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Design and Fabrication of Experimental Dryer for Studying Agricultural Products

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ABSTRACT

Because of the importance of rice cracking in milling process, precision control of drying conditions is important. For this purpose, it is necessary to determine drying kinetics and obtain the moisture change during the drying process. In this paper, design, fabrication and testing of an automated thin-layer dryer is presented. Experiments on the drying kinetics of rice paddy (Fajr cv.) were conducted at five drying air temperatures, ranging from 30 to 70°C, in four air velocities, ranging from 0.25 to 1.0 ms^{-1} and three replicas (60 runs altogether) with initial moisture content of 25% (d.b.) at the start of all runs. During drying, the mass loss was measured continuously. Experimental curves of the drying rate versus time grouped by air temperature showed the strong dependence of drying rate with temperature revealed that: (a) drying rate increased when air temperature increased and (b) moisture transfer occurred during the falling rate period of drying. However, when the curves of moisture ratio verses time were grouped by air velocity, very weak dependence of moisture ratio with velocity was observed. Increase in air velocity from 0.25 to 1 ms^{-1} had little effect on the drying period paddy. Drying curves obtained from the experimental data, fitted to eight thin layer models and compared with three statistical parameters, showed that two terms model can predict moisture change with grater accuracy than other models.

Key Words: Thin layer; Drying; Paddy; Regression; Mass loss; Temperature; Moisture content

INTRODUCTION

Rice is one of the most important food crops, as 80% people around the world consume rice. World rice production in 2004 was just less than 610 million tons and Asian farmers produced about 90% of this total. In the same year, Iran rice production was about 3,400 tons and rice yield was calculated as 5.96 tons ha^{-1}. Currently, Iran ranks 23rd in terms of rice production and 26th in terms of the areas under the crop's cultivation, but is among the top 10 states in terms of average rice productivity (faostat.fao.org).

Thin-layer drying is the process of removal of water from a porous media by evaporation, in which excess drying air is passed through a thin layer of the material until the equilibrium moisture content (EMC) is reached. Moisture removal from an agricultural product depends on their drying temperature, velocity and relative air humidity, variety and maturity. Hence, various isolated and combined parameters are involved in moisture removal from a grain (Couto, 2002). The simplest situation is when the drying resistance (isothermal process) lies on the grain surface, for which the decay of moisture with time follows approximately an exponential law. Lewis was first to recognize the moisture transfer from the solid materials is analogous to that of the flow of heat from a body immersed in cold fluid. Comparing the drying phenomenon with Newton's law of cooling in heat transfer, the drying rate will be approximately proportional to the difference in moisture content between the material being dried and EMC at the drying air state. Theories have been proposed to describe mechanisms of moisture movement in solids during drying in the falling rate period.

Drying of agricultural materials such as grains is a non-linear process with long time delay and considerable complexity. Therefore, it is very difficult to establish a precise mathematical model for grain drying control (Cao, 2002). Although some mathematical models of drying process itself have been established, their structures are often too complex to be used for control model and hence effective control is very difficult to be realized (Marchant, 1985; Courtois *et al*., 1995). Akpinar (2002) developed a cyclone type thin-layer dryer for drying agricultural materials. This system was introduced in the literature for drying study of some vegetables and fruits including potato, red pepper, apple, strawberry, pumpkin and eggplants slices (Akpinar *et al*., 2003, Akpinar, 2005). Byler *et al*. (1989) constructed a microprocessor-based system to control experimental conditions in the study of the moisture content of agricultural products. The authors described the hardware and software, which were developed for used in the study of the properties of parboiled rice.

The objective of this research was to develop and test a general-purpose fully automated thin-layer dryer to study drying characteristics and thin-layer mathematical modeling of various agricultural products.

MATERIALS AND METHODS

The form of Newton's law of cooling in heat transfer (equation 1) is often used to describe the moisture loss in thin-layer grain drying (Brooker *et al*., 1974):

$$\frac{dM}{dt} = -k(M - M_e) \qquad (1)$$

The solution of (1), assuming k is independent of M and M_e, is:

$$MR_{Newton} = \exp(-kt) \qquad (2)$$

where *MR* is moisture ratio given by:

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad (3)$$

where

k = drying constant (min^{-1})

M = instantaneous moisture content (% d.b.)

M_0 = initial moisture content (% d.b.)

M_e = equilibrium moisture content (EMC) of the material (% d.b.)

t = drying time (min).

The Newton's model, (2), is similar to a one-term model that uses the first term of a general series solution of Fick's second law of diffusion, but it appears to be inadequate representation of the drying behavior of most agricultural materials especially in high temperature drying applications i.e., drying air temperature higher than 40°C (ASAE, 2006). Therefore, to provide better fits to observed data, a variety of similar one-term models to (1) and (2) related to the thin-layer drying equations have been introduced (ASAE, 2002). For example, Page (1949) modified the Newton's model by adding n (an empirical constant) as:

$$MR_{Page} = \exp(-kt^n) \qquad (4)$$

The value of n varies for each material being considered. The Page model has produced good fits to describe drying of many agricultural products (Pabis *et al*., 1998) and is also convenient to use compared to more rigorous theoretical diffusion moisture transfer equations, which take more computing time in fitting the data.

A two-term solution similar to that, which uses the first two terms of a general series solution of Fick's second law of diffusion, was also introduced in literature (Pabis *et al*., 1998) as this model might better take into consideration the different drying characteristics of the material components:

$$MR_{Two-term} = a\exp(-k_1 t) + b\exp(-k_2 t) \qquad (5)$$

Where k_1 and k_2 are drying constant (min^{-1}) and *a* and *b* are empirical constants. A summary of thin-layer models used here to describe the drying kinetics of rice paddy (Fajr cv,) is given in Table I. Similarly, the drying rate will be approximately proportional to the difference in moisture content between the product being dried and EMC at the drying air state:

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (6)$$

where

DR = drying rate (g H_2O g^{-1} DM min^{-1})

M_t = moisture content at time *t* (% d.b.)

M_{t+dt} = moisture content at time t + dt (% d.b.)

dt = time of successive measurements (min)v

Statistical analysis of the drying data. Modeling the drying behavior of different agricultural products often requires the statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationship between different variables, especially, for which no established empirical relationship exists. The empirical coefficients in Table I can be estimated by fitting the total model employed to the experimental drying curves. The goodness of fit of the tested models to the experimental data are the coefficients of determination, R^2, the reduced χ^2 and root mean square error (RMSE) of the difference between the experimental and calculated values for the tested models. R^2 was the primary criterion to select the best equation to account for the variation in the drying data obtained here. The higher the values of R^2 and lower values of the χ^2 and RMSE, the better the goodness of the fit. Regression analyses were performed by SPSS 10.5 software. The effects of some parameters related to the product or drying conditions such as rice paddy, drying air temperature, relative humidity etc., were investigated by many researchers (Sarsavadia *et al*., 1999; Akpinar *et al*., 2003; Rafiee *et al*., 2007).

Development and fabrication of dryer. The drying behavior of rice, as described by moisture, temperature and stress distributions inside the material during drying and the quality traits of individual kernels, affect the overall quality of the product dried in a dryer. The moisture must be reduced to a level acceptable for marketing, storage, or processing. Therefore, it is important to control the drying conditions precisely in order to improve the drying process and product quality. Drying of agricultural products is a non-linear process with a long time delay and a considerable complexity. Therefore, it is very difficult to establish a precise mathematical model for material drying control. Although some mathematical models of drying process itself have been established (Brooker *et al*., 1974), their

Table I. Empirical thin-layer models considered in this paper

Model ID No	Model name	Model equation*
E1	Newton	$MR = \exp(-kt)$
E2	Henderson-Pabis	$MR = a\exp(-kt)$
E3	Page	$MR = \exp(-kt^n)$
E4	Logarithmic	$MR = a\exp(-kt) + c$
E5	Wang and Singh	$MR = 1 + at + bt^2$
E6	Two-Terms	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$
E7	Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$
E8	Verma et al.	$MR = a\exp(-k_1 t) + (1-a)\exp(-k_2 t)$

* *n, a, b* and *c* are drying coefficients, and *k*, k_1 and k_2 are drying constants (min^{-1})

Table II. Specifications on measurement instruments including their rated accuracy

ID	Instrument	Model	Accuracy	Make
3	digital balance	GF3000	± 0.02 g	A&D, Japan
8	T-sensor	LM35	$\pm 1^\circ C$	NSC, USA
9	RH-sensor	Capacitive	$\pm 3\%$	PHILIPS, UK
10	V-sensor	405-V1	$\pm 3\%$	TESTO, UK

Table III. Results of the two-term model fitted by regression analysis to the experimental data for drying rice paddy in air velocity of 0.25 ms^{-1}

$$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$$

Temp ($^\circ C$)	a	b	k_1	k_2	RMSE	χ^2	R^2
30	0.51371	0.473896	0.000921	0.009409	0.006612	0.00004	0.0066
40	0.29072	0.655236	0.000794	0.009392	0.00747	0.00006	0.0075
50	0.64452	0.384138	0.007718	0.029457	0.009389	0.00009	0.0094
60	0.43663	0.572783	0.006113	0.033413	0.006789	0.00005	0.0068
70	0.02196	1.008365	-0.01484	0.020113	0.009649	0.00009	0.0096
			Average Values		0.008	0.00007	0.9985

structures are often too complex to be used for control model and hence effective control is very difficult to realize. Both classical and the modern control theories are insufficient for the drying control practice.

Design and fabrication of dryer. For the design and development of a thin-layer dryer, one must fulfill the following guidelines: (a) materials in the thin layer should be exposed fully to the air stream; (b) the air stream approaching the sample should be as uniform as possible in temperature and relative humidity (RH) at a given cross section parallel to the thin layer so that the air contacts sample materials uniformly; (c) continuous recording of the sample mass loss during drying is required (ASAE, 2006). In practice, the experiment should continue until *MR*, defined by equation (3), equals 0.05. M_e can be determined experimentally or numerically from ASAE D245 (ASAE, 2001). RH may be measured directly or computed from measurements of air temperatures (dry bulb & wet bulb). Based on these recommendations a general-purpose thin-layer dryer was designed and implemented to maintain air at a desired temperature. Schematic diagram of total system developed for the experimental work is shown in Fig. 1.

The dryer consisted of centrifugal fan (4), four heating elements (5), air-duct (6), two sample trays (7) placed inside drying tunnel, main controlling board (2), measurement instruments (3, 8-9) and a PC (1) for monitoring and control purposes. A portable, 0-15 m/s range digital anemometer (10) was used to occasionally measure air flow velocity of air passing through the system. The airflow was adjusted by means of a variable speed blower. The heating system comprised four electric 1000 W elements (5) placed inside the duct. The rectangular duct (6), containing guiding rods to produce uniform air-flow through the samples placed inside the tunnel. The trays (7) were supported by lightweight steel rods placed under the digital balance (3). The opening side on the right was used to load or unload the tunnel and to measure drying air velocity occasionally using a manual digital anemometer.

Measurement instruments. Measured variables were air temperature, air velocity, relative humidity (RH) and sample mass loss during drying (Table II). Necessary signal conditioning circuits, which adapt the output signal of each sensor to be easily processed by the microcontroller, have been described elsewhere (Omid, 2004). The temperature was measured by LM35 sensor, which is a precision, easily calibrated IC temperature sensor. When calibrated at $25^\circ C$, the LM35 has typically less than $1^\circ C$ error over a $100^\circ C$ temperature range. The RH was measured with a homemade capacitor-type sensor. The μF output of the RH sensor is easily converted to mV by a simple circuit. The accuracy of RH sensor is $\pm 3\%$ at ambient room temperature.

A portable, 0 - 15 m s^{-1} range digital anemometer was used to occasionally measure air flow velocity of air passing through the system. The digital anemometer was held at the opening end of the tunnel. For continuous recording of the sample mass loss during drying, a digital balance was used.

Main controlling board. The interfacing and controlling circuit of dryer is shown in Fig. 2. The main components on the board are: AT89S52 microcontroller (ATMEL Corporation, 2006), a power supply, relay switches to activate controlling devices, analog to digital converter (ADC-804), analogue switch (IC CD-4066), interfacing card (IC MAX-232) for sending/receiving data to/from the PC via RS232 serial port.

A simple ON/OFF control algorithm (Yadollahinia, 2006) was used to control and adjust the drying tunnel temperature. In order to control the air temperature inside the tunnel, a simple control scheme was implemented. The temperature should be kept within a certain range (1.5°C about set-point). This may be realized by turning on and off the four heating elements installed in the dryer duct. Therefore, two transistors are used to activate the relays connected to heating elements. The microcontroller receives data on the air temperature, transfer them to the PC (via

Fig. 1. Schematic diagram of automated thin-layer drying system: 1. PC; 2. microcontroller; 3. digital balance; 4. fan; 5. heating elements; 6. duct and tunnel; 7. trays; and 8. temperature; 9. relative humidity, and 10. air flow velocity sensors

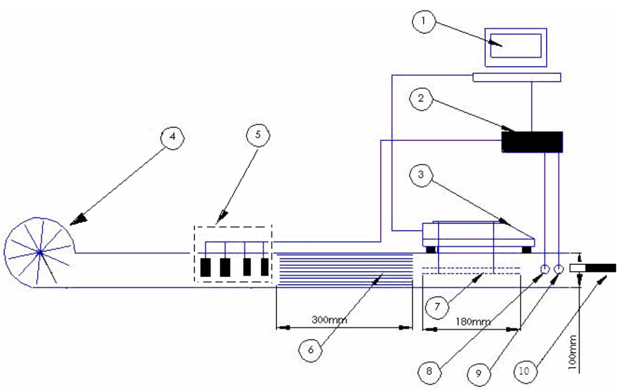
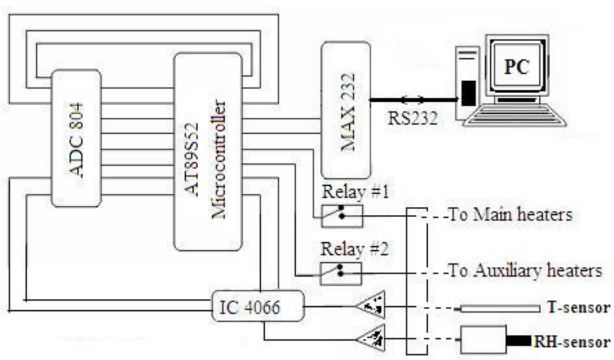


Fig. 2. Block diagram of the proposed data-acquisition system



RS232 port) and it may change the state of heating elements in order to attain the desired temperature. Initially both relays are activated until the air temperature approaches the set-point. Then the main heating elements connected to relay 1 are turned off and the control of air temperature around the set-point is done solely by the auxiliary elements connected to relay 2.

To test the performance of dryer, a set of experiments on freshly harvested rice paddy (Fajr cv.) was conducted at five drying air temperatures, T= 30, 40, 50, 60 and 70 $^\circ C$, in four air velocities, V= 0.25, 0.5, 0.75 and 1.0 ms^{-1} and three replicas (60 runs altogether). The initial moisture content (M_0) was 25% (d.b.) and EMC (M_e) was calculated by using ASAE equations (ASAE, 2001).

RESULTS AND DISCUSSION

Detailed comparisons of R^2, χ^2 and RMSE of each empirical model for drying rice paddy is given in Yadollahinia (2006). It was found that two-term (Equation 5) gave better predictions at all drying air temperatures and air velocities than other models followed by approximation of diffusion (E7), logarithmic (E4), Page (E3) and Henderson-Pabis (E2) models. Drying coefficients and constants of two-term model for different air temperatures in air velocity, V= 0.25 m/s, are given in Table III. For 0.25 ms^{-1} air velocity, the two-term model (Equation 5) gave better predictions at all drying air temperatures, with $R^2 = 0.9985$, $\chi^2 = 6.55 \times 10^{-5}$ and $RMSE = 7.98 \times 10^{-3}$. Typical drying curves obtained in thin-layer drying of paddy rice at different air temperature and V= 0.25 ms^{-1}(Fig. 3) indicated a good correlation between the experimental results and the curves predicted by the two term model (6) with the values of the drying coefficients and constants as in Table III, is obtained.

Fig. 3. Comparison between the curves predicted by the two term model equation and the experimental points at different air temperatures

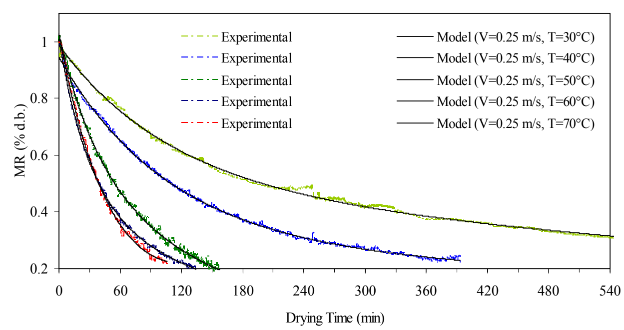


Fig. 4. Relationship between air temperature and drying time for V= 0.75 ms^{-1}

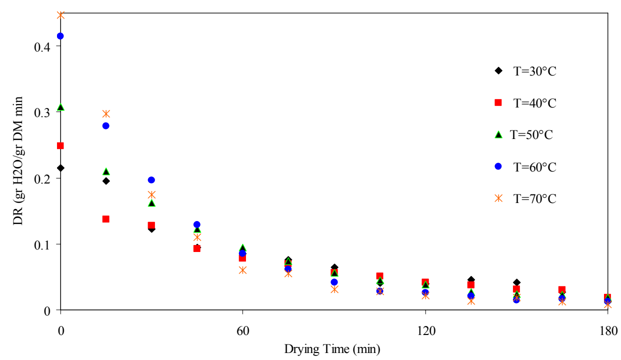


Fig. 4 shows experimental and predicted curves of the drying rate versus time grouped by air temperature for V= 0.75 ms^{-1}. It showed strong dependence of drying rate with temperature: drying rate increases when air temperature increases and moisture transfer occurs in the falling rate period of drying. Patak (1991) and Sun and Woods (1994) observed similar results for rapeseed and wheat, respectively. However, when the curves of moisture ratio verses time were grouped by air velocity very weak dependence of moisture ratio with velocity was observed: increase of V from 0.25 to 1 ms^{-1} had very little effect on the duration of period of drying of rice paddy. Akpinar *et al.* (2003) observed similar results for red pepper.

CONCLUSION

The results for rice paddy drying presented here are useful in calculating the moisture transfer process occurring during high–temperature drying and ventilated storage. Furthermore, expressions for drying rate and drying parameter for different materials can be found as a function of both temperature and velocity, through Arrhenius-type model, using multiple linear regression procedure. The dryer can be adopted for thin-layer modeling of various agro-based products.

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