. It is observed from the experiment that the biomass required for drying in batch process is higher than the continuous process. This is because in the batch process, one batch of paddy is dried, so lot of thermal energy is wasted before loading and after

unloading of paddy. But in case of continuous drying loading of fresh batch was done immediately after drying of previous batch minimizing the loss of thermal energy during loading-unloading processes. Thus there is no requirement of combustion of additional biomass. This significantly reduces the cost of fuel and drying time. In both the cases atmospheric relative humidity is approximately same, so that it will not affect the moisture removal rate of the paddy. It is also observed from the experiment that amount of biomass required and time taken for the moisture removal from one batch of 10 kg of paddy and 15 kg of paddy is 2 kg, 2.5 hrs and 3 kg, 4.5 hrs respectively. Table 5.2 gives the details of the experiment in batch wise (B.D) and continuous (C.D) process.

It is better to dry three batches of 10 kg of paddy due to more expose of hot air to the paddy. In 15 kg batches of paddy due to increase of thickness, contact of hot air to the paddy decreases and take more time to dry.

Generally continuous drying experiments are conducted at night time. Since at night there is very small variation of relative humidity in Guwahati climate.

Table 5.2: Details of the experimental results in B.D and C.D process

Sl. no	Amount of paddy per batch (kg)	Thickness of Paddy per batch (cm)	Total amount of paddy dried (Kg)		Amount of moisture removal (%)		Avg. Atm. Humidity (%)		Time taken for moisture removal (hr)		Amount of biomass required (kg)	
			B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D
1	10	2.5	30	30	16.0,15.9,15.9	16.0,15.8,15.8	65	65	7.5	7.5	6	5
2	15	3.5	30	30	15.9,16.0	15.9,15.8	65	65	9	9	6	5.75

### 5.4 Drying efficiency

Drying efficiency of dryer is the ratio of energy used to evaporate the moisture from the paddy to the energy input to the dryer by burning of biomass. Drying efficiency is calculated in two processes. In batch wise process, when three batches of paddy (total 30 kg, each batch 10kg) is dried at different time by removing total 5.6 kg of water the efficiency is 12%. The initial and final moisture content of three batches paddy is 30.8, 30.6, 30.5 and 14.8, 14.6, 14.6 respectively.

Similarly if experiments are conducted by considering two batches of paddy (Total 30 kg, each 15kg) dried in same way the drying efficiency is again 12%. The amount of moisture removed in this case is 5.6 kg. The initial and final moisture content in two batches of paddy is 30.7, 30.8 and 14.8, 14.7 respectively.

It is observed that the efficiency in case of drying of 10 kg batch or 15 kg batch in batch wise process is same. Since drying efficiency of paddy depends on the amount of moisture removed and the amount of biomass burned and both are same in 10kg and 15kg batches of paddy. It is better to dry 10 kg batches of paddy in batch wise process, since it requires less time to dry. The details are given in table-5.3.

Table 5.3: Drying efficiency in batch wise process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	5.6	6	12
2	15	30kg	5.6	6	12

Drying efficiency in continuous drying process is different than batch wise process. Here approximately same amount of moisture is removed from three batches of paddy (each 10kg) or two batches of paddy (each 15 kg) and time requirement of drying of paddy is

also same as that of batch wise process but amount of biomass requirement is different. Since amount of biomass required in 10 kg batches of paddy (total 30kg) is less than that of 15kg batches of paddy (total 30kg), so drying efficiency of 10kg paddy batches is more than 15 kg paddy batches. The initial and final moisture content in three batches of paddy (each 10kg) is 30.8, 30.4, 30.7 and 14.8, 14.6, 14.8 respectively. The initial and final moisture content in two batches of paddy (each 15kg) is 30.5, 30.3 and 14.6, 14.5 respectively. The sample calculation of efficiency is given in appendix-V. It is better to dry paddy of 10kg batches by continuous drying process rather than batch wise process, since the efficiency in continuous drying process is more than batch wise process. The details are given in table-5.4.

Table 5.4: Drying efficiency in continuous drying process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	5.6	5	14.4
2	15	30kg	5.6	5.75	12.5

It is also found when two batches of each 20 kg of paddy (total 40 kg) having initial and final moisture content 30.7, 30.4 and 14.6, 14.4 are taken in batch wise process, the efficiency was found to be 12.1%. Similarly when same batches are taken in continuous drying process, the drying efficiency was found to be 12.8%. The efficiency of drying of 100kg of paddy of each 10kg batches is found to be 18.4% in continuous drying process. It is found that when more amount of paddy is dried in continuous drying process, the efficiency is more. This is because when more amount of paddy is dried the amount of biomass requirement is less.

### 5.5 Quality aspects of paddy

Figure 5.6 (a)-(b) presents the pictorial view of rice in terms of appearance. Rice after drying has got better acceptability by consumers.

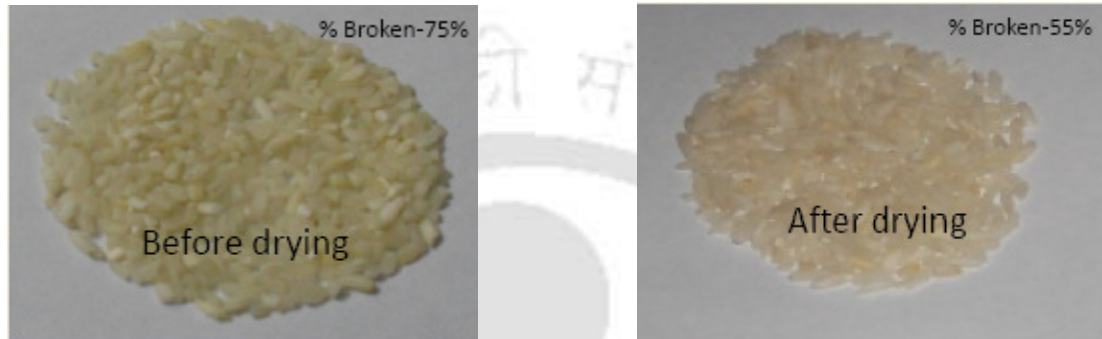


Figure 5.6. (a) Rice before drying (b) Rice after drying

Quality of paddy is determined based on the nutritional and milling value. Carbohydrate and protein percentages based on dry weight of sample are determined to compare the nutritional value of paddy grain. Percentage of kernel broken is considered to be the index of the milling quality. 20 gm of paddy samples were taken from 5 different locations of the tray and percentage of broken kernel was found. Average percentage of broken rice along with carbohydrate and protein contents before and after drying is compared in Table 5.5.

Table 5.5: Detail quality of the raw paddy and dried paddy grain

Sl No		Raw paddy grain	Dried paddy grain
1	Nutritional values		
	Carbohydrate	78% (dw)	52%(dw)
	Protein	7% (dw)	1% (dw)
2	Milling quality (Broken Kernel)	75%	55%

## 5.6 Summary

A simple dryer is designed and fabricated with locally available materials. The developed natural convection paddy dryer is capable of producing drying air temperature above 50<sup>0</sup> C. Experiments were performed in the developed dryer to investigate the effect of various operating parameters on moisture removal rate while drying paddy grains in batches as well as in continuous process. It was found that both the drying time and initial surface moisture transfer rate decreases with the increase in thickness of paddy layer on the drying tray. The amount of biomass required in continuous drying process is observed to be less in comparison to that of the batch process leading to the increase in efficiency of the dryer. It was found that the moisture removal rate from the paddy grain decreases with increase with relative humidity of the atmosphere considering same thickness of paddy in the tray.

There is a significant loss of thermal energy during loading and unloading of paddy on the drying tray. Further, there is large variation of drying air temperature below the paddy tray leading to the degradation of quality of dried product. Minimization of the variation of drying air temperature below the paddy tray and to increase the efficiency of the dryer, heat storage material is used inside the dryer in the next phase of the work (Phase-II-IV). Results and discussion of the same are presented in Chapter 6.

## CHAPTER 6

### PARAMETRIC STUDY ON PADDY DRYING IN PRESENCE OF THERMAL ENERGY STORAGE MATERIALS

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#### 6.1 Introduction

In the present chapter parametric studies on paddy drying in the developed natural convection dryer containing thermal energy storage materials are conducted and presented. Both the sensible heat storage material (SHSM) and phase change material (PCM) are incorporated in the dryer and experiments are performed in 3(three) different phases. Experiments with SHSM and PCM are conducted individually as well as in combination of both. Pebbles are used as sensible thermal energy storage medium (SHSM) in Phase –II and paraffin wax (PCM) is used in Phase –III. Combination of both SHSM and PCM is conducted in Phase-IV. Effect of drying time, thickness of paddy layers, humidity of environment and fuel requirement on the moisture removal rate of paddy grain are presented in the following subsections.

Subsections 6.2 to 6.4 present the detail information regarding the experiments conducted with SHSM (phase-II), PCM (Phase-III) and SHSM and PCM together (Phase-IV), respectively

#### 6.2 Experiments with SHSM (Phase-II)

Experiments were conducted in the developed dryer with the addition of SHSM as thermal energy storage medium. Range of parameters considered are given in Table 6.1. Average air temperatures below the paddy tray measured based on five different locations were calculated to be 46<sup>0</sup>C - 70<sup>0</sup>C after a period of 70 minutes of combustion of biomass

in the furnace. All the experiments were repeated for 3 to 4 times and average value of the parameters was reported. Experiments were conducted in series with increment of paddy of 5kg, starting from 10 kg at the beginning for similar set of input parameters.

Table 6.1 Input parameters under Phase-II (with SHSM)

Sl No	Particulars	Ranges
1	Ambient air temperature	16 <sup>0</sup> C -18 <sup>0</sup> C
2	Relative humidity	65%
3	Amount of paddy per batch	10-25 kg (increment of 5 kg)
4	Drying air temperature	46 <sup>0</sup> C -70 <sup>0</sup> C
5	Particular of dryer	Simple natural convection dryer with thermal storage medium inside ( Phase-II)
6	Initial moisture content of paddy grain	30% (approx)
7	Final Moisture content of paddy grain	14-15%

### 6.2.1 Temperature profile

Figure 6.1(a)-(d) presents the variation of average value of drying air temperature with time during drying of different amount of paddy in Phase-II. When the average drying air temperature of 48<sup>0</sup> C was recorded, paddy was loaded on the drying tray immediately.

It is found from the experiment that there is a moderate temperature variation in the plenum chamber and minimum of loss of thermal energy after the use of thermal energy storage materials. This is because heat energy obtained by combustion of biomass inside the furnace is absorbed by the pebbles as well as the air which flows due to the thermal bouncy capturing the heat from pebbles for evaporation of moisture. Drying air temperature is controlled by controlling the biomass feeding rate. It was observed that

pebbles can retain heat for long time and there is hardly any requirement to re-fire additional biomass once the drying process starts. Once the temperature of drying air falls to  $50^{\circ}\text{C}$  approximately, additional amount of biomass (0.250 kg) is supplied to the furnace so as to maintain the drying air temperature to  $50^{\circ}\text{C}$  (approx). The maximum drying air temperature for drying of 10kg, 15kg, 20kg and 25kg of paddy is  $61.8^{\circ}\text{C}$ ,  $62.6^{\circ}\text{C}$ ,  $69.7^{\circ}\text{C}$ ,  $62.5^{\circ}\text{C}$ , respectively. Similarly minimum drying air temperature for the same amount of paddy (10 -25 kg) were observed to be  $51.2^{\circ}\text{C}$ ,  $50.0^{\circ}\text{C}$ ,  $50.4^{\circ}\text{C}$ ,  $50.1^{\circ}\text{C}$ , respectively.

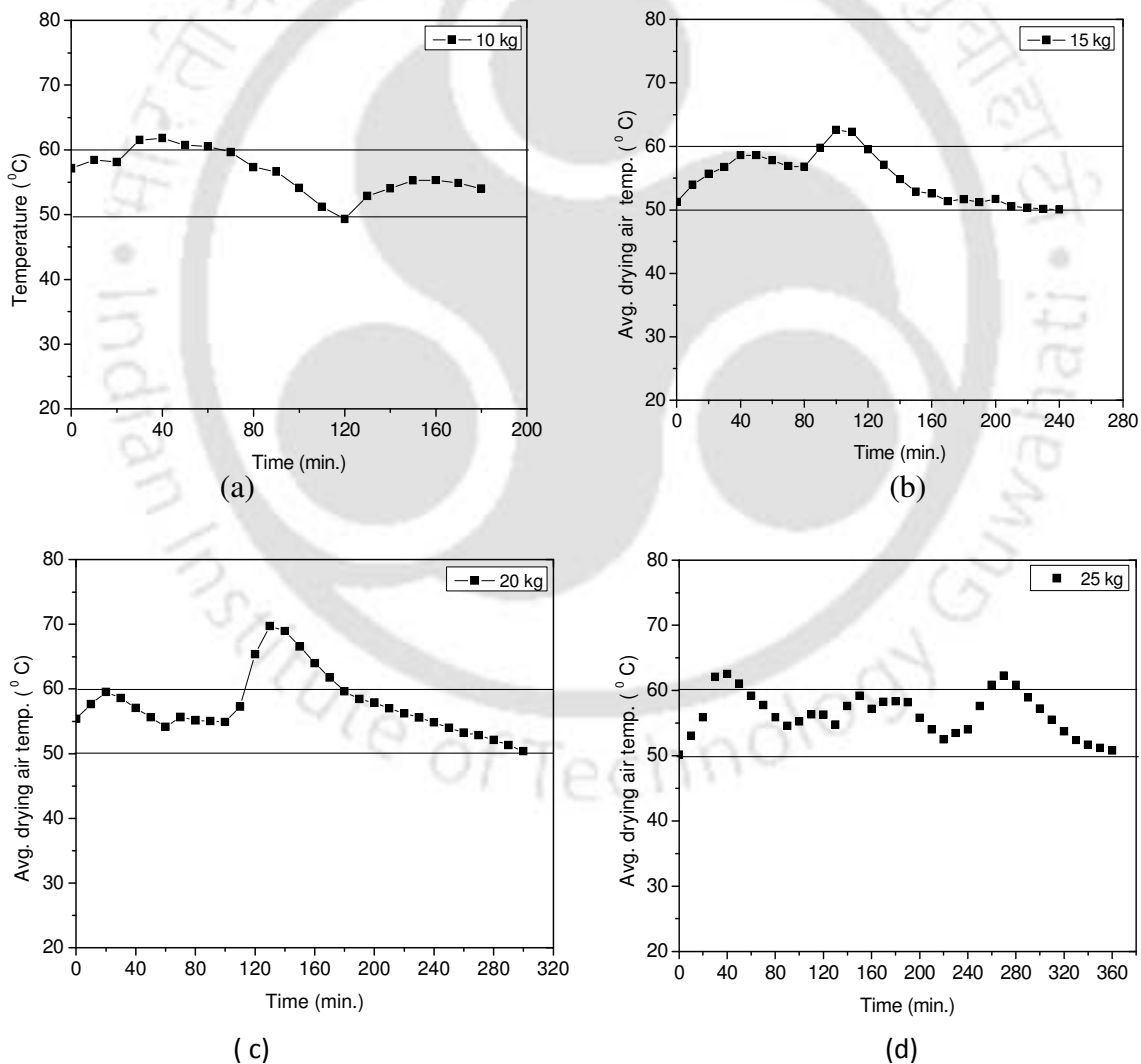


Fig. 6.1: Drying air temperature with time during the experiment by using SHSM.

The average drying air temperature, based on five different positions below the paddy tray were found to be uniform. Such average temperature variation data is given in the Appendix IV for an interval of 5 minutes.

Figure 6.2(a)-(d) presents the variation of average value of paddy grain temperature with time during the drying of different amount of paddy in Phase-II. From the experiment it is found that the variation of temperature of paddy is in the range of 22 - 44°C, 24 - 43°C, 23 - 41°C and 25 - 43°C for 10kg, 15kg, 20kg and 25kg of paddy, respectively. Such variations are found to be similar to that of under phase-I.

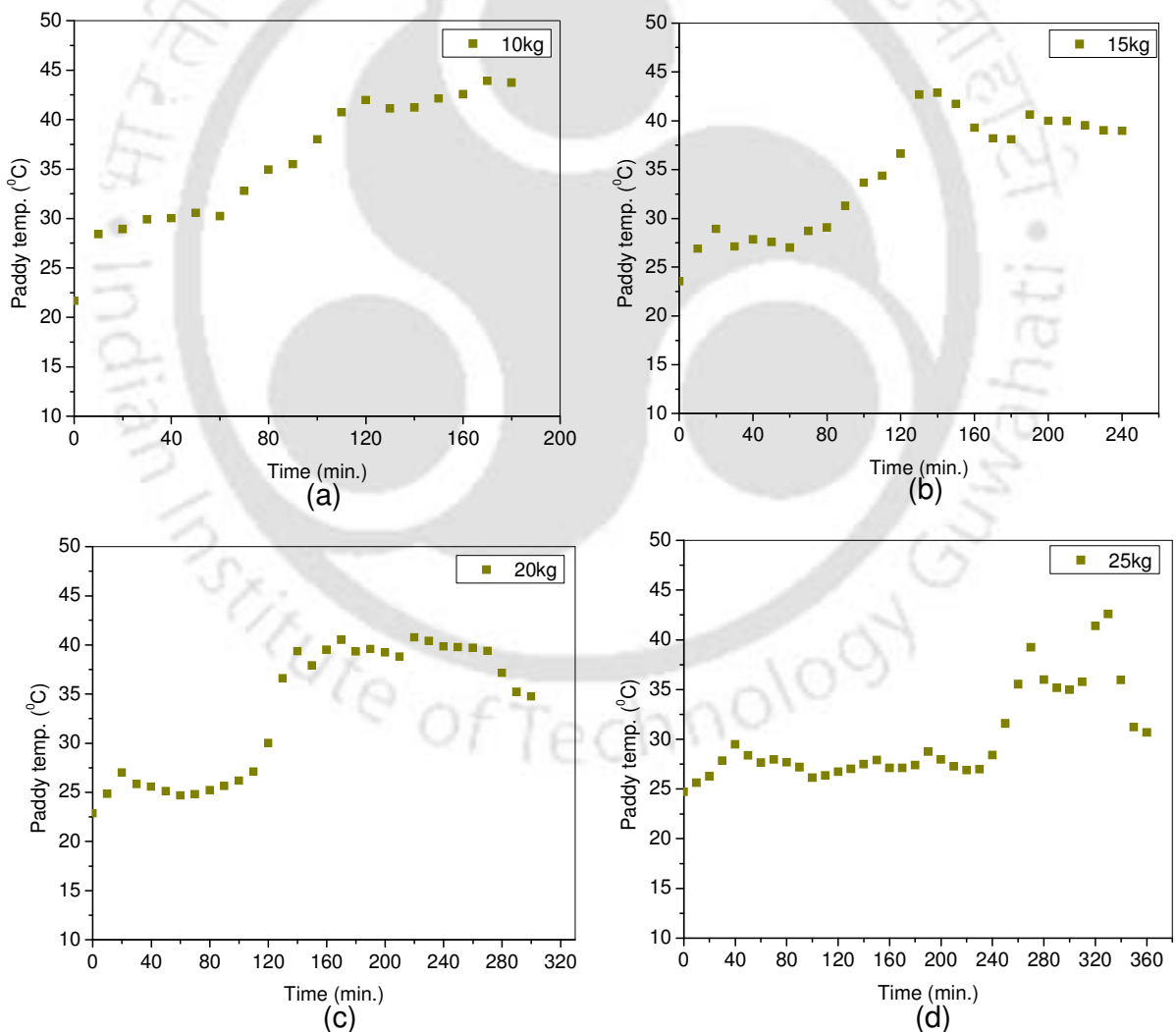


Fig. 6.2: Variation of paddy temperature with time during the drying of different amount of paddy with SHSM.

### 6.2.2 Moisture transfer analysis

Figure 6.3 shows the variation of moisture of different amount of paddy having different thickness. Four batches of paddy of different weights with initial and final average moisture content of 30.5% and 14.5%, respectively under a constant relative humidity of 65% and approximately at same atmospheric air temperature were dried using SHSM. It is observed that drying time increases with increase in thickness of paddy layer which is similar to that of the Phase –I reported in preceding chapter.

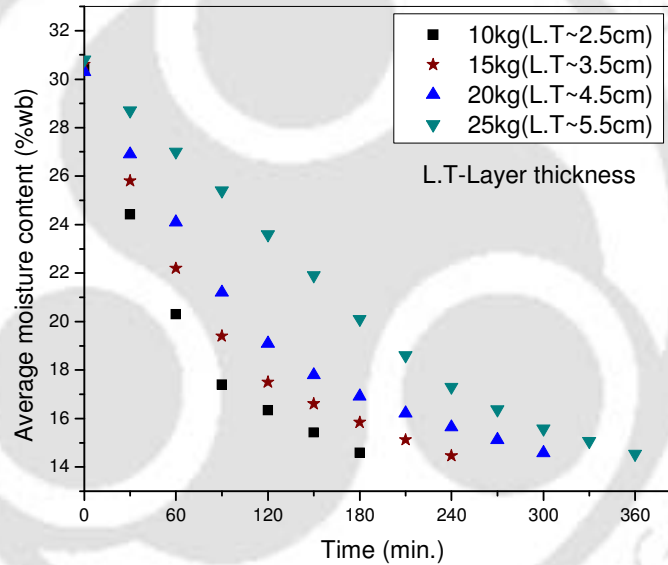


Fig.6.3: Variation of Avg. moisture content of different amount of paddy with time with SHSM at RH-65%.

### 6.2.3 Capacity and drying time

Fuel saving and reduction in drying time were calculated based on the operation of the dryer in batch and in continuous process with SHSM. The time gap between loading and unloading of paddy in the tray in both the process is maintained as that of phase-I for comparison.

Two batches of paddy of different thicknesses are dried in batch and continuous process using the different amount of biomass. In both the process three batches (each 10 kg) and two batches (each 15 kg) of paddy is considered.

It was observed that 1.25kg of biomass is required to raise the temperature of pebble up to 50°C. Amount of biomass required for the drying of one batch of 10kg of paddy to maintain the temperature above 50°C is estimated to be 0.25 kg. Thus total amount of biomass required per batch from moisture content of 30.5 % to 14.5% is estimated to be 1.75 kg. Additional 0.5 kg of biomass were required to maintain the temperature above 50°C for quality drying in case of continuous drying of paddy in a slab of 10 kg (Table 6.2).

Similarly 0.75 kg of biomass was required for drying of 15kg of paddy in a batch to maintain the temperature above 50 °C. Thus total biomass is required to dry one batch of 15 kg of paddy is 2 kg. only. Additional 0.75 kg of biomass required for quality drying of 15 kg batch of paddy continuously. Similar trend were observed in Phase-I.

Table 6.2 gives the details of the experiment in batch wise (B.D) and continuous (C.D) process for three batches of each 10kg and two batches each 15kg of paddy.

Table 6.2: Details of the experimental results in B.D and C.D process

Sl.no	Amount of paddy per batch (kg)	Thickness of Paddy per batch (cm)	Total amount of paddy dried (Kg)		Amount of moisture removal (%)		Avg. Atm. Humidity (%)		Time taken for moisture removal (hr)		Amount of biomass required (kg)	
			B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D
1	10	2.5	30	30	15.8,15.9,15.8	15.8,15.9,15.8	65	65	9	9	5.25	2.75
2	15	3.5	30	30	16.1,16.0	16.1,16.0	65	65	8	8	4	2.75

Similarly, experiments are conducted by considering two batches of paddy grains each of 20 kg and found that 3.25 kg of biomass is required in continuous process to bring the paddy to safe moisture content level in 10 hrs.

From the above it is well established that the best way is to dry either in batches of 15 kg or 20kg paddy in the developed dryer with SHSM with reduction in both the drying time and biomass requirement. However, paddy in a batch of 20 kg has relatively thick layer than that of 15 kg causing uneven temperature distribution between the paddy layers rendering cracking and poor milling quality. Batch of 15 kg of paddy was found to have better temperature uniformity hence the same may be considered to be the optimum quantity to dry in a batch as well as in continuous process. For batch wise drying process more amount of thermal energy is wasted after unloading of paddy. This can be avoided

in continuous process. In continuous process only a small amount of heat is waste during loading and unloading of paddy.

#### 6.2.4 Drying efficiency

Tables 6.3 and 6.4 present the drying efficiency for batch and continuous drying, respectively. It was observed as before (Phase-I), drying efficiency in continuous process is better than that of the batch process with significant reduction in biomass.

Table 6.3: Drying efficiency in batch wise process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	I.M.C	F.M.C	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	30.8, 30.6, 30.5	14.8,14.6, 14.6	5.6	5.25	13.6
2	15	30kg	30.7, 30.8	14.8,14.7	5.6	4	18.1

Table 6.4: Drying efficiency in continuous process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	I.M.C	F.M.C	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	30.8, 30.4, 30.7	14.8,14.6, 14.8	5.6	2.75	26.2
2	15	30kg	30.5, 30.3	14.6,14.5	5.6	2.75	26.2

But when only SHSM is used, the efficiency of drying of 100 kg of paddy of 10 kg batches if each batch remove approximately same 1.857 kg of water is 38.25% in continuous process.

It is observed from the experiments that there is large variation of drying air temperature at the entry to the dryer under Phase-I in comparison to Phase-II (with SHSM). However, temperature variation of drying air using SHSM is reduced but it was difficult to maintain the desired temperature limit for quality drying. Hence, next phase (Phase-III) of experiments are designed to maintain a constant temperature of drying air at the entry to the drying tray with PCM.

### 6.3 Experiments with PCM (phase-III)

Experiments were conducted in the developed dryer in the presence of phase change materials (PCM) to store the thermal energy and to release heat at constant range of temperature for quality drying of paddy. Paraffin wax of grade-II has been selected as the PCM based on its melting and solidification temperatures.

Experiments are conducted to study the characteristics of paraffin wax grade-II and to ascertain the optimum amount of PCM for quality drying of paddy. Experiments were conducted in series with increment of wax of 5kg, starting from 20 kg at the beginning for similar set of input parameters.

To melt 20kg, 25kg and 30kg of paraffin wax and to maintain the constant range of heat release rate a certain amount of biomass is required which is given in the table 6.5. A large amount of heat is absorbed by the paraffin wax during the melting and same is released during the solidification for longer period of time. Once the melting of paraffin wax starts it is not necessary to combust the biomass any more. The melting process completes with the heat available in the dryer. The maximum capacity of the wax tray is 30 kg for the present dryer. All the experiments reported in subsequent sub-sections are conducted with 30 kg of paraffin wax. The details characteristics of paraffin wax and the amount of biomass required is given in table 6.5.

Average drying air temperatures below the paddy tray were measured in the range of 50°C - 58°C after a period of 110 minutes of combustion of biomass in the furnace. All

the experiments were repeated for 3 to 4 times and average value of the parameters was reported. Experiments were conducted by considering 10 kg and 15 kg of paddy, respectively.

Table 6.5 Characteristics study of paraffin wax

Amount of paraffin wax (kg)	Melting range of temp. ( $^{\circ}\text{C}$ )	Time taken for melting of paraffin	Time taken for solidify to come to $50^{\circ}\text{C}$	Amount of biomass required to melt (kg)
20	~48.6- 62.4	~50 min.	~3hrs 20 min.	1.75
25	~48.2- 62.1	~75 min.	~4hrs 35 min.	2.25
30	~47.9- 62.6	~1hrs 50 min.	~5hrs 55 min.	2.5

Range of parameters considered for the experiments with PCM is given in Table 6.6.

Table 6.6 Input parameters under Phase-III (with PCM)

Sl No	Particulars	Ranges
1	Ambient air temperature	$16^{\circ}\text{C}$ - $18^{\circ}\text{C}$
2	Relative humidity	65%
3	Amount of paddy per batch	10 & 15 kg
4	Drying air temperature	$46^{\circ}\text{C}$ - $58^{\circ}\text{C}$
5	Amount of paraffin wax	30kg
6	Particular of dryer	Simple natural convection dryer with phase change materials ( Phase-III)
7	Initial moisture content of paddy grain	30% (approx)
8	Final Moisture content of paddy grain	14-15%

Loading of paddy in the tray is done when the drying air temperature in the plenum chamber is above  $45^{\circ}\text{C}$ . It is found that the solidification of 30 kg of molten paraffin wax releases heat at constant range of temperature ( $50^{\circ}\text{C}$  -  $60^{\circ}\text{C}$ ) for five hours and fifty five

minutes. When temperature of drying air falls near to  $50^{\circ}\text{C}$  during drying process, an additional amount of biomass (0.500 kg) is supplied to the furnace so as to maintain the drying air temperature above  $50^{\circ}\text{C}$  for another 65 minutes.

### 6.3.1 Temperature profile

Figure 6.4(a)-(b) presents the variation of average value of drying air temperature with time during drying of different amount of paddy in Phase-III. When the average drying air temperature of  $45^{\circ}\text{C}$  was recorded in the plenum chamber, paddy was loaded on the drying tray immediately.

It is found from the experiment that the temperature variation in the plenum chamber is very less and is maintained between  $50^{\circ}\text{C}$  to  $58^{\circ}\text{C}$  during drying, which is useful for the quality drying of paddy. This is because the heat obtained by burning of biomass inside the furnace is absorbed by the paraffin wax which releases the same at constant range of temperature during solidification to evaporate the moisture from the paddy grain. The minimum and maximum drying air temperature during drying period for 10kg of paddy is observed to be  $46^{\circ}\text{C}$  and  $58^{\circ}\text{C}$ , respectively. Similarly minimum and maximum drying air temperature for the drying of 15kg of paddy is observed to be  $50^{\circ}\text{C}$  and  $58^{\circ}\text{C}$ , respectively.

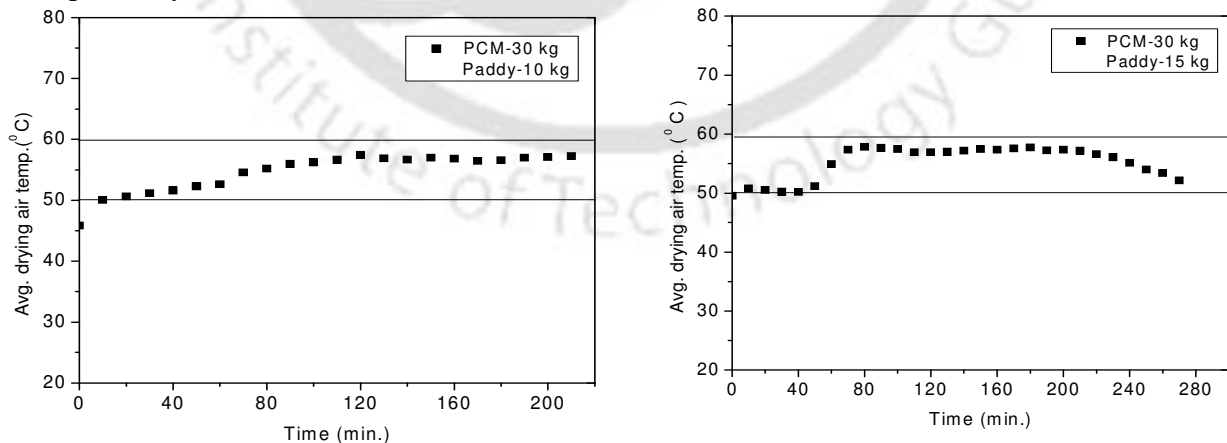


Fig. 6.4: Variation of drying air temperature during the drying of 10kg and 15kg of paddy.

From the experiment it is observed that the variation of atmospheric air temperature is very less (17-21<sup>0</sup>C) without affecting the moisture transfer rate.

### 6.3.2 Moisture transfer analysis

Figure 6.5 shows the variation moisture transfer rate from 10kg and 15 kg of paddy in presence of PCM. The initial and final moisture content from 10 kg of paddy is from 30.6% to 14.8%. Similarly the initial and final moisture content from 15kg paddy is from 30.3% to 14.5%. Relative humidity during the moisture transfer is maintained 65%.

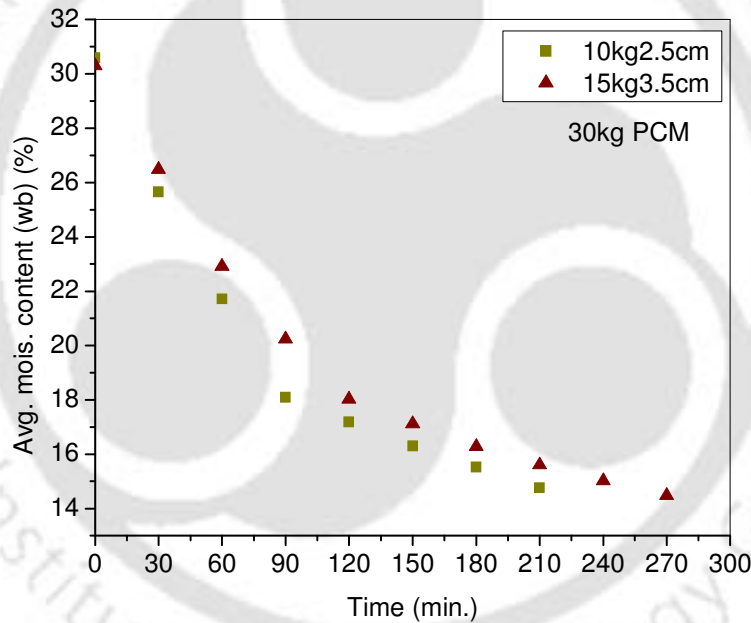


Fig.6.5: Avg. moisture transfer (%) from 10kg and 15kg of paddy in w.b.

It is observed from the Fig. 6.5 that the time taken for the transfer of moisture from 10kg and 15kg of paddy is 3hrs 30 mins and 4 hrs 30mins, respectively.

### 6.3.3 Capacity and drying time

In order to test the feasibility of the dryer in terms of fuel saving as well as drying time,

series of experiments are conducted in the present dryer in both batch and continuous process. The time gap between loading and unloading of paddy in the tray in both the process is same as phase-I and phase-II.

Two batches of paddy of different amount with different thickness are dried in batch and continuous process by using the different amount of biomass. In both the processes three batches (each of 10kg) and two batches (each of 15kg) of paddy are considered.

It was observed in the continuous process that 2.5 kg of biomass is required for the melting of paraffin wax so as to maintain the temperature above 50°C during solidification. Thermal energy released during solidification of PCM has been found to be sufficient to dry one batch of 10kg of paddy from a moisture level of 30.4% to 14.5%. Additional amount of 0.25 kg of biomass is required for subsequent drying of next 10kg batch of paddy so as to maintain the drying air temperature above 50°C. Biomass required for continuous drying of 30 kg of paddy in terms of the batch of 15 kg was found to be 3 kg with intermediate re-firing of 0.25 kg.

Table 6.5 gives the details of the experiment in batch wise (B.D) and continuous (C.D) process for three batches of each 10kg and two batches each 15kg of paddy.

Table 6.5: Details of the experimental results in B.D and C.D process

Sl. no	Amount of paddy per batch (kg)	Thickness of Paddy per batch (cm)	Total amount of paddy dried (Kg)		Amount of moisture removal (%)		Avg. Atm. Humidity (%)		Time taken for moisture removal (hr)		Amount of biomass required (kg)	
			B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D
1	10	2.5	30	30	15.8,15.7,15.8	15.8,15.9,15.8	65	65	10.5	10.5	7.5	3
2	15	3.5	30	30	15.8,15.9	15.8,15.9	65	65	9	9	5.5	3

Similarly, experiments are conducted by considering two batches of paddy grains each of 20 kg and found that 3.5kg of biomass is required to bring the paddy to safe moisture content level in 11 hrs in continuous process.

From the Table 6.5 it is well established that the best way is to dry batches of 15 kg paddy in continuous process in the developed dryer with PCM with reduction in drying time and biomass requirement and to minimize the loss of thermal energy after unloading of paddy. Batches of 20kg of paddy is not suitable to dry in the existing dryer, which is already described in subsection 6.2.3

### 6.3.4 Drying efficiency

Tables 6.6 and 6.7 present the drying efficiency for batch and continuous drying process, respectively. It was observed that the drying efficiency in continuous process is better than that of the batch process with significant reduction in biomass requirement which is similar to the results obtained in Phase-II.

Table 6.6: Drying efficiency in batch wise process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	I.M.C	F.M.C	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	30.7, 30.4, 30.6	14.6,14.8, 14.5	5.5	7.5	9.8
2	15	30kg	30.6, 30.5	14.6,14.7	5.5	5.5	12.9

Table 6.7: Drying efficiency in continuous process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	I.M.C	F.M.C	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	30.5, 30.3, 30.7	14.6,14.8, 14.6	5.5	3	24
2	15	30kg	30.4, 30.3	14.5,14.7	5.5	3	24

Experiments performed with PCM for continuous drying of 100 kg of paddy reveals that the drying efficiency of 50.4% can be achieved with the same range of moisture content (30.4-14.5%).

Better quality and drying efficiency was observed with the use of PCM. However there was significant loss of thermal energy through the walls and with the flue gases as recorded in the experiment. In order to optimize the thermal energy loss, combination of SHSM and PCM are tried on the same dryer under Phase-IV and results are discussed in subsequent sub-sections.

#### 6.4 Experiments with both SHSM and PCM (phase-IV)

In the present phase experiments are conducted by using both SHSM (pebble) and PCM (paraffin wax) to store the thermal energy and to maintain the constant range of temperature for quality drying of paddy.

Experiments are conducted to study the different parameters involves for the melting of wax which is given in Table-6.8. To melt 20 kg, 25 kg and 30 kg of paraffin wax with SHSM and PCM certain amount of biomass is required which is given in the Table-6.8. Here the constant temperature is maintained for long duration by combustion of biomass. Amount of biomass required to achieve the desired temperature is found to be lowest in

the present phase. This is because the thermal energy is stored in the pebble and releases the same for longer period which is received by the paraffin wax for melting purpose. Here more time is required to melt the paraffin wax but the biomass requirement is significantly less.

All the experiments reported in subsequent sub-sections are conducted with 30 kg of paraffin wax. The details characteristics of paraffin wax and the amount of biomass required is given in Table 6.8.

Table 6.8 Characteristics study of paraffin wax in presence of SHSM

Amount of paraffin wax (kg)	Melting range of temp. (°C)	Time taken for melting of paraffin	Time taken for solidify to come to 50°C	Amount of biomass required to melt (kg)
20	~48.8- ~62.7	~1hrs 15min.	~6hrs	1.75kg
25	~48.6- ~62.4	~1hrs 45min.	~7hrs 30mins	2kg
30	~48.3- ~62.1	~2hrs 30min.	~9hrs	2.25kg

Range of parameters considered for the experiment with SHSM and PCM is given in Table 6.9.

Table 6.9 Input parameters under Phase-IV (with SHSM & PCM)

Sl No	Particulars	Ranges
1	Ambient air temperature	19 <sup>0</sup> C -22 <sup>0</sup> C
2	Relative humidity	65%
3	Amount of paddy per batch	10 kg and 15kg
4	Drying air temperature	50 <sup>0</sup> C -60 <sup>0</sup> C

5	Amount of paraffin wax	30kg
6	Particular of dryer	Simple natural convection dryer using both SHSM and PCM ( Phase-IV)
7	Initial moisture content of paddy grain	30% (approx)
8	Final Moisture content of paddy grain	14-15%

Average drying air temperatures below the paddy tray were measured in the range of  $50^{\circ}\text{C}$  -  $60^{\circ}\text{C}$  after a period of 150 minutes of combustion of biomass in the furnace. All the experiments were repeated for 3 to 4 times and average value of the parameters was reported. Experiments were conducted by considering 10 kg and 15 kg batches of paddy, respectively.

It is found that the solidification of 30 kg of molten paraffin wax releases heat at constant range of temperature ( $50^{\circ}\text{C}$  -  $60^{\circ}\text{C}$ ) for nine hours. When temperature of drying air falls near to  $50^{\circ}\text{C}$  during drying process, an additional amount of biomass (0.250 kg) is supplied to the furnace so as to maintain the drying air temperature above  $50^{\circ}\text{C}$  for another 70 minutes.

#### 6.4.1 Temperature profile

Figure 6.6 (a) presents the variation of average value of drying air temperature with time during drying of 10 kg of paddy in Phase-IV. When the average drying air temperature of  $45^{\circ}\text{C}$  was recorded in the plenum chamber, paddy was loaded on the drying tray immediately.

It is found from the experiment that the temperature variation in the plenum chamber is very less and is maintained between  $50^{\circ}\text{C}$  to  $60^{\circ}\text{C}$  during drying, which is useful for the

quality drying of paddy. The minimum and maximum drying air temperature during drying period for 10kg of paddy is observed to be 50°C and 59.8°C, respectively.

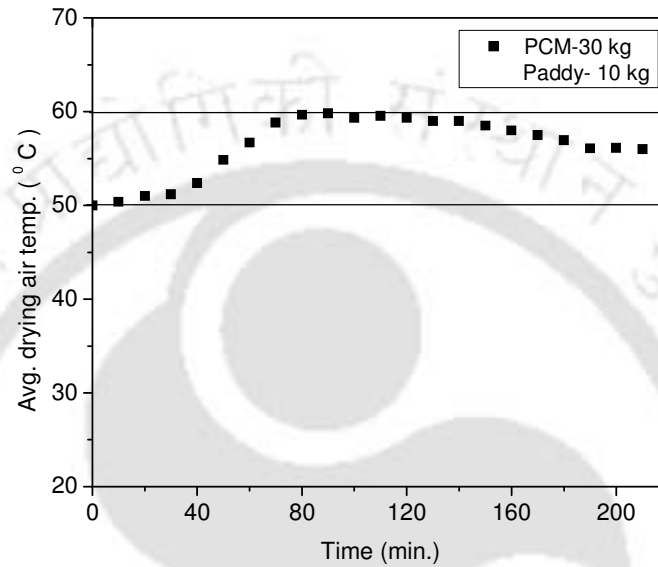


Fig.6.6: Variation of drying air temperature during drying period of paddy.

From the experiment it is found that, once the paraffin wax will melt it will release heat at constant range of temperature and is sufficient to dry three batches of each 10 kg of paddy which is shown in figure 6.7.

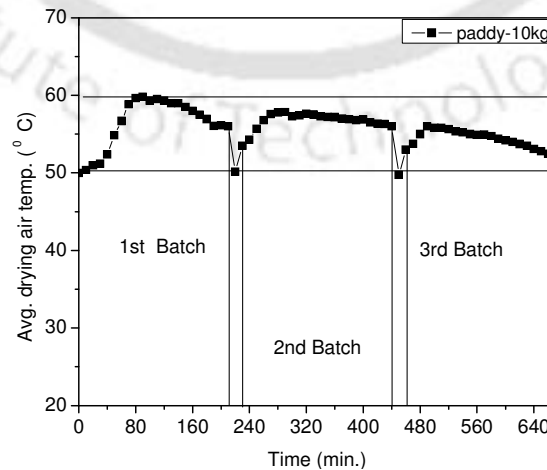


Fig. 6.7: Variation of drying air temperature during the drying of three batches of paddy (each 10kg).

### 6.4.2 Moisture transfer analysis

Figure 6.8 shows the variation of moisture content of 10 kg of paddy in presence of both SHSM and PCM. The initial and final moisture content of 10 kg of paddy is from 30.4 % to 14.6 %. Relative humidity during the moisture transfer is maintained 65 %.

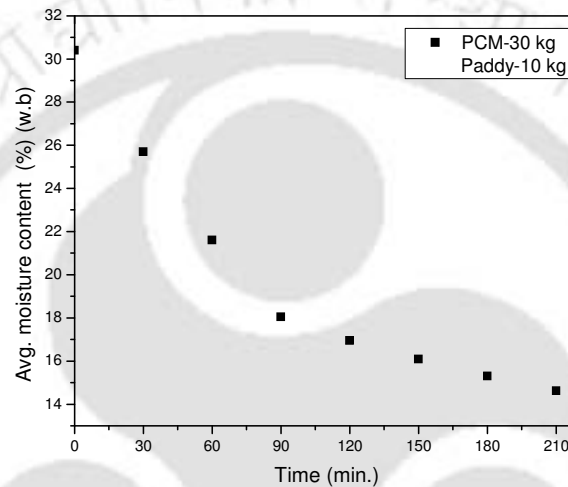


Fig. 6.8: Average moisture transfer from 10kg of paddy with SHSM and PCM

### 6.4.3 Capacity and drying time

In order to test the feasibility of the dryer in terms of fuel saving as well as drying time, series of experiments are conducted in the present dryer in both batch and continuous process. The time gap between loading and unloading of paddy in the tray in both the process is same as phase-I, II and III.

Two batches of paddy of different amount with different thickness are dried in batch and continuous process by using the different amount of biomass. In both the processes three batches (each of 10kg) and two batches (each of 15kg) of paddy are considered.

It was observed in the continuous process that 2.25 kg of biomass is required for the melting of paraffin wax so as to maintain the temperature above 50°C during

solidification. Thermal energy released during solidification of PCM has been found to be sufficient to dry three batches of 10kg of paddy and two batches of 15 kg of paddy from a moisture level of 30.4% to 14.6%. Additional amount of 0.250 kg and 0.500 kg of biomass is required for subsequent drying of next 10 kg and 15 kg batch of paddy, respectively so as to maintain the drying air temperature above 50<sup>0</sup>C. Table 6.10 gives the details of the experiment in batch wise (B.D) and continuous (C.D) process for three batches of each 10kg and two batches each 15kg of paddy.

Table 6.10: Details of the experimental results in B.D and C.D process

Sl.no	Amount of paddy per batch (kg)	Thickness of Paddy per batch (cm)	Total amount of paddy dried (Kg)		Amount of moisture removal (%)		Avg. Atm. Humidity (%)		Time taken for moisture removal (hr)		Amount of biomass required (kg)	
			B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D	B.D	C.D
1	10	2.5	30	30	15.8,15.9, 15.8	15.8,15.9, 15.8	65	65	10.5	10.5	6.75	2.25
2	15	3.5	30	30	16.1,16.0	16.1,16.0	65	65	9	9	4.5	2.25

Similarly, experiments are conducted by considering two batches of paddy grains each of 20 kg and found that 2.75 kg of biomass is required to bring the paddy to safe moisture content level in 11 hrs in continuous process.

From the Table 6.10 it is well established that the best way is to dry batches of 15 kg paddy in continuous process in the developed dryer with the use of both SHSM and PCM with reduction in drying time and biomass requirement and to minimize the loss of

thermal energy after unloading of paddy. Batches of 20kg of paddy is not suitable to dry in the existing dryer, which is already described in subsection 6.2.3

#### 6.4.4 Drying efficiency

Tables 6.11 and 6.12 present the drying efficiency for batch and continuous drying, respectively. It was observed that the drying efficiency in continuous process is better than that of the batch process with significant reduction in biomass. This trend was similar in all the phases of experiments as reported earlier.

Table 6.11: Drying efficiency in batch wise process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	I.M.C	F.M.C	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	30.4, 30.6, 30.7	14.6,14.5, 14.4	5.6	6.75	10.7
2	15	30kg	30.6, 30.4	14.8,14.7	5.6	4.5	16.1

Table 6.12: Drying efficiency in continuous process

Sl. no	Amount of paddy in one batch(kg)	Total amount of paddy dried (kg)	I.M.C	F.M.C	Total amount of moisture removed (kg)	Amount of biomass required (kg)	Drying Efficiency ( $\eta$ ) (%)
1	10	30kg	30.7, 30.3, 30.7	14.4,14.6, 14.6	5.6	2.25	32.1
2	15	30kg	30.7, 30.5	14.5,14.7	5.6	2.25	32.1

Efficiency for drying of 100 kg of paddy in batch of 10 kg was found to be 59.5% with combination of SHSM and PCM in continuous process.

Use of the combination of SHSM and PCM reduced the variation of drying air temperature within the permissible limit of quality drying (50°C-60°C). Further, heat release from the system to drying air was taking place for long duration of time reducing the biomass requirement. Efficiency in this phase is thus more than the other phases.

## **6.5 Comparison of the experimental results with and without energy storage material**

### **6.5.1 Comparison of drying air temperature**

Figure 6.9 shows the variation of drying air temperature below the paddy tray during the drying of 10 kg of paddy in all the four Phases. It is found from the experiment that the drying air temperature variation is large (48 °C – 75 °C) in phase-I which decrease with introduction of SHSM (47 °C – 63 °C) in Phase-II. There is further decrease of the variation of drying air temperature (50 °C - 60 °C) in both Phase-III and IV. This is because in Phase –I, there are no storage materials so it is difficult to control the temperature but in case of Phase-II, the SHSM (pebble) are used so thermal energy is store in the pebble and release the same for longer duration. Similarly in phase III and IV, PCM (paraffin wax) is used to store the thermal energy and release the same at constant range of temperature with small variation.

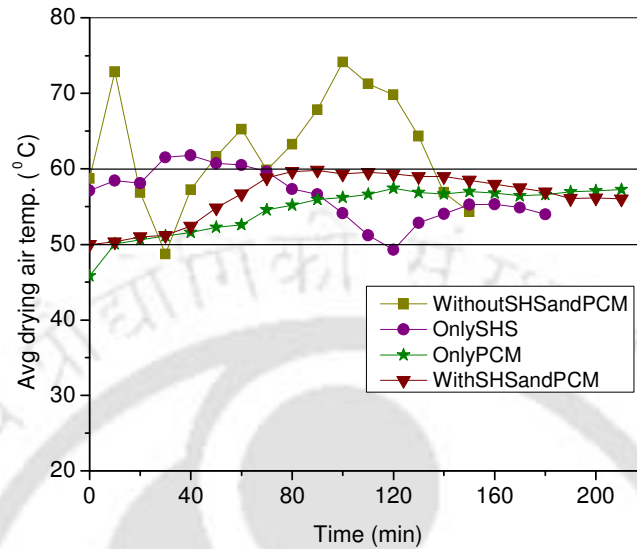


Fig.6.9: Comparison of average drying air temperature during the drying period of 10kg paddy with and without storage materials

### 6.5.2 Comparison of Average moisture transfer rate

Figure 6.10 presents the variation of moisture transfer with time during the drying of 10kg of paddy in Phase I-IV. The initial moisture content for Phase I- IV is 30.8 %, 30.4 %, 30.3 % and 30.4 %, respectively. Similarly the final moisture content for Phase I-IV is 14.7%, 14.6 %, 14.5 % and 14.6 %, respectively. In all phases relative humidity of atmospheric is approximately 65 %.

It is found from the experiment that the initial moisture transfer from the paddy is fast when there is no storage materials are used and the same is decreases when there are storage materials. This is due to the large temperature variation without thermal energy storage materials. Since initial transfer of moisture depends on the temperature, so in Phase-I initial moisture transfer is more than Phase-II (moderate variation of temperature). Similarly the initial moisture transfer is less in Phase-III and IV, since the variation of drying air temperature is less.

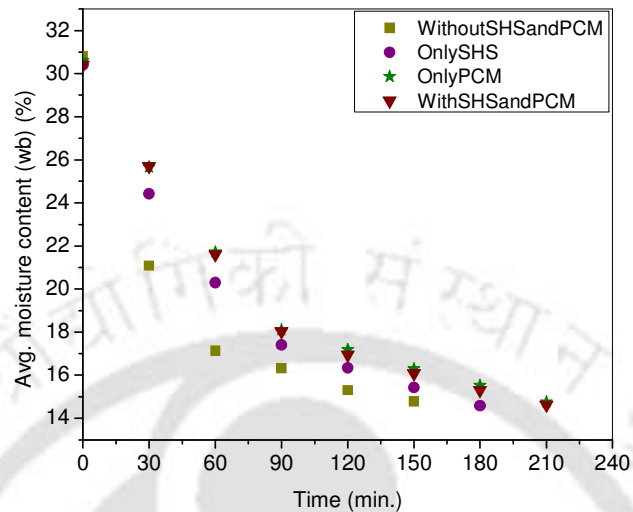


Figure 6.10: Comparison of moisture content at different time for 10kg of paddy with and without storage materials

### 6.5.3 Comparison of drying time

Table 6.13 presents the comparison of drying time for 4(four) Phases in batch process (B.D) and continuous process (C.D). For the comparison three batches with 10kg paddy per batch and two batches (each of 15 kg) are considered. In all the cases average initial and final moisture content of paddy batches is approximately 30.4 % and 14.5 %, respectively. The humidity of atmosphere is 65%. It is found that time requirement for batch process is same as that of continuous process. It is also found that time required for the drying of 30 kg of paddy in 15kg batches is less than for same amount in 10 kg batches.

Table-6.13 Comparison of drying time required in phase I-IV

Sl. no	Amount of paddy per batch (kg)	Total amount of paddy dried	Time required in B.D (hr)				Time required in C.D (hr)			
			Phase-I	Phase-II	Phase-III	Phase-IV	Phase-I	Phase-II	Phase-III	Phase-IV
1	10	30	7.5	9	10.5	10.5	7.5	9	10.5	10.5
2	15	30	9	8	9	9	9	8	9	9

#### 6.5.4 Comparison of biomass requirement

Table 6.14 presents the amount of biomass required in 4 (four) different phases of drying of paddy. In all four phases total 30kg of paddy is dried in either three batches (each 10 kg) or two batches (each 15 kg). In all the cases amount of fuel required is different. It is found from the experiment that amount of biomass requirement in phase-IV is less as comparison to other phases. This is because thermal energy which evolves during the burning of biomass is stored in the pebble and releases the same for the melting of paraffin. Paraffin wax upon solidification releases heat for long duration to continue with the drying of paddy.

Table-6.14 Comparison of biomass required in phase I-IV

Sl. no	Amount of paddy per batch (kg)	Total amount of paddy dried	Amount of biomass required in B.D (kg)				Amount of biomass required in C.D (kg)			
			Phase-I	Phase-II	Phase-III	Phase-IV	Phase-I	Phase-II	Phase-III	Phase-IV
1	10	30	6	5.25	7.5	6.75	5	2.75	3	2.25
2	15	30	6	4	5.5	4.5	5.75	2.75	3	2.25

### 6.5.5 Comparison of efficiency of the dryer

Table 6.15 presents the comparison of efficiency in four phases in both batch and continuous process. Efficiency of the dryer depends on the amount of moisture transfer and the amount fuel combust inside the furnace. It is found from the experiment that the efficiency in Phase-IV is more. Maximum amount of thermal energy is stored in the pebbles which are subsequently released to the paraffin wax reducing the amount of biomass requirement. Efficiency of the dryer is found to be highest in Phase-IV as there is a substantial reduction in biomass requirement in this phase. This observation indicates that the loss of thermal energy from the dryer is minimized.

Table-6.15 Comparison of drying efficiency (phase I-IV)

Sl. no	Amount of paddy per batch (kg)	Total amount of paddy dried	Drying efficiency in B.D (%)				Drying efficiency in C.D (%)			
			Phase-I	Phase-II	Phase-III	Phase-IV	Phase-I	Phase-II	Phase-III	Phase-IV
1	10	30	12.0	13.6	9.8	10.7	14.4	26.2	24.0	32.1
2	15	30	12.0	18.1	12.9	16.1	12.5	26.2	24.0	32.1

### 6.5.6 Comparison of quality of paddy



Table 6.16 gives the comparison of quality of paddy in terms of milling and nutritional value in phase-I-IV. It is found that the quality in phase-IV is better than the other three phases. This is because in phase-IV, drying of paddy takes place at constant and close range of temperature (50 °C-60 °C) so that it will not affect both milling quality as well as nutritional value of paddy. In phase-I, since there is large variation of drying air temperature and also maximum temperature rises to 80 °C, the breaking percentage of

rice kernel increases. Table 6.17 shows the comparison of pictorial view of rice samples before and after the drying of paddy in four phases.

Table 6.16 Comparison of quality of paddy in phase-I, phase-II and phase-III

Sl. no	Quality Parameters	Raw Paddy Grain	Dried paddy grain			
			Phase-I	Phase-II	Phase-III	Phase-IV
1	Nutritional value					
	Carbohydrate % (d w)	78	52	65	72	75
	Protein % (d w)	7	1	3	6	7
2	Milling quality % (Broken Kernel)	75	55	35	3	2

Table 6.17: Pictorial view of the rice sample before and after drying

Sl.no		After drying	Before drying
1	Phase-I	 <p style="text-align: center;">% Broken-55%</p> <p style="text-align: center;">After drying</p>	 <p style="text-align: center;">% Broken-75%</p> <p style="text-align: center;">Before drying</p>
		 <p style="text-align: center;">% Broken-35%</p> <p style="text-align: center;">After drying</p>	

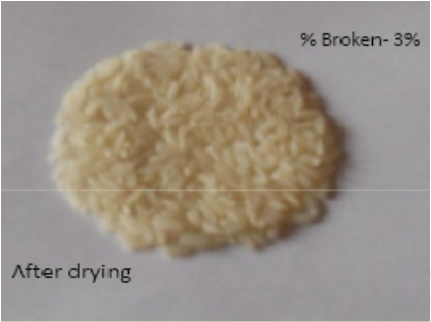

3	Phase-III		
4	Phase-IV		

Figure 6.11 presents the variation of average drying air temperature with average moisture removal rate for drying of 10 kg of paddy. Plots are presented for time interval of two successive hours of drying. From the graph it is observed that there is slight increase in moisture removal rate with temperature. The moisture removal rate for second hour of drying is also similar but the level of moisture in paddy is significantly lower. This graph clearly indicates uniformity of drying with temperature. But if will dry the paddy at very high temperature dry patches will come in the second hour which is due to lack moisture transfer from interior of kernal to the upper surface by capilarity which will affect the milling quality of paddy and paddy will break at the time of milling.

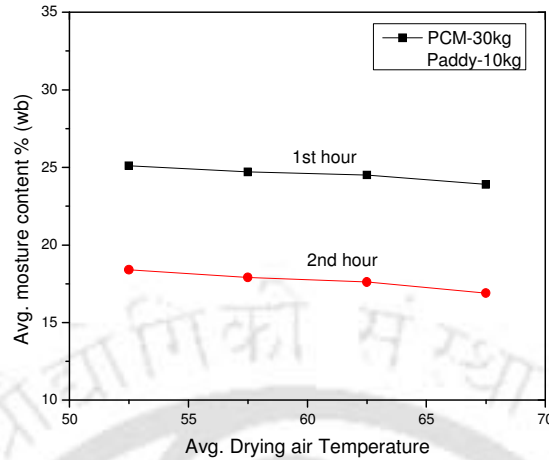


Figure 6.11: Avg. Moisture content Vs. Avg. drying air Temperature

## 6.6 Summary

The objective of this study is to introduce thermal energy storage materials to increase the efficiency of the dryer by minimizing the losses of thermal energy and to improve the quality of the paddy by maintaining the constant range of drying air temperature (50°C-60°C). Pebbles (SHSM) are used only thermal energy storage materials and paraffin wax (PCM) is used for both thermal energy storage and maintaining the quality of paddy. Experiments are done separately by using SHSM and PCM and one experiment using both SHSM and PCM in three phases (Phase II-IV). Parametric study of drying air temperature variation, moisture transfer rate, amount of biomass required, drying time required, efficiency of the dryer for the drying of 10 kg, and 15 kg of paddy are extensively done. Efficiency of the dryer is studied in both batch and continuous process for 10 kg batches and 15 kg batches and found efficiency of continuous drying process is more than the batch process. If we consider drying of 10 kg and 15 kg batches of paddy, it is found, drying of 15kg batches of paddy is more effective (both in terms of requirement of time and biomass). Quality of the paddy in terms of nutritional value and milling value is best when phase change materials are used.

To increase the performance of the drying process, to increase the efficiency of the dryer and to supply a novel dryer which can be easily accessible by the farmer level it is necessary to do the thermo economic analysis of the dryer which is given in chapter-7.

## CHAPTER- 8

### CONCLUSIONS AND SCOPE FOR FUTURE WORK

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#### 8.1 Conclusions

The present research work focuses on the design and development of a novel dryer to reduce the post harvest losses of paddy grain with an emphasis to maintain the quality of final product. An indirect type of natural convection grain dryer using pebble as sensible heat storage materials and paraffin wax as phase change materials is designed, developed and constructed with available materials at IIT Guwahati, India. Performance of the developed dryer is evaluated to investigate the effect of drying parameters on paddy drying. Performance of the dryer is studied with and without using SHSM and PCM in 4 (four) different phases. Paddy was dried from average moisture content of 30% (wb) to 14.5% (wb). Quality of the final product was tested in terms of nutritional value and milling index. Complete thermo-economic analysis of the developed dryer is done to judge its suitability of installation in rural areas. The following important points are drawn in the conclusions.

The variation of moisture removal rate was studied for different thickness of paddy layer (2.5cm, 3.5cm, 4.5cm and 5.5cm). It is observed that moisture transfer rate was decreasing with increase in thickness of paddy layer. Layers with 2.5 to 3.5cm is found to be suitable for drying the paddy grains to the safe moisture content level.

Effect of relative humidity of atmosphere on drying is studied (65%-80%) and it is found that moisture removal rate was decreasing with increasing relative humidity.

It was observed that the time of drying increases by half an hour for 10 kg paddy for every 5% increase of relative humidity of atmosphere. Similar trend was observed for more amount of paddy dried.

Average drying air temperature was maintained at  $54^{\circ}\text{C}$  with the use of PCM and  $56^{\circ}\text{C}$  with the use of the combination of SHSM and PCM. This is well within the range for quality drying as reported in literature.

Average drying air temperature for phase –I (without thermal storage material) was found to be  $67^{\circ}\text{C}$  which is unsatisfactory for quality maintenance of final product. Similarly, drying air temperature with SHSM is in the higher range of prescribed temperature for quality drying. Hence Phase-1 and II are not recommended for quality drying. SHSM can be used to store the thermal energy only.

The duration of release of heat release to drying air is more than 6 hours with the use of combination of SHSM and PCM. Heat release to drying air was 2 hours, 3.5 hours and 4.5 hours in Phase-I, II and III, respectively.

Best quality of product in terms of nutritional value and milling index was observed for Phase-III (with PCM) and Phase-IV (combination of PCM and SHSM). Testing of sample indicates that the Carbohydrate and protein in the final product are 75%, 7%, respectively. Percentage of broken rice was reduced to 2% which is satisfactory. Results for Phase-I and Phase-II are not encouraging.

It was observed that the time and biomass required for continuous drying of 100kg of paddy in batches of 10 kg of paddy were 31.5 hours and 4.75kg, respectively with PCM (Phase-III). Similarly, for drying of 100 kg of paddy in 6 (six) batches of 15kg each and 1 (one) batch of 10 kg 30.5 hour was required. Biomass requirement was slightly reduced (4.25kg) in the process. It is concluded that drying in a continuous process with a batch of 15 kg of paddy is better than batch process. Similarly, batches of

10 kg in continuous process are more suitable with combination SHSM and PCM (Phase-IV) requiring less amount of biomass (4 kg). However, there is hardly any change in duration of drying time in both the Phases.

Drying efficiency for drying of 100 kg of paddy in batch of 10kg was found to be 59.50% with combination of SHSM and PCM (Phase-IV). Same was found to be 50.4% with the use of PCM (Phase-III) and 38.3% with the use of SHSM (Phase-II). The efficiency was poor (18.4%) without any thermal storage medium (Phase-I).

Exergetic efficiency decreases during the moisture transfer process from 37.4% to 9.7% for a batch of 10kg of paddy with the use of SHSM and PCM (Phase-IV). Similar trend were observed for Phase-II and III for different amount of paddy grain loaded on the drying tray. Unpredictable behavior of exergetic efficiency was obtained in Phase-I due to uncontrolled variation of drying air temperature.

Energy utilization ratio (EUR) increases up to the critical moisture content level and subsequently same was decreasing with the falling rate period for all the Phase-II-IV. No particular trend in variation of EUR for Phase-I was observed as the drying air temperature was uncontrolled in this Phase.

Break even point for the developed dryer is calculated to be 28 batches with each batch of 15 kg. paddy to bring the average moisture content of paddy from 30% (wb) to 14.5% (wb).

## 8.2 Scope for Future Work

Present experimental study is limited to drying of paddy. Experiments were conducted for drying of 80 kg of paddy continuously in one day. This dryer is suitable for the rural levels for the small farmers. There is a scope for further analysis of the developed dryer which are discussed below:

The existing dryer is suitable for the drying of paddy as evident from experiments conducted. Various agricultural products such as ginger, garlic, chilli, turmeric, etc requires different drying temperatures for quality drying. The feasibility of dryer can be tested for such products by using different grade of paraffin wax.

This dryer is not suitable for the commercial drying. A detail scale up analysis is required to make it viable for commercial use. Simulation and scale up study are required for the same.

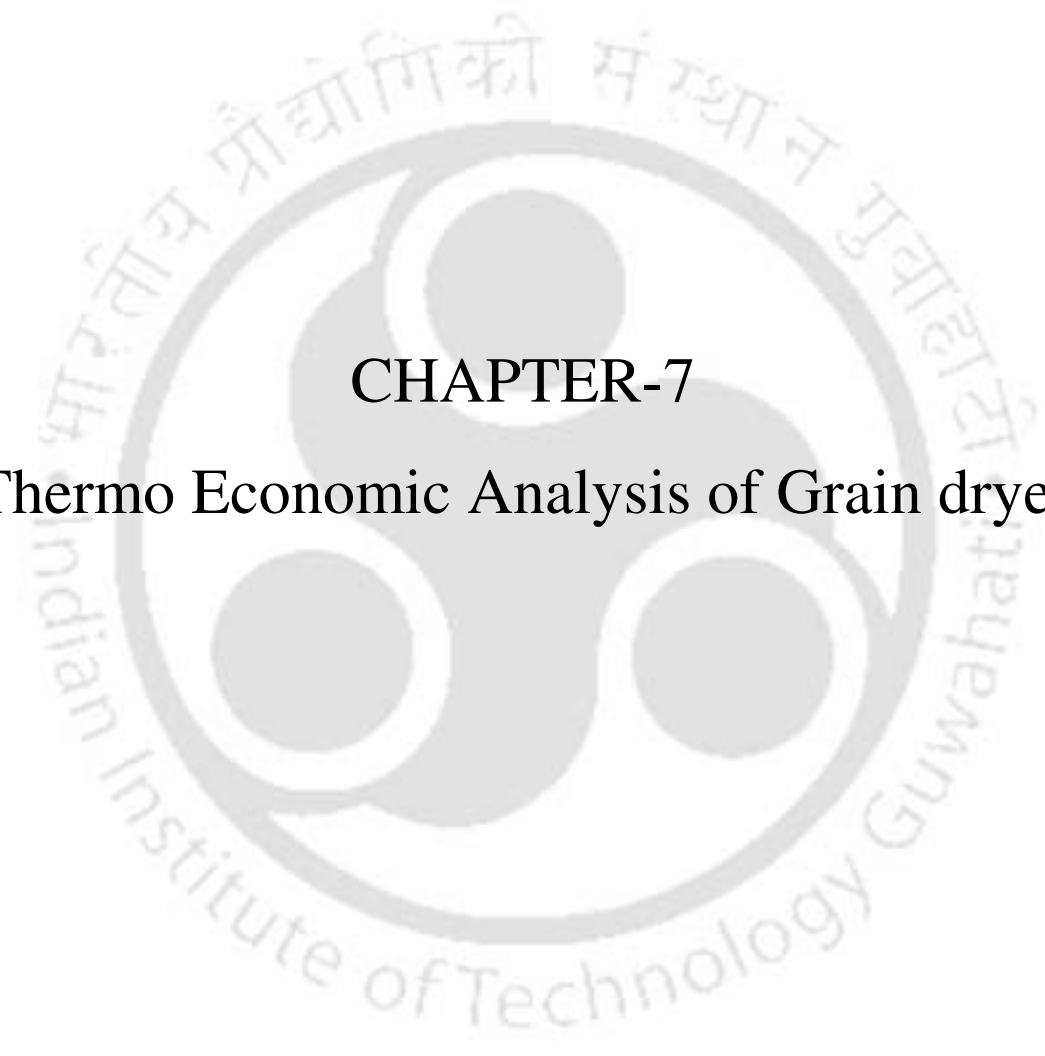
It was observed that there is medium to small temperature heat loss through the out let of the flue gas pipe of the dryer. Waste heat recovery heat exchanger can be designed and incorporated so as to utilize the waste heat for preheating the drying air. This will in turn reduce the amount of biomass requirement leading to the improvement of drying efficiency.

Present dryer is operated by combustion of biomass. The performance of the dryer can be tested by using other renewable source of energy such as solar thermal or combustion of biogas so as to make the system environmentally compatible.

The efficiency of the dryer can be increased by increasing thermal conductivity of paraffin wax. Thermal conductivity of the dryer can be increased by adding the metal matrix or nano- materials in the paraffin wax.

The logo of the Indian Institute of Technology Guwahati is a circular emblem. It features a central stylized figure with three circular elements, resembling a traditional Indian motif. The text "Indian Institute of Technology Guwahati" is written in English around the bottom half of the circle, and "भारतीय प्रौद्योगिकी संस्थान गुवाहाटी" is written in Hindi around the top half.

**CHAPTER-4**  
***EXPERIMENTAL SETUP AND PROCEDURE***

The logo of the Indian Institute of Technology Guwahati is a circular emblem. It features a central stylized figure with three rounded protrusions, resembling a traditional Indian symbol. The text "Indian Institute of Technology Guwahati" is written in English around the bottom half of the circle, and its Assamese equivalent "সৰলীয প্ৰৌদ্যোগিকী সংস্থান গুৱাহাটী" is written along the top half.

## CHAPTER-7

### Thermo Economic Analysis of Grain dryer

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# Nomenclatures

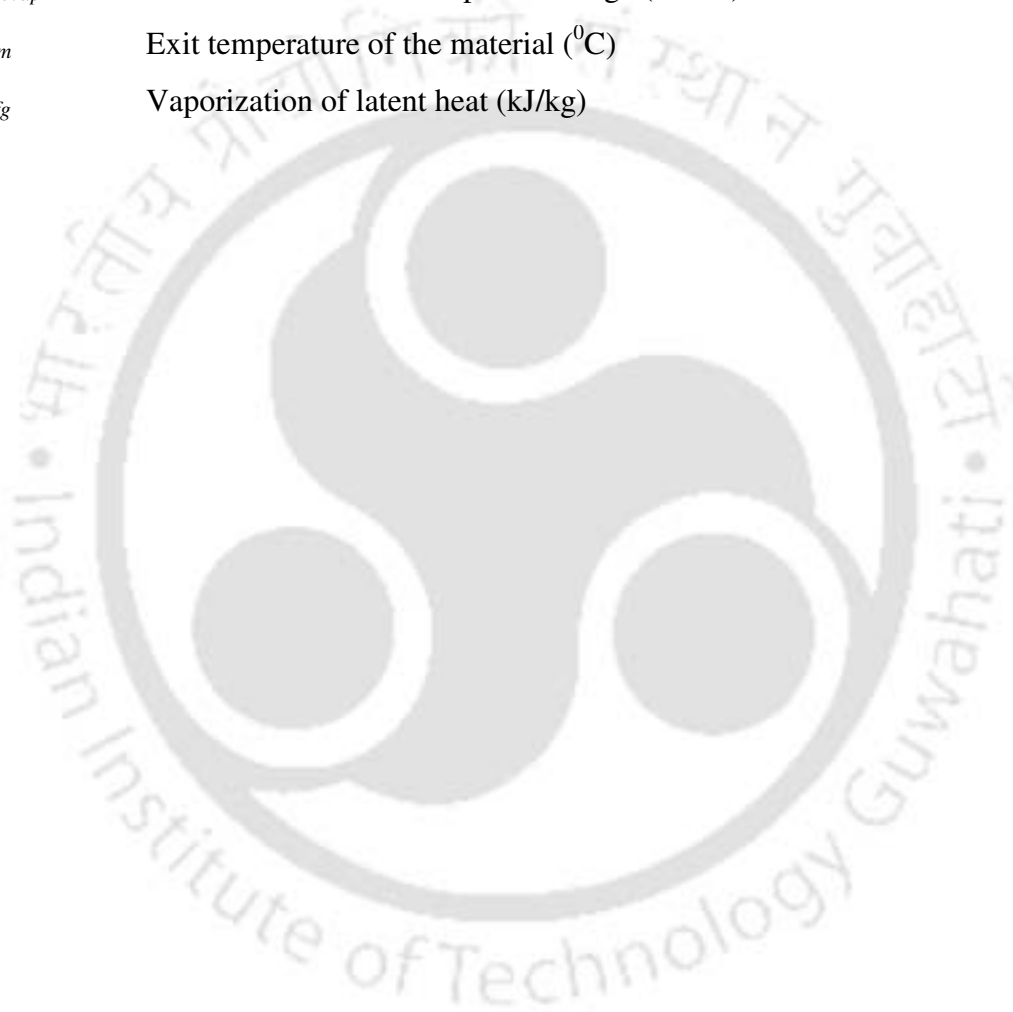
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$M$	Moisture content of the material at any time (% w.b.)
$M_e$	Equilibrium moisture content
$(h^{-1})$	Drying constant
$dM/dT$	Represents the moisture gradient.
$R_m$	Moisture ratio
$M_i$	Initial moisture content of grain, (% d.b.)
$M_e$	Equilibrium moisture content (EMC) of grain, (% d.b.)
$t$	Drying time (h)
$K$ and $N$	Drying parameters
$R_H$	Relative humidity in decimal
$k_1$ and $k_2$	Drying constant ( $\text{min}^{-1}$ )
$\dot{m}_{fg}$	Mass flow rate of flue gas (kg/sec)
$C_{fg}$	Specific heat capacity of the flue gas ( $\text{kJ/Kg } ^\circ\text{C}$ )
$T_{fge}$	Temperature of flue gas exit from the biomass burner (K)
$T_{amb.}$	Ambient temperature (K)
$\Delta P$	Drought or pressure differences produced ( $\text{N/m}^2$ )
$H$	Height of the chimney (m)
$P_a$	Atmospheric pressure ( $1.01 \times 10^5$ pa)
$\bar{\rho}_{fg}$	Average gas density in the chimney ( $\text{kg/m}^3$ )
$T_a$	Absolute ambient air temperature (K)
$\bar{T}_{fg}$	Absolute average temperature of the flue gas inside the chimney (K)
$\Delta T$	Temperature difference between ambient and drying air temperature (K)
$\beta$	Coefficient of thermal expansion ( $\text{K}^{-1}$ )
$\rho_a$	Density of ambient air ( $\text{kg/m}^3$ )
$g$	Acceleration due to gravity ( $\text{m/sec}^2$ )

$\rho^*$	Average air density inside the dryer ( $\text{kg/m}^3$ )
$T_o$	Temperature of drying air above the biomass burner (K)
$h_c$	Heat transfer coefficient ( $\text{W/m}^2\text{k}$ )
$A$	Total surface area of biomass burner ( $\text{m}^2$ )
$T_s$	Burner surface temperature
$Gr$	Grashof number ( $\beta g x^3 \rho^2 \Delta T / \mu_v$ ),
$Pr$	Prandtl number ( $\mu_v c_v / K_v$ )
$Nu$	Nusselt number ( $h_c X / K_v$ ).
$P(T_c)$	Partial vapor pressure at temperature $T_c$ (crop temperature $^{\circ}\text{C}$ ) ( $\text{N/m}^2$ ).
$P(T_e)$	Partial vapor pressure at temperature $T_e$ (temperature just below the crop $^{\circ}\text{C}$ ) ( $\text{N/m}^2$ ).
$\gamma$	Relative humidity
$\beta$	Coefficient of volumetric expansion ( $1/^{\circ}\text{C}$ )
$m$	Mass of heat storage medium (kg)
$C_p$	Specific heat ( $\text{J/kg K}$ )
$C_{ap}$	Average specific heat between initial and final temperature of pebble ( $\text{kJ/kg K}$ )
$T_{ip}$	Initial temperature of the pebble ( $^{\circ}\text{C}$ )
$T_{fp}$	Final temperature of the pebble ( $^{\circ}\text{C}$ ).
$m_w$	Mass of heat storage medium i.e. Paraffin wax (kg)
$T_{iw}$	Initial temperature of paraffin wax ( $^{\circ}\text{C}$ )
$T_{fw}$	Final temperature of melted paraffin wax ( $^{\circ}\text{C}$ )
$T_{mw}$	Melting temperature of paraffin wax ( $^{\circ}\text{C}$ )
$a_m$	Fraction of paraffin wax melted
$\Delta h_m$	Heat of fusion per unit mass ( $\text{J/kg}$ )
$C_{pw}$	Specific heat of paraffin wax ( $\text{J/kg K}$ )
$C_{sw}$	Average specific heat between initial temperature and melting temperature of wax ( $\text{kJ/kg K}$ )
$C_{lw}$	Average specific heat between melting and final temperature of wax ( $\text{kJ/kg K}$ )
$M_w$	Mass of water removed from wet paddy (kg)

$W_p$	Initial mass of the paddy to be dried (kg)
$M_{ip,wb}$	Initial moisture content of paddy on wet basis
$M_{fp,wb}$	Final moisture content of paddy on wet basis
$Q_{da}$	Heat supplied by the drying air during drying
S	Humid heat of ambient air
$\theta$	Total drying time (minute)
$t_{i,da}$	Initial drying air temperature ( $^{\circ}\text{C}$ )
$t_{f,da}$	Final temperature of drying air ( $^{\circ}\text{C}$ )
$t_{p1}$	Initial temperature of paddy ( $^{\circ}\text{C}$ )
$t_{p2}$	Final temperature of paddy ( $^{\circ}\text{C}$ )
$W_w$	Weight of moisture (kg)
$W_{bdp}$	Weight of bone dried paddy (Kg)
$m_1$	Initial moisture content (w.b )
$m_2$	Final moisture content ( w.b)
$m_3$	Initial moisture content in (d.b)
$L_v$	Latent heat of vaporization( kJ/kg)
$W$	Weight of water evaporated (kg)
$L$	Latent heat of evaporation of water (MJ/kg)
$M$	Mass of biomass fuel used in the furnace (Kg)
$C$	Calorific value of biomass fuel (MJ/kg)
$Q_{uda}$	Useful energy or heat gain (kJ)
$C_{pda}$	Specific heat of drying air (J/kg $^{\circ}\text{C}$ )
$T_{dco}$	Temperature of drying chamber outlet ( $^{\circ}\text{C}$ )
$T_{dci}$	Temperature of drying chamber inlet ( $^{\circ}\text{C}$ )
$m_{da}$	Mass flow rate of drying air (kg/sec)
$\phi$	The relative humidity
$T_{da}$	Drying air temperature ( $^{\circ}\text{C}$ )
$h_{sat,T}$	Enthalpy of saturated vapour (kJ/kg)

$h_{dci,T}$	Enthalpy of drying air in the drying chamber inlet (kJ/kg)
$h_{dco,T}$	Enthalpy of drying air in the drying chamber outlet (kJ/kg)
$\dot{E}$	Exergy of the system( kJ/kg)
$\bar{C}_{pda}$	Average specific heat of drying air (kJ/kg)
$Q_{evap}$	Heat transfer rate due to phase change (kJ/sec)
$T_m$	Exit temperature of the material ( $^{\circ}$ C)
$h_{fg}$	Vaporization of latent heat (kJ/kg)



## Publications

### International Journals

- ❖ S. S. Mohapatra and P. Mahanta. Experimental Investigation of an Indirect Type of Natural Convection Dryer for Thin Layer Paddy Drying. *International Journal of Mechanical Engg. and Research*, 2011, vols. 1, pp 47-54.
- ❖ S. S. Mohapatra and P. Mahanta. Performance Evaluation of Quality Drying in a Natural Convection Grain Dryer. *Applied Mechanics and Materials*, 2011, vol. 110, pp 2094-2100.
- ❖ S. S. Mohapatra and P. Mahanta. Energy and Exergy Analysis of Natural Convection Dryer. (Communicated, Energy Journal)
- ❖ S. S. Mohapatra. and P. Mahanta. Effect of Thermal Energy Storage Medium on Quality Paddy Drying. (Communicated, IMechE)

### International Conference:

- ❖ S. S. Mohapatra and P. Mahanta. Thermodynamic Evaluation of Natural Convection Paddy Dryer. *International Conference on Renewable Energy Technology ICDRET-2012, January 5-7, Dhaka, Bangladesh.*

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