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Estimating the theoretical energy required to dry rice

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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.

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. 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 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 (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 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_t). The difference between Q_t 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

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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 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; Iguaz and Vírseda, 2007; Kechaou and Maalej, 1999; Mulet et al., 1999; Tolaba et al., 2004; Toğrul 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 Q_t (Iglesias and Chirife, 1976; McLaughlin and Magee, 1998). However, Iglesias and 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_n 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.

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_t and Q_n at selected MCs and Ts.

2.2. Heat of desorption calculation

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

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

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:

$$\mathrm{ERH} = \frac{p_v}{p_s} \quad (2)$$

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 and Pfost, 1967; Pfost et al., 1976) best describes rice isotherm data (Basunia and Abe, 1999; Ondier et al., 2011):

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

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_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 and Chilton (1973). The net heat of desorption Q_n was then calculated using Eq. (4).

$$Q_t = Q_n + h_{fg} \quad (4)$$

2.3. 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):

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

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

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., 2010).

Temperature, °C	Moisture content, % w.b.							
	8	10	12	14	16	18	20	22
60	26	49	70	84	92	96	98	99
70	37	60	77	88	94	97	99	99
80	46	67	82	91	95	98	99	99
90	53	72	84	92	96	98	99	99

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:

$$Q_{Trice} = \int_{MC_i}^{MC_f} Q_t \mathrm{d}MC \tag{6}$$

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:

$$\begin{aligned} Q_{Trice} &= \int_{MC_i}^{MC_f} (A_1 + B_1 \cdot T + (A_2 + B_2 \cdot T)\exp(-A_3 \cdot MC))\mathrm{d}MC \\ &= A_1[MC_f - MC_i] + B_1 \cdot T \cdot [MC_f - MC_i] + \frac{(A_2 + B_2 \cdot T)}{-A_3} \\ &\quad \times (\exp(-A_3 \cdot MC_f) - \exp(-A_3 \cdot MC_i)) \end{aligned} \tag{7}$$

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 2359 kJ/kg water.

Moisture content, % w.b.	Q_n, kJ/kg water	Q_t, kJ/kg water	SE, kJ/kg water
8	1381	3741	166
10	743	3102	106
12	359	2718	57
14	180	2539	29
16	81	2440	9
18	42	2401	9
20	18	2377	10
22	0	2359	0

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.

Cultivar	Parameter					RMSE
	A_1	A_2	A_3	B_1	B_2	
"Jupiter"	3,150,878	12,725,771	23.2	−2377	−9601	0.22
"Wells"	3,150,927	11,509,211	23.4	−2377	−8683	0.23
"Cybonnett"	3,200,035	19,950,786	27.1	−2521	−15,719	1.15
"CL XL730"	3,150,916	10,117,409	22.7	−2377	−7632	0.23
General	3,189,745	9,742,417	24.2	−2496	–	4.0
Parboiled	3,151,394	8,107,920	23.0	−2377	−6117	0.72

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:

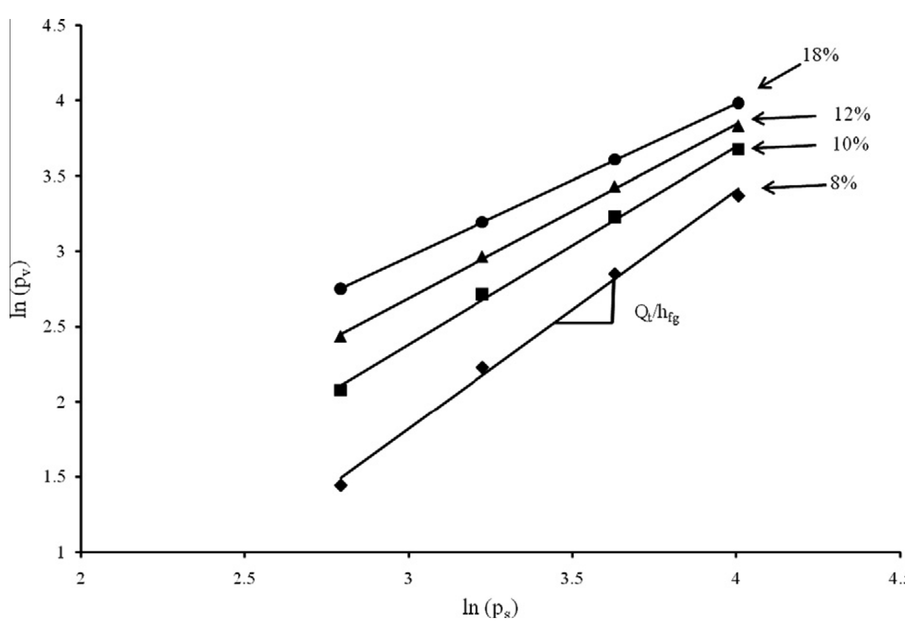

Fig. 1. Natural logarithm of water vapor pressure in the rice kernel vs. the natural logarithm of vapor pressure of pure water, for long-grain "Cybonnett" rough rice at four moisture content levels (w.b.) and temperatures ranging from 60 to 90 °C. The slope of each moisture content level regression line equals the total heat of desorption/latent heat of evaporation of pure water (Q_t/h_{fg}) quotient, per Eq. (1).

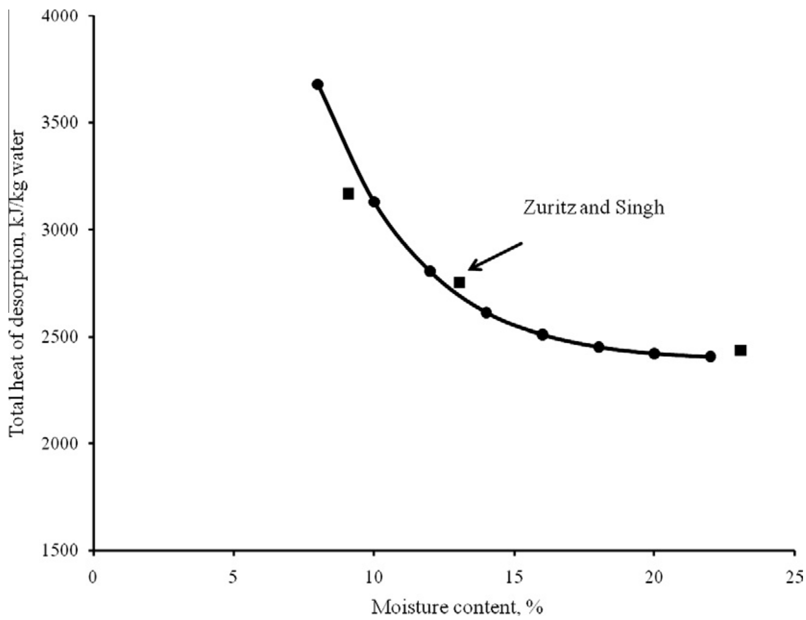

Fig. 2. Total heat of desorption (Q_t) as a function of moisture content (% wet basis) for medium-grain "Jupiter", at 45 °C and those reported for a medium-grain rice at 40 °C by Zuritz and Singh (1985).

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.

Rice type	Q_t, kJ/kg water	95% Confidence interval, kJ/kg water
Medium-grain "Jupiter"	2705	2704–2707
Long-grain "Wells"	2665	2664–2666
Long-grain "Cybonnett"	2665	2659–2672
Long-grain "CL XL730"	2656	2655–2657
Long-grain non-parboiled (general)	2669	2656–2671
Long-grain parboiled	2590	2587–2593

$$\Delta m_{evap} = MC_i - MC_f \quad (8)$$

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.).

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 $\ln(p_v)$ 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 *T*s 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 and Vírseda (2007) reported for medium-grain rough rice, Q_n 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_n 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_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 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_n 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_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

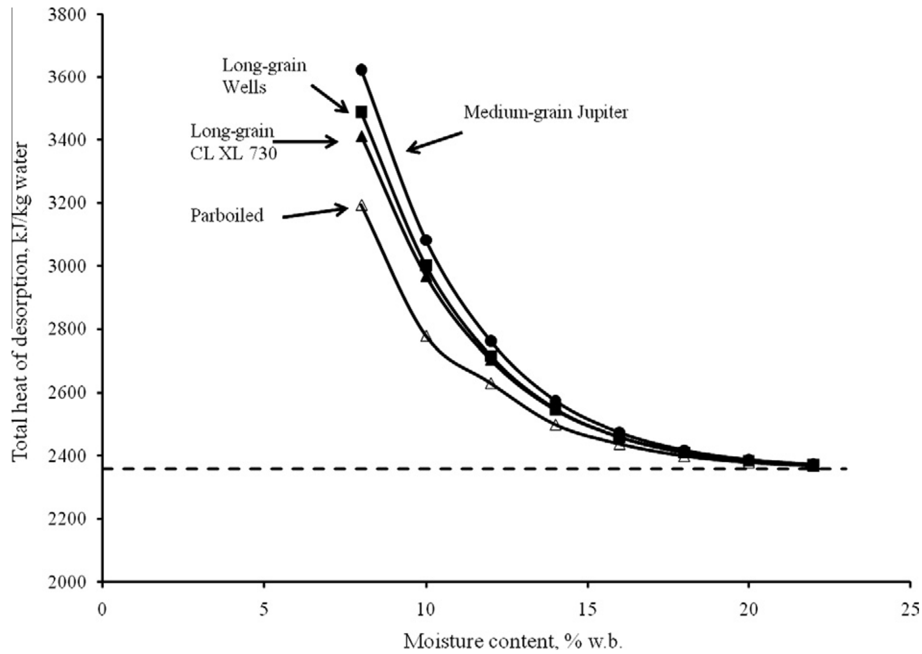

Fig. 3. Total heat of desorption (Q_t) at different moisture content levels for long-grain "CL XL730", long-grain "Wells", medium-grain "Jupiter" and parboiled rice at 60 °C. The value of h_{fg} is indicated and was 2359 kJ/kg water.

Table 5
Equations based on Eq. (7) and Table 3 to predict the energy required to dry rice from an MC_i to a desired MC_f (Q_{Trice}) in J/kg dry matter, for the indicated rice types.[a]

Rice type	Equation	Temp. range,[b] °C
Medium-grain/non-parboiled	$Q_{Trice} = (3,150,878 - 2377T)(MC_f - MC_i) + \left[e^{-23.2MC_f} - e^{-23.2MC_i}\right]\frac{(12,725,771-9601T)}{-23.2}$	10–60
Long-grain/non-parboiled	$Q_{Trice} = (3,189,745 - 2496T)(MC_f - MC_i) + \left[e^{-24.2MC_f} - e^{-24.2MC_i}\right]\frac{(9,742,417)}{-24.2}$	10–90
Long-grain/parboiled	$Q_{Trice} = (3,151,394 - 2377T)(MC_f - MC_i) + \left[e^{-23.0MC_f} - e^{-23.0MC_i}\right]\frac{(8,107,920-6117T)}{-23.0}$	10–60

[a] MC_i and MC_f are inputs on a dry basis.
[b] Temperature range over which EMC data were collected.

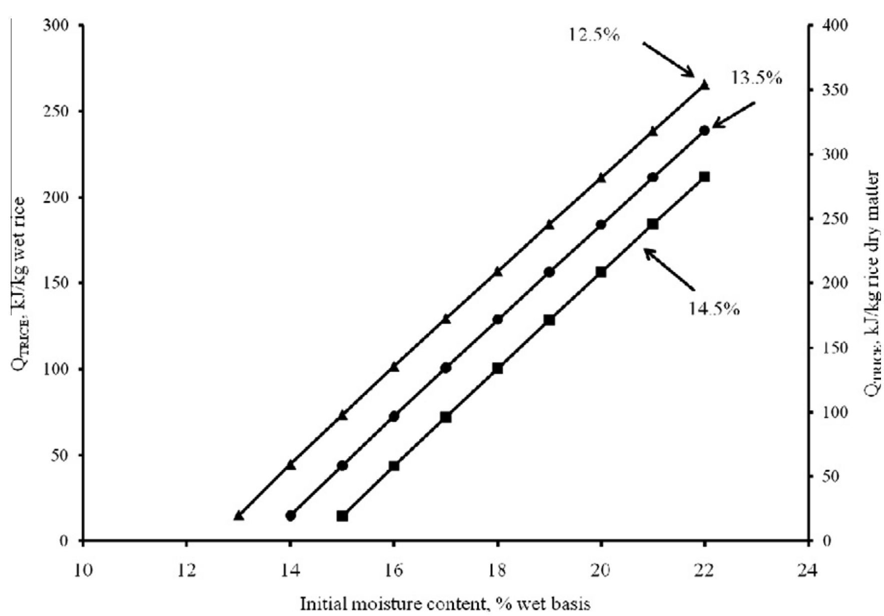

Fig. 4. Total energy required to dry rice (Q_{Trice}) to 12.5%, 13.5% and 14.5% w.b. moisture content, expressed on a per unit mass of wet or dry matter of rice, as a function of the initial moisture content of the rice for long-grain, non-parboiled rice at 60 °C.

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

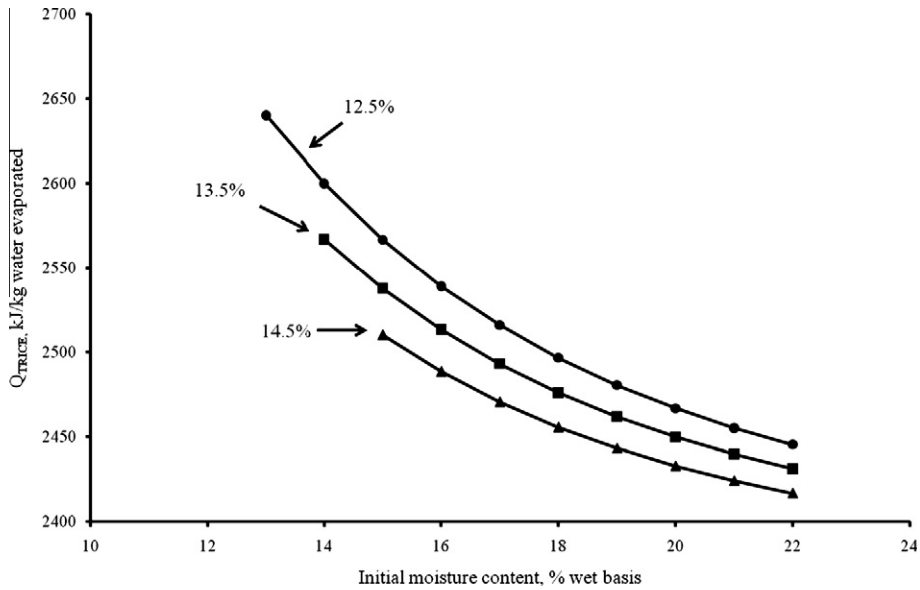

Fig. 5. Energy required to dry rice (Q_{Trice}) to 12.5%, 13.5% and 14.5% w.b. moisture content, expressed on a per unit mass of water removed, basis as a function of the initial moisture content of rice for long-grain non-parboiled rice at 60 °C.

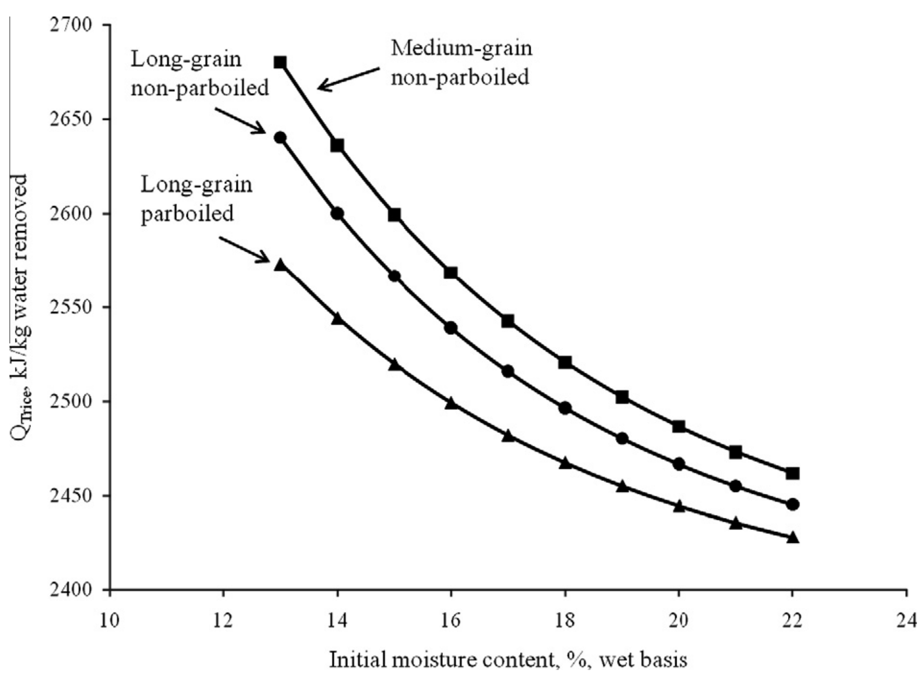

Fig. 6. Energy required to dry rice (Q_{Trice}) to 12.5% w.b. moisture content, expressed on a per unit mass of water removed, basis as a function of the initial moisture content of the rice for long-grain non-parboiled, long-grain parboiled and medium-grain non-parboiled rice at 60 °C.

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,

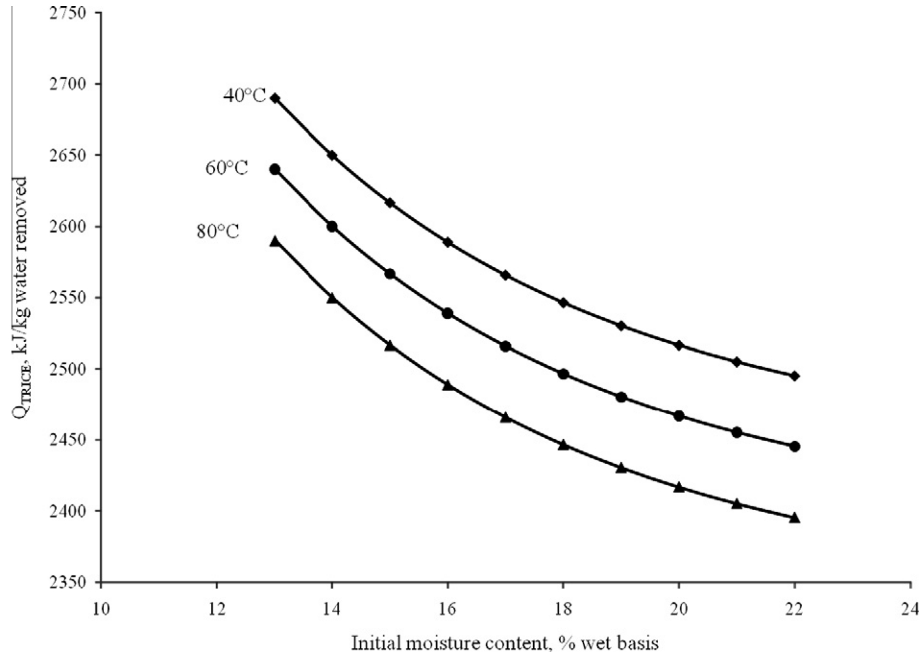

Fig. 7. Energy required to dry rice (Q_{Trice}) to 12.5% w.b. moisture content expressed on a per unit mass of water removed basis as a function of the initial moisture content of the rice for long-grain non-parboiled rice.

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.

3.2. 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 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 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 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).

3.3. Energy requirements to dry rice from an MC_i to an MC_f

Based on Eq. (7), mathematical expressions that predict the energy required to dry rice from an MC_i to a desired MC_f (Q_{Trice}) 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 adjusted 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_{Trice} (drying energy required per unit mass wet rice and per unit dry matter) with MC_i for long-grain, non-parboiled rice for three MC_f levels at 60 °C. Q_{Trice} per unit mass wet rice was obtained by dividing Q_{Trice} (Eq. (7)) by the amount of wet rice corresponding to a unit mass dry matter at the MC_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_{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. Fig. 5 shows the energy required to dry rice from an MC_i to a desired MC_f of 12.5%, 13.5% and 14.5% on a per unit mass of water removed at 60 °C. Q_{Trice} decreased exponentially as MC_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 2517 kJ/kg water removed, at 60 °C was of 2467 kJ/kg water removed and at 80 °C was of 2417 kJ/kg water removed (Fig. 7).

4. 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 10–90 °C and 8–22% 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.

References

Anderson, R.B., 1946. Modifications of the B.E.T. equation. Journal of American Chemical Society 68, 686–691.

Aviara, N.A., Ajibola, O.O., 2002. Thermodynamics of moisture sorption in melon seed and cassava. Journal of Food Engineering 55, 107–113.

Aviara, N.A., Ajibola, O.O., Oni, S.A., 2004. Sorption equilibrium and thermodynamic characteristics of soya bean. Biosystems Engineering 87 (2), 179–190.

ASAE, 1998. Standard D271.2 DEC94. Psychrometric Data, St. Joseph.

Basunia, M.A., Abe, T., 1999. Moisture adsorption isotherms of rough rice. Journal of Food Engineering 42 (4), 235–242, MI, USA.

Boyce, D.S., 1965. Grain moisture and temperature changes with position and time during through drying. Journal of Agricultural Engineering Research 10 (4), 333–341.

Cenkowski, S., Jayas, D.S., Hao, D., 1992. Latent heat of vaporization for selected foods and crops. Canadian Agricultural Engineering 34, 281–286.

Chen, C., 2006. Obtaining the isosteric sorption heat directly by sorption isotherm equations. Journal of Food Engineering 74 (2), 178–185.

Chung, D.S., Pfost, H.B., 1967. Adsorption and desorption of water vapor by cereal grains and their products: Part 2. Development of the general isotherm equation. Transactions of the ASAE 10, 549–555.

Cnossen, A.G., Siebenmorgen, T.J., Yang, W., 2002. The glass transition temperature concept in rice drying and tempering: effect on drying rate. Transactions of the ASAE 45 (3), 759–766.

De Boer, J.H., 1953. The Dynamical Character of Adsorption. Clarendon Press, Oxford.

Fluck, R.C., Baird, C.D., 1980. Energy requirements for agricultural inputs. In: Agricultural Energetics. AVI Publishing Company, Inc., Westport, Connecticut, p. 87.

Guggenheim, E.A., 1966. Application of Statistical Mechanics. Clarendon Press, Oxford.

Gunasekaran, S., Thompson, T.L., 1986. Optimal energy management in grain drying. Critical Reviews in Food Science and Nutrition 25 (1), 1.

Howell Jr., T.A., Cogburn, R.R., 2004. Rough-rice storage. In: Champagne, E.T. (Ed.), Rice Chemistry and Technology, vol. 3. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA, p. 269.

Iglesias, H.A., Chirife, J., 1976. Isosteric heat of water vapour sorption on dehydrated foods: Part 1. Analysis of the differential heat curves. Lebensmittel-Wissenchaft & Technologie 9, 116.

Iguaz, A., Vírseda, P., 2007. Moisture desorption isotherms of rough rice at high temperatures. Journal of Food Engineering 79 (3), 794–802.

Jayas, D.S., Mazza, G., 1993. Comparison of three-parameter equations for the description of adsorption data of oats. Transactions of the ASAE 36, 119–125.

Johnson, H.K., Dale, A.C., 1954. Heat required to vaporize moisture. Agricultural Engineering 35, 705–714.

Kasmaprapruet, S., Paengjuntuek, W., Saikhwan, P., Phungrassami, H., 2009. Life cycle assessment of milled rice production: case study in Thailand. European Journal of Scientific Research 30 (2), 195–203.

Kechaou, N., Maalej, M., 1999. Desorption isotherms of imported banana. Application of the GAB theory. Drying Technology 17 (6), 1201–1213.

McLaughlin, C.P., Magee, T.R.A., 1998. The determination of sorption isotherm and the isosteric heats of sorption for potatoes. Journal of Food Engineering 35 (3), 267–280.

McMinn, W.A.M., Magee, T.R.A., 2003. Thermodynamic properties of moisture sorption of potato. Journal of Food Engineering 60 (2), 157–165.

Mulet, A., García-Reverter, J., Sanjuán, R., Bon, J., 1999. Sorption isosteric heat determination by thermal analysis and sorption isotherms. Journal of Food Science 64 (1), 64–68.

Okos, M.R., Narsimhan, G., Singh, R.K., Weitnauer, A.C., 1992. Food Dehydration Handbook of Food Engineering. Marcel Dekker, New York.

Ondier, G.O., Siebenmorgen, T.J., Mauromoustakos, A., 2010. Equilibrium moisture contents of rough rice dried using high temperature, fluidized-bed conditions. Transactions of the ASABE 53 (1), 1667–1672.

Ondier, G.O., Siebenmorgen, T.J., Bautista, R.C., Mauromoustakos, A., 2011. Equilibrium moisture contents of pureline, hybrid and parboiled rice. Transactions of ASABE 53 (3), 1007–1013.

Othmer, D.F., 1940. Correlating vapor pressure and latent heat data. Industrial and Engineering Chemistry 32 (6), 841–856.

Perry, R.H., Chilton, C.H., 1973. Chemical Engineers' Handbook, fifth ed. McGraw-Hill, Inc., USA.

Pfost, H.B., Maurer, S.G., Chung, D.S., Milliken, G.A., 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520, St. Joseph, Michigan, USA.

Rizvi, S.S.H., 2005. Thermodynamic properties of foods in dehydration. In: Rao, M.A., Rizvi, S.S.H., Datta, A.K. (Eds.), Engineering Properties of Foods, third ed. CRC Press, Boca Raton, FL, p. 239.

Siebenmorgen, T.J., Meullenet, J., 2004. Impact of drying, storage, and milling on rice quality and functionality. In: Champagne, E.T. (Ed.), Rice Chemistry and Technology, third ed. American Association of Cereal Chemists, St. Paul, MN, p. 301.

Souza, C.M. Alves de, Tertuliano, P.C., Rafull, L.Z.L., Prat, M.I.H., Robaina, A.D., 2006. Comparación de modelos matemáticos para descripción de las curvas de entalpia de vaporización de agua de diferentes productos agrícolas. In: Conferencia Científica de Ingenieria Agrícola de La Habana, 2006, Habana. 2ª Conferencia Científica de Ingenieria Agrícola de La Habana, vol. 1, 2006, pp. 1–14.

Thompson, T.L., Peart, R.M., Foster, G.H., 1968. Mathematical simulation of corn drying. Transactions of the ASAE 24 (3), 582–586.

Tolaba, M.P., Peltzer, M., Enriquez, N., Pollio, M.L., 2004. Grain sorption equilibria of quinoa grains. Journal of Food Engineering 6, 365–371.

Toğrul, H., Arslan, N., 2006. Moisture sorption behaviour and thermodynamic characteristics of rice stored in a chamber under controlled humidity. Biosystems Engineering 95 (2), 181–195.

Tsami, E., Maroulis, Z.B., Marinos-Kouris, D., Saravacos, G.D., 1990. Heat of sorption of water in dried fruits. International Journal of Food Science and Technology 25, 350.
Truong, V., Bhandari, T.H., Howes, T., 2005. Optimization of co-current spray drying process of sugar-rich foods: Part 1. Moisture and glass transition temperature profile during drying. Journal of Food Engineering 71, 55–65.
Verma, L.R., 1994. New methods for on-the-farm rice drying: solar and biomass. In: Wayne, E.M., Wadsworth, J.I. (Eds.), Rice Science and Technology. Marcel Dekker, Inc., 270 Madison Avenue, New York, USA.
Zuritz, C.A., Singh, R.P., 1985. An equation to compute the heat of evaporation of water for rough rice during drying. Drying Technology 3 (3), 421–435.