Effect of Bed Thickness on the Drying Rate of Paddy Rice in an Up-flow Fixed Bed Dryer

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Abstract. Rice has played its important role as the world’s major source of food for human and animals. In order to sustain the food supply, many efforts have been conducted to increase the production of paddy rice per acre. The management of highly moist paddy rice during the harvesting period for preserving the paddy rice quality, increase in yield and reduce postharvest losses is greatly challenging. Drying process is one of the postharvest technologies for preserving the quality and extending the storage time of paddy rice. Moisture is removed to retard the development of a favorable environment for growth of molds and insects that lead to cause spoilage. In this paper, an experimental work and development of a simple mathematical model in a fixed bed drying of highly moist paddy rice have been conducted. Effect of bed thickness (6 cm to 12 cm) on the paddy rice drying rate was investigated by flowing drying air at 5.5 m/s with 37.45 % relative humidity at 40°C for 10 to 130 minutes. Drying of paddy rice using 8 cm bed thickness for 60 minutes was found to be the best drying condition to obtain acceptable moisture content of paddy rice for safe storage. The proposed non-equilibrium has shown its suitability for predicting the moisture content of paddy rice with variation of height of a fixed bed under unsteady state conditions. The drying rate constant was found to be a logarithmic function of bed thickness.

1. Introduction
Rice has been one of the most important food crops in the world for millennia as it is consumed by half of the earth population as a basic need, including diets, and source of income [1]. This crop is also one of the major economic contributors, especially in the Asian continent. Depending on the cultivar, climate and cultivation area, the freshly harvested paddy rice may contain around 20–25 % initial moisture by mass wet basis [2]. Therefore, the management of highly moist paddy rice during the harvesting period is highly challenging. If the paddy rice is not dried appropriately, the remained water can trigger the growth of mold and high respiration rate from the grains. As a result, the dry matter of the grain is degraded and the heat coming from its respiration and biological activities may speed up rice yellowing. Based on a survey conducted by the Statistics Indonesia [3], the postharvest losses of paddy rice in...
Indonesia was quite high at 11.27%, which occurred during harvest (1.5%), threshing (0.98%), drying (3.59%), milling (3.07%), storage (1.68%), and transportation (0.38%). Therefore, to obtain high quality paddy rice and to overcome all the issues above, paddy rice moisture content must be reduced to 12–14% (wet basis) [4]. In addition, to guarantee a high head rice yield and a high germination rate of rice, the temperatures of lower than 43 °C are suggested for paddy rice drying [5].

Paddy rice drying is a complex process involving simultaneous heat, mass, and momentum transfers through the porous media of the grains. In the conventional paddy rice dryers, paddy rice is directly contacted to the drying air with relative humidity of lower than its equilibrium value at the outer surface of the paddy rice particles. The most common type of dryers used for the drying of paddy rice is the fixed deep-bed dryer, either in the form of rectangular bins, such as flat bed/inclined bed or circular bins. In a fixed deep-bed drying process, the drying air flows from the bottom to the top of the bed and simultaneously removes the moisture out from paddy rice particles. During the drying process, the temperature and relative humidity of the drying air and the temperature and moisture content of the paddy rice particles depend on their position in the bed (bed thickness) and the drying time. On the other hand, the drying of paddy rice particles has to obtain uniform moisture content and temperature distribution of the final product [6]. A comprehensive and efficient design of the drying equipment has become an essential consideration for the processing operation [7].

Recently, mathematical modeling and computer simulation have been widely used in the agriculture engineering research areas. A number of researchers have proposed theoretical and empirical mathematical models for paddy rice drying using various approaches and assumptions. The fundamental information of the proposed models covers: (a) the physical properties of drying air and water vapor; (b) the heat and mass transfer rate between paddy rice particles and drying air; (c) the equilibrium state of the moisture between paddy rice particles and ambient air; and (d) the heat and moisture transfer rate in the internal structure of paddy rice particles. In order to simplify the simulation process, the deep beds of paddy rice particles were considered to be comprised of many consecutive thin layers [8]. Mathematical modeling and computer simulation have essentially reduced the cost and time for numerous experimentations. They are also proven to be powerful tools in describing the physical phenomena related to the complicated drying processes [9]. Finally, the outcomes of the numerical simulation are expected to end up with the design, fabrication and testing of new drying processes.

The objective of this study were to investigate the effect of bed thickness on the drying rate of paddy rice, to propose a simple non-equilibrium mass transfer model for the estimation of the drying rate constant and moisture content of paddy rice at a given drying time and to validate the proposed model with experimental paddy rice drying data.

2. Materials and Method

2.1. Materials

The freshly harvested paddy rice of Situbagendit cultivar was obtained from rice farms in the district of Matesih, Karanganyar Regency, Central Java Province - Indonesia. Before being subjected to drying experiment, the paddy rice was undergone a pre-treatment, in which, the paddy rice was sieved mechanically to separate the rice straws, soils, and stone from the paddy.

2.2. Methods

Carefully weighed paddy rice was introduced into the drying column to obtain the desirable bed thickness. The paddy rice weights and their respective bed thicknesses data were recorded. Initial moisture content of the paddy rice was determined using a portable moisture meter. The drying experiment began with the conditioning of the drying air by adjusting its flow rate (5.5 m/s) and temperature (40 °C) through setting up the blower and air heater controllers depicted in Figure 1. The temperature and relative humidity (37.45 %) of the drying air were confirmed by a portable digital anemometer. Once the drying air condition was established, the paddy rice was introduced to the drying column at desirable bed thickness. The moisture content of the paddy rice was recorded at every 10
minutes. The experiment was terminated when a close value of two consecutive moisture contents of paddy rice was observed. The moisture content data at various bed thicknesses and drying time were then used for the validation of the proposed mathematical model.

Figure 1. Experimental set-up of fixed bed drying of paddy rice

3. Modeling Of The Kinetics Of Fixed Bed Drying Of Paddy Rice

Drying of freshly harvested paddy rice aims to reduce the moisture content of paddy rice to an acceptable level, which is usually 14% (w. b.) [4]. Depending on the operating conditions, the drying process of paddy rice generally involves the vaporization of moisture and/or mass transfer of moisture from the paddy rice to the drying air. For a small dryer equipment and shallow bed operation, the following assumptions can be taken:

1. The drying process occurs under pseudo-isothermic condition, where the temperature of the drying air entering and leaving the bed is not significantly change.
2. The moisture content of the paddy rice inside the bed is almost uniform.
3. The drying process is batch for the paddy rice particles, but the drying air is continuously flown into the dryer.
4. The drying process obeys the constant drying rate period in the beginning and followed by falling drying rate in the rest of the process until the achievement of an equilibrium condition.
5. The drying rate constant is affected by the bed thickness.

Based on the above mentioned assumptions, the drying rate of freshly harvested paddy rice in a thin-layer bed can be described using an equation similar to Newton’s law for convective heat transfer. A non-equilibrium model of the paddy rice fixed deep-bed drying was derived from the theoretical analysis of the physical phenomena of the drying process [10]. In this regard, the non-equilibrium mass transfer rate of moisture from paddy rice particles to the drying air with the driving force or transfer potential is the difference between moisture content at any time and the equilibrium moisture content [11]:

\[
\frac{dx}{dt} = -k(X - X_{eq})
\]

where \(X\) and \(X_{eq}\) are the moisture content of paddy rice particles at a given drying time \(t\) and at equilibrium (g moisture/ g dry paddy rice). The \(k\) value represents the drying rate constant (1/minutes).

The moisture content of paddy rice particles at equilibrium can be estimated using the equation previously developed by Zare [12]:

\[
X_{eq} = 0.29394 - 0.046015 \times [\ln(-35.703+T)\ln (RH)]
\]

the T and RH are respectively the temperature (°C) and relative humidity (in decimal) of the drying air. The value of drying rate constant \((k)\) can be obtained through the solution of ordinary differential equation and optimization of equation (1) by minimizing the value of average absolute relative deviation
(AARD) between the calculated moisture contents \( (X_{cal}) \) and their respective experimental data \( (X_{exp}) \). The minimization process was carried out using the software packages Excel and SimusolveTM.

\[
AARD = \frac{100}{N} \sum_{i=1}^{N} \left( \frac{X_{exp} - X_{cal}}{X_{cal}} \right)
\]

Further, it can be assumed that the drying rate constant depends on the bed thickness \( (Z) \); therefore the following equation should exist:

\[
k = f (Z)
\]

Since there is no clue of the correlation between drying rate constant and bed thickness, curve fitting using Microsoft Excel was used to quickly find the most suitable correlation.

4. Results and Discussion

Figure 2 shows the profile of moisture contents of paddy rice at various bed thickness and respective drying time. It can be seen that moisture contents of paddy rice drastically decrease with the drying time in the beginning of the experiments. However, extending the drying time would lead to gradual decrease in the moisture contents of paddy rice to an asymptotic value (equilibrium moisture content). This is due to the fact that as time goes by, the rate of evaporation of moisture from paddy rice particles to the drying air decreases [6]. The theoretical value of equilibrium moisture content for paddy rice at 40 °C using 40% relative humidity calculated using Equation (2) is 0.1260 g/g dry paddy rice. The slope of the drying curve shown in Figure 2, which reflects the constant drying rate period, is sharper for the thinner bed. The thicker beds required longer drying time to achieve the acceptable moisture content for paddy rice (14% w/w or equivalent to 0.1628 g/ g dry paddy rice). Srivastava and John [6] and Chakraborty et al. [13] also observed a similar phenomenon during deep bed drying of grains and paddy rice in India. This finding is also in a good accordance with observation reported by Liu et al. during their study on the drying of corn grain in a deep-bed dryer [14]. Based on the technological and economical point of views, fixed bed drying of paddy rice using 8 cm bed thickness for 60 minutes, which achieved 12.80 % w/w moisture content, can be considered as the best operating condition.

Figure 2. Comparison of profile of moisture content obtained from experiment and modeling calculation

Figure 2 also presents the profile of moisture contents of paddy rice at various bed thickness and respective drying time obtained from mathematical modelling and experiments. It can be observed that the calculated moisture contents of paddy rice are closely similar to those recorded from experiments. This result confirms that the proposed non-equilibrium mass transfer model can be used to estimate the
moisture contents of paddy rice at various bed thickness and respective drying time with high accuracy. Similar modelling results were reported previously by Naghavi et al. [10]. They found that the rate of evaporation of moisture from paddy grains decreases as the distance from inlet section of the bed increased. As a result, paddy rice particles residing at the higher positions from the bottom of the bed still contain higher moisture than those stay near the bottom section.

At a given superficial velocity, relative humidity and temperature of drying air, an increased in the bed thickness leads to increase the amount of moisture to be taken away by the drying air. As a result, the values of drying rate constant increased gradually from 0.2332 to 0.2665 (1/minutes) as the bed thicknesses were increased from 6 cm to 12 cm. To find the best correlation between the drying rate constant and bed thickness, curve fitting using the facility available in Microsoft Excel was employed. The plot of drying rate constant and bed thickness is presented in Figure 3.

![Figure 3. Drying rate constants as a function of bed thickness](image)

Based on the curve fitting, the most suitable correlation between drying rate constant ($k$) and bed thickness ($Z$) is a logarithmic function represented by Equation (5).

$$k = 0.047 \ln(Z) + 0.147$$  \hspace{1cm} (5)

The goodness of this logarithmic correlation is indicated by an $R^2$ value of 0.999. A combination between Equation (1), Equation (2) and Equation (5) for the prediction of paddy rice moisture contents during paddy rice drying in an up-flow fixed bed dryer is expected to be satisfactorily. In addition, Wang and Singh [15] have suggested a linear correlation between the drying rate constant and temperature and relative humidity of the drying air.

5. Conclusions

In this study, thin-layer drying tests for paddy rice were conducted using drying air of 5.5 m/s superficial velocity with 37.5 % relative humidity at 40 °C in a fixed bed drying column. Drying of paddy rice using 8 cm bed thickness for 60 minutes was adequate to obtain acceptable moisture content of paddy rice for safe storage. A non-equilibrium mass transfer model under pseudo-isothermic condition was proposed for the fixed bed paddy rice drying and it exhibited satisfactorily moisture content estimation results. The drying rate constant was found to be a logarithmic function of bed thickness.

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