Estimating the theoretical energy required to dry rice

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1. 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 and Cogburn, 2004). To preserve its quality, rice should be thus dried to this safe level (Siebenmorgen and 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. Kasmaprapuet 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 2500 to 2670 kJ/kg water depending on the drying temperature (T) (Fluck and Baird, 1980). However, Gunasekaran and Thompson (1986) stated that drying of crops actually requires from 3000 to 8000 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 (MCi) of the material and the desired final MC level (MCF), 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 and Chirife, 1976), the heat of sorption (Tsami et al., 1990) and the isosteric heat of desorption (Kechaou and Maalej, 1999). Herein, this quantity will be referred to as the total heat of desorption (\( Q_n \)). The difference between \( Q_n \) and \( h_{fg} \), which has been referred to as the net isosteric heat of sorption (Iglesias and Chirife, 1976; Tsami et al., 1990), will be called the net heat of desorption (\( Q_n \)). Aviara et al. (2004), Kechaou and Maalej (1999) and McMinn and 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 and Arslan, 2006; Tsami et al., 1990; Zuritz and 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 and 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, \( Q_n \) 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; Togrul and Arslan (2006) and Zuritz and Singh (1985) estimated \( Q_n \) values at different MC levels for long-grain and medium-grain rough rice, respectively. Researchers have used the Clausius–Clapeyron equation, in combination with sorption isotherm data, to calculate heats of desorption for diverse foodstuffs (Aviara and Ajibola, 2002; Aviara et al., 2004; Chen, 2006; Iglesias and Chirife, 1976; Igzou and Vírseda, 2007; Kechaou and Maalej, 1999; Mulet et al., 1999; Tolaba et al., 2004; Togrul and Arslan, 2006; Tsami et al., 1990).

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 \( Q_n \) 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, \( Q_n \) 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.

2. Materials and methods

2.1. 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. (2010). 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. (2011). The data from both studies were used to calculate \( Q_n \) and \( Q_t \) at selected MCs and Ts.

2.2. Heat of desorption calculation

\( Q_n \) was calculated using the form of the Clausius–Clapeyron equation developed by Othmer (1940):

\[
\ln(p_v) = \left( \frac{Q_n}{h_{fg}} \right) \ln(p_i) + c \tag{1}
\]

where \( p_v \) is water vapor pressure in the rice kernel associated with a particular \( T \), \( p_i \) is vapor pressure of pure water associated with a particular \( T \), \( Q_n \) 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.

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

\[
\text{ERH} = \frac{p_v}{p_i} \tag{2}
\]

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 \( Q_n \). Research indicates that the modified Chung–Pfost equation (Chung and Pfost, 1967; Pfost et al., 1976) best describes rice isotherm data (Busania and Abe, 1999; Ondier et al., 2011):

\[
\text{ERH} = \exp \left[ -\frac{A}{T + C} \exp(-B \cdot \text{MC}) \right] \tag{3}
\]

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. (2010, 2011), depending on the temperature range and cultivar. Zuritz and 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 Eqs. (2) and (3) and \( p_i \) values from the psychometric relationships in ASAE (1998).

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

\[
Q_n = Q_n + h_{fg} \tag{4}
\]

2.3. Heat of desorption prediction

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

\[
Q_n = A_1 + B_1 \cdot T + (A_2 + B_2 \cdot T) \exp(-A_3 \cdot \text{MC}) \tag{5}
\]

where \( A_1, A_2, B_1, B_2 \) and \( A_3 \) are constants of the equation estimated iteratively by fitting the non-linear model. \( Q_n \) 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 \( Q_n \) 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 to a MC 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:

$$Q_{Trice} = \int_{MC_i}^{MC_f} Q_t dMC$$

where $Q_{Trice}$ is the energy required to dry rice from MC to MC 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:

$$Q_{Trice} = \int_{MC_i}^{MC_f} (A_1 + B_1 \cdot T + (A_2 + B_2 \cdot T) \exp(-A_3 \cdot MC)) dMC$$

$$= \frac{A_1 (MC_f - MC_i) + B_1 \cdot T \cdot (MC_f - MC_i) + (A_2 + B_2 \cdot T)}{-A_3} \times (\exp(-A_3 \cdot MC_i) - \exp(-A_3 \cdot MC_f))$$

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, MC 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 to an MC on a per unit mass of water removed basis, $Q_{Trice}$ from Eq. (7) was divided by $D_{m \text{evap}}$, the mass of water removed in the drying process per unit rice dry matter, which can be expressed as:

\[ \frac{Q_{Trice}}{D_{m \text{evap}}} \]

Table 1

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Moisture content, % w.b.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>26</td>
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<tr>
<td>70</td>
<td>37</td>
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<td>80</td>
<td>46</td>
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<tr>
<td>90</td>
<td>53</td>
</tr>
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Table 2

<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>1381</td>
<td>3741</td>
<td>166</td>
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<tr>
<td>10</td>
<td>743</td>
<td>3102</td>
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<tr>
<td>12</td>
<td>359</td>
<td>2718</td>
<td>57</td>
</tr>
<tr>
<td>14</td>
<td>180</td>
<td>2539</td>
<td>29</td>
</tr>
<tr>
<td>16</td>
<td>81</td>
<td>2440</td>
<td>9</td>
</tr>
<tr>
<td>18</td>
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<td>9</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>2377</td>
<td>10</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>2359</td>
<td>0</td>
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Table 3

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Parameter</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Jupiter&quot;</td>
<td>3,150,878</td>
<td>12,725,771</td>
<td>23.4</td>
<td>2377</td>
<td>-9601</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>&quot;Wells&quot;</td>
<td>3,150,927</td>
<td>11,509,211</td>
<td>23.4</td>
<td>2377</td>
<td>-8683</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>&quot;Cybonnett&quot;</td>
<td>3,200,035</td>
<td>19,950,786</td>
<td>27.1</td>
<td>2377</td>
<td>-15,719</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>&quot;CL XL730&quot;</td>
<td>3,150,916</td>
<td>10,117,409</td>
<td>22.7</td>
<td>2377</td>
<td>-7632</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>3,189,745</td>
<td>9,742,417</td>
<td>24.2</td>
<td>2377</td>
<td>-6117</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>Parboiled</td>
<td>3,151,394</td>
<td>8,107,920</td>
<td>23.0</td>
<td>2377</td>
<td>-6117</td>
<td>0.72</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Natural logarithm of water vapor pressure in the rice kernel vs. 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).
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>2705</td>
<td>2704–2707</td>
</tr>
<tr>
<td>Long-grain “Wells”</td>
<td>2665</td>
<td>2664–2666</td>
</tr>
<tr>
<td>Long-grain “Cybonnett”</td>
<td>2665</td>
<td>2659–2672</td>
</tr>
<tr>
<td>Long-grain “CL XL730”</td>
<td>2656</td>
<td>2655–2657</td>
</tr>
<tr>
<td>Long-grain non-parboiled (general)</td>
<td>2669</td>
<td>2656–2671</td>
</tr>
<tr>
<td>Long-grain parboiled</td>
<td>2590</td>
<td>2587–2593</td>
</tr>
</tbody>
</table>

\[ \Delta m_{\text{evap}} = M_{\text{C}} - M_{\text{Cf}} \]  

(8)

It is emphasized that $Q_{\text{Trice}}$ 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 $\Delta m_{\text{evap}}$ (Eq. (8)).

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

3. 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., 2010). For each MC value, linear regressions of $\ln(p_r)$ vs. $\ln(p_v)$ 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 $Q_r$ when using EMC data collected at $T_s$ ranging from 10 to 60 °C for the four lots listed previously (data not shown). $Q_t$ was calculated through Eq. (4). The slope of the $\ln(p_r)$ vs. $\ln(p_v)$ line approaches unity as MC increases (Fig. 1). Consequently, $Q_t$ approaches $h_{\text{fg}}$ 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 $Q_r$ for long-grain “Cybonnett” at 60 °C are tallied in Table 2. The standard error of $Q_r$ is equal to the SE of $Q_t$ because the difference between these two values is a constant ($h_{\text{fg}}$). Iguaz and Vírseda (2007) reported for medium-grain rough rice, $Q_r$ values from 139 to 1021 kJ/kg water for MCs ranging from 19% to 0.04% and $T_s$ from 40 to 80 °C. The $Q_r$ values obtained in this study are greater than those of Iguaz and Vírseda (2007) at low MCs and are lower than those of Iguaz and Vírseda (2007) at high MCs.

3.1. Total heat of desorption prediction

Heats of desorption obtained from Eq. (1), along with corresponding MCs and $T_s$, were used to determine the parameters of Eq. (5) for each type of rice. Because of great differences among the SEs of $Q_r$ 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 and 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 and Mazza, 1993) to predict ERH, they found that the Kechaou and Maalej model (Kechaou and Maalej, 1999) was appropriate in describing $Q_r$ vs. MC data. Heat of desorption data for rice reported by Zuritz and 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 and 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, $Q_r$, 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.

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 "Cybonnett", 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,

![Fig. 5. Energy required to dry rice ($Q_{trice}$) to 12.5%, 13.5% and 14.5% w.b. moisture content, expressed on a per unit mass of water removed, basis as a function of the initial moisture content of rice for long-grain non-parboiled rice at 60 °C.](image1)

![Fig. 6. Energy required to dry rice ($Q_{trice}$) to 12.5% w.b. moisture content, expressed on a per unit mass of water removed, basis 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.](image2)
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 Ta-
ble 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 ef-
fect of cultivar on $Q_t$ was greater than that of $T$ in affecting the
exponential term of Eq. (5). Therefore, when considering all the cul-
tivars 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.

### 3.3. Energy requirements to dry rice from an MC$_i$ to an MC$_f$

Based on Eq. (7), mathematical expressions that predict the en-
ergy required to dry rice from an MC$_i$ to a desired MC$_f$ ($Q_{rice}$) at a
given drying $T$ were developed. These equations were developed
using the appropriate $A_1$, $A_2$, $A_3$, $B_1$, and $B_2$ values from Table 3.
The resulting equations are shown in Table 5. Eq. (7) can be ad-
justed to predict energy requirements to dry rice from an MC$_i$ to
an MC$_f$ 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 $Q_{rice}$ (drying energy required per
unit mass wet rice and per unit dry matter) with MC$_f$ for long-

Fig. 3 in that the energy requirements for drying the medium-grain
cultivar are slightly greater than that of the long-grains for MCs be-
low 15%. Since medium-grain kernels are thicker, wider and short-
er 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 med-
ium-grain cultivar was less significant than for a long-grain, pre-
sumably 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 med-
ium-grain rice at 40 °C reported by Zuritz and 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
and Singh (1985).

The values of $Q_t$ and their corresponding SE for long-grain
“Cybonnett” are shown in Table 2. The total heat of desorption in-
creases exponentially as MC decreases for all rice types (Fig. 3). There
was a sharp increase in $Q_t$ for MCs below 15% and $Q_t$ ap-
proached $h_w$ 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 2371 to 3488, for long-grain “CL XL730”
from 2371 to 3413, for medium-grain “Jupiter” from 2372 to
3624 and for parboiled rice from 2368 to 3194 kJ/kg water, for
MCs from 8% to 22% at 60 °C. Zuritz and Singh (1985) reported $Q_t$
values for medium-grain rough rice from 2438 to 4015 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 gelati-
nizes during the parboiling pathway, 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) re-
ferred 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 be-
low 15%. Since medium-grain kernels are thicker, wider and short-
er 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 med-
ium-grain cultivar was less significant than for a long-grain, pre-
sumably 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 med-
ium-grain rice at 40 °C reported by Zuritz and 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
and Singh (1985).

Fig. 7. Energy required to dry rice ($Q_{rice}$) to 12.5 w.b. moisture content expressed on a per unit mass of water removed basis as a function of the initial moisture content of the rice for long-grain non-parboiled rice.
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_{Trice}. Nevertheless, in order to obtain accurate theoretical energy requirements, including both terms in the equation is necessary because as MC decreases, the contribution of Table 5 exponential term becomes more important. For instance, the exponential term is 4.2% of the Q_{Trice} value when drying from 22% to 12.5% MC at 60 °C but is 10.0% of Q_{Trice} 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. Further, Fig. 6 confirms the findings discussed in Table 5, representing the energy required to remove a unit mass of water from rice should not be considered constant across MC. Q_{Trice} decreased exponentially as MC increases, when expressed on a per unit mass of water removed. In addition, Q_{Trice} increases as MC decreases. Both of these observations reflect the increasing importance of Q_{s} 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. Q_{Trice} decreased exponentially as MC increases, when expressed on a per unit mass of water removed. In addition, Q_{Trice} increases as MC decreases. Both of these observations reflect the increasing importance of Q_{s} 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.

4. Conclusions

The net heat of desorption (Q_{s}) and total heat of desorption (Q_{s}) decreased exponentially as MC increased for all types of rice in the range of 10–90 °C and 8–22 °C MC. Mathematical models were developed to predict the Q, 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_{s} of parboiled rice at 12.5% MC and 60 °C was significantly less than that of unparboiled 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 to a desired MC 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 to a desired MC decreased exponentially as MC 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.

References


