Measuring the Energy Required to Dry Rice in Commercial Rice Dryers

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MEASURING THE ENERGY REQUIREMENTS TO DRY RICE IN COMMERCIAL RICE DRYERS
MEASURING THE ENERGY REQUIRED TO DRY RICE IN COMMERCIAL RICE DRYERS

A dissertation submitted in partial fulfillment
of the requirements of the degree of
Doctor of Philosophy in Food Science

By

Maria Alejandra Billiris
University of the Republic
Bachelor in Food Engineering, 2007

May 2013
University of Arkansas
ABSTRACT

The objective of this research was to quantify and assess the energy use and efficiency of commercial cross-flow dryers when drying rice using a range of drying and ambient conditions. First, equations that predict the theoretical energy required to dry rice from any given initial moisture content to a desired final moisture content were developed for several rice cultivars using a semi-theoretical approach to obtain a basis for comparison to calculate energy efficiency. Theoretical energy requirements, expressed as the energy required per unit mass of water removed, increased exponentially as initial moisture content decreased. Additionally, medium-grains required more energy to be dried than long-grains; non-parboiled rice required more energy to be dried than parboiled rice. Second, a two-year study was performed to measure energy requirements of both an on-farm, cross-flow dryer and a commercial, cross-flow dryer. In 2011 for the on-farm dryer, energy requirements ranged from 2,840 to 5,310 kJ/kg water removed and in 2012 from 3,730 to 5,840 kJ/kg water removed. Energy efficiencies, which were calculated as the ratio of theoretical energy requirements to the measured energy requirements, ranged from 47 to 90% in 2011 and from 44 to 69% in 2012. Thermal energy requirements of the commercial dryer ranged from 6,900 to 9,670 kJ/kg water removed in 2011 and from 8,800 to 9,620 in 2012. Electrical energy use, which ranged from 300 to 400 kJ/kg water removed in 2011 and from 410 to 630 in 2012. Energy efficiency ranged from 26 to 36% in 2011 and from 27 to 29% in 2012. It was found for both dryers that thermal energy requirements were linearly correlated to the difference between drying air temperature and ambient temperature and linearly and inversely correlated to the amount of water removed per mass dry matter. Equations were developed to predict energy use and efficiency as a function of these two parameters.
This dissertation is approved for recommendation to the Graduate Council.

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DISSERTATION DUPLICATION RELEASE

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ACKNOWLEDGMENTS

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- My advisor, Dr. Terry Siebenmorgen, and my graduate committee members, Dr. Andronikos Mauromoustakos, Dr. Ruben Morawicki, Dr. Lanier Nalley and Dr. Darin Nutter for their guidance through my Doctoral Program.

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M. A. Billiris and T. J. Siebenmorgen. 2013. Energy use and efficiency of rice-drying systems. II. Commercial dryer measurements. To be submitted. (Chapter 3)
I. INTRODUCTION

The rice (*Oryza sativa*) industry is one of the most important agricultural industries in the world, since rice is a staple food for the majority of the human population (Roy et al., 2009). Rice production has increased 3.6 fold from the year 1960 to 2012 (USDA, 2013). World grain production, of rice, wheat and corn in 2011 equaled 2,033 mmt (USDA, 2012). World rough rice production, which equaled 464 mmt in 2011, accounted for almost 23% of the 2,033 mmt of grain that is produced globally (USDA, 2012). Therefore, the rice industry would be expected to account for a significant amount of the energy used for processing of crops. Verma (1994) stated that the United States consumes 15 million barrels of crude oil per year for drying grains, making grain drying a major energy-consuming operation. Kasmaprapruet et al. (2009) reported that drying was the unit operation that required the most energy for rice processing, accounting for 55% of the total energy consumed for production and processing of rice. Drying was followed by the operations of harvesting (15%), cultivation (10%), seeding (10%), transportation (6%), and milling (4%). Because of the prominence of rice as a world crop, it is worthwhile to assess and improve energy use for rice drying.

Energy use to dry grains has been reported to vary considerably depending on drying and grain conditions (Otten et al., 1980). Factors such as type and variety of grain, drying air temperature (T), relative humidity and airflow rate affect the drying rate (Cnossen et al., 2002; Henderson & Pabis, 1961; Iguaz et al., 2003; Simmonds et al., 1953). Drying rate affects the duration required to dry the rice to the desired moisture content (MC) and thus, all these factors affect the energy use of the drying process. Moisture content of the grain affects the net heat of sorption of water in foodstuffs, which is the difference between the heat required to remove water from the grain and the latent heat of vaporization of pure water (Aviara et al., 2004;
Cenkowski et al., 1992; Mulet et al., 1999; Toğrul & Arslan, 2006); thus, the initial MC (MC$_i$) as well as the final MC (MC$_f$) affect energy use. Therefore, it is relevant to assess the effects of these factors on energy use in order to recommend drying practices that lead to energy savings.

High-T drying is beneficial to the industry because drying durations are shorter than those of low-T drying and thus, drier capacity is increased. Currently, the U.S. rice industry dries rice in cross-flow dryers using high Ts. To minimize fissuring and potential breakage of rice kernels, rice is usually passed several times through dryers removing limited percentage points of moisture in each pass. Rice is tempered between passes to allow moisture gradients developed inside rice kernels during drying to subside. High drying air Ts ranging from 55 to 70°C are often used for early passes and lesser drying air Ts ranging from 20 to 40°C are used for later passes. High-T drying may require greater amounts of energy than low-T drying, depending on the drying conditions and type of dryer. Therefore, it is crucial to optimize high-T drying energy use to reduce energy consumption, drying costs, and drying duration.

Since drying is known to be such an energy-intensive unit operation (Kasmaprapruet et al., 2009; Thakur & Gupta, 2006; Verma, 1994), the purpose of this work was to assess the energy use and efficiency of two typical commercial dryers. The primary focus of this dissertation was to quantify the energy use and efficiency of commercial cross-flow dryers when drying rice using a range of drying and ambient air conditions. A second focus was to assess the effect of several factors such as drying air T, ambient air T and rice MC on energy use and efficiency of the drying process in order to provide information regarding practices that lead to improve energy efficiency. The specific objectives of this dissertation were:

1. Determine theoretical energy requirements for drying rice as a function of rice MC and T.

The purpose was to obtain a baseline to use as a basis of comparison to compare with
actual energy requirements. The actual energy required for a specific dryer to remove a unit mass of water when drying from an $MC_i$ to an $MC_f$ can be compared to this ideal amount of energy and therefore, its drying performance can be calculated.

2. Measure the energy use of an on-farm cross-flow dryer operating under different drying conditions relative to the amount of drying performed, i.e. the MC reduction of a given mass of rice. This provides relevant information regarding energy requirements to dry rice that could be used as inputs for rice life cycle analyses. Additionally, quantifying actual energy use, relative to the theoretical situation, will provide estimates of the energy that can be saved depending on the drying condition.

3. Determine the energy use and efficiency of a commercial cross-flow dryer using a range of drying and ambient air conditions. This work provides relevant information regarding the energy use and efficiency of the most commonly used type of dryer by the U.S. rice industry and therefore the energy values reported will be good estimates of current energy consumption for rice drying.
LITERATURE CITED


II. CHAPTER ONE
Estimating the theoretical energy required to dry rice

ABSTRACT

The total heat of desorption of rice ($Q_t$) was determined for several rice types as a function of moisture content (MC), and kernel temperature, using a semi-theoretical approach in which desorption isotherms were used in conjunction with the Clausius-Clapeyron equation. $Q_t$ decreased exponentially as MC increased, decreasing sharply for MCs above 15% and approaching the latent heat of vaporization of free water at MCs around 20%. $Q_t$ of parboiled rice at 12.5% MC was significantly less than that of non-parboiled lots. $Q_t$ of medium-grain Jupiter was significantly greater than that of long-grains at 12.5% MC. Equations that predict the energy required to dry a unit mass of rice from an initial MC to a final MC were derived.

INTRODUCTION

In order to maximize field yield and quality, rice is typically harvested at MCs greater than the level deemed safe for long-term storage, which is often taken to be around 13% (Howell & Cogburn, 2004). To preserve its quality, rice should be thus dried to this safe level (Siebenmorgen & Meullenet, 2004).

Verma (1994) stated that the United States consumes 15 million barrels of crude oil per year for drying grains, making grain drying operations a major source of energy consumption. Kasmaprapruet et al. (2009) reported that drying was the most energy-consumptive unit operation in rice processing, accounting for 55% of the total energy consumed for production and processing of rice.

The energy required to dry grains under ideal conditions varies from 2,500 to 2,670 kJ/kg water depending on the drying temperature (T) (Fluck & Baird, 1980). However, Gunasekaran &
Thompson (1986) stated that drying of crops actually requires from 3,000 to 8,000 kJ/kg water. Therefore, the efficiency of a drying process depends on how drying is performed. Considering the ongoing interest in reducing energy requirements and the importance of the rice crop in the United States and globally, it is timely to investigate means of improving rice drying efficiency.

The first step in quantifying the performance of a rice drying process is to calculate the theoretical energy required to remove water from rice. The energy required for drying foodstuffs mainly comprises the thermal energy required to remove water from the food material; the mechanical energy required for conveyance or airflow is less significant. Depending on the initial MC ($MC_i$) of the material and the desired final MC level ($MC_f$), the removal of water from foodstuffs may require more energy than that required to vaporize free water (latent heat of vaporization, $h_{fg}$) (Okos et al., 1992; Rizvi, 2005). Cenkowski et al. (1992) explained that when the MC of a material is below 12% dry basis (d.b.), the increase in intra-particle resistance to moisture migration increases the energy required to remove water. Okos et al. (1992) stated that the energy required to remove water from foods increases as the binding-force between water and the food increases. Rizvi (2005) indicated that, in general, the energy requirement for drying food materials has two main components: the energy required to evaporate free water and the energy required to remove water that is associated with the food matrix.

The entire amount of energy required to remove water from a food material has been referred to as the isosteric heat of sorption (Iglesias & Chirife, 1976), the heat of sorption (Tsami et al., 1990) and the isosteric heat of desorption (Kechaou & Maalej, 1999). Herein, this quantity will be referred to as the total heat of desorption ($Q_T$). The difference between $Q_T$ and $h_{fg}$, which has been referred to as the net isosteric heat of sorption (Iglesias & Chirife, 1976; Tsami et al., 1990), will be called the net heat of desorption ($Q_n$). Aviara et al. (2004), Kechaou & Maalej
(1999) and McMinn & Magee (2003) indicated that $Q_n$ represents the energy beyond $h_{fg}$ required to remove a unit mass of water from a foodstuff due to water-solid bonds. The strength of water-solid bonds in foodstuffs varies with MC, generally increasing as MC decreases (Okos et al., 1992). Consequently, $Q_n$ would be expected to increase as drying progresses. Researchers have confirmed this expectation (Aviara et al., 2004; Cenkowski et al., 1992; Mulet et al., 1999; Toğrul & Arslan, 2006; Tsami et al., 1990; Zuritz & Singh, 1985). Cenkowski et al. (1992) found that the energy required to remove water from grain is close to $h_{fg}$ for MCs above 20% (d.b.). However, Johnson & Dale (1954) reported that energy requirements to remove water from wheat and shelled corn at MCs above 14% (d.b.) are close to $h_{fg}$.

Since $Q_n$ is the theoretical minimum energy above $h_{fg}$ required to remove a unit mass of water from a particular food (Rizvi, 2005), it is important to establish the relationship between $Q_n$ and MC in order to quantify the theoretical energy requirements for drying rice. In addition, it is possible that the relationship between $Q_n$ and MC changes depending on kernel properties, including kernel temperature (Truong et al., 2005). Therefore, it is also relevant to investigate energy requirements of different rice types, cultivars and T levels. Thus, $Q_t$ should be determined as a function of MC and T for a given rice type/cultivar. Actual energy requirements for a specific dryer can be compared to this ideal situation, and thus efficiencies for different commercial dryers can be calculated.

Little research has assessed theoretical energy requirements for drying rice, particularly for different rice types and current cultivars. Iguaz and Vírseda (2007) estimated $Q_n$ values at different MC levels for medium-grain rough rice; Toğrul and Arslan (2006) and Zuritz and Singh (1985) estimated $Q_t$ values at different MC levels for long-grain and medium-grain rough rice, respectively. Researchers have used the Clausius-Clapeyron equation, in combination with

The fact that sorption isotherms of foodstuffs demonstrate hysteresis is an indication of irreversibility, which has posed doubts on the reliability of the Clausius-Clapeyron equation for determining $Q_h$ and $Q_t$ (Iglesias & Chirife, 1976; McLaughlin & Magee, 1998). However, Iglesias & Chirife (1976), after analyzing works performed by other researchers who compared the Clausius-Clapeyron approach to calorimetric heats, concluded that the heats of irreversible processes are small enough to be neglected when calculating energy requirements for drying foodstuffs. Mulet et al. (1999) obtained good agreement between calorimetric heat measurements using a thermogravimetric analyzer (TGA) in combination with a differential scanning calorimeter (DSC) and those obtained from the Clausius-Clapeyron method for potato starch and cauliflower. Consequently, the application of the Clausius-Clapeyron method was deemed appropriate for estimating energy requirements for drying rice.

The objectives of this study were: 1) to calculate $Q_h$ and $Q_t$ values at various MCs and Ts for different types of rice using equilibrium moisture content (EMC) data and the Clausius-Clapeyron equation; 2) to mathematically model $Q_t$ as a function of MC and T for the rice types under study; 3) to develop an equation that predicts the theoretical energy required to dry rice from varying $MC_i$ to a desired $MC_f$. 
MATERIALS AND METHODS

Sorption isotherms

EMC data were obtained from two previous studies. Elevated-temperature desorption isotherms (60, 70, 80 and 90°C) for long-grain Cybonnett rough rice were obtained from Ondier et al. (2010a). In addition, rough rice sorption isotherms at low temperatures (10, 20, 30, 45 and 60°C) for long-grains Wells and CL XL730, medium-grain Jupiter and a long-grain parboiled rice of unknown cultivar were obtained from Ondier et al. (2010b). The data from both studies were used to calculate $Q_t$ and $Q_n$ at selected MCs and Ts.

Heat of desorption calculation

$Q_t$ was calculated using the form of the Clausius-Clapeyron equation developed by Othmer (1940):

$$\ln(p_v) = \left(\frac{Q_t}{h_{fg}}\right)\ln(p_s) + c$$  \hspace{1cm} (1)

where: $p_v$ is water vapor pressure in the rice kernel associated with a particular $T$, $p_s$ is vapor pressure of pure water associated with a particular $T$, $Q_t$ is the total heat of desorption (kJ/kg water), $h_{fg}$ is the latent heat of vaporization of pure water at a given $T$ (kJ/kg water), $c$ is an integration constant.

$Q_t/h_{fg}$ was calculated from the slope of the regression line relating $\ln(p_v)$ to $\ln(p_s)$ at different $Ts$ for a specific MC; the slope of the line equals $Q_t/h_{fg}$ for a specific MC. The $p_v$ values were calculated from ERH data using the following relationship:

$$ERH = \frac{p_v}{p_s}$$  \hspace{1cm} (2)
ERH is equilibrium relative humidity in a decimal form.

It is critical to select an appropriate equation to predict ERH using T and MC as inputs in order to calculate $Q_t$. Research indicates that the modified Chung-Pfost equation (Chung & Pfost, 1967; Pfost et al., 1976) best describes rice isotherm data (Basunia & Abe, 1999; Ondier et al., 2010b):

$$\text{ERH} = \exp\left[-\frac{A}{T+C}\exp(-B \cdot MC)\right]$$

(3)

where, $A$, $B$ and $C$ are constants, MC is expressed in a d.b. decimal form, $T$ is temperature (°C) and ERH is equilibrium relative humidity expressed in a decimal form. The values of the constants $A$, $B$ and $C$ were obtained from Ondier et al. (2010a) and Ondier et al. (2010b), depending on the temperature range and cultivar. Zuritz & Singh (1985) reported that among the isotherm equations at that time, only the Chung-Pfost equation was appropriate for heat of desorption calculations, because it was the only equation in compliance with the necessary mathematical restriction that the heat of desorption decreases with an increase in temperature. Thus, $p_v$ values were calculated using Eq. (2) and (3) and $p_s$ values from the psychometric relationships in ASAE (1998).

Linear regressions of $\ln (p_v)$ vs. $\ln (p_s)$ were developed for selected MCs. $Q_t/h_{fg}$ was estimated from the slope of each curve for a given MC. The ratio $Q_t/h_{fg}$ was assumed to be constant in the temperature range over which the data were collected. Thus, $Q_t$ for a given MC and $T$ combination was calculated using a consistent $Q_t/h_{fg}$ ratio for a given MC level: however, to account for varying $T$ levels, $h_{fg}$ was varied to correspond to the desired $T$ level using Perry & Chilton (1973). The net heat of desorption $Q_n$ was then calculated using Eq. (4).

$$Q_t = Q_n + h_{fg}$$

(4)
Heat of desorption prediction

In order to mathematically express $Q_t$ as a function of MC and T for the different types of rice, $Q_t$, MC and T data were used to statistically determine the constants of the relationship used by Truong et al. (2005):

$$Q_t = A_1 + B_1 \cdot T +(A_2 + B_2 \cdot T) \exp (-A_3 \cdot MC)$$  \hspace{1cm} (5)

where, $A_1$, $A_2$, $A_3$, $B_1$ and $B_2$ are constants of the equation estimated iteratively by fitting the non-linear model. $Q_t$ is in J/kg water, MC is in dry basis, decimal and T is in °K.

Truong et al. (2005) successfully used this model to describe $Q_t$ data for a mixture of maltodextrin-sucrose. Non-linear least squares regression analyses were performed on the data to obtain the constants for Eq. (5). Root mean square error (RMSE) and standard error of the coefficients (SE) were used to assess the fit and precision of the estimates.

2.4. Energy requirements per unit mass of rice and per unit mass of water removed

$Q_t$ data was used to develop an equation that predicts the theoretical energy required per unit mass dry matter of rice ($Q_{Trice}$) to dry rice from a given MC$_i$ to a MC$_f$ when drying at a given T, similar in approach to Tsami et al. (1990). To calculate $Q_{Trice}$, an integration of Eq. (5) was performed:

$$Q_{Trice} = \int_{MC_i}^{MC_f} Q_t \, dMC$$  \hspace{1cm} (6)

where, $Q_{Trice}$ is the energy required to dry rice from MC$_i$ to MC$_f$ per unit dry mass of rice at a given T. Thus, T was considered constant throughout the integration.

Substituting Eq. (5) into Eq. (6) and integrating:

$$Q_{Trice} = \int_{MC_i}^{MC_f} (A_1 + B_1 \cdot T +(A_2 + B_2 \cdot T) \exp (-A_3 \cdot MC)) \, dMC =$$  \hspace{1cm} (7)
By using Eq. (7), expressions for each type of rice were obtained, whereby energy requirements for drying a unit mass of rice dry matter were obtained for given MC_i, MC_f and T inputs. The value of Q_{Trice} (J/kg dry matter rice) is negative but the absolute value was reported.

To express the energy requirements to dry rice from an MC_i to an MC_f on a per unit mass of water removed basis, Q_{Trice} from Eq. (7) was divided by Δm_{evap} the mass of water removed in the drying process per unit rice dry matter, which can be expressed as:

\[ Δm_{evap} = MC_i - MC_f \]  

(8)

It is emphasized that Q_{Trice} can thus be expressed as drying energy required per unit mass of rice dry matter, Eq. (7), or energy per unit mass of water removed by dividing Eq. (7) by Δm_{evap} (Eq.8).

All statistical analyses were performed using JMP 8.0.1 software (SAS Institute, Inc.).

RESULTS AND DISCUSSION

Table 1 shows the predicted ERH values, at temperatures ranging from 60 to 90°C, calculated from Eq. (3), for selected MCs for long-grain Cybonnett rough rice (Ondier et al., 2010a). For each MC value, linear regressions of ln (p_v) vs. ln (p_s) were performed using Eq. (1); Fig. 1 shows the corresponding linear regressions obtained for the MC levels of 8, 10, 12 and 18%. Q_t was calculated from the slope of each line. The same procedure was used for estimating Q_t when using EMC data collected at Ts ranging from 10 to 60°C for the four lots listed previously (data not shown). Q_n was calculated through Eq. (4). The slope of the ln (p_v) vs. ln (p_s) line approaches unity as MC increases (Fig. 1). Consequently, Q_t approaches h_{fg} as MC increases. This can also be interpreted to indicate that the energy required to dry rice, in terms of energy per unit moisture removed, increases as drying progresses. The same trends were
observed for all rice types. Values of $Q_n$ for long-grain Cybonnett at 60°C are tallied in Table 2. The standard error of $Q_n$ is equal to the SE of $Q_T$ because the difference between these two values is a constant ($h_{fg}$). Iguaz & Vírseda (2007) reported for medium-grain rough rice, $Q_n$ values from 139 to 1,021 kJ/kg water for MCs ranging from 19 to 0.04 % and Ts from 40 to 80°C. The $Q_n$ values obtained in this study are greater than those of Iguaz & Vírseda (2007) at low MCs and are lower than those of Iguaz & Vírseda (2007) at high MCs.
Table 1: Equilibrium relative humidities (%) of long-grain Cybonnett rough rice at the indicated moisture contents and temperatures calculated using the Modified Chung-Pfost equation (Ondier et al., 2010a).

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Moisture content, % w.b.</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>8</td>
</tr>
<tr>
<td>70</td>
<td>26</td>
</tr>
<tr>
<td>80</td>
<td>37</td>
</tr>
<tr>
<td>90</td>
<td>46</td>
</tr>
</tbody>
</table>
Table 2. Net heat of desorption ($Q_n$), total heats of desorption ($Q_T$) and standard errors (SE) of $Q_n$ and $Q_T$, calculated from linear regressions using the Clausius-Clapeyron equation at the selected moisture content levels for long-grain Cybonnett rough rice at 60°C. The value of $h_{fg}$ was 2,359 kJ/kg water.

<table>
<thead>
<tr>
<th>Moisture content, %w.b.</th>
<th>$Q_n$, kJ/kg water</th>
<th>$Q_T$, kJ/kg water</th>
<th>SE, kJ/kg water</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1,381</td>
<td>3,741</td>
<td>166</td>
</tr>
<tr>
<td>10</td>
<td>743</td>
<td>3,102</td>
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<td>12</td>
<td>359</td>
<td>2,718</td>
<td>57</td>
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<td>14</td>
<td>180</td>
<td>2,539</td>
<td>29</td>
</tr>
<tr>
<td>16</td>
<td>81</td>
<td>2,440</td>
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<td>10</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>2,359</td>
<td>0</td>
</tr>
</tbody>
</table>
Fig. 1. Natural logarithm of water vapor pressure in the rice kernel versus the natural logarithm of vapor pressure of pure water, for long-grain Cybonnett rough rice at four moisture content levels (w.b.) and temperatures ranging from 60 to 90°C. The slope of each moisture content level regression line equals the total heat of desorption/latent heat of evaporation of pure water \((Q_t/h_{fg})\) quotient, per Eq. (1).
Total heat of desorption prediction

Heats of desorption obtained from Eq. (1), along with corresponding MCs and Ts, were used to determine the parameters of Eq. (5) for each type of rice. Because of great differences among the SEs of Q_t across MCs (Table 2), non-linear regressions were performed using the weighting feature of JMP (SAS Institute, Inc.), in which the SEs were weighted by using the reciprocal of SE (1/SE). RMSE and equation constants obtained for Eq. (5) are shown in Table 3. Eq. (5) describes the experimental data well based on the low RMSE values for every rice type (Table 3). Additionally, the model consistently converged with little iteration to the estimates of the parameters, which is an indication of goodness of fit. When Iguaz & Vírseda (2007) modeled heat of desorption data, using the modified Guggenheim Anderson De Boer (GAB) isotherm equation (Anderson, 1946; De Boer, 1953; Guggenheim, 1966; Jayas & Mazza, 1993) to predict ERH, they found that the Kechaou and Maalej model (Kechaou & Maalej, 1999) was appropriate in describing Q_n vs. MC data. Heat of desorption data for rice reported by Zuritz & Singh (1985), who used the Chung-Pfost equation to predict ERH, showed an exponential trend (Fig. 2), which is in agreement with the results obtained in this study. However, it is noted that Zuritz & Singh (1985) did not test any model to describe heat of desorption vs. MC. Discrepancies in findings can be explained by Souza et al. (2006), in that regardless of the crop, Q_n, and thus Q_t, behavior varies, depending on the equation that is used to predict ERH from sorption isotherm data. Rice was among the crops studied by Souza et al. (2006) who observed that when the modified Chung-Pfost equation was used to predict ERH, the heat of desorption curve followed an exponential trend. In the case of other ERH equations, such as the modified Henderson equation (Thompson et al., 1968), the Q_n curve was linear.
Table 3. Estimated constants of Eq. 5 and associated root mean square errors (RMSEs) for long-grains Wells, CL XL730 and Cybonnett, medium-grain Jupiter, parboiled rice and for a general model describing all non-parboiled, long-grain rice cultivars.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Parameter A₁</th>
<th>Parameter A₂</th>
<th>Parameter A₃</th>
<th>Parameter B₁</th>
<th>Parameter B₂</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>3,150,878</td>
<td>12,725,771</td>
<td>23.2</td>
<td>-2,377</td>
<td>-9,601</td>
<td>0.22</td>
</tr>
<tr>
<td>Wells</td>
<td>3,150,927</td>
<td>11,509,211</td>
<td>23.4</td>
<td>-2,377</td>
<td>-8,683</td>
<td>0.23</td>
</tr>
<tr>
<td>Cybonnett</td>
<td>3,200,035</td>
<td>19,950,786</td>
<td>27.1</td>
<td>-2,521</td>
<td>-15,719</td>
<td>1.15</td>
</tr>
<tr>
<td>CL XL730</td>
<td>3,150,916</td>
<td>10,117,409</td>
<td>22.7</td>
<td>-2,377</td>
<td>-7,632</td>
<td>0.23</td>
</tr>
<tr>
<td>General</td>
<td>3,189,745</td>
<td>9,742,417</td>
<td>24.2</td>
<td>-2,496</td>
<td>------</td>
<td>4.0</td>
</tr>
<tr>
<td>Parboiled</td>
<td>3,151,394</td>
<td>8,107,920</td>
<td>23.0</td>
<td>-2,377</td>
<td>-6,117</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Fig. 2. Total heat of desorption ($Q_d$) at different moisture content levels for medium-grain Jupiter, at 45°C and those reported for a medium-grain rice at 40°C by Zuritz & Singh (1985).
To assess differences in drying energy requirements among rice cultivars, a final, target MC of 12.5% was chosen based on the fact that 12.5% is a typical, desired final MC in the rice industry. Since $Q_t$ increases as MC decreases, $Q_t$ is greatest at the end of drying and consequently it was relevant to evaluate if the differences in energy requirements among rice types were significant at this MC level. In addition, a $T$ of 60°C was selected to compare energy requirements among rice cultivars.

Table 4 shows $Q_t$ values predicted using Eq. (5), and the 95% confidence intervals (CIs) obtained for each predicted $Q_t$ value for the different rice types. The $Q_t$ predicted for medium-grain Jupiter was significantly greater than the other rice types since the CI of Jupiter does not overlap with the other CIs; thus, the energy required to remove a unit mass of water from medium-grain rough rice with 12.5% MC at 60°C is estimated to be significantly greater than that required for the other rice types (Table 4). Long-grain parboiled rice required significantly less energy to remove a unit mass of water from rough rice with 12.5% MC at 60°C than that required for non-parboiled rice. The $Q_t$ CIs of long-grains Wells and Cybonnett do overlap. This indicated that the difference in $Q_t$ between these two cultivars at 12.5% MC and 60°C was not necessarily significant. While $Q_t$ values for long-grain CLXL 730 were significantly lower than those of long-grains Wells and Cybonnet, the general level was similar among long-grains.

As the differences in $Q_t$ between Wells and Cybonnett were not significant and as $Q_t$ of CL XL730 was similar to those of Wells and Cybonnett, one general model for long-grain, non-parboiled rice was developed. The predicted range of $Q_t$ for general, long-grain cultivars at 12.5% MC and 60°C is shown in Table 4, while the RMSE for this general model is shown in Table 3.
It is noted that the term $B_2$ was not significant when fitting the general model. A possible explanation for this could be that the effect of cultivar on $Q_t$ was greater than that of $T$ in affecting the exponential term of Eq. 5. Therefore, when considering all the cultivars separately, the $B_2$ coefficient was significant but when all long-grain cultivars were used to develop the general model, the $B_2$ coefficient was not significant.
Table 4. Predicted values and confidence intervals for the total heat of desorption ($Q_t$) as obtained from Eq. (5) at 12.5% moisture content and 60°C and for the rice types indicated.

<table>
<thead>
<tr>
<th>Rice type</th>
<th>$Q_t$, kJ/kg water</th>
<th>95% Confidence interval, kJ/kg water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-grain Jupiter</td>
<td>2,705</td>
<td>2,704-2,707</td>
</tr>
<tr>
<td>Long-grain Wells</td>
<td>2,665</td>
<td>2,664-2,666</td>
</tr>
<tr>
<td>Long-grain Cybonnett</td>
<td>2,665</td>
<td>2,659-2,672</td>
</tr>
<tr>
<td>Long-grain CL XL730</td>
<td>2,656</td>
<td>2,655-2,657</td>
</tr>
<tr>
<td>Long-grain non-parboiled (General)</td>
<td>2,669</td>
<td>2,656-2,671</td>
</tr>
<tr>
<td>Long-grain parboiled</td>
<td>2,590</td>
<td>2,587-2,593</td>
</tr>
</tbody>
</table>
Total heat of desorption results

The values of $Q_t$ and their corresponding SE for long-grain Cybonnett are shown in Table 2. The total heat of desorption increases exponentially as MC decreases for all rice types (Fig. 3). There was a sharp increase in $Q_t$ for MCs below 15% and $Q_T$ approached $h_{fg}$ at MCs around 20%. The increase in $Q_t$ as MC decreases indicates that water is increasingly bound to the rice matrix as MC decreases. This is of interest to the rice industry as rice is dried within the range in which $Q_t$ increases considerably. $Q_t$ varied for long-grain Wells from 2,371 to 3,488, for long-grain CL XL730 from 2,371 to 3,413, for medium-grain Jupiter from 2,372 to 3,624 and for parboiled rice from 2,368 to 3194 kJ/kg water, for MCs from 8 to 22% at 60°C. Zuritz & Singh (1985) reported $Q_T$ values for medium-grain rough rice from 2,438 to 4,015 kJ/kg water, for MCs from 4.8 to 23%, at 40°C.

Based on the trends shown in Fig. 3, parboiled rice requires less energy to be dried than non-parboiled rice lots at MCs below 15%. A possible explanation for this would be that during the parboiling process, part of the hull typically cracks, reducing the resistance to moisture transfer. Another possibility is that since starch gelatinizes during the parboiling process, the change in starch structure could increase the diffusivity of the endosperm, producing less resistance to moisture flow.

Fig. 3 also shows the general effect of kernel dimensions and shape on the energy requirements to dry rice. Boyce (1965) referred to an unspecified study stating that kernels with similar dimensions would have similar energy requirements. Fig. 3 shows that the energy requirements for long-grain, pureline Wells and for long-grain, hybrid CLXL730 are equivalent, reinforcing the Boyce (1965) statement. Nevertheless, more cultivars should be studied to confirm this hypothesis.
Another observation regarding kernel dimensions is shown in Fig. 3 in that the energy requirements for drying the medium-grain cultivar are slightly greater than that of the long-grains for MCs below 15%. Since medium-grain kernels are thicker, wider and shorter than long-grains, moisture has to migrate through a longer pathway, producing an internal resistance that is greater in medium-grain than long-grain rice. Therefore, the energy required to remove water from medium-grain rice would be expected to be greater than that of long-grain rice. Cnossen et al. (2002) found that the effect of drying air conditions on the drying rate of a medium-grain cultivar was less significant than for a long-grain, presumably due to the fact that internal resistance to moisture transport is greater in the first case. The $Q_t$-results obtained for medium-grain Jupiter at 45°C in this study and those for a medium-grain rice at 40°C reported by Zuritz & Singh (1985) are shown in Fig. 2. The results are in general agreement, although a slight difference exists at the lowest MC level reported by Zuritz & Singh (1985).
Fig. 3. Total heat of desorption ($Q_t$) at different moisture content levels for long-grain CL XL730, long-grain Wells, medium-grain Jupiter and parboiled rice at 60°C. The value of $h_{fg}$ is indicated and was 2,359 kJ/kg water.
Energy requirements to dry rice from an MC\textsubscript{i} to an MC\textsubscript{f}

Based on Eq. (7), mathematical expressions that predict the energy required to dry rice from an MC\textsubscript{i} to a desired MC\textsubscript{f} (Q\textsubscript{rice}) at a given drying T were developed. These equations were developed using the appropriate A\textsubscript{1}, A\textsubscript{2}, A\textsubscript{3}, B\textsubscript{1} and B\textsubscript{2} values from Table 3. The resulting equations are shown in Table 5. Eq. (7) can be adjusted to predict energy requirements to dry rice from an MC\textsubscript{i} to an MC\textsubscript{f} on a per unit mass of water removed basis by dividing by the mass of water removed (Eq. (8)).

Fig. 4 shows the variation of Q\textsubscript{rice} (drying energy required per unit mass wet rice and per unit dry matter) with MC\textsubscript{i} for long-grain, non-parboiled rice for three MC\textsubscript{f} levels at 60°C. Q\textsubscript{rice} per unit mass wet rice was obtained by dividing Q\textsubscript{rice} (Eq. (7)) by the amount of wet rice corresponding to a unit mass dry matter at the MC\textsubscript{i}. The trends indicated in Fig. 4 are practically linear. An explanation for this would be that the linear terms of the equations shown in Table 5, representing the energy required to vaporize free water, are considerably greater than the exponential terms and therefore, the linear terms contribute considerably more to Q\textsubscript{rice}. Nevertheless, in order to obtain accurate theoretical energy requirements, including both terms in the equation is necessary because as MC decreases, the contribution of the Table 5 exponential term becomes more important. For instance, the exponential term is 4.2% of the Q\textsubscript{rice} value when drying from 22% to 12.5% MC at 60°C but is 10.0% of Q\textsubscript{rice} when drying from 14% to 12.5% at 60°C for long-grain, non-parboiled rice.

A conventional way of quantifying drying energy requirements in the grains industry is to express energy requirements on a per unit mass of water removed. Fig. 5 shows the energy required to dry rice from an MC\textsubscript{i} to a desired MC\textsubscript{f} of 12.5%, 13.5% and 14.5% on a per unit mass of water removed at 60°C. Q\textsubscript{rice} decreased exponentially as MC\textsubscript{i} increases, when expressed
on a per unit mass of water removed. In addition, $Q_{Trice}$ increases as $MC_f$ decreases. Both of these observations reflect the increasing importance of $Q_n$ at the lower MC levels. Therefore, the energy required to remove a unit mass of water from rice should not be considered constant across $MC_i$.

Fig. 6 shows that $Q_{Trice}$ decreases exponentially as $MC_i$ increases for the different rice types, when expressed on a per unit mass of water removed. Further, Fig. 6 confirms the findings discussed in Table 4 in that medium-grain rice required more energy than long-grains and that non-parboiled rice requires more energy than parboiled rice, when expressed on a per unit mass of water removed.

The effect of temperature on energy requirements to dry rice from $MC_i$ to 12.5% is shown in Fig. 7. The energy required to dry rice from $MC_i$ to 12.5% decreases as drying $T$ increases. For instance, the energy required to dry rice from 20 to 12.5% at 40°C was of 2,517 kJ/kg water removed, at 60°C was of 2,467 kJ/kg water removed and at 80°C was of 2,417 kJ/kg water removed (Fig. 7).
Fig. 4. Total energy required to dry rice ($Q_{\text{rice}}$) to 12.5%, 13.5% and 14.5% w.b. moisture content, expressed on a per unit mass of wet or dry matter of rice, as a function of the initial moisture content of the rice for long-grain, non-parboiled rice at 60°C.
Table 5. Equations based on Eq. (7) and Table 3 to predict the energy required to dry rice from an MC\textsubscript{i} to a desired MC\textsubscript{f} (Q\textsubscript{Trice}) in J/kg dry matter, for the indicated rice types.\textsuperscript{a}

<table>
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<tr>
<th>Equation</th>
<th>Temp. range\textsuperscript{b}, °C</th>
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</thead>
<tbody>
<tr>
<td><strong>Medium-grain/non-parboiled</strong></td>
<td></td>
</tr>
<tr>
<td>(Q_{\text{Trice}} = (3.150,878 - 2.377T)(M_{\text{Gf}} - M_{\text{Ci}}) + \left[e^{-23.2M_{\text{f}}} - e^{-23.2M_{\text{Ci}}}\right]\frac{(12,725,771 - 9,601T)}{-23.2}</td>
<td>10-60</td>
</tr>
<tr>
<td><strong>Long-grain/non-parboiled</strong></td>
<td></td>
</tr>
<tr>
<td>(Q_{\text{Trice}} = (3.189,745 - 2.496T)(M_{\text{Gf}} - M_{\text{Ci}}) + \left[e^{-24.2M_{\text{f}}} - e^{-24.2M_{\text{Ci}}}\right]\frac{9,742,417}{-24.2}</td>
<td>10-90</td>
</tr>
<tr>
<td><strong>Long-grain/parboiled</strong></td>
<td></td>
</tr>
<tr>
<td>(Q_{\text{Trice}} = (3.151,394 - 2.377T)(M_{\text{Gf}} - M_{\text{Ci}}) + \left[e^{-23.0M_{\text{f}}} - e^{-23.0M_{\text{Ci}}}\right]\frac{8,107,920 - 6,117T}{-23.0}</td>
<td>10-60</td>
</tr>
</tbody>
</table>

\textsuperscript{a} MC\textsubscript{i} and MC\textsubscript{f} are inputs on a dry basis.

\textsuperscript{b} Temperature range over which EMC data were collected.
Fig. 5. Energy required to dry rice ($Q_{\text{rice}}$) to 12.5%, 13.5% and 14.5% w.b. moisture content, expressed on a per unit mass of water removed, as a function of the initial moisture content of rice for long-grain non-parboiled rice at 60°C.
Fig. 6. Energy required to dry rice ($Q_{\text{T}i\text{rice}}$) to 12.5% w.b. moisture content, expressed on a per unit mass of water removed, as a function of the initial moisture content of the rice for long-grain non-parboiled, long-grain parboiled and medium-grain non-parboiled rice at 60°C.
Fig. 7. Energy required to dry rice ($Q_{\text{rice}}$) to 12.5% w.b. moisture content expressed on a per unit mass of water removed as a function of the initial moisture content of the rice for long-grain non-parboiled rice.
CONCLUSIONS

The net heat of desorption ($Q_n$) and total heat of desorption ($Q_t$) decreased exponentially as MC increased for all types of rice in the range of 10 to 90°C and 8 to 22% MC. Mathematical models were developed to predict the $Q_t$ (the amount of energy required to remove a unit mass of water from rice with a specific MC) for rough rice of long-grains Wells, Cybonnett and CLXL730, medium-grain Jupiter and long-grain, parboiled rice. The $Q_t$ of parboiled rice at 12.5% MC and 60°C was significantly less than that of non-parboiled lots, and the net heat of desorption of medium-grain rough rice was significantly greater than that of long-grains at 12.5% MC and 60°C. Equations that predict the energy required to dry a unit mass of rice from an $MC_i$ to a desired $MC_f$ at a given $T$ were obtained for long-grain non-parboiled, medium-grain non-parboiled, and parboiled rice. The energy required to remove a unit mass of water when drying from a given $MC_i$ to a desired $MC_f$ decreased exponentially as $MC_i$ increased at a given $T$. These equations provide a more accurate estimate of the energy required to dry rice than the approach of simply using the latent heat of vaporization when assessing energy efficiency of a drying process.
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APPENDIX 2. Statement.

I verify that Alejandra Billiris provided over 50% of the research work published in the following article that is included in her dissertation:

Estimating the theoretical energy required to dry rice

Dr. Terry J. Siebenmorgen
III. CHAPTER II
Energy use and efficiency of rice drying systems. I. On-farm cross-flow dryer measurements.

ABSTRACT

Energy use and efficiency of an on-farm, cross-flow dryer were measured by performing five tests during the harvest season of 2011 and three tests during the harvest season of 2012. Thermal energy requirements were expressed in terms of energy per unit mass water removed, by dividing the energy requirements of the burner by the total mass of water removed for each drying run. Energy efficiency was calculated as the ratio of theoretical energy requirements to the measured energy requirements. In 2011, energy requirements to dry rice ranged from 2,840 to 5,310 kJ/kg water removed, with harvest moisture contents ranging from 16.6 to 21.7%, and in 2012 from 3,730 to 5,840 kJ/kg water removed, with harvest moisture contents ranging from 17.4 to 18.2%. Thermal energy efficiencies ranged from 47 to 90% in 2011 and from 44 to 69% in 2012. The difference between drying air temperature inside the dryer and ambient air temperature as well as the amount of water removed, expressed on a per unit mass of rice dry matter, significantly impacted energy use. Equations were developed to predict energy use and efficiency as a function of these two parameters.

INTRODUCTION

When rice is harvested at high moisture content (MC) it is typically dried quickly to preserve its quality (Siebenmorgen & Meullenet, 2004). Unless some form of cooling is provided, harvested rice should be dried to a safe MC of 13%\(^1\) to allow long-term storage (Howell & Cogburn, 2004). Because world rough rice production has increased from 220.6 million metric tonnes (mmt) in 1960/61 to 655.5 mmt in 2008/09 (USDA, 2008), the amount of rice that needs

\(^1\) All moisture contents are reported on a wet basis unless otherwise specified.
to be dried has increased significantly. In addition, global rice production is expected to continue increasing due to predicted growth trends in world population.

Verma (1994) reported that the energy equivalent of 630 million gallons of crude oil was used to dry grains in the United States in 1994. The U.S. rice-producing states of Arkansas, California, Louisiana, Mississippi and Texas used on average 316 L/ha (33.8 gal/acre) of diesel, 28 L/ha (3.0 gal/acre) of gasoline, 326 kWh/ha (132 kWh/acre) of electricity and 36,312 L/ha (519 ft³/acre) of natural gas on rice production in 2000 (USDA, 2000). Kasmaprapruet et al. (2009) reported that drying was the unit operation that required the most energy for rice processing, accounting for 55% of the total energy consumed for production and processing of rice. Drying was followed by harvesting (15%), cultivation (10%), seeding (10%), transportation (6%), and milling (4%).

Arkansas is the leading rice producing state in the United States with 47% of the rice-planted acres (USDA, 2011), and is the state in which this study was conducted. While most of the rice produced in Arkansas is dried in commercial, cross-flow driers, a significant portion is dried on farms, and is usually dried in bins at low temperatures (Ts) ranging from 25 to 38°C and airflow rates ranging from 0.03 to 0.10 m³/sec/m³ of grain (2.2 to 7.5 cfm/bu) (Bakker-Arkema and Fontana, 1983). However, because rice production has increased in the past decades, there has been a shift in on-farm drying to portable, cross-flow dryers, similar to the one used in this study, thus relieving pressure on commercial dryers; this trend has also been noted in the corn industry (Morey et al., 1976).

The Economic Research Service (2004) reported that for the rice farms in Arkansas in which rice is dried, drying accounts for ~ 38% of the cost of on-farm production and processing operations, including drying, fertilizers, chemical application and harvest. Drying cost varied
significantly on U.S. rice farms in 2000, ranging from 22 $/ha (9 $/acre) to 72 $/ha (29 $/acre) depending on the rice production region (Economic Research Service, 2004). Because of the relative importance of drying to overall energy use for rice production/processing, and that there is little information on energy requirements of rice drying, it is relevant to measure the amount of energy that is currently required to dry rice and to determine the energy efficiency of rice drying systems in order to maximize the drying achieved per unit energy used.

In order to assess the energy performance of a drying process, the specific heat consumption, calculated by dividing the total energy supplied to the dryer by the mass of water evaporated from the grain (Mujumdar, 1995), may be used to represent the actual energy requirements of a dryer on a per unit mass of water removed. Brinker and Anderley (2012) reported average specific heat consumptions of 4,810 kJ/kg water removed for an on-farm, cross-flow dryer with heat recovery when drying 3,100 metric tonnes (122,076 bu) of corn using an average air T of 4.5°C (40°F) and of 4,203 kJ/kg water removed for another on-farm, cross-flow dryer when drying 31,116 metric tonnes (1,225,000 bu) of grain from 22 to 15% MC using an average ambient T of 3.3°C (38°F). The same study reported that an on-farm, cross-flow horizontal dryer without heat recovery used 6,530 kJ/kg water removed to dry grain.

To determine energy efficiency, the theoretical energy required (E_theo) for moisture removal (Kudra, 2004), which represents the minimum energy required to dry grain, is typically compared to the specific heat consumption. The minimum energy required to dry grains is predominantly the energy required to evaporate water, which varies from 2,500 to 2,670 kJ/kg water depending on the drying T (Fluck & Baird, 1980). Billiris et al. (2011) reported that E_theo to dry long-grain rice to 12.5% ranged from 2,500 to 2,650 kJ/kg water when the initial MC (MC_i) ranged from 22 to 15%, respectively, at a 40°C kernel T.
The objectives of this research were to measure the energy use and efficiency of an on-farm, cross-flow dryer operating across a range of ambient and drying air conditions.

MATERIALS AND METHODS

Dryer and drying system description

Figure 1A shows a side-view of the dryer (Portable grain dryer 1126, GSI Group, LLC, Assumption, IL) used in this study and located at Pocahontas, Arkansas; Fig. 1B shows a vertical cross-section of the dryer. After entering the dryer inlet, rice is transferred to the drying columns by a cross-auger where it flows by gravity through the columns (Fig. 1A). Two variable-speed, feedroll augers located at the bottom of the dryer transport the dried rice to the outlet and controls the flow rate of the rice inside the columns based on a target output MC. Ambient air is forced through the dryer by an axial-flow fan (40 HP 42”, GSI Group, LLC, Assumption, IL). Immediately after exiting the fan, the air is heated by a burner (10.25 mil.btu/hr max, GSI Group, LLC, Assumption, IL) by direct combustion of propane gas before entering the dryer hot-air plenum (HAP) (Fig. 1A). From the HAP, the drying air passes through the rice columns perpendicular to the downward flow of the rice (Fig. 1B). Screens are located on both sides of each drying column, allowing the drying air to enter and exit the columns (Fig. 1B).

The drying system utilized in this study encompasses the dryer described above, two hopper-bottom bins, final storage bins, and a 10” closed-‘loop’ paddle chain conveying system. In this drying system, rice is typically pre-heated, dried in two passes, tempered after each pass and aerated in a storage bin (Fig. 2). More specifically, freshly harvested rice is pre-heated to ~ 30°C (85°F) in a 497 m³ (14,961 bu) hopper-bottom bin (FCHT 45°-24’ diameter, 9 ring, GSI Group, LLC, Assumption, IL) with a 16.18 m peak height. Pre-heating is accomplished by a centrifugal fan (CHS-10hp 3450 rpm, GSI Group, LLC, Assumption, IL) forcing heated air with an
upstream a burner (VHD-18-VN, .4 to 1.4 mil btu/hr, GSI Group, LLC, Assumption, IL), through the rice in the bin. The pre-heating bin is filled with a day’s harvest prior to pre-heating. After pre-heating, rice is conveyed to the inlet of the dryer. During the first drying pass, which is carried out using a target drying air T of 57°C (135°F), rice is dried from the MCi of typically 18 to 21% to ~ 15.5%. After the first drying pass, rice is tempered in the second hopper-bottom bin, identical to the first, for a duration of ~ 1 to 10 hours. During the second pass, which is carried out using a target drying air T of 49°C (120°F), rice is usually dried from ~ 15.5 to ~ 12.5% MC, and is then conveyed from the dryer outlet to a 4,196 m³ storage bin (FCDL 60’ diameter 13 ring, GSI Group, LLC, Assumption, IL) with a 18.29 m diameter and 19.74m peak height where it is first tempered for 2 h and then aerated with ambient air at a rate of 1,643m³/m (58,000 cfm)(60ft diameter bin has 2,827ft² or 262 m²) using two centrifugal fans (CF-40, GSI Group, LLC, Assumption, IL).
Fig. 1 A. Side view of the on-farm, cross-flow dryer. B. Vertical cross-section of the dryer.
Fig. 2. Flow diagram of the drying system operation.
Energy tests

Energy consumption was measured during the 2011 and 2012 rice harvest seasons. Five drying tests were conducted during the first year and three tests were conducted during the second year (Table 1). In 2011, three tests were performed following the typical two-pass drying procedure described above and two tests were performed in which rice was dried in a single pass directly from MC$_i$ to ~12.5% using drying air Ts of ~ 50°C (122°F). All tests comprised drying long-grain, “CL XL745” rough rice for durations ranging from 10 to 20 h, depending on the number of passes, MC$_i$, and ambient conditions. For the terminology of this manuscript, a “run” is a single pass of a given lot of rice through the dryer, a drying test typically comprised two runs.

Energy measurement and calculation

The thermal energy requirements ($E_{\text{thermal}}$) to dry rice in terms of energy per unit mass water removed, referred to above as the specific energy consumption, were calculated using Eq. 1 (Maier & Bakker-Arkema, 2002):

$$E_{\text{thermal}} = \frac{V \times AE}{m_w} \quad (1)$$

$E_{\text{thermal}}$ is the thermal energy supplied to the dryer in kJ/kg of water removed

$V$ is the volume of propane gas used in m$^3$

$AE$ is the available energy from propane ~ 93,743 kJ/m$^3$ (2,516 Btu/ft$^3$), which was obtained from the propane supplier. A similar value was obtained (94,787 kJ/m$^3$) (2,544 Btu/ft$^3$) after multiplying the high heating of propane 50,365 kJ/kg (21,653 Btu/lb) (Neil, 2003) by the density of propane gas at 15°C and 101.3 kPa (1.88 kg/m$^3$).

$m_w$ is the mass of water removed during each drying run in kg

Note: Thermal energy use for an entire test was calculated by summing the volumes of gas propane used ($V$) and the masses of water removed ($m_w$) for all runs comprising a test.

The volume of propane gas used by the burners (dryer and pre-heating bin) was measured using two, diaphragm-flow meters (AL-425, Elster American Meter, Nebraska City, NE) that
had an accuracy of ±1 to 2% of the reading. The flow meters had a maximum operating pressure of 172 kPa (25 psi) and T-compensating capabilities for ambient Ts ranging from -34 to 60°C (-29 to 140°F). Liquid propane was stored in a 21 m³ tank that was equipped with a calibrated gauge (2582C Rotoguage, Bastian Blessing Co, Chicago, IL), which measured the percentage of the tank volume that was occupied by liquid propane. The propane consumption determined using this gauge was used to calibrate the flow meters at the dryer. To obtain the volume of liquid propane used for a given run, percent liquid volume readings were recorded before and after each drying run. The volume of liquid propane used was converted to volume of propane gas; the latter volume was used to calibrate the flow meters. After multiple trials, a calibration factor of 1.45 was obtained. This calibration factor was applied to all flow meter readings to obtain the volume of propane used during the energy runs.

The mass of water removed during each run was calculated using Eq. 2 (Maier & Bakker-Arkema, 2002).

\[
m_w = \frac{m_r \times (MC_i - MC_f)}{100 - MC_f} \tag{2}
\]

\(m_r\) is the mass of incoming rice dried in a drying run in kg
\(MC_i\) is the average moisture content of the rice entering a drying run in %, w.b.
\(MC_f\) is the average moisture content of the rice exiting a drying run in %, w.b.

The mass of incoming rice lots ranged from 109,260 to 271,000 kg for the drying tests of 2011, and from 213,580 to 333,000 kg in 2012. Each rice lot comprised rice from the same field that was harvested and transported using trucks that held approx. 23,000 kg; a typical test run comprised a day’s harvest of 9 to 13 trucks. The mass of incoming rice comprising a rice lot was calculated as the sum of the masses of incoming rice on each truck. To obtain the mass of incoming rice on each truck, the mass of the truck loaded with freshly-harvested rice was
measured on a local elevator scale, and then the mass of the empty truck was subtracted. The mass of incoming rice in subsequent loads was obtained by subtracting the mass of the empty truck previously obtained from the mass of the truck loaded with rice.

The harvest MC (before pre-heating) of each rice lot was obtained from the combine harvester (CR 9070, New Holland), which was equipped with a sensor that provides the average MC of the rice comprising a lot. The MC of the rice entering (after pre-heating) and exiting the dryer throughout a given drying run was measured using shark-fin sensors (GSI Group, LLC, Assumption, IL) that were located at the inlet and outlet of the dryer (Fig. 1A) and that were calibrated weekly using a calibrated, moisture meter (GAC 2100, DICKEY-John, Auburn, IL) that had an accuracy of 0.15%. The shark-fin sensors were programmed to record T and MC of the rice every three minutes. For any given drying run, the MC of the rice entering and exiting the dryer was calculated as the average of the MCs recorded by the inlet and outlet shark-fin sensors during the run. Because pre-heating could have reduced MC, the harvest MC determined by the combine sensor was deemed appropriate to represent the MC of the rice throughout the first drying pass. In addition, it was reasoned that there might be an offset in the reading of the outlet shark-fin sensor, which measures predominantly surface moisture, due to the formation of a moisture gradient inside the rice kernels during drying and thus the MC at the surface would be less than that at the core (Sarker et al., 1996; Yang et al., 2003). Therefore, the MC measured by the inlet shark-fin sensor during the second pass, which represents the MC of the rice after first-pass tempering, was considered to be a better indicator of the rice MC exiting the dryer (MC) of the first pass. Thus, if drying was performed in two passes, to calculate the mass of water removed during the first pass via Eq. 2, the average harvest MC from the combine was used as
the MC, and the average inlet shark-fin sensor MC obtained for the second pass was used as the first-pass MC.

To obtain an appropriate MC for the second pass, the MC of tempered rice was measured on two samples from each run, which were taken from the storage bins after tempering, using the moisture meter described previously. This ensured that MC gradients inside rice kernels had subsided and thus the MC measured was the actual MC of the rice. Thus, to calculate the mass of water removed during the second pass via Eq. 2, the average inlet shark-fin sensor MC obtained for the second pass was used as the MC and the tempered rice MC was used as the MC. If drying was performed in a single pass, the harvest MC was used as the MC of the rice and the tempered rice MC was used as the MC.

Electrical energy requirements to power fans and augers were not measured due to limitations in isolating energy requirements for this equipment. This was not deemed a major study limitation since Hellevang and Reff (1987) reported that propane use is responsible for 98% of the energy requirements when drying grain using high-temperatures.

Energy efficiency calculation

The energy efficiency of the dryer for a given drying run was calculated using Eq. 3.

$$\eta = \frac{E_{\text{theo}}}{E_{\text{thermal}}} \times 100$$  \hspace{1cm} (3)

$\eta$ is the energy efficiency of the drying process
$E_{\text{theo}}$ is the theoretical energy in kJ/kg water removed
$E_{\text{thermal}}$ is the thermal energy supplied to the dryer (specific heat consumption) in kJ/kg water removed.

The theoretical energy requirement ($E_{\text{theo}}$) represents the amount of energy required to dry rice from a given MC to a MC at a given kernel T under ideal conditions. To predict $E_{\text{theo}}$, the
equation developed by Billiris et al. (2011) for long-grain, non-parboiled rice was used (Eq. 4).

\[
E_{\text{theo}} = (3,189,745 - 2,496T)(MC_f - MC_i) + \left[ e^{-24.2MC_f} - e^{-24.2MC_i} \right]^{\frac{9.742.417}{-24.2}} \tag{4}
\]

\(E_{\text{theo}}\) is the theoretical energy requirement in J/kg dry matter  
\(MC_i\) is initial moisture content in dry basis, decimal  
\(MC_f\) is the final moisture content in dry basis, decimal  
\(T\) is the kernel temperature in °K

To express energy requirements on a per unit mass of water removed, Eq. 4 was divided by the mass of water removed during a drying run (\(m_w\); Eq. 2) per mass of rice dry matter associated with a drying run.

**Temperature and relative humidity measurements**

The T and RH of the ambient air and that inside the HAP were measured continuously throughout all drying trials using T and RH sensors (Hobo Pro v2 U23-001, Onset Corporation, Bourne, MA, USA). Sensors had data-logging capability and were programmed to record T and RH measurements every 5 minutes. Ambient conditions were measured using a sensor that was located at the fan inlet. It is noted that the HAP T was obtained as the average T from four sensors located throughout the HAP.
Table 1. Synopsis of drying-energy tests performed using an on-farm, cross-flow drier in 2011 and 2012.

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of passes</th>
<th>MC\textsubscript{i} (first pass) (% w.b.)</th>
<th>Drying pass temperatures (T\textsubscript{da}/T\textsubscript{a})**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>First °C</td>
</tr>
<tr>
<td><strong>Drying season: September – October 2011</strong></td>
<td></td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>21.7</td>
<td>56/23</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>18.6</td>
<td>49/18</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>16.6</td>
<td>48/29</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>18.9</td>
<td>50/27</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>21.0</td>
<td>45/20</td>
</tr>
<tr>
<td><strong>Drying season: August – October 2012</strong></td>
<td></td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>17.6</td>
<td>52/19</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>18.2</td>
<td>49/9.0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>17.4</td>
<td>44/22</td>
</tr>
</tbody>
</table>

*MC\textsubscript{i} is the harvest moisture content  
**T\textsubscript{da} is the average temperature of the drying air inside the hot-air plenum during each run; T\textsubscript{a} is the average ambient temperature during each run.
RESULTS AND DISCUSSION

Figure 3A shows harvest and inlet MCs, which represent rice MCs before and after pre-heating, respectively, for the 2011 drying tests. It is noted that the inlet MC refers to the MC of the rice at the inlet of the dryer (Fig. 1) as measured by the inlet shark-fin sensor. In general, harvest MCs were greater than inlet MCs. It is reasoned that rice was partially dried during the pre-heating step and thus the slight reduction in MC. This trend was more apparent as rice inlet MC increased, speculated to be due to the increasing ease of water removal from rice with greater MCs. It is possible that the pre-heating step improves the energy efficiency of the drying process, not only because rice is heated to the drying T in the pre-heating bin, but also because some moisture is removed during pre-heating.

Figure 3B shows tempered and outlet MCs for the 2011 drying tests. The outlet MC refers to the MC of the rice at the outlet of the dryer (Fig. 1) as measured by the outlet shark-fin sensor. It is noted that the outlet MCs shown in Fig. 3B correspond to the outlet MC of the second pass when tests were carried out in two passes. Tempered rice MCs, which were ~ 13%, were always greater than the outlet MCs measured by the outlet shark-fin sensor. This can be explained by Sarker et al. (1996) and Yang et al. (2003) who stated that during drying a moisture gradient develops inside the rice kernel in which the moisture at the core is greater than that at the surface of the kernel. However, during tempering the moisture at the core migrates to the surface of the kernel, producing a more uniform kernel MC. Because shark-fin and hand-held meters measure predominantly the surface MC, the MC value obtained at the dryer outlet was less than that obtained after tempering, as shown in Fig. 3B. This justifies using tempered rice MC as a more appropriate MC measurement of rice exiting the dryer for energy calculations.
Fig. 3. Initial (A) and final (B) moisture contents (MCs) of the rice lots for the five drying tests carried out in 2011 (Table 1). Harvest MC refers to the average MC of each rice lot measured by the moisture sensor in the combine. Inlet and outlet MCs represent the average MCs measured by the shark-fin sensors at the inlet and outlet of the dryer throughout a drying run, respectively. When tests were conducted in two passes, the inlet MC corresponds to the inlet MC during the first pass and the outlet MC corresponds to the outlet MC of the second pass. Tempered MCs represent the MCs measured using a hand-held meter after the rice had tempered in a storage bin. Data points indicate the mean of two MC measurements of two samples from the same lot.
Energy requirements and efficiency

Table 2 shows $E_{\text{theo}}$, $E_{\text{thermal}}$ and thermal energy efficiency for the drying tests conducted in 2011 and 2012. $E_{\text{thermal}}$ varied from 2,840 to 5,310 kJ/kg water in 2011; whereas the predicted $E_{\text{theo}}$ ranged from 2,480 to 2,560 kJ/kg water removed. In addition, $E_{\text{thermal}}$ varied from 3,730 to 5,840 kJ/kg water in 2012; whereas the predicted $E_{\text{theo}}$ ranged from 2,550 to 2,570 kJ/kg water removed. Thus, energy requirements obtained for the second year of testing were consistent to those of the first year. In general, the $E_{\text{thermal}}$ values reported in Table 2 are within the values reported by Maier and Bakker-Arkema (2002), which ranged from 3,480 to 10,450 kJ/kg water removed. In addition, Otten et al. (1980), who performed drying tests to determine the energy required to dry corn in a commercial cross-flow dryer, reported that $E_{\text{thermal}}$ varied from 3,860 to 11,960 kJ/kg water removed.

Energy efficiencies were calculated using Eq. 3 for each test and ranged from 47 to 90% in 2011 and from 44 to 69% in 2012 (Table 2). Otten et al. (1980) reported thermal energy efficiencies to dry corn in a cross-flow dryer of 24 to 76%, which were calculated by dividing the heat of vaporization of corn at 40°C and 15% MC dry basis by the specific heat consumption. The following sections discuss the effects of various factors on $E_{\text{thermal}}$ and energy efficiency.
Table 2. Energy requirements and energy efficiency for the tests conducted in 2011 and 2012.

<table>
<thead>
<tr>
<th>Test</th>
<th>MC$_i$*</th>
<th>E$_{theo}$**</th>
<th>E$_{thermal}$***</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>kJ/kg</td>
<td>kJ/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Drying season: September – October 2011</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21.7</td>
<td>2,480</td>
<td>4,870</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>18.6</td>
<td>2,540</td>
<td>4,340</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>16.6</td>
<td>2,560</td>
<td>2,840</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>18.9</td>
<td>2,520</td>
<td>4,250</td>
<td>59</td>
</tr>
<tr>
<td>5</td>
<td>21.0</td>
<td>2,510</td>
<td>5,310</td>
<td>47</td>
</tr>
<tr>
<td><strong>Drying season: July-October 2012</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>17.6</td>
<td>2,560</td>
<td>5,840</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>18.2</td>
<td>2,550</td>
<td>5,070</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>17.4</td>
<td>2,570</td>
<td>3,730</td>
<td>69</td>
</tr>
</tbody>
</table>

*MC$_i$ is the initial moisture content of the rice in % wet basis.
**E$_{theo}$ is the theoretical energy requirement in kJ/kg water removed
***E$_{thermal}$ is the measured thermal energy requirement in kJ/kg water removed

Note: Energy efficiency was calculated as the ratio of E$_{theo}$ divided by E$_{thermal}$.
Effect of drying air and ambient temperature on energy use and efficiency

The different passes through the dryer were carried out under considerably different ambient conditions (e.g., the first pass was always conducted during the day whereas the second pass was always at night). Thus, it was reasoned that the effect of ambient conditions on energy requirements should be analyzed in terms of energy per unit mass water removed for each drying pass.

Figure 4 shows the $E_{\text{thermal}}$, $MC_i$, average ambient T and RH, and drying air T and RH for each drying run of the five drying tests performed in 2011. For tests 1, 4 and 5, which were conducted in two passes, it was observed that $E_{\text{thermal}}$ of the second pass was considerably greater than that of the first pass. A possible explanation could be that more energy is required to remove a unit mass of water from rice with lesser MCs (Aviara et al., 2004; Mulet et al., 1999; Toğrul & Arslan, 2006; Tsami et al., 1990; Zuritz & Singh, 1985). It might also be that the second passes were conducted at night when ambient air Ts were less (Fig. 4). As average ambient T decreases, more energy is required to heat the air to the drying T. It is observed in Fig. 4 that test 3, which comprised a single pass and had the greatest average ambient T, required the least $E_{\text{thermal}}$. Otten et al. (1980) reported that $E_{\text{thermal}}$ to dry corn in a commercial, cross-flow dryer increased from 4,970 to 11,960 kJ/kg water removed when ambient T correspondingly decreased from 16.7 to -4.4°C.

Based on the results shown in Fig. 4, a potential approach to save energy could be to dry rice from $MC_i$ to ~ 15% using the cross-flow dryer and to remove the remaining moisture using low-T or natural air in-bin drying as suggested by Morey et al. (1976) for corn. Considerable energy savings could be achieved using this approach because the sensible heat that remains inside rice kernels after high-T drying could be used to help reduce the MC to the desired $MC_f$; Morey et al.
(1976), who used computer simulation to predict energy requirements, reported that 60% more energy is required to dry corn from 32 to 15% in a high-T dryer than to dry corn from 32 to 24% in a high-T dryer and complete drying to 15% in-bin using ambient air.

Figure 5 shows the effect of ambient T on $E_{\text{thermal}}$ for the drying tests performed in 2011 and 2012. Thermal energy requirements were inversely and linearly correlated ($R^2=0.62$) to average ambient T. Otten et al. (1980) showed that the greater $E_{\text{thermal}}$ values observed when drying at lesser ambient Ts could be partly due to greater heat losses to the surroundings. Bakker-Arkema (1978) explained that the magnitude of the heat losses by radiation and convection to the atmosphere, through cracks in hot-air ducts and due to inefficiencies in fuel combustion depends on the type of dryer. It is reasonable that the heat losses described by Bakker-Arkema (1978) increase as ambient T decreases. It is then possible that the Fig. 5 trend indicating that as ambient T decreases, $E_{\text{thermal}}$ increases, is not only due to an increase in the energy required to heat the ambient air to the drying T, but also to an increase in heat losses throughout the dryer. The simple linear regression model suggests that 38% of the variability in $E_{\text{thermal}}$ was not explained by ambient T. It is possible that other factors, such as rice MC and drying air conditions were responsible for some of the variability in $E_{\text{thermal}}$.

Figure 6 shows the effect of ambient T, RH and equilibrium MC on the thermal energy efficiency (Eq. 3) per drying run. Equilibrium MC was calculated from the ambient air T and RH using the Chung-Pfost equation (Chung and Pfost, 1967; Pfost et al., 1976) and the coefficients reported by Ondier et al. (2011) for long-grain rice cultivars. Energy efficiency might be a more appropriate indicator than $E_{\text{thermal}}$ of the effects of ambient conditions because the effects of $MC_i$, $MC_f$ and kernel T are accounted for in the calculation of $E_{\text{theo}}$. Energy efficiency was strongly and linearly correlated ($R^2=0.74$) to average ambient T, as it also was to RH ($R^2=0.41$). Because
energy efficiency increased as average ambient T increased, it is reasonable to suggest that as RH decreased, as is often associated with increasing ambient T, energy efficiency increased. Equilibrium MC accounts for both T and RH associated with the drying air and reflects the drying potential of the drying air, which decreases as T increases and RH decreases. Energy efficiency increased linearly as the rice equilibrium MC decreased.

There was no correlation between drying air T and E_thermal. It is noted that drying air T, which is expected to be a relevant factor affecting E_thermal, ranged narrowly from ~45 to 55°C (Table 1) during the tests; this may have caused the effect of drying air T on E_thermal to be lessened. The considerable variation in average ambient T observed among runs (14 to 29°C) was considered an additional drawback when assessing the effect of drying air T.
Fig. 4. Thermal energy ($E_{\text{thermal}}$) per drying run, to dry rice from the indicated initial moisture contents ($MC_i$) using the indicated drying air $T$s and RHs for the five tests conducted during 2011, each with the indicated ambient temperatures ($T_s$) and relative humidities (RHs). Final moisture contents of the first pass were taken as the inlet $MC$s of the second pass. Final moisture contents of the second pass were ~ 13%.
Fig. 5. Thermal energy requirements ($E_{\text{thermal}}$) per rice drying run, as a function of average ambient temperature for the energy tests performed in 2011 and 2012.

$R^2 = 0.62$
Fig. 6. Thermal energy efficiency per drying run, calculated as the ratio of theoretical energy requirements ($E_{\text{theo}}$) divided by the measured thermal energy ($E_{\text{thermal}}$), of the on-farm dryer as a function of average ambient temperature (A), average ambient relative humidity (B) and rough rice equilibrium moisture content associated with the ambient air temperature and relative humidity predicted by the Chung-Pfost equation (C).
Prediction of energy use and efficiency

Energy use

Even though there was no correlation between drying air T and E\textsubscript{thermal}, drying air T was included in the model predicting E\textsubscript{thermal} in a term that quantified the difference between drying air T and ambient air T (T\textsubscript{da} - T\textsubscript{a}), which determines the amount of energy required to heat ambient air to the drying T. Additionally, the amount of water removed, expressed per unit of rice dry matter (m\textsubscript{w}/dm) was reasoned to affect energy use and was included as an independent variable of the model. Multiple linear regression analysis was used to obtain the coefficients (b\textsubscript{0}, b\textsubscript{1} and b\textsubscript{2}) of Eq. 5.

\[ E_{\text{thermal}} = b_1(T_{\text{da}} - T_{\text{a}}) + b_2 \left(\frac{m_w}{dm}\right) + b_0 \quad R^2 = 0.80 \quad \text{RMSE} = 815 \quad (5) \]

\[ b_0 = 2,048 \]
\[ b_1 = 214 \]
\[ b_2 = -54,792 \]

m\textsubscript{w} is the mass of water removed in a drying run in kg

dm is the mass of rice dry matter in a drying run in kg

Dry matter was calculated using Eq. 6.

\[ dm = \left(1 - \frac{MC_i}{100}\right)m_r \quad (6) \]

MC\textsubscript{i} is the average moisture content of the rice entering a drying run in %, w.b.
m\textsubscript{r} is the mass of incoming rice dried in a drying run

The model suggests that E\textsubscript{thermal} increased linearly as T\textsubscript{da} - T\textsubscript{a} increased. This is reasonable given that the greater the difference between drying air T and ambient air T, the greater the amount of energy required to heat the air. The model also indicated that as m\textsubscript{w}/dm increased, E\textsubscript{thermal} decreased. In general, the drying operation consisted of two passes; the first pass, in which rice was dried from harvest MC (~21 to 18%) to ~15%, and the second pass, in which rice was dried from ~ 15 to ~ 13%. Thus, on average m\textsubscript{w}/dm was greater during the first pass (~
0.070) than during the second pass (~0.030). Because it is increasingly difficult to remove water as MC decreases it is then reasonable that \(E_{\text{thermal}}\) increased as \(m_w/dm\) decreased (Fig. 7A).

**Thermal energy efficiency**

In an effort to model thermal efficiency, multiple linear regression analysis was used to obtain the coefficients \(b_0\), \(b_1\) and \(b_2\) of Eq. 7.

\[
\eta_{\text{th}} = b_1(T_{da} - T_a) + b_2 \left(\frac{m_w}{dm}\right) + b_0 \quad R^2=0.72 \quad \text{RMSE}=11 \quad (7)
\]

\(\eta_{\text{th}}\) is thermal energy efficiency of a drying run

\(b_0=95.2\)

\(b_1=-2.4\)

\(b_2=520\)

The model shows that the greater the difference, \(T_{da}-T_a\), the lesser the thermal efficiency. An explanation for this would be that as ambient T decreases, which leads to an increase in \(E_{\text{thermal}}\) (Fig. 5), \(E_{\text{thermal}}\) becomes greater relative to \(E_{\text{theo}}\). In addition, as \(m_w/dm\) increased, energy efficiency increased (Fig. 7B). It was reasoned that because \(E_{\text{thermal}}\) increased as \(m_w/dm\) decreased (Fig. 7A), thermal efficiency decreased as \(m_w/dm\) decreased.

**Drying cost**

To perform cost calculations, the price of liquid propane was taken as $529/m$^3\ ($2.0/gal), which was the price paid for propane in 2011. The heat of combustion for propane gas was taken as \(~93,743\ \text{kJ/m}^3\ (2,516 \text{ Btu/ft}^3)\). The density of liquid propane was taken as 500 kg/m$^3$ and the density of propane gas was taken as 1.9 kg/m$^3$ (at 15°C and 101.3 kPa). Thus, 263 m$^3$ of gas are obtained from 1 m$^3$ of liquid propane. Equation 8 was developed using Eq. 7 and the price of propane in \(2.1^{-3} \ \text{¢/kJ}\).

\[
\text{Cost} = 2.1^{-3}E_{\text{thermal}} = 4.5^{-1}(T_{da} - T_a) - 115 \left(\frac{m_w}{dm}\right) + 4.3 \quad (8)
\]

Cost is the cost to dry rice in ¢/kg water removed.
The family of curves for drying cost as a function of $T_{da} - T_a$ for two levels of $m_w/dm$ is shown in Fig. 7. As expected, the trends in Cost are similar to those of $E_{thermal}$, given that the greater the energy use the greater the amount of propane used and thus the greater the cost.
Fig. 7. Family of curves predicting thermal energy use (A) and thermal energy efficiency (B) as a function of the difference between drying air temperature and ambient temperature ($T_{da} - T_a$) at the indicated levels of water removed per mass dry matter ($m_{w/dm}$) for drying tests conducted in 2011 and 2012. Drying air temperatures ranged from 45 to 55°C and ambient air temperatures ranged from 15 to 30°C.
Fig. 8. Family of curves predicting drying cost as a function of the difference between drying air temperature and ambient temperature ($T_{da} - T_{a}$) at the indicated levels of water removed per mass dry matter ($m_{w}/dm$) for drying tests conducted in 2011 and 2012. Drying air temperatures ranged from 45 to 55°C and ambient air temperatures ranged from 15 to 30°C.
CONCLUSIONS

Thermal energy use ($E_{\text{thermal}}$) to dry rice in the on-farm, cross-flow dryer ranged from 2,840 to 5,840 kJ/kg water removed for the eight tests conducted during the 2011 and 2012 harvest seasons. Thermal energy efficiency, which was calculated as the ratio of the theoretical energy requirements ($E_{\text{theo}}$) to $E_{\text{thermal}}$, ranged from 44 to 90%. The cost to dry rice from the initial moisture contents, ranging from 16.6 to 21.7 to ~13% ranged from 7.7 to 12.0 ¢/kg water removed. There was a strong correlation between $E_{\text{thermal}}$ and ambient air temperature. It was also found that $E_{\text{thermal}}$ was linearly correlated to the difference between the drying air temperature and ambient air temperature, which is an indicator of the energy required to heat the air to the drying temperature. $E_{\text{thermal}}$ was also inversely correlated to the amount of water removed, expressed per unit mass of dry matter. Equations were developed to predict $E_{\text{thermal}}$, energy efficiency and drying cost as a function of these variables.
LITERATURE CITED


I verify that Alejandra Billiris provided over 50% of the research work published in the following manuscript that is included in her dissertation:

Energy use and efficiency of rice-drying systems. I. On-farm dryer measurements.

Dr. Terry J. Siebenmorgen
IV. CHAPTER III.

Energy use and efficiency of rice-drying systems. II. Commercial, cross-flow dryer measurements

ABSTRACT

Energy use and efficiency of a commercial, cross-flow dryer were measured when drying rough rice across a range of ambient conditions and drying air temperatures. Four tests were conducted during the 2011 harvest season using rice that had moisture contents ranging from 19.0 to 21.7% wet basis and three tests were conducted during the 2012 harvest using rice with moisture contents from 15.4 to 18.3%. To obtain thermal energy requirements in terms of energy per unit mass water removed, the energy consumed by the burner was divided by the total amount of water removed. In addition, electrical energy requirements were determined by multiplying the average power draw of the fan motor by the fan operating duration. Overall energy efficiency was calculated by dividing theoretical energy requirements by the total, measured energy use, which was calculated as the sum of thermal and electrical energy use. Total energy requirements to dry rice ranged from 7,170 to 10,010 kJ/kg water removed in 2011 and from 9,170 to 10,070 in 2012. Electrical energy use, which ranged from 265 to 370 kJ/kg water removed in 2011 and from 365 to 520 in 2012, accounted for ~ 4% of the total energy used to dry rice. Thermal energy requirements were linearly correlated to the difference between drying air temperature and ambient temperature and linearly and inversely correlated to the amount of water removed per mass dry matter. Energy efficiency ranged from 26 to 36% in 2011 and from 27 to 29% in 2012.

INTRODUCTION

Rice drying is an energy-intensive unit operation (Verma, 1994; Thakur & Gupta, 2006). Energy use for drying rice may vary considerably depending on the dryer type and design. Most
commercial facilities use high-temperature, continuous-flow dryers including cross-flow, mixed-flow, concurrent-flow and counter-flow dryers; the most widely used type of dryer in North America is the cross-flow dryer (Bakker-Arkema et al., 1995).

Besides the type of dryer, several factors affect energy use and energy efficiency of the drying process. The effect of drying air temperature (T) on energy efficiency, as well as on grain quality, has been addressed by Gunasekaran & Thompson (1986) who stated that drying corn at ambient Ts required from 3,250 to 3,750 kJ/kg of water removed and required from 4,500 to 8,000 kJ/kg of water removed when drying with high Ts. However, Morey et al. (1976), who used computer simulation to predict energy requirements to dry corn using a cross-flow dryer, reported that as drying air T increased, energy use decreased. Also of major importance is grain moisture content (MC), which affects the net heat of sorption of water in foodstuffs (Aviara et al., 2004; Toğrul & Arslan, 2006; Tsami et al., 1990; Zuritz & Singh, 1985), thus affecting energy use. Other factors, such as the type and variety of grain, the drying air relative humidity (RH) and airflow rate affect the drying rate (Aviara et al., 2004; Cnossen et al., 2002; Henderson & Pabis, 1961; Iguaz et al., 2003; Morey et al., 1976; Simmonds et al., 1953), and therefore the energy requirements of the drying process. Thus, it is relevant to specify these factors when quantifying the energy use and efficiency of a drying system.

To assess the thermal energy performance of a drying process, the specific heat consumption, calculated by dividing the thermal energy supplied to the dryer ($E_{\text{thermal}}$) by the mass of water evaporated from the grain ($m_w$) (Mujumdar, 1995), may be used to represent the energy use of a dryer on a per unit mass of water removed basis. The specific heat consumption to dry grains has been reported to range from 2,330 to 2,790 kJ/kg water removed using natural air, 2,790 to 3,490 kJ/kg water removed when using low Ts, 3,490 to 4,650 kJ/kg water removed for batch-in-bin
dryers, and 4,650 to 6,980 kJ/kg of water evaporated when drying at high Ts without recirculation (Hellevang and Reff, 1987). Brinker and Anderley (2012) reported that a commercial, cross-flow dryer with heat recovery consumed on average 3,520 kJ/kg water removed when drying 21,590 tonnes (850,000 bu) of corn from an average initial MC (MC$_i$) of 18%$^2$ to 15% using an average ambient T of 6.6°C (44°F).

Because there is little information regarding energy use and efficiency for rice drying, measuring the amount of energy that is required to dry rice in large-scale driers and determining the energy efficiency is relevant. The objectives of this research were to measure the energy use and efficiency of a commercial, cross-flow dryer operating across a range of ambient and drying air conditions, as well as varying rice delivery MCs. A companion manuscript, “Energy use and efficiency of rice-drying systems. I. On-farm cross-flow dryer measurements”, will be herein referred to regarding concepts developed in that manuscript.

**MATERIALS AND METHODS**

**Dryer and drying system description**

Figure 1 shows a cross section of the commercial, cross-flow dryer (Twin inside dryer 3R4.5, Shanzer Dryer, Sioux Falls, SD, USA) used in this study and located at Corning, Arkansas. The configuration of the dryer consists of two sub-units with each comprising two drying columns and a hot-air plenum (HAP). Rice flows by gravity into each drying column from a garner bin positioned immediately above the dryer sub-units. The flow rate of rice through the columns is controlled by variable-speed augers located at the bottom of each column. Rice exiting the drying columns is combined and transported to concrete tempering/storage bins. Ambient air is forced through the dryer by a centrifugal fan (DWDI No 660 type BAF, Twin City Fan &

$^2$ All moisture contents are reported on a wet basis unless otherwise specified.
Blower, Minneapolis, MN). It is noted that the fan speed remained constant across drying runs; the volumetric flow rate of the drying air was approx. 4,500 m$^3$/min. After exiting the fan, the air is heated by a burner (MAXON, NP5) by direct combustion of natural gas before entering the dryer HAPs. From the HAP, the drying air passes through the rice columns perpendicular to the downward flow of the rice (Fig. 1). Screens are located on both sides of each drying column, allowing the drying air to enter and exit the columns (Fig. 1). The dryer is equipped with turnflows that are intended to reduce rice T and MC gradients across the column by exchanging the rice on the HAP side with that on the exhaust side; two turnflows are positioned ~ 4 m apart throughout each column.

Along with the aforementioned dryer, the drying system comprises several concrete tempering and storage bins. In this system, rice is usually dried in three passes, tempered after each pass and aerated in a storage bin after the final pass. A conventional drying procedure for incoming rice at 19 to 21% MC would be to dry to ~17% in the first pass. During the second pass, rice is usually dried from ~17% to ~14%. Finally, during the third pass, rice is dried from ~14 to ~12.5%. It is possible that a fourth pass is performed if the incoming rice MC exceeds 21%, or the desired MC of 12.5% is not reached during the third pass. After each drying pass, rice is conveyed to a concrete bin with a 7.6 m diameter and 30.5 m height to be tempered. After the final drying pass, rice is tempered and then intermittently aerated in storage bins that had 9 m diameter and 37 m height (surface area=28 m$^2$) using ambient air at a rate of 220 m$^3$/min (7,800cfm) for an apparent velocity of 7.8 m$^3$/min/m$^2$. 
Inlet and outlet locations at which rice was sampled for moisture content determination

Gas meter for natural gas consumption measurement

Ampere meter for electricity measurement

Fig. 1. Front view of the commercial, cross-flow dryer.
Energy tests

Four drying tests were conducted during the 2011 harvest season and three during the 2012 season. These tests comprised drying a lot of a cultivar mixture of long-grain rice with MC$_i$s ranging from 19.0 to 20.4% in 2011 and from 15.4 to 18.3% in 2012. Table 1 provides a summary of the tests. For the terminology of this manuscript, a “run” is a single pass of a given lot of rice through the dryer, and thus a drying test comprised multiple runs.

Energy measurements and calculations

The thermal energy requirements to dry rice were calculated using Eq. 1 (Maier & Bakker-Arkema, 2002):

$$E_{\text{thermal}} = \frac{V \times AE}{m_w}$$

(1)

$E_{\text{thermal}}$ is the thermal energy supplied to the dryer over the course of a drying run in kJ/kg of water removed

$V$ is the volume of natural gas used during a drying run in m$^3$

$AE$ is the available energy from natural gas; taken as 37,260 kJ/m$^3$, as provided by (Centerpoint Energy)

$m_w$ is the mass of water removed during each drying run in kg

Note: Thermal energy use for an entire test was calculated by summing the volumes of natural gas used ($V$) and the masses of water removed ($m_w$) for all runs comprising a test.

The volume of natural gas, which was recorded using a gas meter (F126 AEGIATP, FlowComptor by Turbines Inc) that had an accuracy of 0.5 to 1%, during each run was obtained as the difference between the gas meter reading at the end and at the beginning of each drying run. The mass of water removed during each run was calculated using Eq. 2 (Maier & Bakker-Arkema, 2002).

$$m_w = \frac{m_r \times (MC_i - MC_f)}{100 - MC_f}$$

(2)
$m_r$ is the mass of incoming rice dried in a drying run in kg
$MC_i$ is the average moisture content of the rice entering a drying run in %, w.b.
$MC_f$ is the average moisture content of the rice exiting a drying run in %, w.b.

The mass of incoming rice lots ranged from 731,470 to 856,050 kg (1.61 to 1.89 million lb) for the 2011 drying tests and from 750,638 to 780,000 kg (1.65 to 1.72 million lb) for 2012. The total mass of each rice lot was obtained by adding the mass of rice from individual trucks comprising a lot. The MCs entering and exiting the dryer throughout each drying run were measured by manually taking samples every 15 minutes from the inlet and outlet of the dryer (Fig. 1) and measuring MC using a moisture meter (Infratec 1229 Grain Analyzer, Foss Tecator) that had an accuracy of 0.02 percentage points of moisture. These 15-minute readings were averaged over the course of a run to represent the average MCs for a drying run. These average inlet and outlet MCs were used in Eq. 2 to calculate the moisture removed during a given run.

Electrical energy ($E_{elec}$) to operate the fans was calculated by first measuring the electrical current drawn by the fan motor every 15 minutes using an ampere meter (Square D (Integrated in motor control center)). The average power was calculated via Eq. 3 for each drying run; this value was then multiplied by the fan operating duration, divided by $m_w$ and divided by the power factor in order to obtain the total kVA to operate the fan during each drying run. Electrical energy was measured in terms of kWh per kg water removed but expressed for convenience of comparison in terms of kJ per unit mass water removed.

$$P = V \times I \times \sqrt{3}$$  \hspace{1cm} (3)

$P$ is the average electrical power drawn by the fan during a drying run in W
$V$ is the voltage in volts ~ 480 V
$I$ is the average electrical current drawn by the fan motor during a drying run in ampere

Note:
The power factor was taken as 0.884 as provided by the electric company.
**Energy efficiency calculation**

To determine energy efficiency, the theoretical energy required \((E_{theo})\) for moisture removal (Kudra, 2004), which represents the minimum energy required to dry rice (Billiris et al. 2011), is typically compared to the specific heat consumption. Thus, thermal energy efficiency was calculated by dividing \(E_{theo}\) by \(E_{thermal}\) following the procedure described in Billiris and Siebenmorgen (2013).

**Temperature and relative humidity measurements**

The T and RH of the ambient air and that inside the HAP were measured continuously throughout all drying runs using two types of sensors (Hobo U12-011 and Pro v2 U23-001, Onset Corporation, Bourne, MA, USA) as described in Billiris and Siebenmorgen (2013).

All statistical analyses were performed using JMP Pro 10 software (SAS Institute, Inc.). Significance of independent variables was set at \(\alpha=0.05\).
Table 1. Synopsis of drying-energy tests performed using a commercial, cross-flow drier in 2011 and 2012.

<table>
<thead>
<tr>
<th>Test</th>
<th>MC&lt;sub&gt;i&lt;/sub&gt;* (first pass) (% w.b.)</th>
<th>Number of passes</th>
<th>Drying pass temperatures (T&lt;sub&gt;da&lt;/sub&gt;/ T&lt;sub&gt;a&lt;/sub&gt;) **</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>First °C</td>
<td>Second °C</td>
</tr>
<tr>
<td>1</td>
<td>20.4</td>
<td>4</td>
<td>68/23</td>
<td>58/23</td>
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<td>19.4</td>
<td>3</td>
<td>70/23</td>
<td>59/12</td>
</tr>
<tr>
<td>4</td>
<td>19.4</td>
<td>4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Drying season: September – October 2011**

<table>
<thead>
<tr>
<th>Test</th>
<th>MC&lt;sub&gt;i&lt;/sub&gt;* (first pass) (% w.b.)</th>
<th>Number of passes</th>
<th>Drying pass temperatures (T&lt;sub&gt;da&lt;/sub&gt;/ T&lt;sub&gt;a&lt;/sub&gt;) **</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.5</td>
<td>2</td>
<td>54/23</td>
<td>39/26</td>
</tr>
<tr>
<td>2</td>
<td>18.3</td>
<td>3</td>
<td>68/20</td>
<td>61/18</td>
</tr>
<tr>
<td>3</td>
<td>15.4</td>
<td>3</td>
<td>60/25</td>
<td>35/11</td>
</tr>
</tbody>
</table>

**Drying season: July - October 2012**

*MC<sub>i</sub> is the initial moisture content of the rice entering the first pass

**T<sub>da</sub>** is the average temperature of the drying air inside the hot-air plenum during each run; T<sub>a</sub> is the average ambient temperature during each run.

N/A refers to information that was not available due to problems with sensors.

#Refers to runs in which the burner was off during part, or all, of the run.
RESULTS AND DISCUSSION

Energy requirements and efficiency

Table 2 shows MC$_i$, MC$_f$, $E_{\text{theo}}$, $E_{\text{thermal}}$ and $E_{\text{elec}}$ for each of the energy tests conducted in 2011 and 2012. Thermal energy use ranged from 6,900 to 9,670 kJ/kg water removed in 2011 and from 8,810 to 9,620 kJ/kg water removed in 2012. These $E_{\text{thermal}}$ values were within the range reported by Otten et al. (1980) for corn (from 3,860 to 11,960 kJ/kg water). However, the $E_{\text{thermal}}$ values for the cross-flow dryer used in this study were greater than the 5,185 kJ/kg water reported by Bakker-Arkema (1983) for a cross-flow dryer when drying rice from 16.4 to 13.4% using a drying air $T$ of 66°C. It might be that the differences in energy use found between this study and that of Bakker-Arkema were due to several factors, including the lesser average drying air $T$s of this study. In addition, the average MC$_f$ of the rice used for this study (12.3%) was less than that of Bakker-Arkema’s study (13.4%). Since it is increasingly more difficult to remove water as rice MC decreases (Billiris et al. 2011; Tsami et al., 1990; Zuritz & Singh, 1985), this could be another reason why the energy requirements of this study were greater.

The energy use of the commercial dryer used in this study was greater than that of the tested on-farm dryer (Billiris and Siebenmorgen, 2013), which ranged from 2,840 to 5,310 kJ/kg water. This might be in part due to the greater average rice MC$_f$ attained with the on-farm dryer (13.2%), as explained with the comparison to the Bakker-Arkema study.

Electrical energy requirements were considerably lesser than $E_{\text{thermal}}$; on average, $E_{\text{elec}}$ was 4% of $E_{\text{thermal}}$ in 2011 and 5% of $E_{\text{thermal}}$ in 2012 (Table 2). These results are somewhat similar to those of Hellevang and Reff (1987) who reported that $E_{\text{thermal}}$ accounted for 98% of the total energy requirements when drying using high air $T$s. Electrical energy use ranged from 300 to 400 kJ/kg water removed in 2011 and from 410 to 630 kJ/kg water removed in 2012 (Table 2).
Thermal energy efficiency, which was calculated by dividing $E_{\text{theo}}$ by $E_{\text{thermal}}$, ranged from 26 to 36% for the tests conducted in 2011 and from 27 to 29% for the tests conducted in 2012 (Table 2). Otten et al. (1980) reported energy efficiencies, which were calculated as the ratio of the heat of vaporization of water at specified grain conditions to the experimentally-determined energy use for five drying tests, ranging from 24 to 64% when drying corn from ~ 25 to ~ 15% MC using a commercial cross-flow dryer; the authors explained that differences in energy use and efficiency among tests could be due to several factors including ambient, drying air, and grain conditions. Otten et al. (1980) reported an additional drying test, in which corn was dried from 32 to 18% MC, that had the greatest energy efficiency (76%), suggesting that grain MC is a critical factor affecting drying energy use and efficiency. In the study herein, ambient, drying air and grain conditions varied considerably among tests, which may explain the differences in energy use and efficiency among tests.

In general, thermal efficiencies obtained in the first part of this study using an on-farm dryer (from 47 to 90%) were greater than those of the commercial dryer used in this part of the study. While both cross-flow dryers, the dryers are different in terms of scale and to a certain extent, the configuration. Kudra (2003), suggests that energy use and efficiency may be affected by dryer design factors such as shape, configuration and mode of heating. It might also be that the on-farm drying process was in part more energy efficient due to pre-heating the rice in a pre-heating bin prior to the first drying pass. Heating of the rice in the commercial dryer occurred in the drying columns during the first drying pass.

In order to better evaluate test variables, energy use was also assessed on a per pass basis. Figure 2 shows $E_{\text{elec}}$, $E_{\text{theo}}$ and $E_{\text{thermal}}$ for the four tests conducted in 2011 in terms of energy use per drying pass. Thermal energy use ranged from ~7,000 to 9,000 kJ/kg water removed for most
passes. There were a few exceptions. E.g., the second pass of test 3 required considerably more energy than the other drying passes; the average ambient T during this pass was 12°C, which was considerably less than during the other tests/passes. Similar instances were reported in Part 1, in which the drying passes that required the most energy corresponded to those that had the least average ambient Ts.

The electricity required to operate the fans (E_{elec}), in terms of kJ per kg water removed, progressively increased with the drying pass number (Fig. 2). Because greater drying air Ts were used for the early passes (Table 1), the drying rates were greater, and consequently the drying durations to remove a given amount of water were less. Since the operating duration is a fundamental factor affecting the amount of electricity used by the fans, E_{elec} was less for the earlier passes. This is in agreement with Morey et al. (1976) who reported that energy requirements to power fans delivering air to a cross-flow dryer increased as drying air T decreased; this effect was more pronounced at greater airflow rates. Hellevang and Reff (1983) reported that $E_{elec}$ could be similar to $E_{thermal}$ when drying at low Ts. It is noted that the fourth pass of test 4 had greater $E_{theo}$ than $E_{thermal}$; this was because natural air was used for drying during the entire run. Thus, the only energy used was that of the fans; whereas the energy for drying was provided by that naturally available in the ambient air.
Table 2. Energy requirements and energy efficiency of the tests conducted in 2011 and 2012.

<table>
<thead>
<tr>
<th>Test</th>
<th>MC_i # (first pass) (% w.b.)</th>
<th>MC_f ## (final pass) (% w.b.)</th>
<th>E_theo * kJ/kg</th>
<th>E_thermal ** kJ/kg</th>
<th>E_elec *** kJ/kg</th>
<th>η_th &amp;%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.4</td>
<td>12.2</td>
<td>2,530</td>
<td>8,700</td>
<td>360</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>19.0</td>
<td>13.0</td>
<td>2,510</td>
<td>7,380</td>
<td>380</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>19.4</td>
<td>12.7</td>
<td>2,530</td>
<td>9,670</td>
<td>400</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>19.4</td>
<td>12.5</td>
<td>2,520</td>
<td>6,900</td>
<td>300</td>
<td>36</td>
</tr>
</tbody>
</table>

**Drying season: September – October 2011**

<table>
<thead>
<tr>
<th>Test</th>
<th>MC_i # (first pass) (% w.b.)</th>
<th>MC_f ## (final pass) (% w.b.)</th>
<th>E_theo * kJ/kg</th>
<th>E_thermal ** kJ/kg</th>
<th>E_elec *** kJ/kg</th>
<th>η_th &amp;%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.5</td>
<td>12.2</td>
<td>2,620</td>
<td>9,620</td>
<td>510</td>
<td>27</td>
</tr>
<tr>
<td>2</td>
<td>18.3</td>
<td>12.2</td>
<td>2,560</td>
<td>8,810</td>
<td>410</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>15.4</td>
<td>11.7</td>
<td>2,660</td>
<td>9,300</td>
<td>630</td>
<td>28</td>
</tr>
</tbody>
</table>

**Drying season: July - October 2012**

#MC_i is the initial moisture content of the rice entering the first pass
##MC_f is the final moisture content of the rice exiting the final pass
*E_theo is the theoretical energy in kJ/kg water removed
**E_thermal is the measured thermal energy in kJ/kg water removed
***E_elec is the measured electrical energy to power the fan in kJ/kg water removed
& η_th is the thermal energy efficiency, calculated as E_theo divided by E_thermal

Note:
E_theo for each test was calculated as the weighted average of the theoretical energy requirements calculated for each drying
Fig. 2. Electrical ($E_{\text{elec}}$), theoretical ($E_{\text{theo}}$) and thermal ($E_{\text{thermal}}$) energy requirements, to dry rice from the indicated initial moisture contents ($MC_i$) for the four drying tests conducted in 2011. Electrical energy was measured in terms of kWh per kg water removed but expressed as kJ per kg water removed.
Effect of drying air and ambient temperature on energy use

Thermal energy requirements

The effect of drying air $T$ on energy use is shown in Fig. 3A. A trend suggesting that as drying air $T$ increased $E_{\text{thermal}}$ increased was observed, however, there was no significant correlation (Fig. 3A). A possible explanation for the apparent increase in $E_{\text{thermal}}$ with increasing drying air $T$ may be that energy use was not only affected by the drying rate of the rice but also by the rate of fuel consumption required for increasing the drying air $T$. An increase in drying air $T$ may increase rice drying rate (leading to a shorter drying duration) but it also invariably increases the rate of fuel consumption. Thus, the net effect of drying air $T$ on energy use is a balance between the increase in drying rate and the increase in the fuel consumption rate. If the increase in the rate of fuel consumption was more impactful than the increase in drying rate, energy use would increase as drying air $T$ increases as suggested in Fig. 3A. Hellevang and Reff (1987) reported energy requirements ranging from 2,790 to 3,490 kJ/kg water when drying at low $T_s$ and from 4,650 to 6,980 when drying at high $T_s$ without recirculation. However, Morey et al. (1976) reported that when drying air $T$ increased from 55 to 115 °C, energy use decreased from 8,500 to 5,500 kJ/kg water removed when drying corn and explained that the decrease in drying duration compensated the increase in fuel consumption to heat the air. It may also be that the effect of drying air $T$ on $E_{\text{thermal}}$ is related to the degree of saturation of the exhaust air (Kudra, 2004). Thus, in order to explain the variability in $E_{\text{thermal}}$ among runs and among dryers in depth, it may be necessary to also assess HAP-to-exhaust air-condition changes and correlate these profiles to energy efficiencies.

Figure 3B shows there was an apparent, yet statistically insignificant, reduction in energy use with ambient air $T$ increases. The inability to control other factors affecting $E_{\text{thermal}}$, such as
drying air T and MC, during tests may have led to the lack of correlation between \( E_{\text{thermal}} \) and ambient air T. It might be that the wide range of drying air Ts from 12 to 70°C that occurred in this study (Table 1) may have masked a correlation between \( E_{\text{thermal}} \) and ambient T. The opposite scenario was observed for the on-farm dryer; drying air Ts ranged narrowly from 43 to 55°C and ambient T was linearly and inversely correlated to \( E_{\text{thermal}} \). It is possible that for the on-farm dryer, drying air T did not vary sufficiently to affect the correlation between \( E_{\text{thermal}} \) and ambient T; whereas for the commercial dryer the variation in drying air T was such that the correlation between \( E_{\text{thermal}} \) and ambient T was masked. Morey et al. (1976) reported that \( E_{\text{thermal}} \) to dry corn from 24 to 15% decreased from ~ 10,000 to 6,000 kJ/kg water removed when ambient T increased from -10 to 20°C; it is noted that the authors used computer models to predict \( E_{\text{thermal}} \), which allowed them to maintain a constant drying air T at 95°C.

**Electrical energy requirements**

Electrical energy use, in terms of energy per unit mass water removed, was linearly and inversely correlated to drying air T (\( R^2 = 0.86 \)) (Fig. 3A). It is possible that because the rate of power drawn by the fans was somewhat constant (airflow rate remained constant among drying runs), the main factor affecting \( E_{\text{elec}} \) was the drying rate, and resultant duration required for a drying run. As such, as drying air T increases, drying rate increases and drying duration decreases, \( E_{\text{elec}} \) would hypothetically decrease. There was no correlation between \( E_{\text{elec}} \) and average ambient T (Fig. 3B). This is reasonable given that ambient T does not affect drying rate.
Fig. 3. Thermal ($E_{\text{thermal}}$) and electrical ($E_{\text{elec}}$) measured energy use to dry rice per drying pass as a function of drying air temperature (A) and as a function of ambient air temperature (B) in terms of energy per unit mass water removed for the drying tests conducted in 2011 and 2012. Electrical energy was measured in terms of kWh per kg water removed but expressed as kJ per kg water removed.
Prediction of energy use and efficiency

Energy use

Considering that $E_{\text{thermal}}$ might be affected by several variables simultaneously, it was reasoned that a multiple linear regression analysis may be appropriate to describe $E_{\text{thermal}}$ data. It was reasoned that the amount of energy required to heat the ambient air to the drying air $T$, would be an important parameter affecting $E_{\text{thermal}}$; thus, the difference between drying air $T$ and ambient $T$, referred to as $T_{da} - T_a$, was used as an independent variable of the model. It was also reasoned that the amount of moisture removed per pass, expressed per unit of rice dry matter, would also significantly impact energy use. Multiple linear regression analysis was used to obtain the regression coefficients ($b_0$, $b_1$ and $b_2$) of Eq. 4.

$$E_{\text{thermal}} = b_1(T_{da} - T_a) + b_2\left(\frac{m_w}{dm}\right) + b_0 \quad R^2=0.65 \quad \text{RMSE}=1049 \quad (4)$$

$b_0$ = 6,180
$b_1$ = 250
$b_2$ = -432,723

$dm$ is the mass of rice dry matter in kg

Dry matter was calculated using Eq. 5.

$$dm = \left(1 - \frac{MC_i}{100}\right) m_r \quad (5)$$

$MC_i$ is the average moisture content of the rice entering a drying run in $\%$, w.b.
$m_r$ is the mass of incoming rice dried in a drying run in kg

The difference between drying air $T$ and ambient $T$ was linearly correlated to $E_{\text{thermal}}$. This is reasonable since the greater $T_{da} - T_a$, the greater the energy required to heat the air from ambient to drying $T$. Likewise, the amount of water removed per unit mass dry matter ($m_w/dm$) was linearly and inversely correlated to $E_{\text{thermal}}$. This behavior is graphically represented in Fig. 4A, in which for any given $T_{da} - T_a$, $E_{\text{thermal}}$ increased as $m_w/dm$ decreased. This may be explained
by the fact that low values of \( \frac{m_w}{dm} \) such as 0.006, in which little moisture was removed per unit mass dry matter, usually corresponded to the third drying pass, in which case the rice was in the low-MC range; whereas high values of \( \frac{m_w}{dm} \) such as 0.020, in which a greater amount of moisture is removed per unit mass dry matter, usually corresponded to the first drying pass, at greater MCs. \( E_{\text{thermal}} \) increasing as \( \frac{m_w}{dm} \) decreased could then be explained by the fact that moisture removal becomes increasingly difficult as MC decreases (Billiris et al. 2011; Tsami et al., 1990; Zuritz & Singh, 1985). This is in agreement with Morey et al. (1976) who predicted that \( E_{\text{thermal}} \) increased as MC decreased when drying corn.

The model explains 65% of the variability in \( E_{\text{thermal}} \). It is possible that there are other factors affecting \( E_{\text{thermal}} \), such as incoming rice \( T \), which varies depending on the ambient \( T \), particularly for rice entering the first pass. The degree of saturation of the exhaust air, which determines how much of the energy supplied to the drying air is used to remove water, could also impact \( E_{\text{thermal}} \). The impacts of these factors on \( E_{\text{thermal}} \) will be assessed in a subsequent manuscript.

The variation in \( E_{\text{elec}} \) was adequately explained by the effect of drying air \( T \). Thus, simple linear regression analysis was used to obtain the regression coefficients \( (b_0 \text{ and } b_1) \) of Eq. 6.

\[
E_{\text{elec}} = b_1 T_{\text{da}} + b_0 \quad R^2 = 0.86 \quad \text{RMSE} = 108
\] (6)

\( b_0 = 1.366 \)
\( b_1 = -17.0 \)

\( E_{\text{elec}} \) is electrical energy requirements in kJ/kg water removed
\( T_{\text{da}} \) is drying air \( T \) in °C

Equation 6 confirms as previously discussed and illustrated in Fig. 3A, that \( E_{\text{elec}} \) was linearly and inversely correlated to drying air \( T \).
Thermal Efficiency

Multiple linear regression analysis was used to obtain the regression coefficients \( b_0, b_1 \) and \( b_2 \) of Eq. 7.

\[
\eta_{th} = b_1 (T_{da} - T_a) + b_2 \left( \frac{m_w}{dm} \right) + b_0 \quad R^2=0.74 \quad \text{RMSE}=3.8 \quad (7)
\]

\( b_0 = 40.8 \)
\( b_1 = -1.01 \)
\( b_2 = 1,682 \)

\( \eta_{th} \) is thermal energy efficiency of a drying run.

A graphical representation of this model is shown in Fig. 4B, which shows that as \( T_{da} - T_a \) increased, energy efficiency decreased. This is reasonable since energy efficiency would be expected to decrease as the energy required to heat ambient air to the drying \( T \) increased.

Drying cost

The US Energy Information Administration (2012) reported the price of natural gas to be $3.1/million kJ ($3.3/million Btu) in 2011 and $2.6/million kJ ($2.8/million Btu) in 2012. Thus, drying costs associated with \( E_{\text{thermal}} \) were calculated using a $2.8/million kJ ($3.0/million Btu) price for natural gas for the 2011 and 2012 harvest seasons corresponding to an average price for the two years. In addition, the cost of electricity was taken to be ¢4.6/kWh, which was obtained by multiplying the average household electricity price for Arkansas of ¢7.7/kWh (Institute for Energy Research, 2012) by 0.6, which was the fraction of the household price for electricity that was paid by industries in the U.S. (IEA, 2010).

The total cost to dry rice from \( \text{MC}_i \) to \( \text{MC}_f \) (~12.5%) using the commercial dryer ranged from 2.4 to 3.3 ¢/kg water removed in 2011 and from 3.1 to 3.5 ¢/kg water removed in 2012. Eighty four percent of the drying cost was associated with \( E_{\text{thermal}} \) and the remaining 16% was
Equation 8 was developed to predict the total cost to dry rice in terms of cents per unit mass water removed.

\[ \text{Cost}_{\text{tot}} = 2.8^{-4}E_{\text{thermal}} + 1.3^{-3}E_{\text{elec}} \]  

\[ \text{Cost}_{\text{tot}} = 5.1^{-2}T_{\text{da}} - 7.0^{-2}T_a + 121 \left( \frac{m_w}{dm} \right) + 3.2 \]

Cost\text{tot} is the total cost to dry rice from MC_i to MC_f for a given drying air and ambient T including the cost to operate the burner and fans in ¢/kg water removed.

Figure 5 shows the family of curves of Cost\text{thermal} and Cost\text{tot} as a function of T_{\text{da}}-T_a for three levels of m_w/dm. To generate these curves, ambient T ranged from 15 to 25°C and drying air T ranged from 30 to 70°C. It is observed that as T_{\text{da}}-T_a increased, drying cost, in terms of ¢/kg water removed, increased and that as m_w/dm increased drying cost decreased; similar to the behavior observed for energy use. In addition, Fig. 5 shows that as T_{\text{da}}-T_a increased, the difference between Cost\text{tot} and Cost\text{thermal} decreased, reflecting the increasing proportion of E\text{thermal} in the total energy requirements.
Fig. 4. Family of curves predicting thermal energy use ($E_{\text{thermal}}$) (A) and thermal energy efficiency (B) as a function of the difference between drying air temperature and ambient temperature ($T_{\text{da}} - T_{\text{amb}}$) at the indicated levels of water removed per mass dry matter ($m_w/dm$) for drying tests conducted in 2011 and 2012. Drying air temperatures ranged from 30 to 70°C and ambient air temperatures ranged from 10 to 25°C.
Fig. 5. Family of curves predicting total drying cost (Cost$_{tot}$) and thermal drying cost (Cost$_{thermal}$), in terms of cents per unit mass water removed, as a function of the difference between drying air temperature and ambient temperature (T$_{da}$-T$_{a}$) at the indicated levels of water removed per mass dry matter (m$_w$/dm) for the drying tests conducted in 2011 and 2012. Drying air temperatures ranged from 30 to 70°C and ambient air temperature ranged from 10 to 25°C.
CONCLUSIONS

Thermal energy use ($E_{\text{thermal}}$) to dry rice in the commercial cross-flow dryer described herein ranged from 6,900 to 9,670 kJ/kg water removed for seven tests conducted during the 2011 and 2012 harvest seasons. Electrical energy use ($E_{\text{elec}}$) to operate fans delivering drying air to the dryer ranged from 300 to 630 kJ/kg water removed. Electrical energy use decreased linearly as drying air T increased. Thermal energy efficiency, which was calculated as the ratio of $E_{\text{thermal}}$ to theoretical energy requirements ($E_{\text{theo}}$), ranged from 26 to 36%. Drying cost ranged from 2.3 to 3.3 ¢/kg water removed. Drying air T, ambient air T and rice MC were found to be relevant factors affecting energy use and efficiency. Multiple linear regression analysis was used to develop equations that predict $E_{\text{thermal}}$ and thermal energy efficiency when drying rice from a given MC$_i$ to a desired MC$_f$ at given drying air and ambient air Ts. Thermal energy use was linearly correlated to the difference between drying air T and ambient air T ($T_{\text{da}}$-$T_a$). In addition, $E_{\text{thermal}}$ was linearly and inversely correlated to the amount of water removed per pass, expressed per unit mass of dry matter. The multiple linear regression model explained 65% of the variation in $E_{\text{thermal}}$; thus, it was reasoned that there might be other factors affecting energy use, such as the degree of saturation of the exhaust air and burner efficiency. The effects of these factors on energy use will be investigated in a subsequent manuscript.
LITERATURE CITED


I verify that Alejandra Billiris provided over 50% of the research work published in the following manuscript that is included in her dissertation:

Energy use and efficiency of rice-drying systems. II. Commercial dryer measurements.

Dr. Terry J. Siebenmorgen
V. OVERALL CONCLUSIONS

Since rice drying is known to be such an energy-intensive unit operation, the purpose of this dissertation was to assess the energy use and efficiency of commercial rice dryers. The three main objectives of this dissertation were: 1) to determine the theoretical energy required to dry rice as a function of the initial and final moisture content of the rice, which is needed to calculate energy efficiency; 2) to quantify, and assess the factors impacting, thermal energy use and efficiency when using an on-farm, cross-flow dryer operating across a range of ambient and drying conditions; 3) to quantify thermal and electrical energy use and efficiency of a commercial cross-flow dryer operating across a range of ambient and drying conditions. The overall aim of this dissertation was to provide useful information regarding energy use and efficiency of commercial, cross-flow dryers that could be used as inputs of a rice life cycle assessment and to provide recommendations on drying practices that lead to energy savings.

From the first objective, it was found that theoretical energy requirements, in terms of energy per unit mass water removed, to dry rice to 12.5% moisture content increased exponentially as initial moisture content decreased. Energy requirements to dry rice also increased as final moisture content decreased. Additionally, differences in energy requirements were observed among cultivar types. Medium-grain “Jupiter” required more energy to be dried than long-grain cultivars. Additionally, parboiled rice required less energy than non-parboiled rice. Equations were developed that predict theoretical energy requirements to dry rice from an initial moisture content to a desired final moisture content. These equations were subsequently used as a basis of comparison to calculate the energy efficiency of rice dryers.

To fulfill the second objective, a two-year study was conducted to measure the energy required to dry rice using an on-farm, cross-flow dryer. Energy requirements ranged from 2,770
to 5,170 kJ/kg water removed when harvest moisture contents ranged from 16.6 to 21.7% for the five tests performed in 2011 and from 3,640 to 5,690 kJ/kg water removed when harvest moisture contents ranged from 17.4 to 18.2% for the three tests performed in 2012. Thermal energy efficiencies ranged from 48 to 92% in 2011 and from 45 to 70% in 2012. It was found that the difference between drying air temperature and ambient air temperature, as well as the amount of water removed, expressed on a per unit mass of rice dry matter basis, significantly impacted energy use. Equations were developed using multiple linear regression analysis that predict energy use, energy efficiency and drying cost as a function of these two parameters.

To fulfill the third objective, the energy required to dry rice using a commercial cross-flow dryer was measured. Thermal energy requirements ranged from 6,900 to 9,670 kJ/kg water removed when initial moisture contents ranged from 19.0 to 21.7% for the four tests performed in 2011 and from 8,800 to 9,620 kJ/kg water removed when initial moisture contents ranged from 15.4 to 18.3% for the three tests performed in 2012. Electrical energy use, which was measured in terms of kWh per kg water removed, but expressed for convenience of comparison as kJ per kg water removed, ranged from 300 to 400 kJ/kg water removed in 2011 and from 410 to 630 in 2012. Thermal energy efficiency ranged from 26 to 36% in 2011 and from 27 to 29% in 2012.

Thermal energy requirements were linearly correlated to the difference between drying and ambient air temperature and linearly and inversely correlated to the amount of water removed per mass dry matter for both, the on-farm and the commercial dryer. Equations were developed that predict energy use, energy efficiency and drying cost as a function of these two parameters.
The equations developed for the on-farm and the commercial cross-flow dryers provide valuable information regarding the effects of drying and ambient air temperature, as well as the effects of the amount of water removed per mass dry matter of rice on energy use and efficiency. These equations serve to assess energy requirements of different drying scenarios. Therefore, rice-drying personnel could use these equations as a tool to select drying conditions that lead to energy savings. For instance, based on the initial moisture content and the ambient air temperature, an assessment of the combinations of final moisture content and drying air temperature that lead to energy savings could be performed. The dryer throughput should be taken into account in this assessment so as to avoid slowing down the drying capacity of the facility. In this way, drying procedures could be developed that specify drying air temperature and final moisture content based on the initial moisture content and ambient air temperature with the aim of minimizing energy requirements while maintaining the desired drying throughput. In addition, rice-drying personnel could adjust their drying schedule based on the findings of this study. For instance, it was found that the on-farm dryer required considerably more energy for the second pass, which took place during the night hours, than for the first pass, which took place during the day hours. The greater energy requirements for the second pass were correlated to the lesser temperatures at night. Thus, drying schedules could be adjusted to take advantage of the greater ambient temperatures during the day.

The models developed to predict actual energy requirements explained 80% of the variation in thermal energy use for the on-farm dryer and 65% of the variation in thermal energy use for the commercial dryer. It is noted that in the case of the on-farm dryer incoming grain temperature was relatively constant because rice was pre-heated before entering the dryer. However, the incoming grain temperature varied for the first drying pass of the commercial
dryer; this could also be contributing to the variation in thermal energy use of the commercial dryer. It is also reasoned that there are other factors affecting thermal energy use besides those included in the multiple regression model. It may be that the degree of saturation of the exhaust air, which determines how much of the drying capacity of the drying air was not utilized, has an impact on thermal energy use. Additionally, an assessment of burner efficiency and energy losses from the dryer may help explain some of the variation in thermal energy use. Thus, future studies should focus on assessing hot air plenum-to-exhaust air-condition changes and correlate these profiles to energy efficiencies. These studies may address the unexplained variation in thermal energy use found in the herein study.