Computational Investigation of Fluidized Drying of Paddy by Air with a State Variable of Time

by

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20123

Dissertation submitted in partial fulfillment of

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(Mechanical)

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CERTIFICATION OF APPROVAL

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(MECHANICAL)

Approved by,

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January 2017

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertake or done by unspecified sources or persons.

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SITI SUAIDAH BT SHAKIDI

ABSTRACT

In study of improvement drying paddy, experimental and industrial investigation for paddy are inefficient in both time and resources compare to computational investigation. Experimental and industrial investigation are limited to estimate and predict the output parameter compared to numerical and computational investigation. A mathematical model of fluidized drying of paddy by air with a state variable of time were formulate. Drying process were simulate computationally for various given boundary conditions. Literature review were studied to understand the drying formula used for drying paddy and a quality paddy specification. Mathematical formulation for numerous heat and mass transfer equations for drying paddy were modified from previous study. Initial condition used based on previous study was initial moisture content of paddy of 24% dry basis, air temperature of 115^{o}C, air velocity of 2.3 ms^{-1}. For the fluidized dryer specification, this project also used the same parameter as the experimental fluidized industrial dryer with these criteria; bed thickness 10cm, and 4.85 x 0.97 m^{2} bed area. With the same initial condition used from the experimental study, computational investigation were done using numerical model and 4th order Runge-Kutta formulation. Coding in MATLAB was applied to numerical calculation of partial differential model and results were simulated for both data reported from experimental and mathematical model. The two result were compared and showed that the computational approach were capable to predict moisture content of paddy. Graph plotted by simulation shows very insignificant difference from result obtained by experimental results. This computational approach provide easy and comprehensive method for research and development of fluidized drying in further improvement.

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In the name of Allah, all praises be to Allah for I was given the strength and opportunity to complete the final phase of my degree study successfully. May He be pleased with all the time and effort that I have spent through the accomplishment of this project.

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

Fluidized drying is an innovation which is broadly applied in industry for the drying of particulate solid. One of the significant preferences of fluidized bed system because of the way that the high turbulence created in the bed or drying chamber gives high heat and mass exchange, and in addition a good mixing of the solid inside the bed. Other than that, it conduct good temperature control, which perform a viable drying heat sensitive materials such as food or pharmaceutical products.

Figure 1.1: Industrial fluidized bed drying

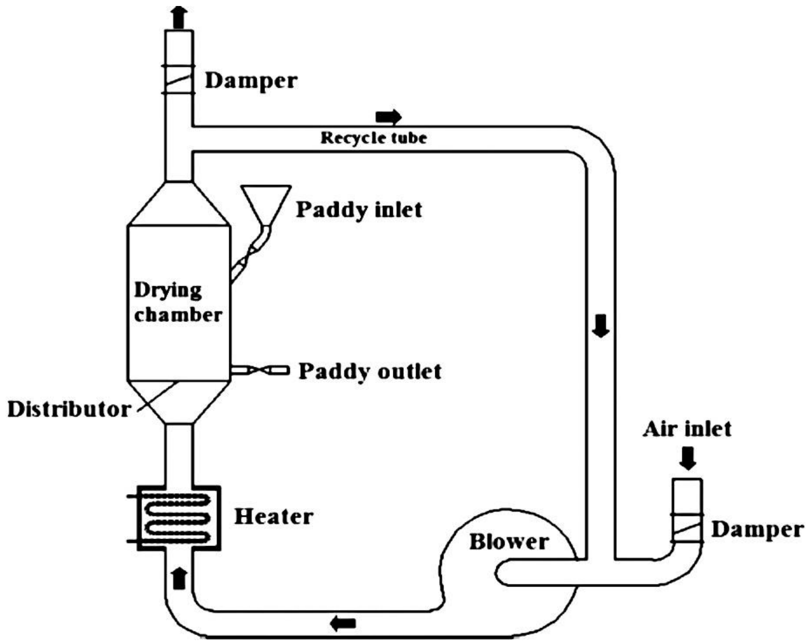

Figure 1.2: Schematic diagram of fluidized drying of paddy

In agricultural and food industry, the principle focus of drying is to decrease the moisture substance which depends straightforwardly on the moisture content, keeping in mind the end result to empower their capacity at encompassing temperature and to enhance its shelf time. By knowing the moisture content value [1], it is conceivable to anticipate microorganisms growth. Notwithstanding affecting microbial deterioration, moisture content may assume a significant affect in deciding the activity of enzymes and vitamins in foods and may have a major impact on their color, taste, and smell. It might as well significantly affect the potency and consistency of pharmaceuticals.

Speaking in term of agricultural and food industry, Malaysia is known to produce its own rice which come to its annual production of paddy over 3.3 million tone matric [2] reported last 2014. Drying as known by its name is a process of removal of moisture from solid by applying heat to it. As Malaysia has a climate that is very high in humidity, with an average temperature of 26.7^{o}C throughout the year [3], this process is essential to paddy production as it is crucial in maintaining the paddy quality during storage and to prevent the growth of micro bacteria and fungi as well as mites and insects. Moisture content for quality paddy is best kept at 11-14%.

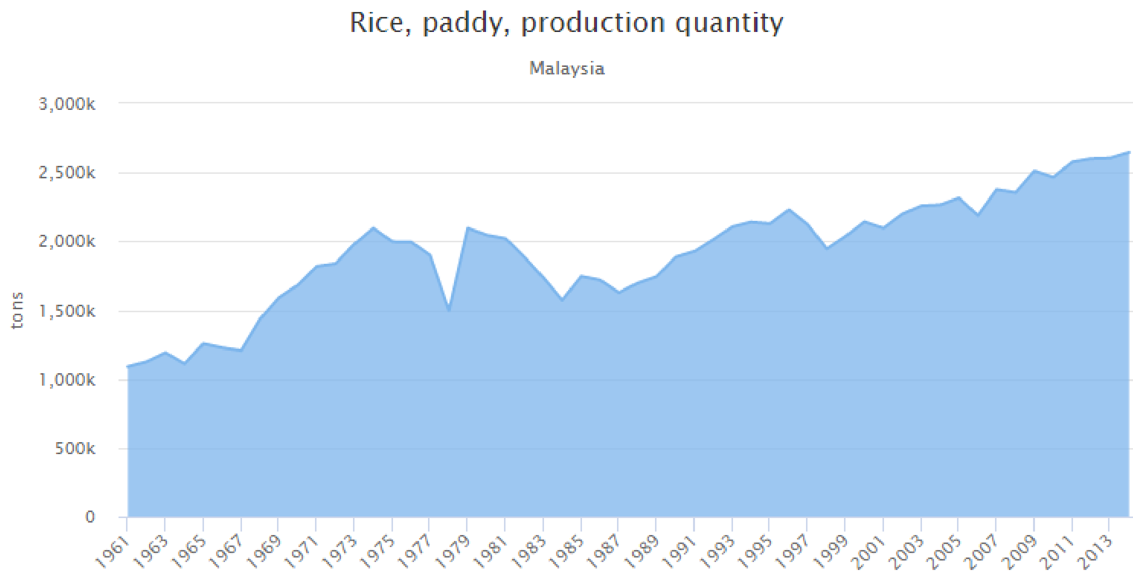

Figure 1.3: Annual paddy production in Malaysia

The usual harvest moisture content of paddy is about 24-26 % (wet basis), which get high value percentage during monsoon season and lower value percentage during dry season. A high moisture content of newly harvested paddy must be dried within 24 hours to reach its safe-storage levels, which 14% moisture content reduction. A 18% moisture content reduction can reach up to 2 weeks of storage time with an at less than 14% moisture content, paddy will be less affected by fungus and likely to maintain its germination capability thus increasing shelf time and the most important part - preserving its quality.

Table 1.1: Value of paddy moisture content and its estimated shelf life

Shelf life	Moisture content, % d.b.
2-3 week	14-18
8-12 month	< 13
More than 1 year	< 9

During monsoon season, a high number of harvested paddy loose its quality due to its high moisture content and due to failure to keep the moisture content below its specific percentage. This can be improved by using calibrated drying machinery such as fluidized drying.

1.2 Problem Statement

Problem statement for this study have been identified and listed below:

i. In study of improvement drying paddy, experimental and industrial investigation for suitable parameter to achieve quality paddy are inefficient in both time and resources compare to computational investigation.
ii. Experimental and industrial investigation are limited to estimate and predict the output parameter based on the paddy initial condition compared to numerical and computational investigation.

1.3 Objective

By the end of this study, few objectives that have been identified and listed must be achieve. The list are as below:

i. To formulate the mathematical model of fluidized drying of paddy by air with a state variable of time.
ii. To simulate the drying process computationally for various given boundary conditions.

1.4 Scope of Study

This study is focused on deriving a formula fluidized drying of paddy by using mathematical formulation and computational investigation.

The mathematical formula and simulation technique used in this study were modified from data reported in the literature. A laboratory scale experimental, batch fluidized bed dyer with bed thickness 10cm, inlet air temperature 115^{o}C, and paddy initial moisture content of 23-25% dry basis were used. Its results were then compared with the numerical model simulated in MATLAB. The rice used for experimental purposes were also mention in the data reported in the literature.

All the data collected were to compare for both experiment and mathematical model by using MATLAB simulation to find paddy moisture content and paddy temperature with time.

CHAPTER 2: LITERATURE REVIEW

2.1 Drying Concept of Grain

Drying of grain is the post-harvest phase which the grain will be removed of its moisture content until it reaches its optimal level [4]. This drying phase will involve simultaneous heat and mass transfer process [5]. By using the convection concept of drying, moisture in the form of evaporated liquids need an external medium which usually is air to get it dry.

The drying procedure involves two fundamental mechanism; the relocation of moisture trapped inside of a paddy grain to the outside surface and the moisture evaporation from the surface to the encompassing air [6]. Grain drying can be attained by circulating air with certain degree of temperature through a mass of grain [4]. As it moves, the air confers heat to the grain, while engrossing the humidity of the furthest layer. In any case, this procedure does not occur consistently inside the drying chamber or among the individual grain, especially inside each grain. In reality, the water content in the external layer of the paddy evaporates considerably faster and more easily than that of the inner layer. This infers it is significantly easier to reduce the moisture content of the paddy from 35% to 25% than from 25% to 15%. Proctor expressed that drying operation must not be considered as only the removal of moisture since there are numerous quality components that can be antagonistically influenced by incorrect selection of drying condition and equipment. The same concept is applied to drying paddy. It is very crucial to comprehend the standard of paddy drying to obtain a high quality paddy.

2.2 Drying Development

Due to development in agriculture, postharvest processes have been developing new technologies to improve the grain quantity and quality [7]. Over the past three decades, there are increasing growth in drying research and development. At which during the initial stage, they were focused on conservation of energy but now R&D are more focusing on product quality, impact to environment, safety, new product, processes and etc [8]. There are few drying methods used in the industry used for drying grain. The method used are based on different scale and complexity.

Table 2.1: Drying grain technique overview

Drying technique	**Harvest type**	**Drying technology**	**Description**
Paddock drying	-	Piles, rack	-Rapid quality reduction
Sun drying	Batch	Drying on nets, mats or plastic sheets	-Cheap -Labor intensive -Very poor milling quality
Heated air drying	Batch	Fixed bed dryer	-Low price, in small scale operation -Local construction from various materials -No need expert labor to operate machine -Moisture gradient -Labor intensive
		Re-circulating batch dryer	-Good mixing of rain -Conduct at large capacity -Produce good quality grain -Labor with skilled required -Medium capital investment
	Continuous	Continuous flow dryer	-Can conduct very large capacity -Economics on scale -High capital investment -Not feasible for small batches of different varieties -Complicated to operate
In-store drying	Batch	Storage bin with aeration components and pre-heater for adverse weather and nighttime	-Excellent grain quality -Large capacity range -Pre-drying oh high moisture grain -Risk of spoilage low

2.2.1 Sun-drying

Figure 2.1: Sun-drying of paddy method

Sun drying paddy experiment were done by Mehdizadeh and Zomorodian [9] and were compared with solar drying technique. They showed that solar and sun-dry took longer duration of time to reach certain level of paddy moisture content, which is about 90 minutes to 10 hours of drying at mean temperature of 50^{o}C for solar drying and 26^{o}C for sun-drying. On the other hand, another study which compared fluidized drying with sun-drying were done by Karbassi and Mehdizadeh [10]. Their result showed that rough rice was dried in the fluidized bed drier at 140^{o}C in 2 minutes while another sample were dried for 8-10 hours using the sun-drying method.

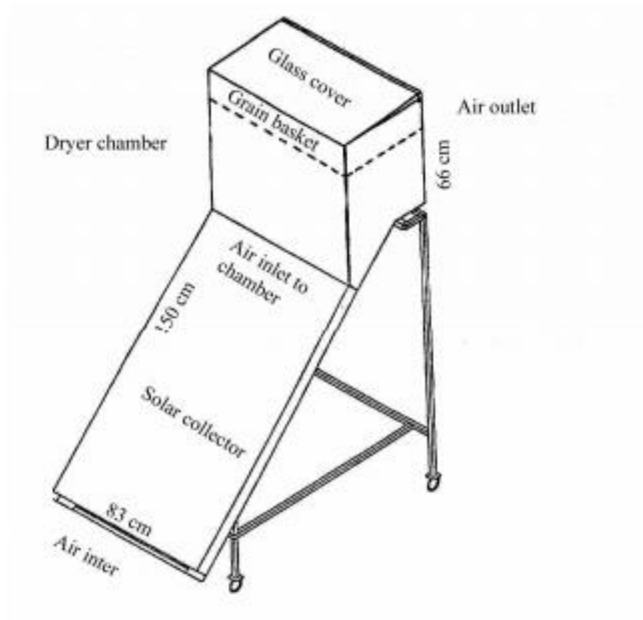

Figure 2.2: Solar drying paddy method

2.2.2 Fluidized bed drying

Single and multi-phase models have been used in order to simulate fluidized bed drying by some researchers. In a single phase model, the fluidized bed is regarded essentially as a continuum. Heat and mass balances are applied over the fluidized bed. It is assumed that particles in the bed are perfectly mixed [11].A multi-phase model of fluidized bed drying treats the fluidized bed to be composed of a bubble phase (dilute phase) and a suspension phase (dense phase). In some research, the suspension phase itself as assumed to be composed of the particles and intermediate gas phase [12]. Khanali et al. [13] examined different drying models and found that the model proposed by Midilli et al. [14] was the best for describing fluidized bed drying characteristics of rough rice. The incremental model was modified by modelling the cross-flow of the drying medium and removing the need to use the time increment and bed velocity for computing the distance along the dryer [15]. Queiroz et al. developed a model to simulate the moisture diffusion during the drying process of rough rice by using finite element analysis. Their simulated model could predict the temperature of the air and grain and the moisture movement inside the rough rice kernel. Izadifar and Mowla [16] developed a mathematical model to simulate the drying of moist paddy in a cross-flow continuous fluidized bed dryer. The model is based on the differential equations, which are obtained by applying the momentum, mass and energy balances to each element of the dryer and also on the drying properties of paddy. The optimum drying parameters have been reported based on energy consumption and drying capacity for achieving acceptable rice quality, while the basis of fixing the operating parameters such as feed rate, air velocity and bed thickness have been rarely mentioned. Soponronnarit et al. [17] studied the performance evaluation of commercial fluidized bed dryer with 1e2, 2.5e5.0 and 5e10 t h_1 capacity having the provision of recycling the exhaust air while the heat source was from burning diesel or oil fuel. They reported that energy consumption decreased with increasing paddy moisture content and drying temperature. Paddy drying is a highly energy-intensive process and sensitive to the quality of rice [18].To reduce paddy moisture down to 22% (db) in a single pass, they recommended a maximum drying temperature of 150 _C to achieve acceptable quality of product. Fluidization techniques have been reported to produce increased head rice yield compared to conventional drying methods [19].The use of simulation can help to draw conclusion regarding potential operating conditions of the dryer, which would not otherwise be possible without extensive experimental measurements.

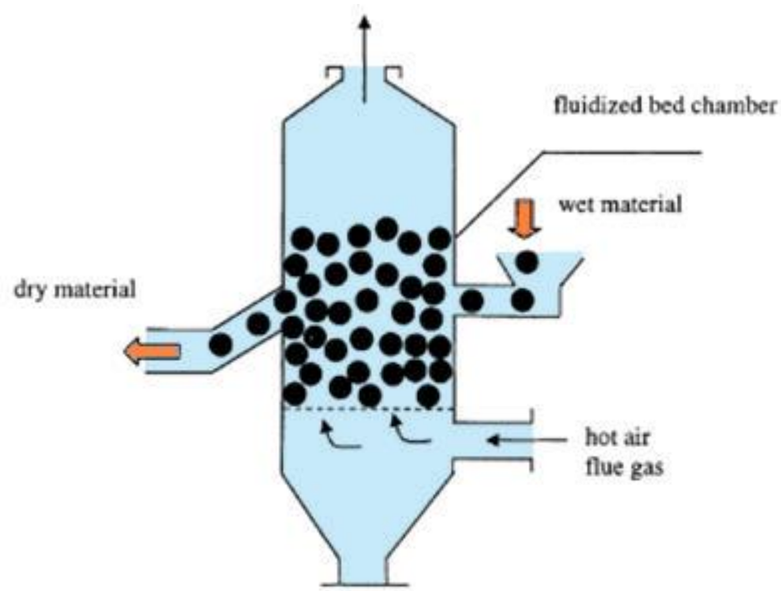

Figure 2.3: Schematic diagram of fluidized bed drying

A simplified method of calculation and procedures were created using a continuous fluidized bed drying system [20]. There was also a study on a very systematic sequence to develop a model of continuous fluidized bed paddy dryer [21]. This method was based on dividing the dryer into few sections in series with ideal mixing solid and gas phase in each section.

2.3 The equilibrium moisture content of grain

Equilibrium moisture content (EMC) in grain drying is one of the most important parameter to know as it decides the base of moisture content to which grain can be dried under a given drying condition [22]. Accordingly, the EMC of a grain as characterized by Brokker et al, is the moisture content of a material after it has been exposed to a controlled environment for a period of time. On the other hand, they characterized EMC as the moisture content at which the interior product vapor pressure is in equilibrium with the vapor pressure of the environment.

The EMC is valuable in deciding if a product will gain or lose moisture under a given value of temperature and relative humidity conditions. Along these lines, EMC is straightforwardly related to drying and storage [5]. Distinctive materials have different equilibrium moisture content. It is reliant upon the temperature and relative humidity (RH) of the environment and etc. Particular estimations of EMC are classified in table.

Table 2.2: Equilibrium moisture content of grain (% wet basis)

Grain	Temperature (ºC)	Relative humidity (%)									
		10	20	30	40	50	60	70	80	90	100
Rice, milled	25	4.9	7.7	9.5	10.3	11.0	12.0	13.4	15.3	18.3	23.3
Rice, rough	25	4.6	6.5	7.9	9.4	10.8	12.2	13.4	14.8	16.7	25.7

From the table, it is able deduce that the EMC value will be increased if the RH value increases. For example, when rough rice exposed to air at 25°C and 80% RH, moisture content of only 14.8% can be obtained.

2.4 Numerical model of fluidized drying

2.4.1 Heat and mass transfer

For the gas phase, thermal energy equation [23] can be derived as equation below:

$$\varepsilon_g \rho_g C_{gs} \left(\frac{\partial}{\partial t} T_g + \overrightarrow{V_g} . \nabla T_g\right) = -\sum_{m=1}^{2}\left(H_{gm}\right) - \nabla H_{rg} \tag{1}$$

For the solid phase, thermal energy equation is given as:

$$\varepsilon_s \rho_s C_s \left(\frac{\partial}{\partial t} T_s + \overrightarrow{V_s} . \nabla T_s\right) = \nabla . \varepsilon_s k_s - H_{rs} + H_s \tag{2}$$

The heat transfer between the gas and the solid is a function of temperature difference between the gas and solid phases:

$$H_g = -\gamma_g \left(T_s - T_g\right) \tag{3}$$

The heat transfer coefficient is related to the particle Nusselt number using the following equation:

$$\gamma_g = \frac{C_{pg} R_0}{e^{\left(\frac{C_{pg} R_0}{\gamma_g^0}\right)} - 1} \tag{4}$$

$$\gamma_g^0 = \frac{6 k_g \varepsilon_s N u_m}{d_p^2} \tag{5}$$

The Nusselt number is determined by applying the following operation:

(6)

$$Nu_m = \left(7 - 10\varepsilon_g + 5\varepsilon_g^2\right)\left(1 + 0.7Re_m^{0.2}\, pr^{\frac{1}{3}}\right) + \left(1.33 - 2.3\varepsilon_g + 1.2\varepsilon_g^2\right)Re_m^{0.7}\, pr^{\frac{1}{3}}$$

For mass transfer equation, the surface moisture of the sample will be assumed to be at equilibrium with the drying air. The equation for the gas phase is:

$$\frac{\partial}{\partial t}(\varepsilon_{\boldsymbol{g}}\rho_{\boldsymbol{g}}\boldsymbol{X_g}) + \nabla\,.\left(\varepsilon_g\rho_g\boldsymbol{X}_g\,\overrightarrow{V_g}\right) = \boldsymbol{R}_g \tag{7}$$

Where X_g is the mass fraction and R_g is the evaporation rate. The equation for the solid phase is as the following:

$$\frac{\partial}{\partial t}(\varepsilon_{\boldsymbol{s}}\rho_{\boldsymbol{s}}\boldsymbol{X_s}) + \nabla\,.\left(\varepsilon_{\boldsymbol{s}}\rho_{\boldsymbol{s}}\boldsymbol{X_s}\,\overrightarrow{V_{\boldsymbol{s}}}\right) = \boldsymbol{R_{sm}} \tag{8}$$

Where R_m is the moisture evaporation from the particle surface.

2.6 Computational simulation

There are a number of modeling software used to develop computational model of fluidized drying process and perform simulation and validation of the model. Generally, researchers and professionals use Aspen Plus, Computational Fluid Dynamics (CFD), ChemCAD and MATLAB software package to develop and optimize the drying process.

Khalani [13] conducted a study on fluidized bed drying for rough rice. Non-liner regression technique were used to obtain the different constants in each selected model, using Curve Fitting Toolbox of MATLAB software based on the Levenberg-Marquardt algorithm. Harchegani [24] studied on energy consumption and quality rough rice drying process-the partial differential equations of rough rice drying were solve in MATLAB software. Other studies [25-27] also used MATLAB to obtain parameter graph and curve of drying time. But for Momenzadeh [28], he used MATLAB for training and testing of neutral work of his study.

Other than that, Ayobi [29] investigated computationally of CO_2 absorption from the flue gases using potassium carbonate. He compared between CO_2 concentrations at the reactor outlet from CFD simulation. Kuriakose [30] used CFD in his study to predict gas flow pattern and particle histories such as temperature, velocity, residence time, and impact position. CFD is a powerful software, the programs have high computational requirements. Taghipour ran a simulation of fluidized bed by solving the governing equations of mass, momentum and energy conservation using Fluent 6.0 CFD software [31].

CHAPTER 3: METHODOLOGY

3.1 Project Activities

This project was done according to the flow chart in figure.

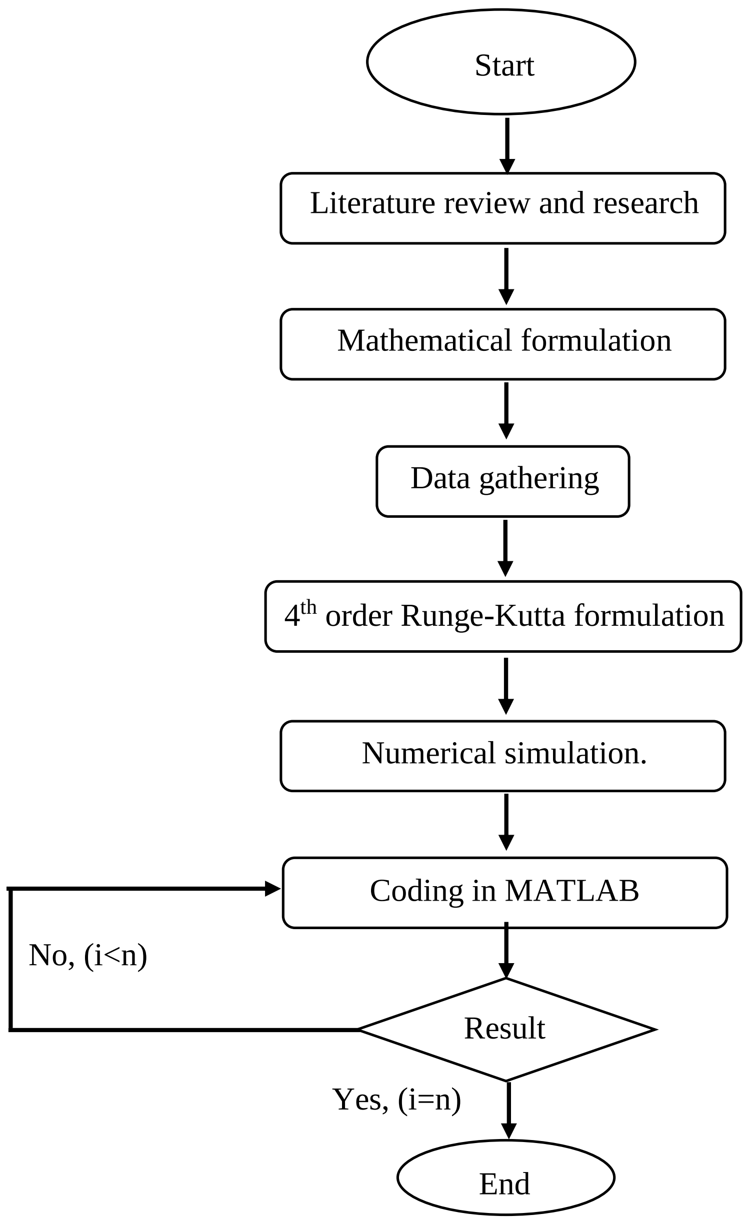

Figure 3.1: Flow chart of main activities

The flow chart shows the stages taken to complete this project which involve few main activities and stages:

i. Literature review to understand the drying formula used for drying paddy and a quality paddy specification.
ii. Mathematical formulation for numerous heat and mass transfer equations for drying paddy.
iii. Data gathering and collecting all data related to drying of paddy.
iv. 4^{th} order Runge-Kutta formulation to solve and predict moisture content and temperature during drying.
v. Numerical simulation.
vi. Coding in MATLAB was applied to numerical calculation of partial differential model. The flow chart of using MATLAB for numerical calculation of partial differential model is shown in figure 3.2.
vii. Result representation and discussion.

3.2 Mathematical model and Methods

The equation of paddy drying model were based on the heat and mass transfer equations. The drying component is the dyer bed that needs thermal balance which is derived by mass application, energy and enthalpy balance to the drying bed.

3.2.1 Development of mathematical model

Few assumptions were considered to derive the mathematical model based on Rakesh and Bharat experiment [32]:

1. The shrinkage volume during the drying process are negligible.
2. Temperature change inside the grain kernels are negligible.
3. Moisture inside grain kernels are uniform at the start.
4. Heat loss to surrounding and fluidized bed wall is negligible.

3.2.1.1 Removal time equation

Removal time, τ, is the average time in second needed by the paddy to remove its moisture in a control volume. The equation of τ used is as below.

$$\tau = \frac{hu}{F} \tag{9}$$

Where,

$$hu = \rho_p A h \tag{10}$$

F = rate of feed, kg s^{-1}

ρ_p = paddy bulk density, kg m^{-3}

A = the bed area, m^2

h = the bed thickness, m

3.2.1.2 Moisture content equation

The experiential equation for drying of paddy using fluidization was developed by Page [33] and was used in this project as follows:

$$MR = \exp(-xt^{y}) \tag{11}$$

Where,

$$MR = \frac{(M - M_{eq})}{(M_{in} - M_{eq})} \tag{12}$$

MR is moisture ratio

T = time drying process take place, min

M = moisture content of paddy at any time

M_{eq} = moisture content of paddy in equilibrium

$$\frac{dM}{dt} = (-xy)\,.\,\left(M_{in} - M_{eq}\right).\; t^{(y-1)}\,.\;\exp(-xt^{y}) \tag{13}$$

Or it can be written as infinite difference:

$$\Delta M = (-xy).\left(M_{in} - M_{eq}\right).\Delta t^{(y-1)}.\exp(-x\Delta t^{y}) * \Delta t \tag{14}$$

Where,

X = 0.001631 T_d – 1.16202 (M_a / HP) + 0.004153 (M_a / HP) + 0.147383 In(M_a / HP) + 0.474743

Y = -0.00322 T_d – 0.83596 (M_a / HP) + 0.020319 (M_a / HP) - 0.14315 In(M_a / HP) + 0.54893

T_d = inlet air temperature, ^oC

M_a = dry air mass flow rate, kg s^{-1}

HP = hold up (dry paddy), kg

At any time, t, moisture content can be calculated by using equation 13 and differentiate the equation with respect to time and the finite difference technique was applied in equation 14.

3.2.1.3 Model parameter

Table 3.1: Simulation initial condition based on Sarker [34] experimental setup

Parameter	Value
Initial moisture content paddy (% d.b)	24
Initial paddy temperature (^oC)	23-27
Drying temperature(^oC)	115
Air velocity (ms^{-1})	2.3
Bed depth (m)	0.1

3.2.2 MATLAB simulation

MATLAB codes were generated to determine feed rate for different bed depth from the calculation at targeted residence time. Flowchart of the calculation steps is shown in figure.

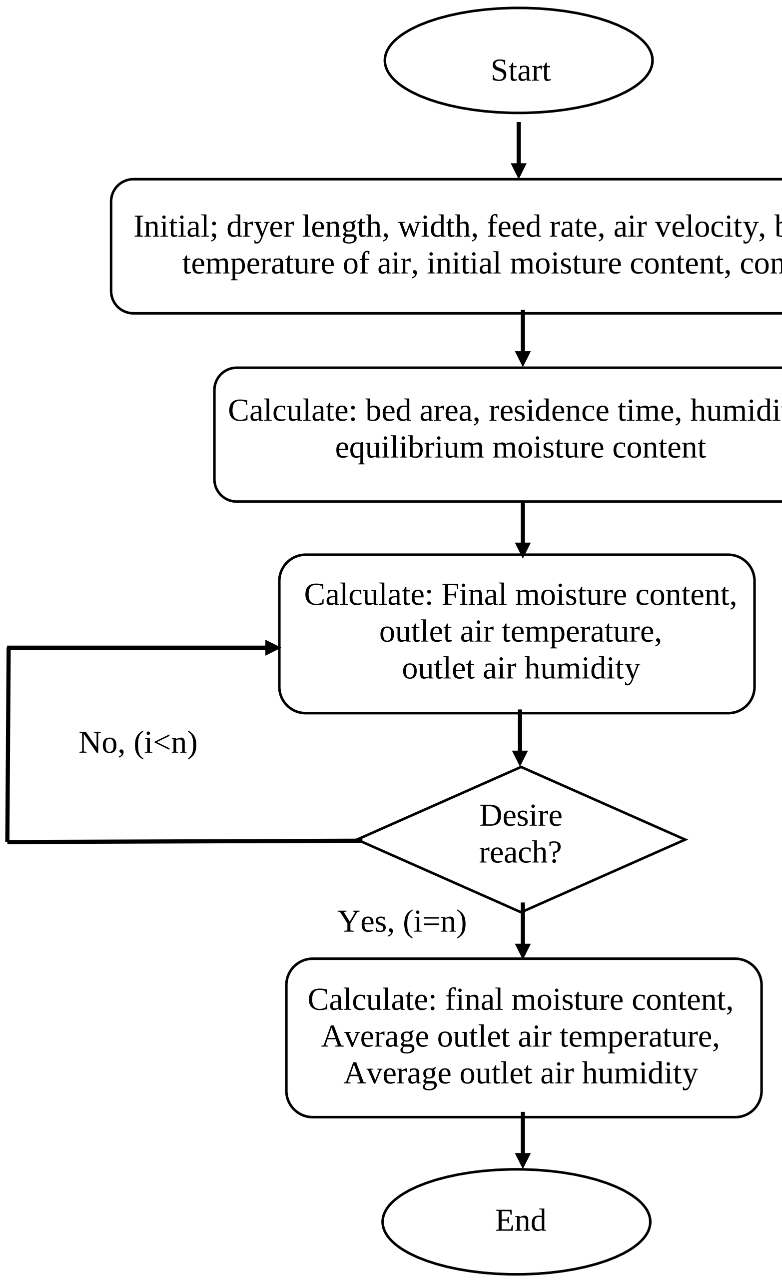

Figure 3.2: Simulation program flow chart

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Simulation Result

Several data was collected from the experimental result done by Sarker [34] and numerical model done in this project with Sarker initial condition parameter.

From the experimental, the result was recorded before the experiment is done, during and also after the drying paddy process. They monitor and record the result from time to time until the drying process finished.

In the other hand, numerical model done in this project were only used Sarker initial parameter and the rest were done by using MATLAB simulation. This were done to predict and compare the final condition for this drying process.

With same initial condition for experimental and computational investigation, several result were compared and can be seen in the table 4.1 below:

Table 4.1: Result based on Sarker's experimental [34] and computational investigation

Time, s	Moisture content paddy, % d.b		Temperature paddy ^{o}C	
	Simulation	Experimental	Simulation	Experimental
0	24	24	25	25
30	21	21	41	40
60	13	12	57	54
95	4	5	80	78
120	3	2	97	91

4.1.1 Paddy temperature with time

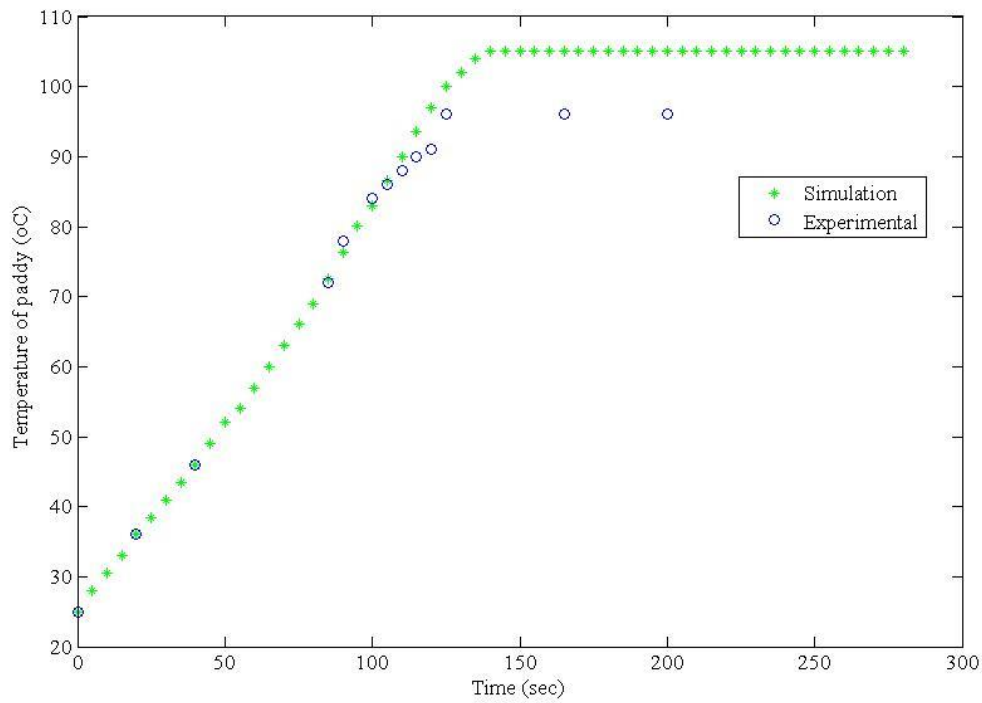

Figure 4.1: Comparison between simulated and experiment of paddy temperature with time

From Figure 4.1 shows that the comparison of paddy temperature during drying process between the experimental and simulation results. During the experimental result, it was told that, they recorded the paddy temperature by using the fluidized bed dryer thermometer.

As shown in figure 4.1, simulation program can predict the temperature of paddy during drying process. This can be said due to the very slightly different in graph plotted in the first 120 second of drying process.

After the 120 second, experimental result differ from simulation which have lower temperature but both come to constant temperature after approximately at 140 second. Experimental temperature was much lower due to heat loss to the surrounding and the fluidized bed wall. Simulation results always shows the ideal condition and environmental since the assumption were made before.

4.1.2 Moisture content of paddy with time

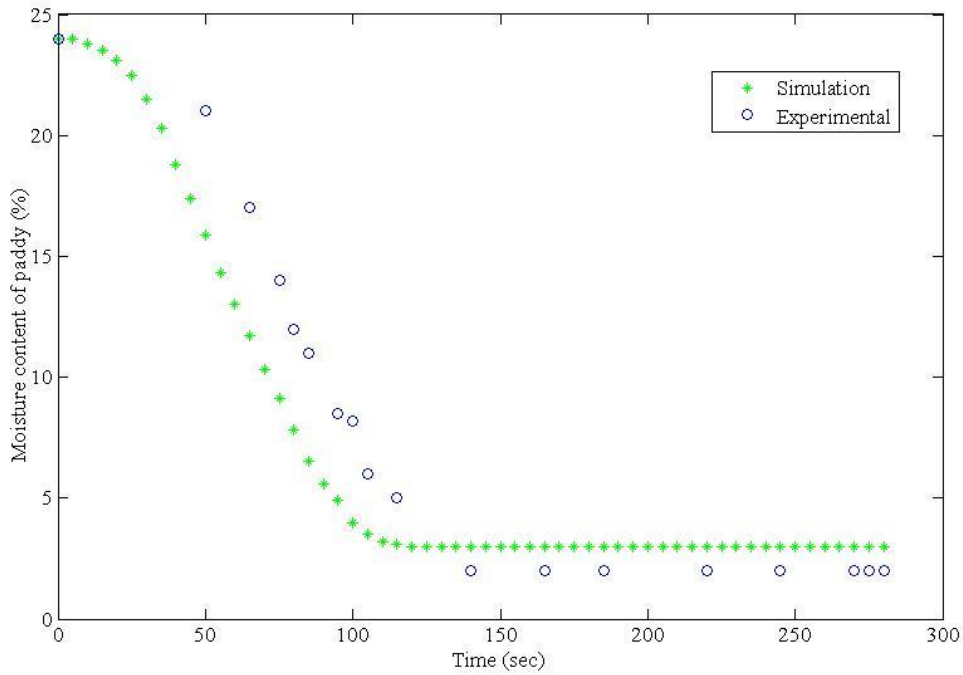

Figure 4.2: comparison between simulated and experimental result of paddy moisture content during drying with time

Figure 4.2 shows the comparison of paddy moisture content between the experimental and simulation results. The graph shows that both experimental and simulation plotted curve and have directly proportional decrees of moisture content with time between 10 second until 90 second. After 90 second, both plotted data come to constant value of moisture content until the end of drying process.

4.1.3 Air temperature with time

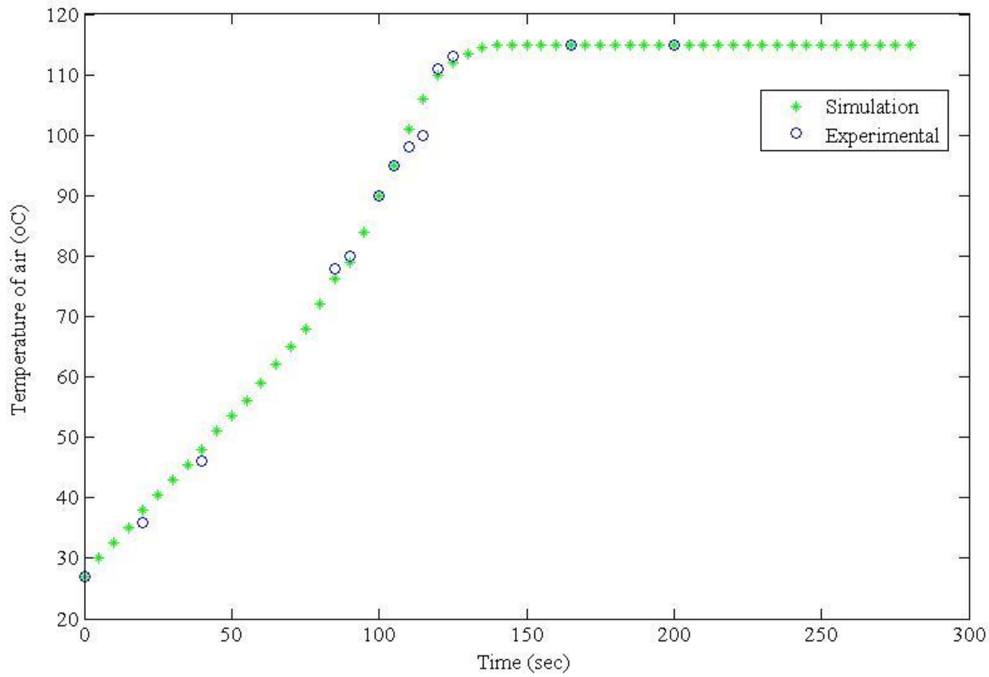

Figure 4.3: Comparison between simulated and experimental air temperature with time

Figure 4.3 shows the comparison of air temperature during drying process recorded and simulated between experimental and simulation results. It can be seen that plotted graph increasing with increase in time and reach to constant value at 125 second and afterwards.

The air temperature during drying process need to be recorded as to monitor the drying temperature as well as to make sure they reaches desired operating temperature. A good and controlled temperature will ensure the quality of paddy at the end of its drying state.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion and Recommendation

Mathematical model is very comprehensive approach for fluidized drying process in MATLAB simulation. This mathematical and computational approach allows to describe the complex parameter of heat and mass transfer during drying process take place.

This study clarify the prediction of various outcome parameter in the computer simulation, based on the same initial condition used. The experimental results was compared with the simulation results and shows not much different between them.

The few different plotted graph was due to the environmental factors influenced the experimental result. It was also due to human error during measurement and data collection.

A numerical simulation for fluidized drying was modified based on the previous study mention in the literature review and applying the by MATLAB.

This computational approach might provide easy and comprehensive method for research and development of fluidized drying for further improvement.

Based on the objectives, this project is considered as a success as all the objective are achieved.

NOMENCLATURE

C_s = Specific surface of solid kJ kg^{-1} ^oC

C_{gs} = Specific surface of gas kJ kg^{-1} ^oC

C_{pg} = Specific surface of gas on surface particle kJ kg^{-1} ^oC

ε_g = Void fraction of gas

ε_s = Void fraction of solid

H_s = Heat transfer of solid

H_{rs} = Thermal energy of solid

H_{gm} = Heat transfer of gas

H_{rg} = Thermal energy of gas

k_s = Thermal conductivity of solid kJ kg^{-1} ^oC

k_g = Thermal conductivity of gas kJ kg^{-1} ^oC

ρ_s = Density of solid kg m^{-3}

ρ_g = Density of gas kg m^{-3}

R_0 = Evaporation rate at initial

R_m = Evaporation rate of moisture

T_s = Temperature of solid ^oC

T_g = Temperature of gas ^oC

V_g = Axial velocity of gas m s^{-1}

V_s = Axial velocity of solid m s^{-1}

γ_g^0 = Heat vaporization kJ kg^{-1}

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