Simulation and Analysis of Plug Flow Fluidized Bed Dryer

Rakesh Verma, H.K.Paliwal

Abstract: Today many industries now use the dryer as a part of grain-drying process even during wet and dry seasons. This helps in reducing spoilage and wastage of paddy. Mostly the available industrial dryers are expensive to purchase and to maintain its smooth functioning. This study therefore is a step to design a simple Plug flow fluidized dryer that can lead to introduce small scale dryers to paddy process industry. The Plug flow fluidized bed dryers are designed and fabricated in this study consists of the drying chamber, hot air distributer plate, hot air inlet and exit system, paddy entry and exit system, fluidization chamber unit with temperature control unit and the centrifugal fan. The evaluation of dryer is based on drying time and reduction in moisture content and outlet temperature of paddy on quality parameters. Dryer dimensions are very important to analyze heat and mass transfer analysis of the Plug flow fluidized bed drying process of paddy grains. It was found d that heat and mass transfer properties of paddy grains in fluidized bed dryer was decreases as the time of drying passes and very rapid at the start of drying. The model present here predicts about dryer dimensions along safe zone of rough rice moisture content with other parameters. Simulation results show a good agreement between the simulation model and the existing simulation models.

Keywords Plug Flow, Fluidization Chamber, Centrifugal Fan, Hot Air Distributer Plate

I. INTRODUCTION

Rough rice (Paddy) drying process is now very important in rice industries throughout the world to dry rough rice grains at wet season and dry season as well. Industries and farmers have been used dryer as a part of their grain-harvesting system throughout year. Drying improves the quality of rough rice at the stage of early harvesting. The fluidized bed dryers have been developed for different streams like Mechanical industries, Agricultural industries, Pharmacy and chemical industries as explained by many researchers (Kunii and Levenspiel, 1991) [1].

Many researchers found that the conventional dryers consume considerable time and energy in their operations as compared to commercial grain dryers but they are very expensive. Therefore, there is the need to design and fabrication of dryers that would take less time to reduce moisture content of grains without compromising dryer efficiency and also reduced the operating cost.

Revised Manuscript Received on May 30, 2020.
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In this work an attempt is made to make a simulation model to design and construct the fluidized bed dryer that will be used in the drying of food grains.

L. Garnavi et al. [2006], built up a numerical model dependent on the two-stage theory of fluidization is introduced for the continuous fluidized bed dryers. As opposed to the past models, the consistency of the air pocket size along the height of the bed isn't expected. Accordingly, the air pocket breadth fluctuates along the dryer bed height. The numerical arrangement of the model shows that dryer performance is influenced by the gas speed, average stay time of particles at bed, water content in gas, temperature and diameter of solid grain. The outcomes of model found from using different gas speed that shows the drying is very crucial at the stage of constant rate drying [2].

Ramli and Daud [2007] developed a mathematical model for plug flow fluidized-bed dryer and enumerate some interrelated correlations that include gas-grain stream relation, particular heat demand, total moisture amount in dimensionless form and amount of energy used in dryer, amount of hot air consumption and its temperature and humidity. Model predicts all about the grain moisture content and exit temperature of grain and deviation from the experimental results [3].

Hall,C.W.[1980] studied about different grains characteristics like its preservation time. Preservation time is very important as concerns about the safe storage of grains. Quality deterioration characteristics start from the harvesting of grains and mainly depend upon the moisture content of grains. To store rough rice at safe level, the moisture content of rough rice may lie in between 13-14% wet basis, found safe up to quite a lot of months without significant deterioration in grains. This safe storage level found good for milling process and improves quality of grains [4]. Celia sobrino and Naoko Ellis [2009] considered impact of two sorts of plates, perforated plate and bubble-cap distributor plate .The flow of air inside fluidized bed dryer was considered as full of air pockets and turbulent in nature that produce much of mixing inside the dryer. In case of the perforated plate increasing the air velocity produces intense bed height of grains but decrease in the air velocity leads to make a low intense zone of grains. Perforated plate distributer produces the higher grains transformation from higher intense zone to lower intense zone. In case of bubble-cap distributors near to bottom a higher density of grains found but in some bottom region there was air pockets also available at bottom .the air pockets was calculated with the help of probes that found these air pockets are more in radial direction as in compared to vertical direction [5].

Renjie Dong et.al.[2009] has studied moisture distribution inside a single grain considering a uniform size of grains and also discussed the tempering process of rough rice .

During tempering process the moisture of grains are redistributed through whole grain after time passes .The tempering effect on drying characteristics and moisture distribution inside the grain was also investigated for long and short-grain rough rice. Moisture contents increased at the surface of grain but decreased inside the rough rice during the tempering drying process .The change in moisture content at the surface of rice had a much larger than that of the centre. Tempering processes produced a zero moisture gradient after some time but it have large at the initial stage. Gradient in the grains may increase or decrease the drying duration. Almost all moisture content removed from grains in four hours and half in two hours [6].
Picado and Gamero [2014] has reported a methodology for iterative sequential solution of five coupled equations governing heat and mass transfer phenomenon during falling rate drying of particulates material. He has developed a comprehensive algorithm for fluidized bed drying of wheat material through discritization of governing heat and mass equations and their numerical solutions and to study the effect of exhaust air recirculation on overall performance of the dryer [7].
Worldwide majorly three food grains are used to receive energy into the human being they are Rice, Wheat and Maize. These three provides almost 42% caloric requirement from all over the world and among three rice consumption was 78% of the total produced rice. More than 3.5 billion people from all over the world consumed rice as their main food, to fulfill the calorie requirement. South Asian countries like China, India, Indonesia, Bangladesh, Thailand, Vietnam, Burma, the Philippines, Cambodia and Pakistan produce such amount of rice that can fulfill the whole world demand. These south Asian countries supply the rice to other continents like in Africa, America, and the Middle East.
These rice producing Asian countries also have largest consumption in world so almost major rice consumption is in the Asian countries [8].
Moisture content in paddy (rough rice), between 19 to 33% (d.b) is very high and very important factor to decide quality of paddy (rough rice) during storage and harvesting periods. Low level of moisture content within the rough rice is essential to keep rice safe. PF drying process is to reduce moisture content in most food grains. The process of fluidization with high speed hot air is the way to dry the rough rice up to safe storage level. This method has been used by many industries and is very useful to dry out several varieties of grains materials [9].
Rough rice characteristics have been examined by many researchers and use various models for the prediction of drying process. Mathematical modeling of drying is very challenging part for researchers to get optimum operating parameters to enhance the performance of the drying systems. In this study an attempt is made to design a PF fluidized dryer up to a small scale and also investigate the various drying affecting parameters.

NOMENCLATURE

V	volume of bed	(m^3)
A_g	Surface area of paddy grain	(m^2)
C_{pa}	specific heat of air	(kJ/kg·K)
C_{wa}	specific heat of water	(kJ/kg·K)
D	moisture diffusivity	(m^2·s^{-1})
D_{wa}	diffusivity of water in air	(m^2·s^{-1})
H_a	enthalpy of air	(kJ/kg)
H_m	enthalpy of material	(kJ/kg)
g	gravitational acceleration	(m·s^{-2})
H	specific enthalpy	(kJ/kg)
H_{fg}	latent heat of vaporization	(kJ/kg)
X_{avg}	average grain moisture content of (d.b)	kg water/kg of dry product
X	moisture content of grain (d.b)	kg water/kg of dry product
X_{in}	initial moisture content of grain (d.b)	kg water/kg of dry product
W_m	mass flow rate	(kg·s^{-1})

P_v	vapor pressure of air	P_v
R	gas constant	R
RH	relative humidity	RH
T	temperature	T
T_{amb}	ambient air temperature	T_{amb}
T_m	material temperature	T_m
T_{out}	Outlet grain temperature	T_{out}
T_{in}	Inlet grain temperature	T_{in}
t	time	t
U_{op}	Hot air velocity	U_{op}
U_{mf}	minimum fluidization velocity of hot air	U_{mf}
W_{hold}	Material hold in dryer	W_{hold}
y	absolute humidity	y

II. METHODOLOGY

Plug flow fluidized bed dryer simulation Solution consist of following steps:

a. Calculate the number of parts along dryer
b. Decide the number of nodes along dryer
c. Calculate the numbers of parts along radius of the grain
d. Start calculation from node first to end.
e. Repeat calculation from a-d until safe level and find out moisture content and temperature.

III. PLUG FLOW FLUIDIZED BED DRYER

Many researchers have been developed the fluidized bed dryers among all the plug flow fluidized bed dryer is well suitable to find out predetermined amount of moisture content within numerous grains.
The advantages of using plug flow dryers over others are almost constant temperature throughout the fluidized bed by enhanced heat transfer Improved gas-solid contact, which results in faster rate of reaction [10].

International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9, Issue-7, May 2020

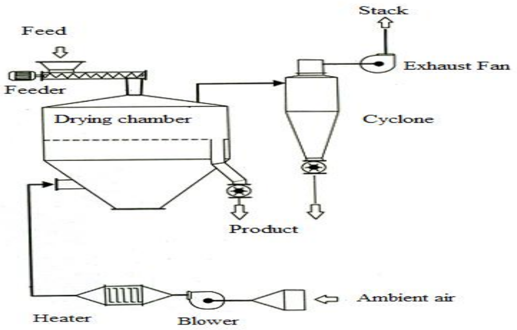

Fig.1 Fluidized bed dryer

The good quality rough rice grain was found from intense mixing of grains and hot air that may used for different types of natural and non-natural products. Drying is extensive used in such situations, where a controlled environment is needed to drying of products (natural and non-natural) and other uses that depend upon the types of operation performed in the industries. There are many disadvantages of fluidized beds dryers like sparkling beds of superior grains, quick mixing of grains causes turbulent and causes unequal distribution of residence time into flow dryer, large erosion takes place inside dryer and its fittings. There are many other factors that are very important to design an efficient dryer like temperature inside dryer, grain size (long-short-medium), fluidization air minimum velocity, grain movement in vertical direction, heat and moisture transport constants and variables, drag force.

Model Description of Plug Flow Fluidized Bed Dryer

Drying of solid grain model used differential equations that are solved on the basis of conservation of mass and energy in, to solve the heat and solid moisture transfer. Plug flow bed drying machines having different components like temperature controlled heater, high speed centrifugal fan, air ducts, drying space. In drying operation drying space is very prominent to us because all the mixing of solid grains and hot air takes place into the space there moisture balance, total energy balance and mass flow rates calculated [11].

Solid Grain Moisture Balance

Solid grain moisture calculated after moisture moved from the solid into air

$$-m\frac{\partial X}{\partial t} = \rho_a U_{op} A(y_{out} - y_{in}) \quad (1)$$

Total Enthalpy Balance

Calculation of total enthalpy of solid grain and hot air balanced to each other as follows with equation

$$m\frac{\partial H_m}{\partial t} = \rho_a U_{op} A(H_{in} - H_{out}) \quad (2)$$

Mass Transfer Rate

Movement of water vapor from solid to surrounding air is governed by mass transport phenomena at the outer surface of the solid and is expressed as

$$-m\frac{\partial X}{\partial t} = h_m A_{gt} (\Delta Y)_m \quad (3)$$

Heat Transfer Rate

The total heat being transferred from air to the solid material, in general, performs two tasks; raising the temperature of the solid material and supplying latent heat for vaporizatation.

This is stated by

$$m\frac{\partial H_m}{\partial t} - mL\frac{\partial X}{\partial t} = hA_{gt}(\Delta T)_m \quad (4)$$

Moisture Diffusion Equation

Here Rough rice (paddy) assumes short in length and the shape of grain is sphere. During Drying moisture stars evaporate from its surface and then from inner core, transfer of moisture from the inner core to outer surface is under falling rate drying phenomenon and calculate with Fick's second of diffusion using equation as

$$M_1\frac{\partial X}{\partial t} = D(V_G)\rho_p[\frac{\partial^2 X}{\partial r^2} + \frac{2}{r}\frac{\partial X}{\partial r}] \quad (5)$$

Volume of Dryer

Calculation of the volume of dryer (V) and cross sectional area (A) of a cylinder was given as:

$$V = LBxWBxHB \quad (6)$$

$$A = LBxWB \quad (7)$$

Drag force

The total drag force needed by grains (Δp) needed in the fluidized Dryer that is sufficient to fluidize grain particles (Kunii and Levenspiel, 1991).

$$\Delta F = g(\rho_{g-}\rho_a)HB \quad (8)$$

Porosity of paddy grains

The porosity of the grains is the calculated at the point of the minimum fluidization as: (Kunii and Levenspiel, 1991).

$$por = \left[\frac{18Re_p + 0.36 \times Re_p^2}{Ar}\right]^{0.21} \quad (9)$$

Paddy Grain Reynolds number

Minimum and the maximum fluidization state of paddy grains are characteristics on the basis of these velocities that may calculate as (Geldart, 1986).

$$Re_p = \rho_a U_p D_p / \mu_a \quad (10)$$

Minimum fluidization velocity

This is the minimum hot air velocity at which the total drag force on grains equal to the total weight of the paddy grains required to start the fluidization state after passing from the distributor plate.

$$Umf = \frac{Re_{mf} * \mu_a}{\rho_a * D_p} \quad (11)$$

Hot air operating velocity

This is the hot air velocity at which total grains are in the stage of fluidization. (Kunii and Levenspiel, 1991)

$$U_{op} = (1 + U_{opf})\, U_{mf} \quad (12)$$

Volumetric flow rate of Hot Air

The volumetric flow rate is calculated on the basis of following equation expression.

$$VF = A \times U_{op} \quad (13)$$

Mean residence time

This is the mean time during drying of paddy grains according to model the mean time is constant for each section into dryer.

$$MRT = \frac{w_m}{W_m} \quad (14)$$

Moisture content calculation

Moisture content in Rough rice = initial weight of paddy –

Final weight of paddy
Percentage moisture content in paddy is

$$X = \frac{\text{Moisture content in rough rice}}{\text{initial weight of paddy} - \text{Final weight of paddy}} * 100 \quad (15)$$

Equilibrium Moisture Content (EMC)

Along with the modified Henderson equation, the empirical Chung equation (Chung) is frequently employed to predict the moisture content values of grains. Xeq represents the EMC (decimal d.b.) and T denotes the temperature of air in (°C); C, E and F are product constants. The values for the values for the major grains are tabulated in Table.1 If moisture critical content is less than initial moisture content than Constant rate period prevails (Xcr<Xin) and if moisture critical content is greater than initial moisture content than Falling rate period prevails (Xcr>Xin).to calculate the critical moisture content the temperature is taken at wet bulb temperature (Kunii and Levenspiel, 1991) [1].

$$X_{eq} = E - F \times \ln\left[-(T + C) \times \ln\left(\frac{p_v}{p_{vs}}\right)\right] \quad (16)$$

Fabrication of the Plug Flow Fluidized Bed Dryer

The fabrication of the plug flow fluidized bed was carried out using the following prerequisite assumptions.

a) The grain shrinkage amount is not considered in the model.
b) The conduction between rough rice grains is very-very small.
c) During the drying process pressure is constant inside the drying space.
d) Solid grains moved in plug flow manner in horizontal direction and hot air moved into same section in upward direction.
e) The solid grain and hot air mixed together at particular sections and therefore the temperature and moisture at each section is constant with respect to time.
f) The solid grain made of concentric spheres having non- zero nucleolus.
g) Solid grain diffuses moisture in term of small amount of packets at regular interval of time.

Solutions to Simulation

To solve all dryer equations analytically, the plug flow dryer is essentially divided into number of sub sections. It was assumption that rough rice grains movement in the sub section in such a manner that one vertical layer of grains not crosses to other layer of grains. The amount of grains put into the inlet feeder was constant at a time. The input for the next sub section was considered as output coming from the previous sub section .The solution of the governing equations involves the following steps.

a) The time interval needed for drying is equally divided for bed entire length of bed.
b) The moisture distribution with in paddy grain and the change in average moisture content for a given time interval.
c) To find outlet moisture content of paddy grains and outlet air humidity.
d) Find the temperatures of grain outlet and air outlet for every section.
e) The steps from 1-4 is repeated for all section of bed until attainment the paddy exit from dryer.
f) Find the dryer other parameters

IV. RESULTS AND ANALYSIS

Simulation results come out with the support of a C Language program. For simulation purpose 2.4m length dryer was divided into equal number of sections. The dryer section width taken identical and suppose homogeneous temperature and wetness along the dryer length. The input paddy inlet temperature and moisture content was taken of 30ºC and 0.25 kg/kg (d.b) for one simulation. The Simulation results were examined for material mass flow rate like 40Kg/hr, 50Kg/hr and 60Kg/hr respectively. To find minimum fluidization velocity into the dryer the inlet hot air velocities maintains 3, 4 and 5 m/s respectively. The drying rate of grains depends upon hot air velocity across the distributer plate higher the air flow rate higher the rate of drying. Table 1 elaborates the variation of moisture content of paddy and temperature of grain at various input parameters.

The simulation results shows that grains moving from one end of dryer to exit end of dryer due to a potential force . From the opening of dryer it was seen that grains movement along the dryer length in such a way that grains move from one section to other section in plug flow manner and hot air crosses section in a way that fluidizes the grains fully into the chamber. In the mixing zone air gets cooled and grains heated from hot air like in case concurrent flow of two streams.

The set of partial differential equations derived for the modeling of the drying process in the fluidized bed dryer was solved simultaneously by using the finite difference method. Conservation equations for all the cases were discretized by using differencing scheme in space while Gauss Seidel iteration scheme was employed for differencing to complete the discretization of the governing equations. All Results for constant rate period of drying were used as an initial data for falling rate period of the solid particles.

In the first numerical time step, set of partial differential equations for whole flow were solved by using Gauss elimination method with an initial guess and then the first results were used as initial data for next time step. Solution of the first time step goes into the next time step. This procedure continues until the system converges.

For simulation purpose we need to take some initial input parameters such as the dryer dimension, moisture content of rough rice, air humidity, rough rice temperature, diameter of grain etc..

On the basis of input data we get the output data that shown in graphs and these graphs interpretate about the moisture content along the dryer length ,moisture content decreases in a very fast manner during initial drying time but from graphs it is clear to us that after some time rate of drying decrease when a moisture content on the surface is not sufficient further evaporate but inner surfaces having more moisture content as compared to outer surface so, moisture move towards surface in a very slower manner during this time period.

(a)Performance Comparisons for Variation in Operating Conditions

Table 1

Y_{amb} (kg/kg)	XA_{in} (%)	Ta_{in} (^{0}C)	W_m (kg/hr)	Material outlet conditions	Y_{amb} (kg/kg)
				XA_{out} (%)	Tm_{out} (^{0}C)
0.01329 (T_{amb}=30^{0}C RH=50%)	25	43.0	50	14.94	42.23
	25	43.5	51	14.95	42.68
	25	43.8	52	14.98	42.96
	25	43.0	50	15.00	42.12
	25	44.5	51	14.99	42.91
	25	43.0	45	14.52	42.52
	25	43.0	45	14.96	42.16
	25	44.0	50	14.79	43.14
	25	44.0	50	14.95	42.46
	18	43.0	215	14.99	41.54
	18	44.0	220	14.96	42.47
	18	44.2	235	15.00	42.91
	30	43.0	50	16.83	42.00
	30	43.0	36	14.95	43.00
	30	43.8	32	14.96	42.98
0.00725 (T_{amb}=20^{0}C RH=50%)	25	43.0	65	15.07	41.97
	25	44.0	65	14.97	42.95
	30	43.0	43	14.97	42.07
	30	43.9	44	15.00	43.00
0.02348 (T_{amb}=40^{0}C RH=50%)	25	43.0	33	14.96	42.44
	30	43.0	30	15.87	42.43
	30	43.0	25	14.98	42.54
	25	43.5	42	14.97	42.84
0.01877 (T_{amb}=30^{0}C RH=70%)	30	43.0	30	15.06	42.42
	30	43.5	30	14.95	42.92

Simulation data shows for different operating conditions to decide the dryer can be used at optimal conditions.

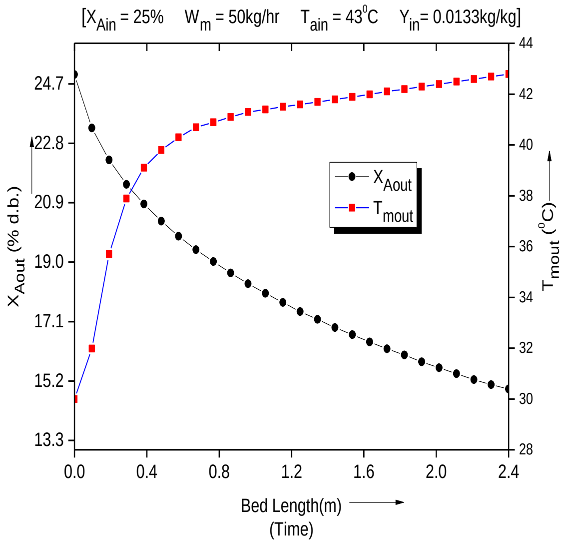

Fig2.Variation of Grain Moisture Content, Temperature of Grain Vs Dryer Length

Figure2. Shows outlet grain moisture content decreases endlessly the length of the dryer as time passes, but on the other hand temperature of grain is more rapidly increases at the start then decrease with length the dryer. During the start and end of drying grain moisture content and temperature of grain changes rapidly due to more heat and moisture transfer involves but as time passes ,drying rate changes slower. Because there is large moisture gradient at starting time that causes more moisture mass transfer with time. Moisture transfer force is responsible to move moisture from grain, it decreases with time and at the end is reduces more rapidly as shown in above figure. Temperature curve shows in figure conclude that temperature of grain increases endlessly through the length of the dryer with decreasing rate. Moisture content and temperature of grain predicted after simulation are good enough to preserve grains for long time without any spoilage.

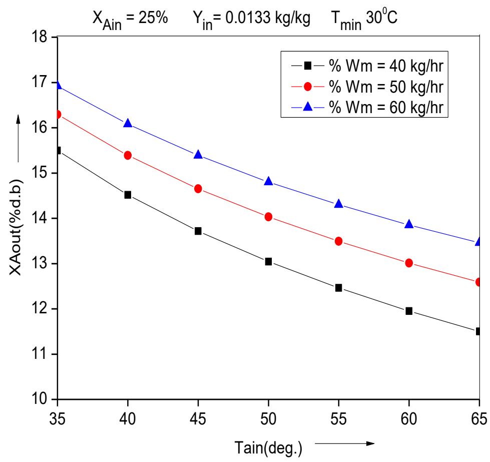

Fig 3.Variation of Outlet Moisture Content Vs inlet Air Temperature at different Material flow rate

Figure3. Shows Outlet average moisture content in the grain decreases with air temperature because on increasing the temperature driving potential for mass transfer increases at the same time by increasing material flow rate outlet moisture content increases means drying is less because residence time decreases.

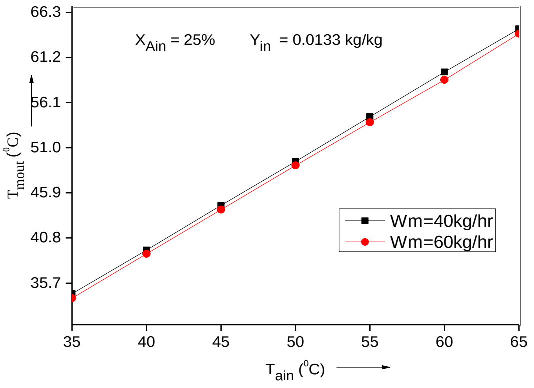

Fig4.Variation of Outlet Temperature of the Grain Vs Inlet Air Temperature at Different Material Flow Rate

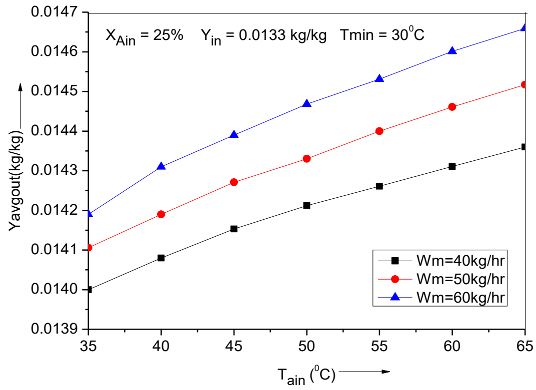

Fig 5.Variation of Average Outlet Humidity of the Air Vs Inlet Air Temperature at Different material Flow Rate

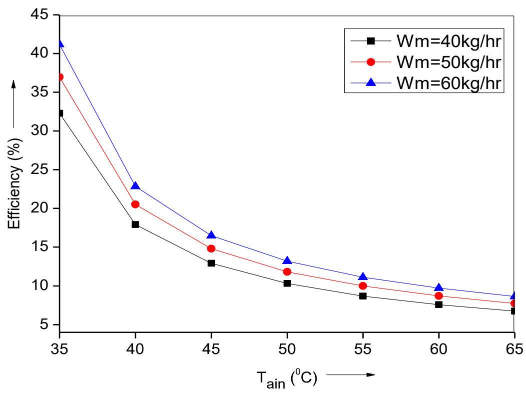

Fig 6.Variation of Efficiency Vs Inlet Air Temperature at Different Material Flow Rate

On increasing hot air temperature material temperature, outlet average air temperature and outlet average humidity increases but efficiency decrease because of cross flow behavior as shown in figure4-6 respectively in the same figures on increasing material flow rate both the outlet temperatures decrease and outlet humidity and efficiency increases because at higher flow rate resistance time decrease.

V. RESULT AND DISCUSSION

Various experimental tests were carried out on the designed machine to check its performance. The analysis was carried out on the plug flow fluidization bed dryer to evaluate the moisture reduction of paddy during the drying process. The temperature and pressure were kept constant at the heating chamber throughout the whole process and the time was varied between ten and thirty minutes for different quantities of food samples. Inlet air temperature inside the dryer chamber varies from 35ºC-65ºC. The aim of the experiment was to monitor the reduction of moisture in paddy grains at different time intervals and constant temperature during drying process with samples. The final moisture content in paddy was done using the following as the formula. All above figures shows that the simulated paddy drying model agreed well with the safe zone of storage value of rough rice values. The outlet temperature of paddy increases slower rate in the first phase and then increased gradually for further drying.The estimated average output conditions of paddy from initial to final stage in the various drying condition is illustrated in Fig.4-6 that may fulfill the safe storage condition of paddy. Since the drying process took place from the outer to the centre of the paddy grain, the temperature of kernel centre kept almost unchanged during the initial drying time after it increased sharply and then it is almost constant at outlet.

VI. CONCLUSIONS

The simulation results show that drying of paddy grains during drying the amount of moisture content decreases at a faster rate at initial dying period than becomes slower and finally flat or no moisture inside the paddy grain. It is seen that the initial drying is very fast a large amount of moisture is removed from outer peripheral of the grain and slow at later. So, the dryer dimensions are well suitable to the drying the paddy drying. The change in the temperature of paddy grain is fast in initial stage but at later as drying proceeds then it almost constant. The temperature outlet gradient vs. Fluidized Bed dryer length for paddy becomes very prompt during increase of inlet air temperature that helps us to understand the demarcation between seed and food grain element.

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