MODELING IN-BIN RICE DRYING USING NATURAL AIR AND CONTROLLED AIR DRYING STRATEGIES

J. Lawrence, G. G. Atungulu, T. J. Siebenmorgen

ABSTRACT. *Uncontrolled air conditions during natural air drying (NAD) often result in over-dried rice, especially in the bottom layers of bins. In order to reduce such over-drying and associated economic loss for farmers, some control of the inlet air temperature and relative humidity is needed. In this study, a software program, Post-Harvest Aeration Simulation Tool (PHAST), based on the Thompson equilibrium moisture content model, was used to simulate NAD of rice at four representative rice-growing locations in Arkansas (Jonesboro, West Memphis, Stuttgart, and Monticello). Hourly weather data, including ambient air temperature and relative humidity, were downloaded from the National Climatic Data Center website for each location. Different combinations of controlled and uncontrolled NAD strategies were simulated using three levels of initial rice moisture content (16%, 18%, and 20%), four airflow rates (0.6, 1.1, 1.7, and 2.2 m^3 min^{-1} t^{-1}), four bin diameters (7.3 m (24 ft), 9.1 m (30 ft), 11.0 (36 ft), and 12.8 m (42 ft)), three varieties of rice (Jupiter, Wells, and CL XL 730), and three harvesting dates (August 15, September 15, and October 15). It was found that drying strategy, airflow rate, harvest date, and initial grain moisture content had significant effects on NAD of rice. An airflow rate of 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu^{-1}) was found to be optimum in terms of minimizing drying cost, which included over-drying and dry matter loss costs. The controlled drying strategy was found to be superior in terms of drying and fan operating costs.*

Keywords. *Controlled drying, Modeling, Natural air drying, Simulation, Uncontrolled drying, Weather data.*

Generally, rough rice is harvested in the U.S. at moisture contents (MCs) ranging from 14% to 24% (MCs are expressed on a wet basis unless otherwise stated) and subsequently dried to 12% to 13% for safe storage. High-temperature, cross-flow drying is the most common method used in the U.S. to dry rough rice (Schluterman and Siebenmorgen, 2004). However, in recent years, in-bin natural air drying (NAD) of rough rice has received increased attention, partly because it is a low-temperature, relatively slow drying process that is generally known to prevent kernel fissuring and maintain high rice milling yield. The rice milling yield, in large part, is quantified by the head rice yield (HRY) (USDA, 2010). Head rice yield comprises milled rice kernels that are at least three-fourths of the original kernel length; HRY represents the mass percentage of a rough rice lot that remains as head rice after milling. Preventing HRY reduction during drying is critical and has significant economic importance in the rice industry (Cnossen and Siebenmorgen, 2000).

Natural air drying uses unconditioned ambient air to dry grain. As such, the MC of grain in a bin, along with the air equilibrium moisture content (EMC) associated with a particular grain, determines whether drying or rewetting occurs when air is passed through the mass of grain. The duration required to dry a bin of grain depends on the weather, airflow rate, grain depth, and grain initial MC. NAD airflow rates for rice drying generally range from 1.1 to 2.2 m^3 min^{-1} t^{-1} (1.0 to 2.0 cfm bu^{-1}). As NAD depends on ambient air conditions, particularly air temperature and relative humidity, the weather in a given location plays an important role in determining the extent to which drying can be accomplished to achieve a specific grain final MC, drying duration, and rice quality, including HRY, yellowing, mold growth, and germination percentage (Sahay and Gangopadhyay, 1985; Tirawanichakul et al., 2003).

Two strategies are normally used in NAD: (1) uncontrolled drying and (2) EMC-controlled drying. In the uncontrolled drying strategy, the bin fan is operated continuously during the drying season. Using this strategy, periods of drying and rewetting are common, which increase the duration required to dry a bin of grain and consequently increase the fan operating costs. In addition, if over-drying of rice occurs followed by rapid rewetting, fissuring due to rapid moisture adsorption may occur, resulting in reduced HRY (Siebenmorgen and Jindal, 1986). However, with EMC-controlled drying, the bin fan is operated based on whether or not the grain-specific EMC of the ambient air is within set limits. This drying strategy not only reduces the fan operating costs but also prevents over-drying and rewetting.

To study the effectiveness of NAD of rice, the impacts of variables including airflow rate, grain depth, and ambient air conditions for a location must be quantified. Com-

---

Submitted for review in August 2014 as manuscript number PRS 10911; approved for publication by the Processing Systems Community of ASABE in June 2015.

The authors are **Johnselvakumar Lawrence, ASABE Member,** Lead Researcher and Director, IntelliAir, Archie, Missouri; **Griffiths G. Atungulu, ASABE Member,** Assistant Professor, and **Terry J. Siebenmorgen, ASABE Fellow,** University Professor, Department of Food Science, University of Arkansas Division of Agriculture, Fayetteville, Arkansas. **Corresponding author:** Griffiths Atungulu, 2650 N. Young Ave., University of Arkansas Division of Agriculture, Fayetteville, AR-72704; phone: 479-575-6843; e-mail: atungulu@uark.edu.

Transactions of the ASABE

Vol. 58(4): 1103-1111 ISSN 2151-0032 DOI 10.13031/trans.58.10911

puter simulation models enable these variables to be assessed relatively rapidly. The most commonly used models for simulating deep-bed drying of grains are equilibrium and non-equilibrium based models. Equilibrium-based models use EMC relationships of a particular grain and assume that equilibrium exists between the air and grain within a defined layer after drying for a certain duration (Thompson, 1972). Non-equilibrium-based models use thin-layer drying characteristics of the grain being dried to describe moisture transfer during a drying step or duration, and use four non-linear, partial differential equations developed based on energy and moisture balances (Brooker et al., 1992) to predict grain temperature, grain MC, air temperature, and air humidity at the end of the drying step. This latter approach assumes no thermal and moisture equilibrium between the grain and the drying air in the bed layer under consideration.

Several researchers have used equilibrium models for studying deep-bed drying of various grains (Sharma and Muir, 1974; Mittal and Otten, 1982; Soponronnarit, 1988; Jindal and Siebenmorgen, 1994; Saksena et al., 1998; Bartosik and Maier, 2004). Jindal and Siebenmorgen (1994) validated an equilibrium model for rice with experimental data and concluded that the model predicted grain temperature and MC with reasonable accuracy. Saksena et al. (1998) developed nine in-bin NAD strategies using a finite-difference method based on an equilibrium model; this resulted in a program termed the Post-Harvest Aeration Simulation Tool Finite Difference Method (PHAST-FDM). Bartosik and Maier (2004) developed and simulated different NAD strategies using PHAST-FDM for in-bin drying of corn.

Controlled NAD processes have been used to successfully dry various grains. However, this success is based on the availability of suitable ambient air for drying, which is dictated by location-specific weather patterns, and applying appropriate strategies based on these weather patterns. The goal of this study was to evaluate the potential for in-bin NAD of rough rice using an EMC-based simulation model in conjunction with weather data from representative rice-producing locations. The specific objectives were: (1) to evaluate the effect of airflow rate on drying for selected location and harvest date combinations, and (2) to determine the economically optimum drying strategy (controlled or uncontrolled fan operation) for given grain depths.

MODEL DESCRIPTION

The PHAST-FDM model (Bartosik and Maier, 2004) was used in this study, with modifications for use with rice. For example, the PHAST-FDM model was originally developed using corn dry matter loss (DML) equations (ASABE, 2005) for predicting DML during the drying period; the model was modified to use rice DML equations (Seib et al., 1980). The time step used by Bartosik and Maier (2004) in the PHAST-FDM model was 1 h, whereas a 10 min time step was used in the modified model for rice. The reason for this is that in most commercial EMC-based controllers used in the rice industry, a fan operation decision is made on time intervals ranging from 10 to 15 min, which means that if the drying fan is stopped, at least 10 to 15 min must elapse prior to restarting the fan. This minimum duration is designed into the controller software to avoid fan damage by frequent starting and stopping. As such, a time step of 10 min was used in the rice-modified PHAST-FDM model to represent EMC-based controller decision durations.

The computational domain of the rice bed was divided into a series of thin layers. The various components of the PHAST-FDM model are summarized as follows:

ENERGY BALANCE

Energy transfer in each layer was described using a balance in which the change in energy of a rice layer was equal to the amount of energy exchanged with the moving air. It was assumed that the drying air and the rice within each layer reached thermal equilibrium within a specified time step (10 min). This assumption is valid, as the change in ambient temperature within a 10 min time step is small. In addition, the layer thickness varies from 0.18 to 0.30 m with respect to different grain depths. The air velocities range from 0.07 to 0.13 m s^{-1} for 1.1 m^3 min^{-1} t^{-1} airflow and different grain depths (3.7 to 6.1 m) and are relatively slow. Bartosik and Maier (2007) experimentally validated this model in a farm bin for corn, and the standard error of prediction for moisture content ranged from 0.44% to 0.70% using the same assumption. The assumption forms the basis of the equilibrium modeling of rice drying in bins for low airflow rates such as used in this research. The energy balance applied to a thin rice layer, as shown in figure 1, is given by Jindal and Siebenmorgen (1994):

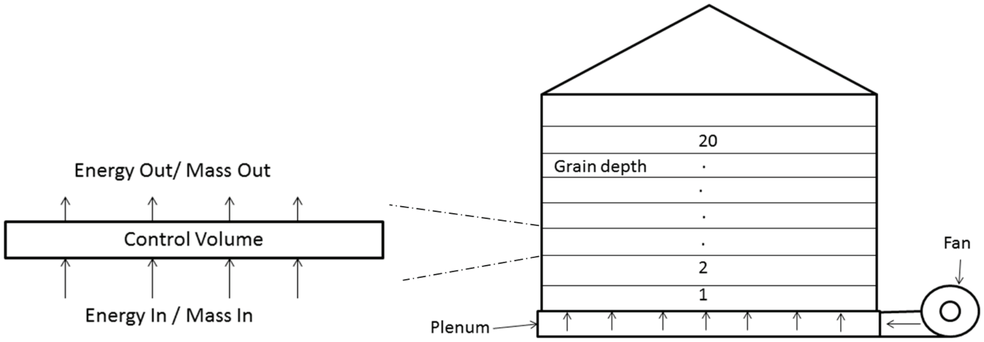

Figure 1. Schematic of the energy and mass balance approach used in equilibrium moisture content modeling of deep-bed drying of rice.

$$c_a T_o + H_o\left(h_v + c_v T_o\right) + c_g G_o R + c_w G_o\left(H_f - H_o\right) = c_a T_f + H_f\left(h_v + c_v T_f\right) + c_g T_f R \quad (1)$$

The variables in equation 1, and in subsequent equations, are defined in the Nomenclature section. The first term in the equation represents the enthalpy of dry air entering a given layer, while the second term represents the enthalpy associated with the water vapor of the air entering the layer. The third term represents the initial enthalpy of the grain mass in the layer. The fourth term represents the enthalpy of water added to or taken from the layer due to absolute humidity differences (humidity ratio) between the entering and exiting air through the layer. The three terms on the right side of the equation are analogous to the first three terms on the left side and represent energy terms of the exiting air.

MOISTURE BALANCE

The moisture balance applied to a thin rice layer (fig. 1), with the assumption that the mass of water evaporated from the grain in the layer is equal to the change in mass of water vapor in the air passing through the layer, is given by Jindal and Siebenmorgen (1994):

$$H_f - H_o = \left(M_o - M_f\right) R / 100 \quad (2)$$

$$R = \left(\rho_g \times dx \times dmf\right) / \left(\rho_a \times v_a \times t\right) \quad (3)$$

Equation 2 represents the change in air absolute humidity associated with given moisture content changes of the rice during a time step. Equation 3 represents the grain dry matter to air ratio, which is the mass ratio of grain and air within the layer thickness.

Using equations 1 through 3, the air conditions exiting the rice layer and the final rice temperature at the end of a time step were determined based on a finite difference program routine in MATLAB. As the model assumes thermal equilibrium between the air and grain at the end of a time step, the final rice temperature was equated to the exiting air temperature. Using the rice temperature and exiting air RH, the rice MC in each layer at the end of a time step was determined using the modified Chung-Pfost equation with constants specified for each rough rice cultivar (Ondier et al., 2011). For subsequent layers, the exiting air temperature and absolute humidity from one rice layer were the initial air temperature and absolute humidity entering the next layer; these inputs and equations 1 through 3 were sequentially used to predict the exiting air conditions, as well as rice MC and temperature, for each layer.

For all drying strategies, each rice bed depth was divided into 20 thin layers for simulation purposes. For each 10 min time step, the air input parameters to the bottom grain layer were varied according to location-specific weather data. These weather data were downloaded from the National Climatic Data Center (NCDC) website (www.ncdc.noaa.gov).

DRY MATTER LOSS

The DML equation in the PHAST-FDM program was modified for rough rice based on Seib et al. (1980). The DML equation used is:

Table 1. Constants used for dry matter loss equation (eq. 4) for rice.

Kernel Type	*A*	*B*	*C*	*D*
Long grain	0.00189	0.654	0.068	33.61
Medium grain	0.00091	0.710	0.049	31.62

$$\text{DML} = 1 - \exp\left(-At^B \exp\left[C(T - 15.6) + D(M - 0.14)\right]\right) \quad (4)$$

where

DML = dry matter loss (decimal)
t = storage duration (h/1000)
T = temperature (°C)
M = moisture content (decimal, w.b.)
A, *B*, *C*, and *D* = constants of the equation.

The constants used for the DML equation (table 1) for rice were adopted from Seib et al. (1980). The generalized approach of using constants designated for long-grain and medium-grain rice was adopted in this study. The effects of the studied rice cultivars on the DML constants in equation 4 have not yet been verified, nor have constants been established.

MODEL INPUTS AND OUTPUTS

Inputs for the model were hourly weather data, rice bed depth, airflow rate, rice kernel type (along with associated physical and thermal properties), simulation start date, initial rice MC and temperature, target average bin MC, maximum layer MC, rough rice price, and electricity cost. The specific heat and latent heat of vaporization of water were taken from Brooker et al. (1992). The equation to determine rough rice specific heat for long-grain and medium-grain rice types was taken from ASABE Standard D243.4 (ASABE, 2008). The average bin MC refers to the overall average MC of all 20 layers. Because the target average bin MC cannot be achieved in every layer, the maximum layer MC represents the maximum MC that is allowed in any layer (typically the topmost layer in a drying situation). For the simulations herein, the maximum layer MC was one percentage point greater than the average bin MC. Simulations were terminated when the rice MC in all layers was reduced below the maximum layer MC. In this study, the target average bin MC was taken as 13%; thus, the maximum layer MC was taken as 14%. If the target bin MC (all layers) was selected as the simulation stop condition, with over-dried bottom layers and under-dried top layers, the simulation would stop when the average MC achieved in the entire bin was 13%. However, if the simulation stop condition was set as the target bin MC plus one percentage point higher in any one layer (most probably the top layer), it is possible for all layers to achieve MC close to the target MC, with the highest MC within a one percentage point difference. This type of simulation stop condition was used by Bartosik and Maier (2007) in the PHAST program. The same type of simulation stop condition used in the model has been adopted by mainline commercial in-bin, grain drying systems.

Model outputs included fan operating duration, electricity required, total drying cost, final bin average rice MC, minimum rice MC predicted in any layer, bin average DML, maximum DML predicted in any layer, and simulation termination date. The total drying cost comprised the electricity cost of operating the fan as well as the cost of grain mass loss due to over-drying (below 13% MC). Drying and fan operating costs were expressed in dollars per tonne (cents per bushel).

METHODS

Four representative rice-growing locations across Arkansas, namely Jonesboro, West Memphis, Stuttgart, and Monticello, were selected for the simulations. To obtain representative weather conditions, six years of hourly weather data, from 2005 to 2010, were downloaded from the NCDC website (www.ncdc.noaa.gov) for each location. Since each simulation time step was 10 min, the temperatures used for each time step were linearly interpolated between successive 1 h data. The effects of independent variables, listed in table 2, were assessed for each location and year combination.

The four airflow rates listed in table 2 were selected based on commonly used airflow rates for rice storage in the U.S. Mid-South region. The three harvest dates (simulation start dates) were selected based on the generally widest range of harvest dates from various locations in Arkansas. Per USDA-NASS data, the beginning rice harvest date in Arkansas ranged from August 15 to 29 over the study years, and the final harvest date occurred mostly during the last week of October. Generally, the harvested MC of rice dried in farm bins varies from 16% to 20%; three MCs of 16%, 18%, and 20% were thus selected. Long-grain cultivars Wells and CL XL 730 and medium-grain cultivar Jupiter were representative cultivars in Arkansas during 2005 to 2010 and were thus used for simulation. The grain depths and bin diameters shown in table 2 were selected based on average Arkansas farm-size rice bins, having capacities of 82 to 449 tonnes (4000 to 22,000 bushels).

Two drying strategies, namely controlled (C) and uncontrolled (UC) fan operation, were investigated. In the uncontrolled drying strategy, the drying fan was operated continuously from the harvest date until all rice layers had dried to less than or equal to the set maximum rice layer MC, which for this study was 14%. In the controlled drying strategy, the fan was operated only when the rice EMC corresponding to the plenum air was within certain limits. During the initial drying period, until the simulated bottom layer (0.6 to 1.0 m) reached the target average MC of 13%, the fan was operated only when air conditions corresponded to an EMC less than the bottom layer rice MC. After that, the fan operating window narrowed, and the fan was operated only if the rice EMC corresponding to the plenum air was within ±1 percentage point of the target bin average rice MC, which for this study was set at 13%. Thus, for the target MC of 13%, the fan was operated when the rice EMC corresponding to the plenum air was between 12% and 14%. With this strategy, over-drying of the bottom layer was avoided.

Table 2. Independent variables and levels used in simulations of natural air drying of rice.

Variable	Levels
Arkansas locations	Jonesboro, West Memphis, Stuttgart, Monticello
Simulated years	2005 to 2010
Airflow rates, m^3 min^{-1} t^{-1} (cfm bu^{-1})	0.6 (0.5), 1.1 (1.0), 1.7 (1.5), 2.2 (2.0)
Harvest dates	August 15, September 15, October 15
Bin diameters, m (ft)	7.3 (24), 9.1 (30), 11.0 (36), 12.8 (42)
Rice depth, m (ft)	3.7 (12), 4.9 (16), 6.1 (20)
Cultivars	Wells, CL XL 730, Jupiter
Initial MCs, % w.b.	16, 18, 20

The effects of Arkansas drying location, year being simulated, rice cultivar and type, airflow rate, rice bed depth, bin diameter, and initial rice MC on controlled and uncontrolled NAD strategies were analyzed using SAS 9.1 (SAS Institute, Inc., Cary, N.C.). The SAS GLM (generalized linear model) of analysis of variance (ANOVA) was used to determine significant differences among variable responses. To study each effect in an unbalanced fractional statistical design, 31,104 simulations would be necessary, which would be impractical. Therefore, the number of simulations was reduced based on preliminary study. The numbers of observations were reduced as follows:

- The effect of airflow was studied with the following single-level independent variables: one location (Jonesboro), one cultivar (wells), one grain depth (20 ft or 6.1 m), one bin diameter (36 ft or 11.0 m), and with multi-level independent variables including 6 years of cultivation (replications), 4 airflow rates, 3 MCs, 3 harvest dates, 2 strategies. The total number of simulations was 432 (6 × 4 × 3 × 3 × 2).
- The effect of diameter and grain depth were studied with the following single-level independent variables: one location (Jonesboro), one cultivar (wells), one airflow rate (1.0 cfm bu^{-1} or 1.1 m^3 min^{-1} t^{-1}), and one diameter (36 ft or 11.0 m), and with multi-level independent variables including 6 years of cultivation (replications), 4 bin diameters, 3 grain depths, 3 MCs, 3 harvest dates, and 2 strategies. The total number of simulations was 1296 (6 × 4 × 3 × 3 × 3 × 2).
- The effect of cultivar was studied with the following single-level dependent variables: one location (Jonesboro), one airflow rate (1.0 cfm bu^{-1} or 1.1 m^3 min^{-1} t^{-1}), one grain depth (20 ft or 6.1 m), and one bin diameter (36 ft or 11.0 m), and with multi-level dependent variables including 6 years of cultivation (replications), 3 cultivars locations, 3 MCs, 3 harvest dates, and 2 strategies. The total number of simulations was 324 (6 × 3 × 3 × 3 × 2).
- The effect of location was studied with the following single-level dependent variables: one airflow rate (1.0 cfm bu^{-1} or 1.1 m^3 min^{-1} t^{-1}), one grain depth (20 ft or 6.1 m), and one bin diameter (36 ft or 11.0 m), and with multi-level dependent variables including 6 years of cultivation (replications), 4 locations, 3 cultivars, 3 MCs, 3 harvest dates, and 2 strategies. The total number of simulations was 1296 (6 × 4 × 3 × 3 × 3 × 2).

The initial MC, harvest date, year of cultivation, and drying strategy were studied independently for the airflow rate alone and similarly studied independently for location, rice cultivar, and bin diameter and height. However, the results of the effect of initial MC, harvest date, year of cultivation, and drying strategy are discussed only for the airflow simulations.

RESULTS AND DISCUSSION

EFFECT BIN DIAMETER AND RICE BED DEPTH

Table 3 shows the results of the statistical analyses of the effects of bin diameter and grain depth versus drying strategy on the dependent variables. The p-values of 1 for drying cost, fan operating duration and cost, MC, DML, and drying duration in combination with different bin diameters and drying strategies indicate that there was no significant effect of bin diameter on these dependent variables. The non-significance for fan operating duration, MC, DML, and drying duration was due to the same air velocity established for different bin diameters at the same grain depth. However, there was a significant difference in fan energy consumption for different bin diameters. For a constant grain depth, increasing bin diameter resulted in increased grain holding capacity; therefore, the total airflow requirement increased in order to achieve the same design airflow rate in terms of m^3 min^{-1} t^{-1} (cfm bu^{-1}). Generally, in order to maintain this constant airflow rate for larger diameter bins, an appropriately increased fan size and capacity are selected. For this reason, the total fan energy consumption increased as the bin diameter increased (tables 3 and 4). Similarly, the total drying cost and total fan operating cost increased as the bin diameter increased because of the larger fan size and capacity. However, the drying cost and fan operating costs per bushel were constant for all bin diameters at a constant grain depth (table 4). This is because the airflow resistance of rice (measured in terms of static pressure) at a constant air velocity remained the same. Table 4 shows the mean values of the dependent variables with respect to bin diameter when the drying fan was operated using the controlled and uncontrolled drying strategies. The drying cost and fan operating cost were respectively 1.8 times and 2.6 times less for the controlled strategy as compared to the uncontrolled strategy. Greater fan operating cost with the uncontrolled drying strategy was due to fan operation during both drying and rewetting periods.

From table 3, it was found that the grain depth versus drying strategy combination had significant effects with respect to all dependent variables, such as drying cost, fan operating duration and cost, MC, DML, fan energy consumption, and drying duration. At a constant bin diameter (fixed bin floor area), as the grain depth increases, the air velocity increases with respect to a fixed airflow rate in terms of m^3 min^{-1} t^{-1} (cfm bu^{-1}). Therefore, there was a change in fan operating duration, which was also reflected in the fan operating cost. Similarly, as the grain depth increased, the uniformity of rice drying in different layers in the bin was also affected (table 5), that is, more over-dried rice occurred in the bottom layer, which was reflected in the total drying cost (drying cost includes fan operating cost and over-dried/shrinkage cost).

Table 5 shows the mean values of the dependent variables with respect to grain depth when the drying fan was operated using the controlled and uncontrolled strategies. Drying cost and fan operating cost were respectively 1.7 to 1.8 times and 2.1 to 3.4 times lower for the controlled strategy as compared to the uncontrolled strategy. The greater drying cost for the uncontrolled strategy was due to the low MC achieved (i.e., the average MC was lower than the target MC of 13%), which led to greater over-drying cost as well as greater fan operating duration. This was obvious because the controlled strategy used air EMC suitable for drying, whereas the uncontrolled strategy operated continuously with resultant rewetting and over-drying of the rice. The fan operating duration for the controlled strategy was 2.1 to 3.2 times lower than for the uncontrolled strategy, which was reflected in the fan operating cost. At a constant bin diameter, the fan operating duration decreased as the

Table 3. Significant differences (p-values) for the dependent variables, including total drying cost, fan operating cost, average MC, minimum MC, average DML, maximum DML, fan operating duration, fan energy consumption, and drying duration, and the independent variable drying strategy in combination with grain depth and bin diameter.[a]

Parameters	Total Drying Cost	Fan Operating Cost	Avg. MC	Min. MC	Avg. DML	Max. DML	Fan Operating Duration	Fan Energy	Drying Duration
Bin diameter vs. drying strategy	1	1	1	1	1	1	0.96	<0.01	1
Grain depth vs. drying strategy	<0.01	<0.01	0.05	0.01	<0.01	0.01	<0.01	<0.01	<0.01

[a] Level of significance: $p < 0.5$. MC = moisture content, and DML = dry matter loss

Table 4. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different bin diameters were taken into account.[a]

Drying Strategy	Bin Diameter, m (ft)	Total Drying Cost, \$ $tonne^{-1}$ (c bu^{-1})	Fan Operating Cost, \$ $tonne^{-1}$ (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	7.3 (24)	7.9 (16.0)	4.1 (8.4)	12.3	11.2	0.10	0.15	1349	3777	56
	9.1 (30)	7.9 (16.0)	4.1 (8.4)	12.3	11.2	0.10	0.15	1349	6114	56
	11.0 (36)	7.9 (16.0)	4.1 (8.4)	12.3	11.2	0.10	0.15	1349	8806	56
	12.8 (42)	7.9 (16.0)	4.1 (8.4)	12.3	11.2	0.10	0.15	1349	10909	56
C	7.3 (24)	4.5 (9.1)	1.6 (3.2)	12.5	12.1	0.11	0.18	471	1527	41
	9.1 (30)	4.5 (9.1)	1.6 (3.2)	12.5	12.1	0.11	0.18	471	2412	41
	11.0 (36)	4.5 (9.1)	1.6 (3.2)	12.5	12.1	0.11	0.18	471	3475	41
	12.8 (42)	4.5 (9.1)	1.6 (3.2)	12.5	12.1	0.11	0.18	471	4730	41

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel.

Table 5. Mean values of dependent variables with respect to grain depth when the drying fan was operated using controlled (C) and uncontrolled (UC) drying strategies.[a]

Drying Strategy	Grain Depth, m (ft)	Total Drying Cost, \$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, \$ tonne^{-1} (c bu^{-1})	Avg. MC, % w.b.	Min. MC, % w.b.	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	3.7 (12)	6.2 (12.6)	2.7 (5.6)	12.4	11.2	0.12	0.16	1644	3687	68
	4.9 (16)	8.1 (16.6)	4.5 (9.1)	12.3	11.3	0.11	0.15	1417	7877	58
	6.1 (20)	9.3 (18.9)	5.1 (10.4)	12.2	11	0.08	0.13	985	10637	40
C	3.7 (12)	3.5 (7.1)	0.8 (1.6)	12.5	12.1	0.11	0.19	509	1057	43
	4.9 (16)	4.4 (9.0)	1.5 (3.0)	12.5	12.1	0.11	0.18	472	2659	40
	6.1 (20)	5.5 (11.3)	2.4 (4.9)	12.4	12	0.1	0.17	464	5390	37

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel.

grain depth increased. This was due to the fact that as the grain depth increased for a fixed design airflow rate of 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu^{-1}), the air velocity increased. Because of greater air velocity with greater grain depth, the drying duration was reduced. However, fan energy consumption increased as grain depth increased because of the larger fan size required to achieve greater airflow and because more energy was needed to overcome the airflow resistance of the rice, which increased the drying and fan operating costs. A similar pattern was observed for both drying strategies.

EFFECT OF AIRFLOW RATE

Table 6 shows the mean values of the dependent variables with respect to airflow rate when the drying fan was operated using the controlled and uncontrolled drying strategies. The total drying cost and fan operating cost for the controlled strategy were respectively 1.1 to 1.7 times and 1.1 to 3.0 times lower as compared to the uncontrolled strategy for all four airflow rates (0.6, 1.1, 1.7, and 2.2 m^3 min^{-1} t^{-1}). Similarly, the fan operating duration was 1.1 to 2.9 times lower for the controlled strategy as compared to the uncontrolled strategy. Conversely, there was a longer drying duration for uncontrolled drying with the 0.6 m^3 min^{-1} t^{-1} (0.5 cfm bu^{-1}) and 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu^{-1}) airflow rates. For higher airflow rates, there were shorter drying durations for uncontrolled drying as compared to the controlled strategy. This was due to the higher static pressure developed in the plenum with higher airflow. For example, for a rice bed depth of 6 m (20 ft) and 1.7 m^3 min^{-1} t^{-1} (1.5 cfm bu^{-1}) airflow, the static pressure developed was 3.7 kPa (15 in. of water). Due to this static pressure, a temperature rise of nearly 8°C (15°F) developed. This increase in temperature favored drying instead of rewetting. The increase in temperature also favored over-drying of the bottom layers and increased the over-drying cost. The over-drying cost was included in the total drying cost. The controlled drying strategy had \$2 per tonne less total drying cost as compared to the uncontrolled strategy. For both drying strategies, the total drying cost was lower at lower airflow rates than at higher airflow rates because of less over-drying of the grain in the bottom layers. The controlled drying strategy (with average minimum MC of 12%) was better in terms of reducing over-drying cost as compared to the uncontrolled strategy (average minimum MC of 11%). For modeling purposes, simulations of uncontrolled drying were stopped when the top layer and average of all layers reached the set MC. In actual practice, it would be difficult to stop the fan operation based on the top layer MC and average MC in all layers without installing a moisture cable in the grain mass. Therefore, the costs determined for the uncontrolled strategy might be higher in practice.

EFFECT OF LOCATION

Table 7 shows the mean values of the dependent variables with respect to location when the drying fan was operated using the controlled and uncontrolled drying strategies. On average, the total drying cost and fan operating cost were respectively 1.5 and 1.8 times higher for uncontrolled drying as compared to controlled drying for all locations. Among all locations, Jonesboro had higher drying and fan operating costs for controlled drying, whereas Monticello had higher drying and fan operating costs for uncontrolled drying. West Memphis provided the best NAD of rice in terms of drying cost, fan operating cost, fan operating duration, and drying duration. Among all locations, Jonesboro had the highest over-drying as compared to the other locations in terms of minimum MC.

EFFECT OF HARVEST DATE

Table 8 shows the mean values of the dependent variables with respect to harvest date when the drying fan was operated using the controlled and uncontrolled drying strat-

Table 6. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different airflow rates were taken into account.[a]

Drying Strategy	Airflow, m^3 min^{-1} t^{-1} (cfm bu^{-1})	Total Drying Cost, \$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, \$ tonne^{-1} (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	0.6 (0.5)	6.3 (12.9)	3.3 (6.6)	12.5	11.5	0.21	0.28	2868	8230	119
	1.1 (1.0)	9.3 (18.9)	5.1 (10.4)	12.2	11.0	0.08	0.13	986	13082	41
	1.7 (1.5)	9.7 (19.8)	4.4 (9.0)	11.9	10.8	0.04	0.07	335	11236	13
	2.2 (2.0)	12.3 (25.2)	5.9 (12.0)	11.6	10.6	0.03	0.05	228	14984	9
C	0.6 (0.5)	3.8 (7.8)	1.1 (2.3)	12.6	12.2	0.20	0.33	995	2855	92
	1.1 (1.0)	5.5 (11.2)	2.4 (4.9)	12.4	12.0	0.10	0.17	464	6161	37
	1.7 (1.5)	7.7 (15.7)	3.9 (7.9)	12.3	11.7	0.07	0.12	296	9922	22
	2.2 (2.0)	10.7 (21.8)	5.5 (11.2)	12.0	11.4	0.05	0.08	213	14041	15

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel.

Table 7. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different locations were taken into account.[a]

Drying Strategy	Location	Total Drying Cost, $\$$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, $\$$ tonne^{-1} (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	Jonesboro	8.5 (17.3)	4.4 (8.9)	12.2	11.1	0.08	0.13	840	11142	37
	Monticello	9.0 (18.4)	4.7 (9.7)	12.2	11.3	0.09	0.13	917	12169	38
	Stuttgart	8.2 (16.7)	4.6 (9.4)	12.3	11.5	0.09	0.13	891	11819	37
	West Memphis	7.5 (15.2)	4.1 (8.3)	12.4	11.5	0.08	0.12	782	10382	32
C	Jonesboro	5.9 (12.1)	2.6 (5.3)	12.4	11.8	0.10	0.17	503	6669	36
	Monticello	5.6 (11.4)	2.4 (4.9)	12.4	12.0	0.11	0.19	465	6176	35
	Stuttgart	5.6 (11.4)	2.5 (5.1)	12.4	12.0	0.10	0.18	481	6384	34
	West Memphis	5.5 (11.3)	2.5 (5.0)	12.4	12.0	0.10	0.17	473	6279	35

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel.

Table 8. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different harvest dates were taken into account.[a]

Drying Strategy	Harvest Date	Total Drying Cost, $\$$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, $\$$ tonne^{-1} (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	Aug. 15	9.2 (18.7)	3.7 (7.6)	11.9	10.8	0.09	0.15	765	9575	31
	Sept. 15	9.4 (19.1)	4.1 (8.4)	12.0	10.9	0.09	0.13	953	10512	39
	Oct. 15	9.7 (19.7)	6.1 (12.4)	12.3	11.2	0.10	0.13	1595	15563	66
C	Aug. 15	7.4 (15.1)	3.1 (6.4)	12.2	11.7	0.11	0.19	475	8044	32
	Sept. 15	7.3 (14.3)	3.2 (6.5)	12.3	11.7	0.10	0.17	481	8111	38
	Oct. 15	6.4 (13.0)	3.4 (6.8)	12.5	12.0	0.10	0.17	520	8578	55

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel. Initial MC was 16%, 18%, and 20%; years of cultivation were 2005 to 2010.

egies. Delay in harvest date increased the drying cost, fan operating cost, fan operating duration, and drying duration for both drying strategies. This was due to the higher ambient temperature during the August 15 harvest period; the air had greater water holding capacity, which enhanced the drying potential. However, delay in the harvest date avoided much of the over-drying of the bottom layers. Overall, the controlled drying strategy was good in all respects except DML as compared to the uncontrolled strategy in terms of harvest date. The average maximum DML for all harvest dates with controlled drying was only 0.18%, which was not bad when compared to the limit for one grade reduction, which is typically set at 0.5%. The fan operating duration was respectively 1.6, 2, and 3 times less for August 15, September 15, and October 15 with controlled drying as compared to uncontrolled drying. With uncontrolled drying, the October 15 harvest date required a maximum of 1595 h for drying. This was due to the low ambient temperature and high humidity of the air that prevailed during this period, resulting in low water holding capacity of the air and thus lower drying potential. However, with controlled drying, the October 15 harvest date required only 520 h for drying; this was due to proper selection of air for drying, thereby avoiding rewetting.

EFFECT OF YEAR OF CULTIVATION

Table 9 shows the mean values of the dependent variables with respect to year of cultivation when the drying fan was operated using the controlled and uncontrolled drying strategies. The drying and fan operating costs were respectively 1.2 to 1.6 times and 1 to 2.2 times less for controlled drying as compared to uncontrolled drying during different years of cultivation with 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu^{-1}) airflow. The years 2006, 2008, and 2009 had higher fan operating costs compared to the other years for the uncontrolled drying strategy because they were relatively wetter years.

Table 9. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different years of cultivation were taken into account.[a]

Drying Strategy	Year of Cultivation	Total Drying Cost, $\$$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, $\$$ tonne^{-1} (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	2005	8.0 (16.2)	3.4 (6.9)	12.1	11.3	0.07	0.12	600	8640	25
	2006	8.3 (16.9)	5.7 (11.5)	12.5	11.7	0.10	0.14	1347	14491	56
	2007	9.1 (18.6)	3.6 (7.4)	11.9	10.8	0.08	0.12	878	9306	36
	2008	8.3 (16.9)	4.8 (9.8)	12.3	10.6	0.09	0.13	1196	12232	49
	2009	10.2 (20.7)	7.4 (15.1)	12.6	11.4	0.14	0.19	1984	18931	82
	2010	12.7 (25.9)	3.0 (6.1)	11.0	10.0	0.06	0.10	620	7699	25
C	2005	6.6 (13.5)	3.2 (6.4)	12.4	11.9	0.09	0.15	487	8079	30
	2006	6.1 (12.4)	3.4 (7.0)	12.5	12.2	0.11	0.19	527	8803	48
	2007	7.3 (15.0)	3.1 (6.2)	12.2	11.6	0.09	0.17	467	7810	40
	2008	6.4 (13.0)	3.3 (6.8)	12.5	12.0	0.11	0.18	503	8520	43
	2009	6.2 (12.6)	3.4 (7.0)	12.6	12.2	0.15	0.24	525	8722	61
	2010	8.9 (18.1)	2.9 (6.0)	11.8	11.1	0.07	0.13	444	7534	29

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel. Initial MC was 16%, 18%, and 20%; harvest dates were August 15, September 15, and October 15.

In addition, in these three years, there was low over-drying in the bottom layers. For the years 2007 and 2010, dry weather prevailed during the harvest season, which resulted in significantly higher over-drying in the bottom layers of the bin for the uncontrolled strategy as compared to controlled drying. In 2009, the fan operating duration was 1984 h with uncontrolled drying, whereas it was only 525 h with controlled drying. The 3.8 times higher fan operating duration for uncontrolled drying was due to rewetting of the rice because of the wet weather that prevailed in 2006, 2008, and 2009. This rewetting during high-humidity conditions typically results in rice fissuring, which in turn reduces HRY. In this study, the simulation stopped when the appropriate rice MC was reached. However, in actual uncontrolled drying, without moisture cables installed in the bin, it would be very difficult to determine the set moisture (maximum layer MC and average bin MC) to stop the fan operation. The actual fan operating duration would be always higher than the simulated fan operating duration.

EFFECT OF INITIAL MOISTURE CONTENT

Table 10 shows the mean values of the dependent variables with respect to initial moisture content when the drying fan was operated using the controlled and uncontrolled drying strategies. The total drying cost, fan operating cost, fan operating duration, fan energy consumption, and drying duration increased when the initial moisture content increased for both drying strategies and 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu^{-1}) airflow. For 16% initial MC, the DML values were low, which suggests less or no mold growth. For 18% and 20% initial MC, the maximum DML values were greater than 0.1%, which implies that conditions were more susceptible to mold growth in the top layers. For rough rice at 20% initial MC, the maximum DML was greater than 0.32% with controlled drying, which was within 0.5% DML. Seib et al. (1980) found that rice grade fell below U.S. Grade No. 1 and No. 2 when the DML percentage reached 0.75% when rice was stored at 15% and 18% MC. Based on these DML data and taking into account drying duration, it was found that NAD was effective for rice at up to 20% initial harvest MC using an airflow rate of 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu^{-1}).

EFFECT OF CULTIVAR

Table 11 shows the mean values of the dependent variables with respect to cultivar when the drying fan was operated using the controlled and uncontrolled drying strategies. With uncontrolled drying, the total drying cost, fan operating cost, fan operating duration, and drying duration were greater for medium-grain rice (cv. Jupiter), whereas for the same rice with controlled drying, the total drying cost, fan operating cost, fan operating duration, and drying duration were lower. This is because the drying rate of the medium-grain rice (cv. Jupiter) was higher than that of the long-grain rice (cv. Wells). Ondier et al. (2010) proved that the drying duration for the rice cultivar Jupiter was less than for the rice cultivar Wells. With uncontrolled drying, the medium-grain rice (cv. Jupiter) absorbed more moisture than the long-grain rice (cv. Wells), thereby requiring a longer fan operating duration as well as drying duration. However, with controlled drying, this rewetting period was avoided, resulting in a shorter fan operating duration for Jupiter than for Wells and CL XL 730.

CONCLUSION

The effectiveness of using controlled versus uncontrolled NAD strategies for different cultivars of rough rice was studied for the years 2005-2010. The NAD of rice was modeled using an equilibrium-based model. Process parameters including airflow rate, bin diameter, grain depth, initial grain MC, rice variety, and weather pattern were

Table 10. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different initial moisture contents were taken into account.[a]

Drying Strategy	Initial MC, %	Total Drying Cost, \$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, \$ tonne^{-1} (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	16	8.0 (16.4)	3.5 (7.2)	12.1	10.9	0.05	0.06	899	9334	37
	18	9.3 (18.9)	4.6 (9.4)	12.1	11.0	0.08	0.11	1090	11836	45
	20	10.9 (22.3)	5.8 (11.8)	12.0	11.0	0.14	0.23	1323	14480	55
C	16	6.2 (12.6)	2.6 (5.3)	12.3	11.8	0.05	0.06	393	6759	31
	18	7.1 (14.4)	3.2 (6.5)	12.3	11.7	0.09	0.14	488	8184	40
	20	7.5 (15.3)	3.9 (8.0)	12.4	11.9	0.18	0.32	596	9791	55

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel. Harvest dates were August 15, September 15, and October 15; years of cultivation were 2005 to 2010.

Table 11. Mean values of dependent variables with respect to controlled (C) and uncontrolled (UC) drying strategies when different cultivars were taken into account.[a]

Drying Strategy	Cultivar	Total Drying Cost, \$ tonne^{-1} (c bu^{-1})	Fan Operating Cost, \$ tonne^{-1} (c bu^{-1})	Avg. MC, %	Min. MC, %	Avg. DML, %	Max. DML, %	Fan Operating Duration, h	Fan Energy, kWh	Drying Duration, days
UC	CL XL 730	7.6 (16.0)	4.0 (8.2)	12.3	11.4	0.08	0.13	770	10220	33
	Jupiter	9.0 (18.3)	5.3 (10.7)	12.3	11.3	0.09	0.13	1014	13455	42
	Wells	8.0 (16.4)	4.1 (8.4)	12.2	11.3	0.08	0.13	788	10459	32
C	CL XL 730	5.9 (12.0)	2.6 (5.3)	12.4	11.9	0.10	0.17	502	6663	35
	Jupiter	5.5 (11.2)	2.4 (4.9)	12.4	12.0	0.10	0.18	467	6189	35
	Wells	5.6 (11.4)	2.5 (5.0)	12.4	12.0	0.10	0.18	473	6280	35

[a] MC = moisture content, DML = dry matter loss, and c bu^{-1} = cents per bushel. Initial MC was 16%, 18%, and 20%; harvest dates were August 15, September 15, and October 15; years of cultivation were 2005 to 2010.

considered in the NAD simulations. The following conclusions were made based on the various simulations:

- For a given airflow rate, bin diameter did not have any effect on NAD of rice, whereas grain depth, drying strategy, harvest time, and initial grain moisture content had significant effects.
- Airflow rate had a significant effect on NAD of rough rice. An airflow rate of 1.1 m^3 min^{-1} t^{-1} (1.0 cfm bu bu^{-1}) was found to be optimum with regard to drying cost and DML.
- Harvest date had a significant effect on NAD of rough rice. August 15 and September 15 harvest dates were found to be most suitable for NAD in the studied locations with regard to drying cost and drying duration.
- The controlled drying strategy was found to be the most suitable considering drying cost (which included costs associated with over-drying and DML) and fan operating cost.

ACKNOWLEDGEMENTS

The authors greatly appreciate the support and collaboration from Arnelia Couch, HouMin Zhong, and Dr. Brandon Briggs of the Rice Processing Program, Department of Food Science, University of Arkansas Division of Agriculture.

REFERENCES

ASABE. (2005). D535: Shelled corn storage time for 0.5% dry matter loss. St. Joseph, Mich.: ASABE.

ASABE. (2008). D243.4: Thermal properties of grain and grain products. St. Joseph, Mich.: ASABE.

Bartosik, R. E., & Maier, D. E. (2004). Evaluation of three NA/LT in-bin drying strategies in four corn belt locations. *Trans. ASAE, 47*(4), 1195-1206. http://dx.doi.org/10.13031/2013.16552.

Bartosik, R. E., & Maier, D. E. (2007). Field implementation and model validation of a model-based fan and burner control strategy for the in-bin drying and conditioning of corn. *Applied Eng. Agric., 23*(2), 195-205. http://dx.doi.org/10.13031/2013.22599.

Brooker, D. B., Bakker-Arkema, F. W., & Hall, C. W. (1992). *Drying and Storage of Grains and Oilseeds.* New York, N.Y.: Van Nostrand Reinhold, AVI

Cnossen, A. G., & Siebenmorgen, T. J. (2000). The glass transition temperature concept in rice drying and tempering: Effect on milling quality. *Trans. ASAE, 43*(6), 1661-1667. http://dx.doi.org/10.13031/2013.3066.

Jindal, V. K., & Siebenmorgen, T. J. (1994). Simulation of low-temperature rough rice drying and rewetting in shallow beds. *Trans. ASAE, 37*(3), 863-871. http://dx.doi.org/10.13031/2013.28152.

Mittal, G. S., & Otten, L. (1982). Simulation of low-temperature corn drying. *Canadian Agric. Eng., 24*(2), 111-118.

Ondier, G. O., Siebenmorgen, T. J., & Mauromoustakos, A. (2010). Low-temperature, low-relative humidity drying of rough rice. *J. Food Eng., 100*(3), 545-550. http://dx.doi.org/10.1016/j.jfoodeng.2010.05.004.

Ondier, G. O., Siebenmorgen, T. J., Bautista, R. C., & Mauromoustakos, A. (2011). Equilibrium moisture contents of pureline, hybrid, and parboiled rice. *Trans. ASABE, 54*(3), 1007-1013. http://dx.doi.org/10.13031/2013.37085.

Sahay, M. N., & Gangopadhyay, S. (1985). Effect of wet harvesting on biodeterioration of rice. *Cereal Chem., 62*(2), 80-83.

Saksena, V., Montross, M. D., & Maier, D. E. (1998). NA/LT drying strategies for white corn in two Corn Belt locations. ASAE Paper No. 986049. St. Joseph, Mich.: ASAE.

Schluterman, G., & Siebenmorgen, T. J. (2004). Air and rice property profiles within a commercial cross-flow dryer. *Appl. Eng. Agric., 20*(4), 487-494. http://dx.doi.org/10.13031/2013.16479.

Seib, P. A., Pfost, H. B., Sukabdi, A., Rao, V. G., & Burroughs, R. (1980). Spoilage of rough rice measured by evolution of carbon dioxide. In *Proc. 3rd Annual Workshop on Grains Post-harvest Technology* (pp. 75-94). Kuala Lumpur, Malaysia: Southeast Asia Cooperative Post-Harvest Research and Development Program.

Sharma, S. C., & Muir, W. E. (1974). Simulation of heat and mass transfer during ventilation of wheat and rapeseed bulks. *Canadian Agric. Eng., 16*(1), 41-44.

Siebenmorgen, T. J., & Jindal, V. K. (1986). Effects of moisture adsorption on the head rice yields of long-grain rough rice. *Trans. ASAE, 29*(6), 1767-1771. http://dx.doi.org/10.13031/2013.30386.

Soponronnarit, S. (1988). Energy model of grain drying system. *ASEAN J. Sci. Tech. Devel., 5*(2), 43-68.

Thompson, T. L. (1972). Temporary storage of high-moisture shelled corn using continuous aeration. *Trans. ASAE, 15*(2), 333-337. http://dx.doi.org/10.13031/2013.37900.

Tirawanichakul, Y., Prachayawarakorn, S., Tungtrakul, P., Chaiwatpongskorn, W., & Soponronnarit, S. (2003). Experiments on in-store paddy drying under tropical climate: Simulation and product quality. *Drying Tech., 21*(6), 1049-1064. http://dx.doi.org/10.1081/DRT-120021873.

USDA. (2010). *United States Standards for Rice.* Washington, D.C.: USDA Grain Inspection, Packers and Stockyards Administration.

NOMENCLATURE

c_a = specific heat of dry air (J kg^{-1} K^{-1})

c_g = specific heat of grain (J kg^{-1} K^{-1})

c_v = specific heat of water vapor (J kg^{-1} K^{-1})

c_w = specific heat of water (J kg^{-1} K^{-1})

dmf = dry matter fraction

dx = layer thickness (m)

G_o = initial grain temperature (°C)

H_f = absolute humidity of air leaving the control volume (kg water kg^{-1} dry air)

H_o = absolute humidity of air entering the control volume (kg water kg^{-1} dry air)

h_v = latent heat of vaporization (J kg^{-1})

M_f = final moisture content of grain (% w.b.)

M_o = initial moisture content of grain (% w.b.)

R = grain dry matter to dry air mass ratio (kg^{-1} grain kg^{-1} dry air)

t = time (s)

T_f = final air and grain temperature (°C)

T_o = initial air temperature (°C)

v_a = velocity of air (m s^{-1})

ρ_a = density of air (kg m^{-3})

ρ_g = density of grain (kg m^{-3})