ENERGY USE AND EFFICIENCY OF RICE-DRYING SYSTEMS II. COMMERCIAL, CROSS-FLOW DRYER MEASUREMENTS

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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 with initial moisture contents ranging from 19.0% to 21.7% wet basis and three tests were conducted during the 2012 harvest using rice with initial 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. Thermal energy efficiency was calculated by dividing theoretical energy requirements by the measured thermal energy requirements. Thermal energy requirements to dry rice ranged from 6,900 to 9,670 kJ/kg water removed in 2011 and from 8,810 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, accounted for ~4% to 5% 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. Thermal energy efficiency ranged from 26% to 36% in 2011 and from 27% to 29% in 2012.*

Keywords. *Commercial dryer, Rice drying, Electrical energy requirements, Thermal energy efficiency, Thermal energy requirements.*

Rice drying is an energy-intensive process (Verma,1994; Thakur and 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. In North America, the most widely used type of dryer 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 and 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. Another factor affecting the energy requirements to dry rice is grain moisture content (MC), since it is increasingly more difficult to remove water as rice MC decreases, which in turn affects the net heat of sorption of water in foodstuffs (Zuritz and Singh, 1985; Tsami et al., 1990; Aviara et al., 2004; Toğrul and Arslan, 2006). Other factors, such as the type and variety of grain, the drying air relative humidity (RH) and airflow rate affect the drying rate (Simmonds et al., 1953; Henderson and Pabis, 1961; Morey et al., 1976; Cnossen et al., 2002; Iguaz et al., 2003; Aviara et al., 2004), 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 energy performance of a drying process, the specific heat consumption, calculated by dividing the energy supplied to the dryer by the mass of water evaporated from the grain (mw) (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 the energy requirements for a commercial, cross-flow dryer with heat recovery were 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% (All moisture contents are reported on a wet basis unless otherwise specified.) to 15% using an average ambient T of 6.6°C (44°F).

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There is little information regarding energy use and efficiency for drying rice; thus, it is appropriate to quantify the energy requirements and energy efficiency of commercial rice dryers. 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 article.

Materials and Methods

Dryer and Drying System Description

A commercial, cross-flow dryer (Twin inside dryer 3R4.5, Shanzer Dryer, Sioux Falls, S. Dak.), which had a holding capacity of 2,340 bu (47,700 kg), located at Corning, Arkansas, was used in this study. Figure 1 shows a cross section of the dryer tested. 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 and Blower, Minneapolis, Minn.). It is noted that the fan speed remained constant across drying runs; the volumetric flow rate of the drying air was approximately 4,500 m^3/min. After exiting the fan, the air is heated by a burner (NP5, MAXON Corp., Muncie, Ind.) 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

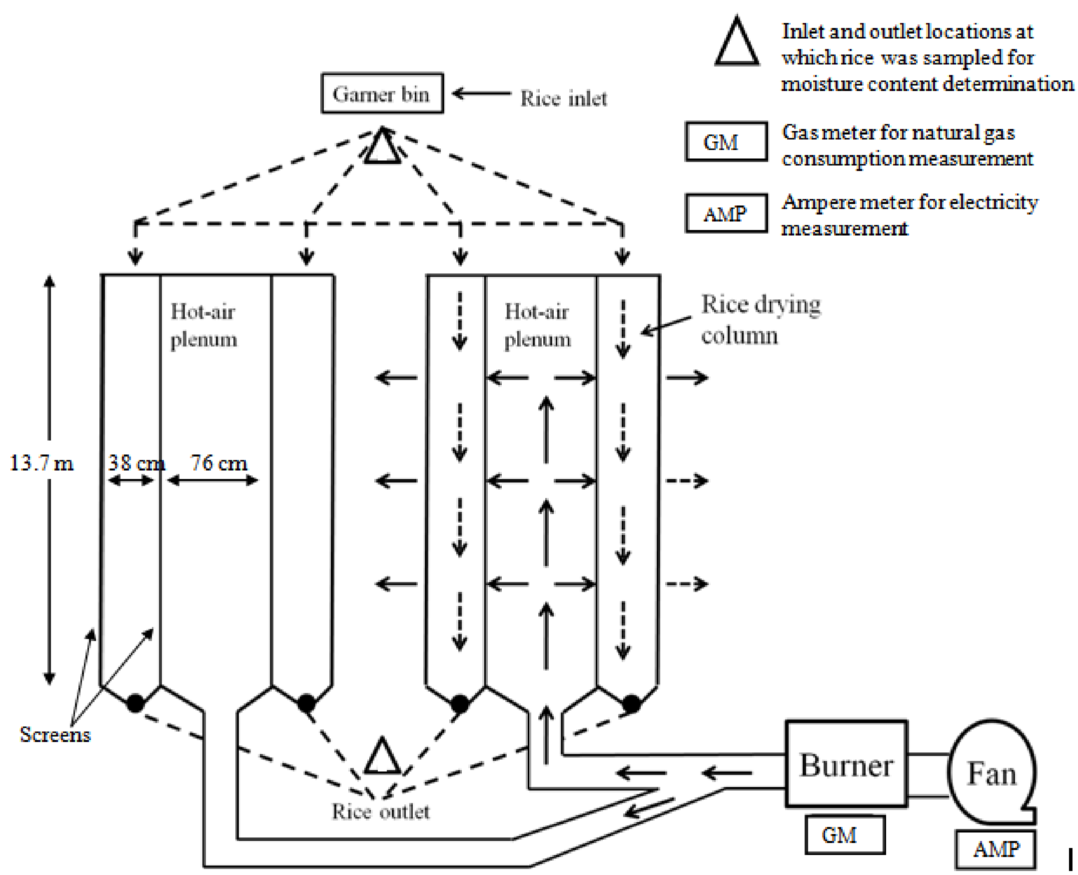


Figure 1. Front view of the commercial, cross-flow dryer.

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 $m^3/min/m^2$.

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 MCs 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 article, a "run" is a single pass of a given lot of rice through the dryer, and thus a drying test comprised multiple runs.

Energy Measurement and Calculation

The thermal energy requirements ($E_{thermal}$) to dry rice were calculated using equation 1 (Maier and Bakker-Arkema, 2002):

$$E_{thermal} = \frac{V \times AE}{m_w} \tag{1}$$

$E_{thermal}$ = the thermal energy supplied to the dryer in kJ/kg water removed,
V = the volume of propane gas used (m^3),
AE = the available energy from natural gas; taken as 37,260 kJ/m^3, as provided by (Centerpoint Energy, Houston, Tex.),
m_w = the mass of water removed during each drying run (kg).

Note: Thermal energy use for an entire test was calculated by summing the volumes of propane 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., Altus, Okla.) 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 equation 2 (Maier and Bakker-Arkema, 2002).

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

m_r = the mass of incoming rice dried in a drying run (kg),
MC_i = the average moisture content of the rice entering a drying run (%, w.b.),
MC_f = the average moisture content of the rice exiting a drying run (%, 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 drying durations to dry the aforementioned rice lots ranged from 8.2 to 11 h in 2011 and from 9.2 to 12.0 h in 2012. The MCs entering and exiting the dryer throughout each drying run were measured by manually taking samples every 15 min from the inlet and outlet of the dryer (fig. 1) and measuring MC using a moisture meter (Infratec 1229 Grain Analyzer, Foss Tecator), which was available at the drying facility. These 15-min 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 equation 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 min using an ampere meter [Square D (Integrated in motor control center)]. The average power was calculated via equation 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. In order to allow a comparison between thermal and electrical energy requirements, electrical energy requirements were also converted to the terms of kJ per unit mass water removed.

$$P = V \times I \times \sqrt{3} \tag{3}$$

P = the average electrical power drawn by the fan during a drying run (W),
V = the voltage (volts ~ 480 V),

Table 1. Synopsis of drying-energy tests performed using a commercial, cross-flow drier in 2011 and 2012.

Test	Natural Gas Consumed (m^3)	No. of Passes	Drying Pass Temperatures (T_{da}, T_a)[a] First (°C)	Second (°C)	Third (°C)	Fourth (°C)
Drying Season: September-October 2011						
1	15,960	4	68, 23	58, 23	53, 22	37, 14
2	12,480	3	65, 18	54, 25	38, 25[b]	….
3	14,830	3	70, 23	59, 12	38 ,25[b]	….
4	11,530	4	N/A	N/A	N/A	N/A[b]
Drying Season: July-October 2012						
1	7,300	2	54, 23	39, 26	….	….
2	13,180	3	68, 20	61, 18	20 ,12[b]	….
3	8,800	3	60, 25	35, 11	15 ,15[b]	….

[a] T_{da} is the average temperature of the drying air inside the hot-air plenum during each run;
T_a is the average ambient temperature during each run.
N/A refers to information that was not available due to problems with sensors.
[b] Refers to runs in which the burner was off during part, or all, of the run.

I = the average electrical current drawn by the fan motor during a drying run (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 (Etheo) 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 Etheo by Ethermal 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, Mass.) as described in Billiris and Siebenmorgen (2013).

All statistical analyses were performed using JMP Pro 10 software (SAS Institute, Inc.). Significance of independent variables [T_a, T_{da}, and mass of water removed/mass dry matter (m_w/dm)] was set at α=0.05.

Results and Discussion

Energy Requirements and Efficiency

Table 2 shows MC_i, MC_f, E_{theo}, $E_{thermal}$, and E_{elec} for the 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 $E_{thermal}$ values were within the range reported by Otten et al. (1980) for corn (from 3,860 to 11,960 kJ/kg water). However, the $E_{thermal}$ values for the cross-flow dryer used in this study were greater than the 5,185 kJ/kg water reported by Bakker-Arkema and Fontana (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 Ts 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 (Zuritz and Singh, 1985; Tsami et al., 1990; Billiris et al., 2011), this could be another reason why the energy requirements of this study were greater.

Additionally, 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 $E_{thermal}$; on average, E_{elec} was 4% of $E_{thermal}$ in 2011 and 5% of $E_{thermal}$ in 2012 (table 2). These results are somewhat similar to those of Hellevang and Reff (1987) who reported that $E_{thermal}$ accounted for 98% of the total energy requirements when drying using high air Ts. 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_{theo} by $E_{thermal}$, 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 (2004), 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.

Table 2. Energy requirements and energy efficiency for the tests conducted in 2011 and 2012.

Test	MC_i[a] (first pass) (% w.b.)	MC_i[b] (final pass) (% w.b.)	E_{theo}[c] (kJ/kg)	$E_{thermal}$[d] (kJ/kg)	E_{elec}[e] (kJ/kg)	η_{th}[f] (%)
Drying Season: September-October 2011						
1	20.4	12.2	2,530	8,700	360	29
2	19.0	13.0	2,510	7,380	380	34
3	19.4	12.7	2,530	9,670	400	26
4	19.4	12.5	2,520	6,900	300	36
Drying Season: July-October 2012						
1	15.5	12.2	2,620	9,620	510	27
2	18.3	12.2	2,560	8,810	410	29
3	15.4	11.7	2,660	9,300	630	28

[a] MC_i is the initial moisture content of the rice entering the first pass.
[b] MC_f is the final moisture content of the rice exiting the final pass.
[c] E_{theo} is the theoretical energy in kJ/kg water removed.
[d] $E_{thermal}$ is the measured thermal energy in kJ/kg water removed.
[e] E_{elec} is the measured electrical energy to power the fan in kJ/kg water removed.
[f] η_{th} is the thermal energy efficiency, calculated as Etheo divided by Ethermal.

Note: E_{theo} for each test was calculated as the weighted average of the theoretical energy requirements calculated for each drying.

Energy use was also assessed on a per pass basis. Figure 2 shows E_{elec}, E_{theo}, and $E_{thermal}$ 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.

Effect of Drying Air Temperature and Ambient Temperture on Energy Use

Thermal Energy Requirements

The effect of drying air T on energy use is shown in figure 3A. A trend was observed suggesting that as drying air T increased, $E_{thermal}$ increased, however, there was no significant correlation (fig. 3A). A possible explanation for the apparent increase in $E_{thermal}$ 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 figure 3A. Hellevang and Reff (1987) reported energy requirements ranging from 2,790 to 3,490 kJ/kg water when drying at low Ts and from 4,650 to 6,980 when drying at high Ts without recirculation. However, Morey et al. (1976) reported that when drying air T increased from 55°C 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 $E_{thermal}$ is related to the degree of saturation of the exhaust air (Kudra, 2004). Thus, in order to explain the variability in $E_{thermal}$ among runs and among dryers in depth, it may be necessary to also assess HAP-to-

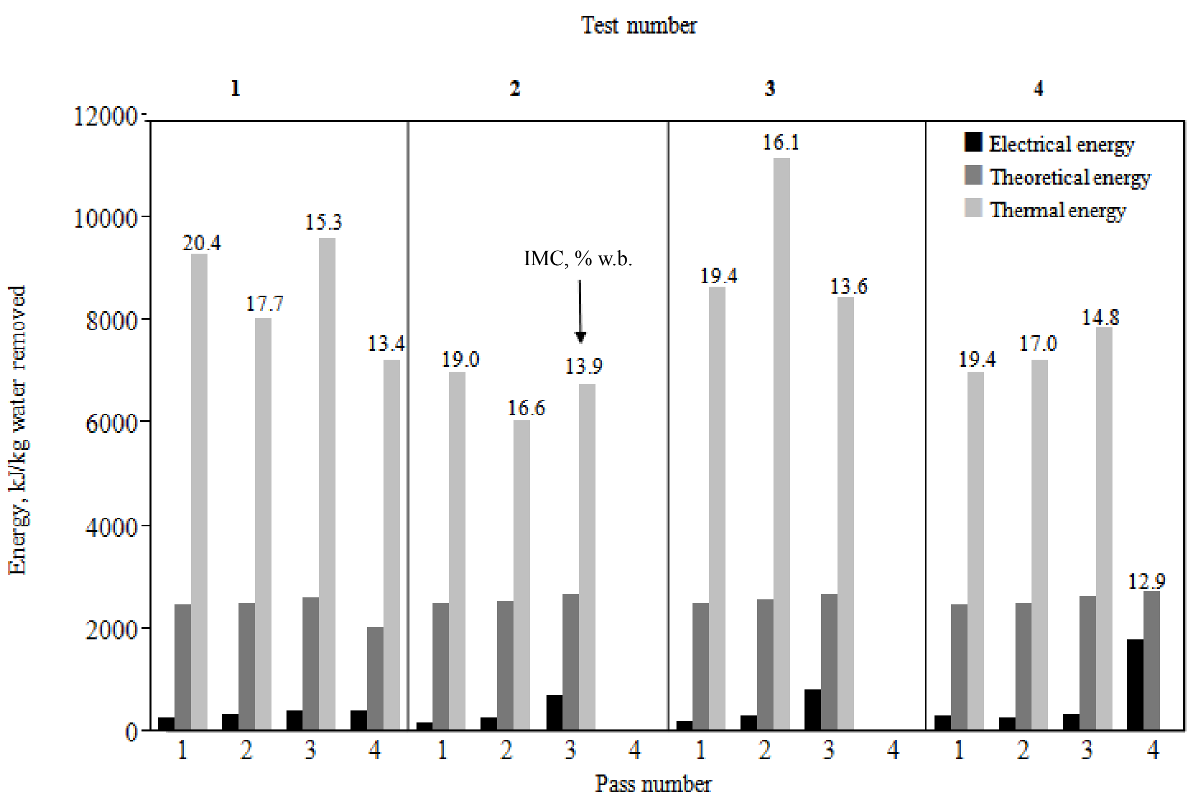


Figure 2. Electrical (E_{elec}), theoretical (E_{theo}) and thermal ($E_{thermal}$) energy requirements, to dry rice from the indicated initial moisture contents.

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 $E_{thermal}$, such as drying air T and MC_i, during tests may have led to the lack of correlation between $E_{thermal}$ and ambient air T. It might be that the wide range of drying air Ts from 12°C to 70°C that occurred in this study (table 1) may have masked a correlation between $E_{thermal}$ and ambient T. The opposite scenario was observed for the on-farm dryer; drying air Ts ranged narrowly from 43°C to 55°C and ambient T was linearly and inversely correlated to $E_{thermal}$. It is possible that for the on-farm dryer, drying air T did not vary sufficiently to affect the correlation between $E_{thermal}$ and ambient T; whereas for the commercial dryer the variation in drying air T was such that the correlation between $E_{thermal}$ and ambient T was masked. Morey et al. (1976) reported that $E_{thermal}$ to dry corn from 24% to 15% decreased from ~10,000 to 6,000 kJ/kg water removed when ambient T increased from -10°C to 20°C; it is noted that the authors used computer models to predict $E_{thermal}$, 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_{elec} was the drying rate, and resultant duration required for a drying run. As drying air T increases, drying rate increases and drying duration decreases, E_{elec} would hypothetically decrease. There was no correlation between E_{elec} and average ambient T (fig. 3B). This is reasonable given that ambient T does not affect drying rate.

Prediction of Energy Use and Efficiency

Energy Use

A multiple linear regression analysis was used to describe $E_{thermal}$ data since $E_{thermal}$ was reasoned to be affected by several variables simultaneously. Additionally, since the amount of energy required to heat the ambient air

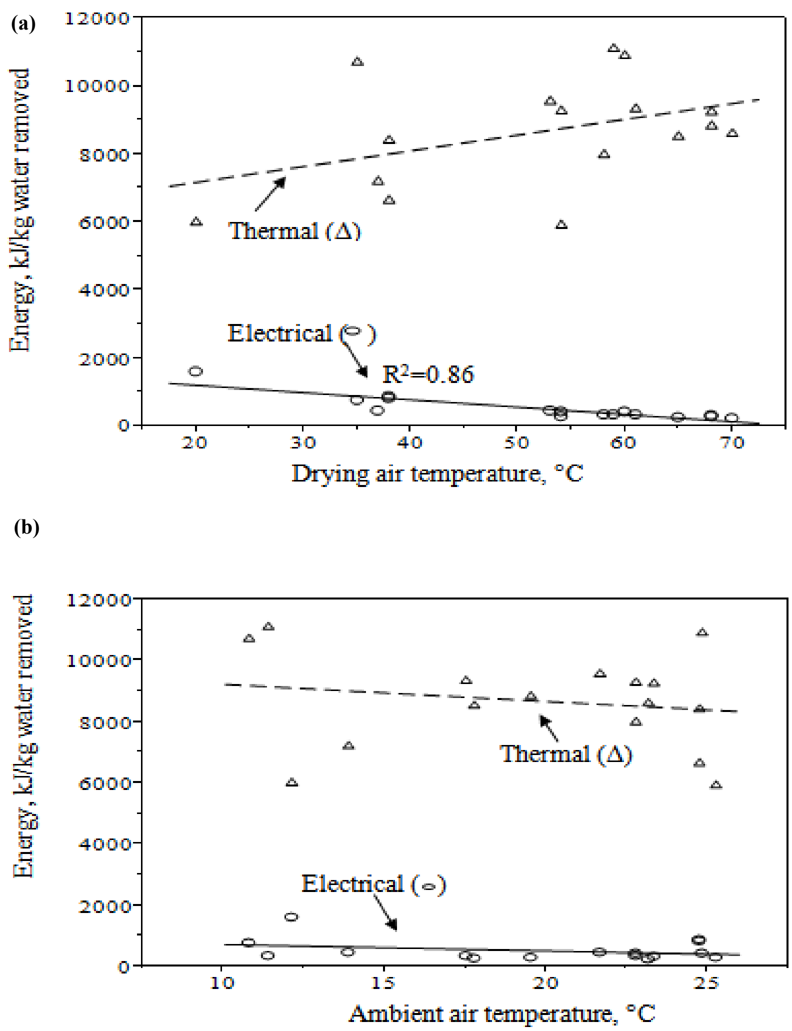


Figure 3. Thermal ($E_{thermal}$) and electrical (E_{elec}) measured energy use to dry rice per drying pass as a function of drying air temperature (a) and as a function of ambient air temperature (b) in terms of energy per unit mass water removed for the drying tests conducted in 2011 and 2012. Electrical energy was measured in terms of kWh per kg water removed but expressed as kJ per kg water removed.

to the drying air temperature was deemed to be an important parameter affecting $E_{thermal}$, the difference between drying air temperature and ambient temperature, 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 equation 4.

$$E_{thermal} = b_1 \left(T_{da} - T_a\right) + b_2 \left(\frac{m_w}{dm}\right) + b_0$$

$$R^2 = 0.65 \quad RMSE = 1049 \tag{4}$$

b_0 = 6,180
b_1 = 250
b_2 = -432,723
dm = the mass of rice dry matter (kg).

Dry matter was calculated using equation 5.

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

MC_i = the average moisture content of the rice entering a run (%, w.b.)
m_r = the mass of incoming rice dried in a drying run

The difference between drying air T and ambient T was linearly correlated to $E_{thermal}$. 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 $E_{thermal}$. This behavior is graphically represented in figure 4A, in which for any given T_{da}-T_a, $E_{thermal}$ increased as m_w/dm decreased. This may be explained by the fact that low values of 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 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. $E_{thermal}$ increasing as m_w/dm decreased could then be explained by the fact that moisture removal becomes increasingly difficult as MC decreases (Zuritz and Singh, 1985; Tsami et al., 1990; Billiris et al., 2011). This is in agreement with Morey et al. (1976) who predicted that $E_{thermal}$ increased as MC_i decreased when drying corn.

The model explains 65% of the variability in $E_{thermal}$. It is possible that there are other factors affecting $E_{thermal}$, 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 $E_{thermal}$. The impacts of these factors on $E_{thermal}$ will be assessed in a subsequent article.

The variation in E_{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 and b_1) of equation 6.

$$E_{elec} = b_1 T_{da} + b_0$$

$$R^2 = 0.86 \quad RMSE = 108 \tag{6}$$

b_0 = 1,366
b_1 = -17.0
E_{elec} = electrical energy requirements in kJ/kg water removed
T_{da} = drying air T (°C).

Equation 6 confirms, as previously discussed and illustrated in figure 3A, that E_{elec} was linearly and inversely correlated to drying air T.

Thermal Efficiency

Multiple linear regression analysis was used to obtain the regression coefficients (b0, b1, and b2) of equation 7.

$$\eta_{th} = b_1 \left(T_{da} - T_a\right) + b_2 \left(\frac{m_w}{dm}\right) + b_0$$

$$R^2 = 0.75 \quad RMSE = 3.8 \tag{7}$$

b_0 = 40.8
b_1 = -1.01
b_2 = 1,682
η_{th} = thermal energy efficiency of a drying run.

A graphical representation of this model is shown in figure 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 U.S. 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 $E_{thermal}$ 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 United States (EIA, 2012).

The total cost to dry rice from MC_i to 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 $E_{thermal}$ and the remaining 16% was associated with E_{elec}. Equation 8 was developed to predict the total cost to dry rice in terms of cents per unit mass water removed.

$$Cost_{tot} = 2.8^{-4} E_{thermal} + 1.3^{-3} E_{elec} \tag{8}$$

$$Cost_{tot} = 2.8^{-4} \left(250\left(T_{da} - T_a\right) - 432,723 \frac{m_w}{dm} + 6,180\right) + 1.3^{-3}\left(-17.0 T_{da} + 1,366\right)$$

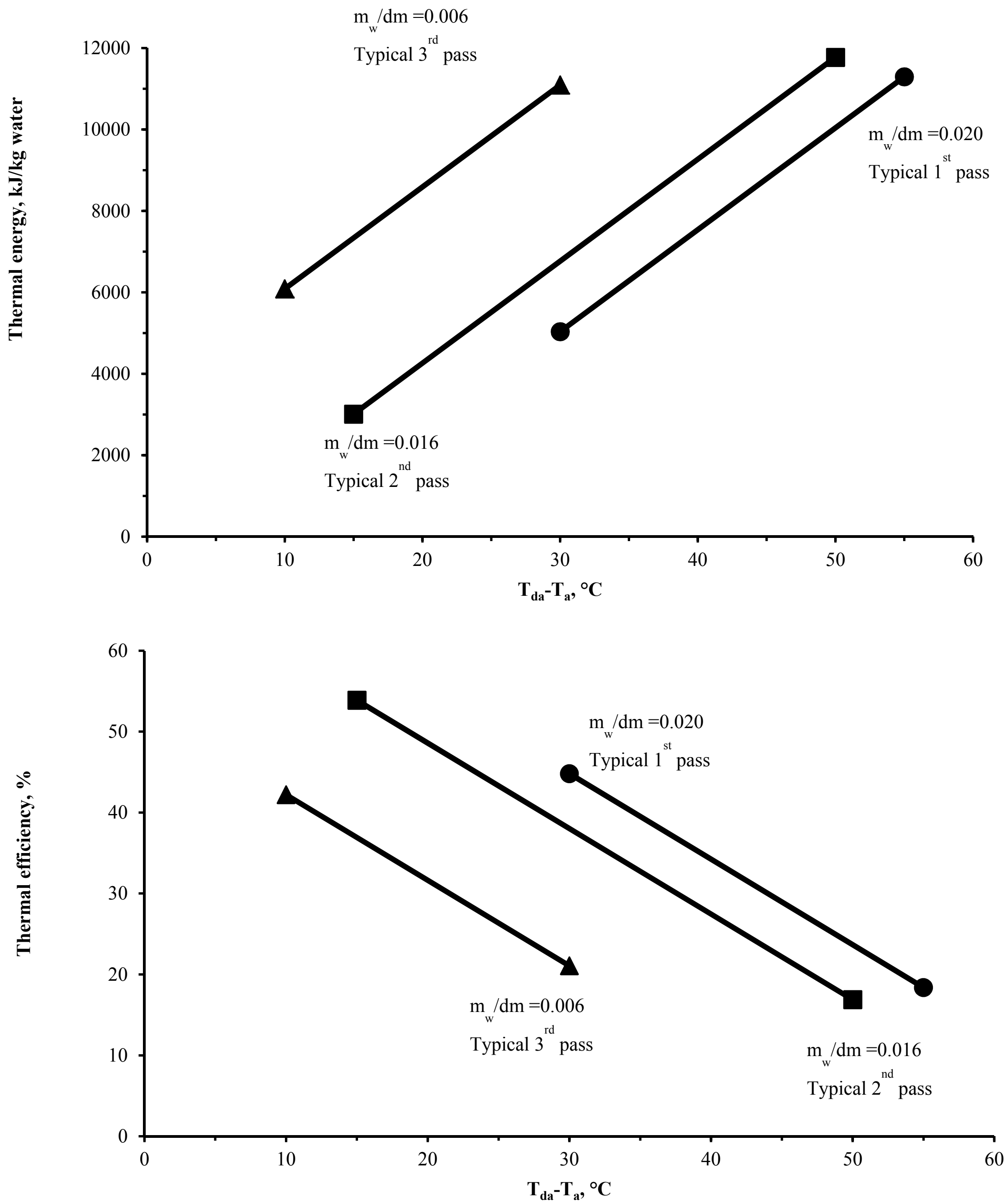


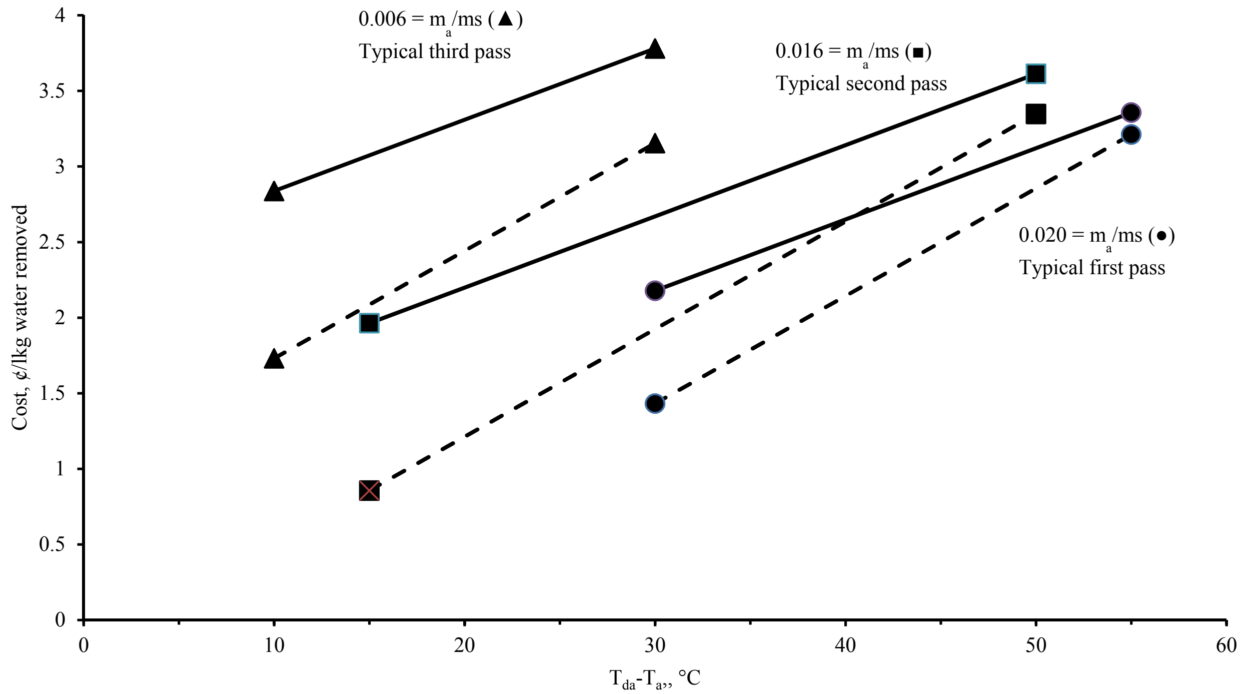
Figure 4. Set of curves predicting thermal energy use ($E_{thermal}$) (A) and thermal energy efficiency (B) as a function of the difference between drying air temperature and ambient temperature (T_{da}-T_a) at the indicated levels of water removed per mass dry matter (m_w/dm) for drying tests conducted in 2011 and 2012. Drying air temperatures ranged from 30°C to 70°C and ambient air temperatures ranged from 10°C to 25°C.

$Cost_{tot}$ 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 set of curves of $Cost_{thermal}$ and $Cost_{tot}$ as a function of T_{da}-T_a for three levels of m_w/dm. To generate these curves, ambient T ranged from 15°C to 25°C and drying air T ranged from 30°C to 70°C. It is observed that as T_{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, figure 5 shows that as T_{da}-T_a increased, the difference between $Cost_{tot}$ and $Cost_{thermal}$ decreased, reflecting the increasing proportion of $E_{thermal}$ in the total energy requirements.

Conclusions

Thermal energy use ($E_{thermal}$) 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_{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.



Figue 5. Set 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°C to 70°C and ambient air temperature ranged from 10°C to 25°C.

Thermal energy efficiency, which was calculated as the ratio of $E_{thermal}$ to theoretical energy requirements (E_{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 $E_{thermal}$ 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_{da}-T_a). In addition, $E_{thermal}$ 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 $E_{thermal}$; 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.

The statistical equations developed 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. 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. Moreover, rice-drying personnel could adjust their drying schedule based on the findings of this study. For instance, schedules could be adjusted to take advantage of the greater ambient temperatures during the day vs. drying during night hours.

The data provided herein could serve as inputs to life cycle assessments. The statistical equations allow users to assess changes in drying conditions/schedules on carbon footprint values.

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