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Original Article

Thin layer drying model for gas-fired infrared drying of paddy

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Abstract

Wet Paddy (KDML 105 variety) was dried under different process conditions applying a pilot scale experimental gas-fired infrared dryer. The infrared radiation is expressed in terms of peak wavelength of infrared emitter, and the initial moisture content of paddy were varied to study the drying behavior. Five existing mathematical models describing thin layer drying have been investigated. The experimental results were compared considering their goodness of fit in terms of coefficient of determination, R^2, root mean square deviation, RMSD, and Chi-square, χ^2. The available thin layer drying models were fitted to the drying data resulting in the Modified Page Model being chosen, with a high average value of $R^2 = 0.9952$. This model was considered to be best fitted over other models, because it gave the lowest RMSD and χ^2 values, which were compared between the observed and predicted moisture ratios. A combined regression equation was developed to predict the drying parameters *k* and *n*, which gave a good fit, with $R^2=0.9635$ (*k*) and $R^2=0.9328$ (*n*).

Keywords: gas-fired infrared, paddy drying, modeling

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1. Introduction

Presently, infrared (IR) drying, which is the most efficient form of electromagnetic radiation for heat transfer, has been gaining interest in the agro-industry because of its high thermal efficiency, fast heating response time, and direct absorbability by the material. This drying technology has appeared as one of the potential alternatives to the traditional heating methods for obtaining high-quality dried food, because of several intrinsic advantages, such as simplicity of the required equipment, easy adaptation of the IR heating with conductive, convective, and microwave heating, and significant energy conservation.

Thermal radiations from infrared waves are generated from a heat source. During drying, the infrared rays penetrate into the moist materials to a certain depth and increase their temperature. Then, the diffusion rate of the water through the material increases and consequently the radiation properties of the material are changed due to decreasing water content, which diffused out of the materials into the surrounding air. Moist materials are able to absorb high IR energy so that the power required to heat them can be minimized, depending on the specific drying process. Therefore, the appropriate IR peak wavelengths for heating moist materials are considered. The infrared emitters radiating in the range of 2.5 to 7 microns (μm) maximum wavelength (λ_{max}), and they are located in the medium-to-far infrared range, which has been proved suitable for agricultural product drying. The associated maximum or peak wavelength can be calculated from the absolute temperature of the emitter, according to Wien's displacement law (Ozisik, 1985; Sandu, 1986; Ratti and Mujumdar, 1995).

In general, sun drying and hot-air drying are the common methods for paddy drying. However, many researchers have specifically aimed at the infrared dryer, Schroeder and Roseberg (1961), Stephenson and Mckee (1963), Ginzburg (1969), and Abe and Afzal (1997). The reports were concerned with simulation models required for the use in the process design. Jenkins and Forth (1965) found that when the IR energy was absorbed on the surface, it allowed only a shallow layer to be dried. Nindo *et al.* (1995)

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further reported that the vibration bed could be used to turn the grains, especially in deeper bed, to receive a uniform radiation. The investigations of infrared radiation drying of high-moisture paddy and parboiled rice was continued by Das *et al.* (2004), who reported that both radiation intensity and bed-depth significantly affected the drying performance and rice qualities.

Many published studies were primarily interested in infrared drying of agricultural materials using a conventional electric emitter (Abe and Afzal, 1997; Afzal and Abe, 2000; Das *et al.*, 2004; Jain and Pathare, 2004; Meeso *et al.*, 2004; Sharma *et al.*, 2005; Kamar *et al.*, 2006). Research on paddy drying by using the IR emitter, in which heat was generated from natural gas, was carried out by Amaratunga *et al.* (2005). The catalytic infrared (CIR) drying in a tempering experiment produced high quality rice compared to the hot-air column dryer, with a higher drying rate and a uniform heating of the medium-sized rice grains. The maximum operating temperature of the emitter was 500°C at 3.3 μm. In addition, moist materials have also displayed a strong energy absorption using an infrared emitter, which radiated wavelengths in the range of 2.5-3.0 μm (Sandu, 1986), such as the gas-fired infrared (GIR) emitter with a maximum operating temperature up to 900°C.

However, there is at present a lack of reports exploring the GIR drying kinetics for long grain paddy, especially the premium grade rice, such as the KDML105 variety (Khao Dok Mali 105 or Jasmine rice). The objective of this study is to find a model to describe the gas-fired infrared radiation drying characteristics of this paddy type.

2. Materials and Methods

2.1 Experiment apparatus

A pilot scale experimental gas-fired infrared dryer was developed for this study (Figure 1). The batch type dryer consisted of two components: a drying chamber and a data logging unit. The chamber wall was formed from aluminized steel, with a length of 1.2 m, a breadth of 0.9 m, and a height of 1.2 m, equipped with a slide-up door, which allowed insertion and removal of the sample. The gas-fired infrared emitter, which has a working temperature of up to 900°C at 2.5 μm, was installed on the top panel, and the radiated power could be controlled by using a natural gas flow regulator. Burnt gas and moist air in the chamber flowed out through a vent hole, which was fixed at the top of the chamber. The emitter temperature was measured by Type K thermocouples at the perforated plate of the emitter. In the drying chamber, a paddy sample was placed on a wire mesh drying tray (0.9 m x 0.45 m), to which a vibrating unit had been attached for mixing the paddy during the drying process (Nindo 1995). The tray was placed parallel to the GIR, and the distance between the radiator and the paddy sample was set constant at 40 cm in order to maintain a uniform radiant distribution throughout the experiments. The vibrating frequency was set at 450 cycles/min and the amplitude of the vibration was approximately 0.01 m in the vertical direction (Das *et al.*, 2004; Amaratunga *et al,.* 2005). A data logging unit was set up for measuring the temperatures of the emitter, as well as the ambient air outside and inside the chamber. These measurements with the Type K thermocouples were recorded every 20 seconds by using a data logger (YOKOGAWA Model DX200).

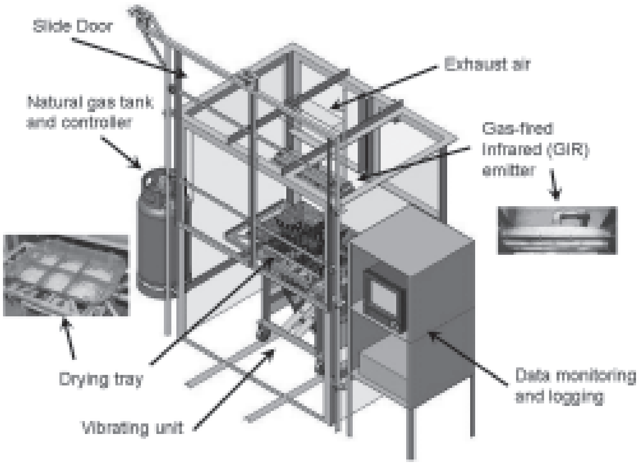

Figure 1. Schematic diagram of the laboratory scale gas-fired infrared (GIR) dryer.

2.2 Sample preparation

Fresh long grain paddy samples of KDML105, the premium grade rice with an amylose content of 12-17%, were used for this experiment. The samples were harvested in Thailand's Northeast region. After harvesting, the samples were thoroughly cleansed of foreign materials and immature, undersized, and oversized grains. Fresh paddy was rewetted, mixed, and kept in cold storage at temperatures of 4-7°C for 7 days. Before the experiment, the paddy was brought out to be kept in ambient air until grain temperature was close to the ambient temperature. The moisture content of the grain sample was determined using an oven-drying method (ASAE, 1996), with the values calculated on a dry basis (d.b.).

2.3 Mathematical modeling of gas-fired infrared drying curves

Numerous empirical and semi-empirical models have been proposed to describe the drying behavior of agricultural products. The drying curves fitted for the models are often used to explain the mass transfer in thin layer drying. Presently, infrared drying has been investigated and simulated as a potential method for obtaining high quality dried grains, foodstuffs, fruits and vegetables (Hebbar and Ramesh, 2001; Hebbar and Rostagi, 2001; Das *et al.*, 2004; Nowak and Levieki, 2004; Togrul, 2005; Kumar *et al.*, 2006). For infrared drying, thin layer models are widely reported in the literature. Abe and Afzal (1997) have described the thin layer drying of rough rice and established a drying equation. Later, a simulation of moisture changes in barley has been published by Afzal and Abe (2000). Subsequently, Das *et al.* (2004) evaluated the performance of a batch type vibration aided infrared dryer for high moisture paddy and indicated that the Page Model adequately fitted the experimental drying data.

In recent years, various exponential forms, empirical and semi-empirical, have been developed and tested by many researchers. The applicable mathematical models given by various authors for drying curves are presented in Table 1. In the present study, the constants and coefficients of the models have been written as power and exponential functions of the infrared peak wavelength of the emitter and the initial moisture content of paddy.

1) Drying conditions and procedure

The drying experiments were conducted using 0.5 kg of wet paddy samples with three replications at four initial moisture contents (M_0) of 0.22, 0.27, 0.32 and 0.37 decimal dry basis (d.b.). Three infrared radiation intensities were applied at specific emitted maximum wavelengths (λ_{max}), which were close to the absorption peak of moist materials in the infrared ray range (*IR*) of 2.70, 2.58 and 2.47 µm, emitter temperature of 800, 850 and 900°C, respectively. The moisture content at considered time (M_t) was obtained from the experiment at each testing condition with drying times (*t*) of 0, 0.5, 1.0, 1.5, 2.0, 3.0, 5.0, 7.0 and 10.0 minutes. These experiments were conducted at ambient inlet air temperatures of approximately 28-30°C.

The moisture ratio (*MR*) was (M_t-M_e) / (M_0-M_e), where M_t is the moisture content at time (*t*) and M_e and M_0 are equilibrium and initial moisture contents on dry basis, respectively. For infrared drying, Fasina *et al.* (1998) explained that the M_e has been numerically set to zero, since prolonged exposure of grain to *IR* radiation eventually causes the burning of the material, which happens only at nearly zero moisture content. This is similar to the M_e value, which was determined and published by Abe and Afzal (1997) reported on the rough rice drying by using infrared radiation. For this reason, dry matter content of the paddy may be dried by using infrared radiation until only dry matter content is left (Das *et al.*, 2004). Therefore the moisture ratio (*MR*) was simplified to M_t/M_0 instead of (M_t-M_e) / (M_0-M_e).

2) Determination of coefficient and error analyses

The regression technique was used to develop a combined equation for predicting the moisture ratios. The performance of derived new models at varied drying conditions was determined using various statistical parameters. An acceptable model was considered and evaluated by using the goodness-of-fit test of different models. Several criteria are available to evaluate the fitting of a model to experimental data. A model is considered to be good when the coefficient of determination (R^2) is high and close to 1.0, whereas the root mean square deviation (RMSD) and Chi-square (χ^2) are low. These parameters can be calculated as follows:

Root mean square deviation (RMSD)

$$RMSD = \sqrt{\frac{\sum_1^N \left(MR_{exp\ i} - MR_{prd\ i}\right)^2}{N}} \tag{1}$$

Chi-square (χ^2)

$$\chi^2 = \frac{\sum_1^N \left(MR_{exp\ i} - MR_{prd\ i}\right)^2}{N-n} \tag{2}$$

where MR_{exp} and MR_{prd} are experimental and predicted moisture ratio values, respectively, *n* is the number of constants, and *N* is the number of observation in each set.

3. Results and Discussion

3.1 Effect on drying curves of GIR paddy drying

The changes in the moisture content with time during gas-fired infrared drying of the paddy have been determined. The drying plots of dried paddy at infrared peak wavelength of 2.70 µm as a function of drying time (*t*) versus initial moisture contents (M_0) of 0.22, 0.27, 0.32 and 0.37 d.b. are shown in Figure 2, whereas the drying plots of paddy at initial moisture content of 0.37 d.b. as a function of drying time versus infrared peak wavelength, with 2.47, 2.58, and 2.70 µm, are shown in Figure 3.

The plots in these figures are relative similar as they all show a typical drying trend, where the moisture content decreases exponentially with time. The moisture content of the paddy at considered time (M_t) rapidly decreases during the first 5 minutes of the drying process, and then decreases slowlier with further drying time. In the case of a high initial moisture content, the time required to achieve a certain

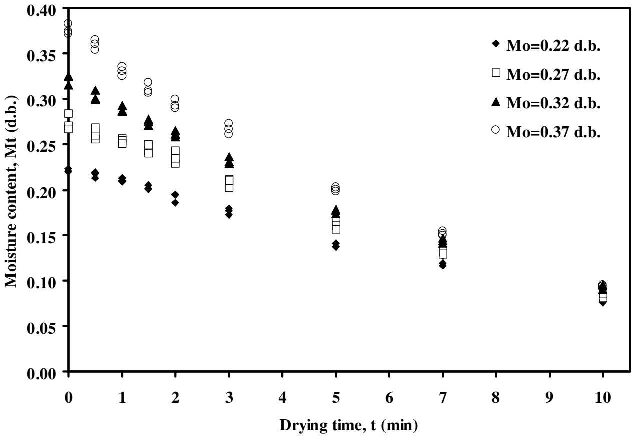

Figure 2. Infrared radiation drying plots of paddy at different initial moisture contents (in dry basis), evaluated at an infrared peak wavelength of the emitter of 2.70 micron.

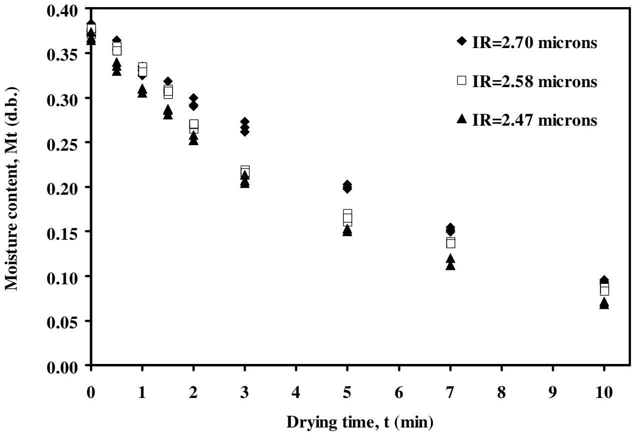

Figure 3. Infrared radiation drying plots of paddy at different infrared (IR) peak wavelengths (in microns), evaluated at initial moisture content of the paddy of 0.37 (in dry basis).

moisture content should increase. In addition, the results show that infrared peak wavelength (λ_{max}) has a significant effect on the drying rate of the paddy. The drying rate increases significantly with increased intensity level (decreased λ_{max} value), as the higher energy was absorbed by the paddy, so that the time required to achieve a certain moisture content decreases.

3.2 Mathematical model considerations

The change of drying rate with time and moisture content was analyzed. Actual values of moisture content have been calculated into moisture ratio (*MR*). A non-linear regression analysis has been carried out for the five thin layer drying models (Table 1) relating to the drying time and moisture ratio for various experimental conditions. The applicable mathematical models for drying curves, according to various authors, and the values of regression for each model are shown in Table 2. The criterion used for the model selection is the magnitude of the average value of the coefficient of determination (R^2_{av}) for each model. Other associated regression values are also shown, the standard deviation (STDEV), and percentage coefficient of relative variation (%CV). Given such, the Page and Modified Page Model have R^2_{av} values higher than other models, while the STDEV and %CV values are lowest. Therefore, these models can be proposed for predicting changes in moisture content with time. However, the models do not have the combined effects of other drying parameters relating to the initial moisture content of paddy and infrared peak wavelength. Therefore, multiple regression analyses have to be employed to relate the coefficient of drying model with different combinations of the independent parameters.

The drying constants or coefficients of each model for all the 36 drying tests, which have been estimated by

Table 1. Mathematical models given by various authors for infrared drying curves, with *MR* = initial moisture content (d.b.), *k, n, a* and *b* = drying coefficients.

Model equation	Name of model	References
$MR = exp(-kt)$	Newton	Abe and Afzal (1997); Hebbar and Rostagi (2001)
$MR = exp(-kt^n)$	Page	Afzal and Abe (2000); Das *et al.* (2004); Kumar *et al.* (2006).
$MR = exp[-(kt)^n]$	Modified Page	Togrul (2005); Kumar *et al.* (2006)
$MR = a\ exp(-kt)$	Henderson	Chhinman (1984); Abe and Afzal (1997).
$MR = 1 + at + bt^2$	Wang and Singh	Wang and Singh (1978); Ozdemir and Devres (1999).

Table 2. Result of the statistical analyses on the modeling of moisture content and drying time, with *MR* = initial moisture content (d.b.), *k, n, a* and *b* = drying coefficients, R^2_{av} = average coefficient of determination, STDEV = standard deviation, %CV = percentage coefficient of relative variation.

Model Name	Model	*Coefficient of determination, R^2*		
		R^2_{av}	STDEV	%CV
Newton	$MR = exp(-kt)$	0.9913	0.00705	0.71156
Page	$MR = exp(-kt^n)$	0.9952	0.00262	0.26368
Modified Page	$MR = exp[-(kt)^n]$	0.9952	0.00262	0.26368
Henderson	$MR = a\ exp(-kt)$	0.9933	0.00417	0.41978
Wang and Singh	$MR = 1 + at + bt^2$	0.9944	0.00294	0.29619

Table 3. Coefficient equations and statistical analysis for the comparison of experimental and predicted moisture values, with M_0 = initial moisture content (d.b.), *IR* = infrared peak wavelength (micron), k, n, a and b = drying coefficients, RMSD = root mean square deviation, χ^2 = Chi-square.

Model name	Coefficient equations	Statistical analyses	
		RMSD	χ^2
Newton	$k = 3.1189 - (2.1784\ IR) + (0.3874\ IR^2) + (0.5295\ M_0^2)$	0.00194	0.0000038
Page	$k = 0.7435 - (0.2936\ IR) + (0.4555\ M_0)$ $n = 0.2339 - (0.2397\ IR^2) + (5.9422\ M_0^2) - (1.7195\ IR\ M_0)$	0.00179	0.0000032
Modified Page	$k = 3.5905 - (2.5730\ IR) + (0.4709\ IR^2) + (0.4506\ M_0^2)$ $n = 0.2339 + (0.2397\ IR^2) + (5.9422\ M_0^2) - (1.7195\ IR\ M_0)$	0.00144	0.0000021
Henderson	$a = 0.7313 + (0.1222\ IR) - (0.0475\ IR\ M_0)$ $k = 0.4718 - (0.1490\ IR) + (0.4854\ M_0^2)$	0.00177	0.0000032
Wang and Singh	$a = -0.5375 + (0.2003\ IR) - (0.3242\ M_0)$ $b = 0.0195 + (0.02667\ M_0) - (0.0035\ IR^2)$	0.00211	0.0000045

multiple regression analysis are presented in Table 3. The regression coefficients as a function of drying parameter are assumed to correlate with a second order polynomial equation. The moisture ratios have been estimated using the predicted parameters and compared with experimental values. The best-fit model has been chosen based on the lowest values of root mean square deviation, and Chi-square.

The Modified Page Model gives the lowest RMSD values, and c^2 values over other models as shown in Table 3, and is therefore considered as the best fit for the given conditions. The average value of coefficient of determination, R^2_{av}, of the Modified Page Model is 0.9952. The combined regression equation developed to predict the drying parameters gives a fairly good fit for the drying constant *k* ($R^2 = 0.9635$) and the exponent *n* ($R^2= 0.9328$). Equation (3) indicates that mainly both *IR* and M_0 influence the drying coefficients *k* and *n*. For the exponent n, M_0 affects this value as indicated by the large coefficient. Validation of the Modified Page Model is confirmed by comparing the predicted moisture ratio at any particular drying condition. The predicted and observed values are in good agreement.

$$MR = exp[-(kt)^n] \tag{3}$$

with

$k = 3.5905 - (2.5730\ IR) + (0.4709\ IR^2) + (0.4506\ M_0^2)$

$n = 0.2339 + (0.2397\ IR^2) + (5.9422\ M_0^2) - (1.7195\ IR\ M_0)$

Equation (3) and subsequent equations can be used to estimate the moisture content of paddy with high accuracy at any given time within the range of given operating drying parameters. The change of moisture ratio with drying time at different levels of initial moisture content and at constant peak wavelength of 2.47 micron is shown in Figure 4.

4. Conclusions

Infrared drying characteristics of paddy were investigated at different initial moisture content levels and infrared peak wavelengths. The effective drying of paddy occurred during the period of falling drying rate. Estimated moisture ratios using predicted drying parameters, gave a good fit using the Modified Page Model, with a high average value of the coefficient of determination, $R^2_{av} = 0.9952$. The combined regression equation gave a good fit for the drying constant *k* ($R^2 = 0.9635$) and the exponent *n* ($R^2= 0.9328$). The statistical analysis for the comparison between experimental and predicted moisture values showed the lowest root mean square deviation and Chi-square values. In conclusion, the GIR model developed here gave a good fit and has the potential to be used in engineering applications concerning paddy drying.

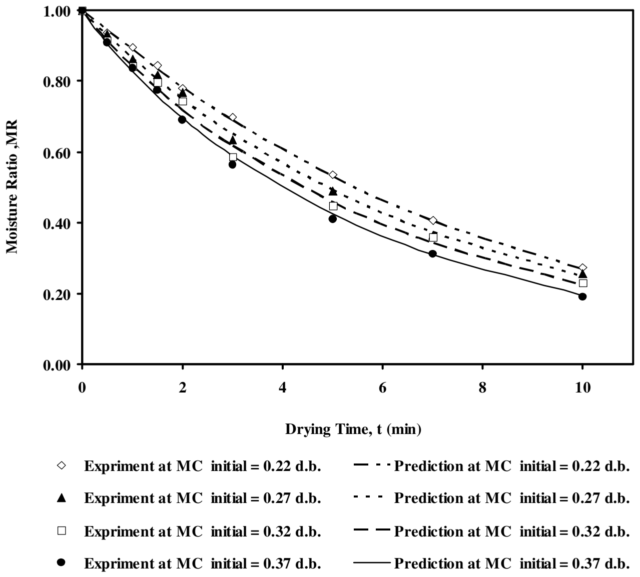

Figure 4. Comparison of the experimental and predicted moisture ratios (*MR*) for the Modified Page Model at an infrared peak wavelength of 2.47 µm. MC is the moisture content (in dry basis).

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