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Original Article

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Latent Heat of Water Vapor of Rough Rice, Brown Rice, White Rice and Rice Husk

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Abstract

The latent heat of vaporization in rough rice, brown rice, white rice and rice hull was calculated by Clausius-Clapeyron equation, which does not require complex constraints as in Othmer method. Equilibrium relative humidity and ratio of the latent heat of vaporization with $\ln P_v$ and $\ln P_s$ were estimated with moisture contents ranging from 10% (d.b.) to 36% (d.b.) with 2% (d.b.) increment and temperatures ranging from 10℃ to 50℃ with 2.5℃ increment. An empirical equation for calculating the latent heat of vaporization in rice was developed as a function of moisture content and temperature. The equation agreed well with the calculated results. The ratio for latent heat of vaporization were the greatest for white rice while they were similar among rough rice, brown rice and rice hull.

Keywords : Latent heat of vaporization, Rice, Equilibrium moisture content, Clausius-clapeyron equation

1. INTRODUCTION

Latent heat of vaporization is energy needed for evaporating moisture, and the latent heat of vaporization for grains is greater than that for free moisture. Extra energy is required to evaporate free moisture from the grains due to their hygroscopicity comparing to evaporating free moisture (Gallaher, 1951; Keum, 1986). The latent heat of vaporization model for rice is a critical factor for better understanding in post-harvest process such as drying, storage, and distribution providing fundamentals for the system design and operation. Equilibrium moisture content models are functions of moisture content and temperature (Han et al., 2010; Kaleemullah and Kaliappan, 2005; Kuwairi and Maddox, 1984; Murata et al., 1988).

The latent heat of vaporization can be directly measured through a direct measurement method using a calorimeter or estimated by thermodynamic calculation using adsorption isotherm curve (Tagawa et al., 1993). Among thermodynamic calculation methods, the Othmer method (Othmer, 1940) is usually widely employed (Kato, 1979; Strohman and Yoeger, 1967). however, due to many constraints of Othmer method, Clausius-Clapeyron method has been alternatively used (Murata et al., 1988; Tagawa et al., 1993). The latent heats of vaporizations for rough rice, wheat, two-row barley, adlay, and soybean were calculated by Clausius-Clapeyron equation considering their equilibrium moisture contents; latent heats of vaporizations for those grains were 1.1~1.7 times greater than that for free moisture at 10% (d.b.) of moisture content while there was no difference in latent heat of vaporization between those grains and free moisture at more than 40% (d.b.) of moisture contents (Murata et al., 1988). In Korea, equilibrium moisture content models have been developed for major grains (Choi et al., 1992; Duc and Han, 2009; Keum et al., 2000; Keum et al., 2002; Kim and Han, 2009;

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Kim et al., 2008) while researches for latent heat of vaporization has not been reported.

Aims of this research are: to develop an experimental model for the latent heat of vaporization by Clausius-Clapeyron equation employed by Murata et al. (1988) and Tagawa et al. (1993) and to evaluate the model by an equilibrium moisture content model (Keum et al., 2000) on domestic rough rice, brown rice, white rice, and rice hull.

2. MATERIAL AND METHODS

A. Equilibrium moisture content model

The equilibrium moisture content was calculated by the model of Keum et al. (2000), which employed static method on Chu-cheong variety rough rice, brown rice, white rice, and rice hull. Keum et al. (2000) determined experimental constants by applying equilibrium moisture contents into modified Henderson's model (Henderson, 1952) at 20, 30, and 40℃ along with 8 different levels of air condition raging from 11.2% to 85.0%. The equilibrium moisture content model used in the experiment is stated in the equation below, and the experimental constant is described in Table 1.

Modified Henderson model $$M = 0.01\left[\frac{\ln(1-RH)}{-K(T+C)}\right]^{\frac{1}{N}} \quad (1)$$

$$RH = 1 - \exp[-k(T+C)(100 \cdot M)^N]$$

where, M : equilibrium moisture content (dec., d.b.)
RH : relative humidity (dec.)
T : temperature (℃)
C, K, N : regression coefficients

B. Latent heat of water vapor

A method was proposed to determine the latent heat of vaporization of moisture for any liquid by vapor pressure data. The thermodynamic function Clausius-Clapeyron equation, which expresses the temperature dependency of vapor pressure for phase transition from an adsorbed liquid to the vapor phase, was used.

$$\frac{dP}{dT} = \frac{h_{fg}}{T(v_v - v_f)} \quad (2)$$

where, P : actual pressure of vapor (kPa)
T : absolute temperature (K)
h_{fg} : latent heat of vaporization of liquid (kJ/kg)
v_v : specific volume of vapor (m^3/kg)
v_f : specific volume of liquid (m^3/kg)

At normal temperature and pressure, the specific volume of liquid can be considered to be negligible compared to the specific volume of vapor. For water, the ratio of v_v/v_f is about 1,700:1 and Eq. (2) can be expressed as Eq. (3).

$$\frac{dP}{dT} = \frac{h_{fg}}{v_v T} \quad (3)$$

By assuming the vapor behaves like an ideal gas, the following equation is derived.

$$v_v = \frac{RT}{P} \quad (4)$$

where, R : gas constant of vapor

Combining Eq. (3) and (4), Eq. (5) is obtained.

$$\frac{1}{h_{fg}}\frac{dP}{P} = \frac{dT}{RT^2} \quad (5)$$

Eq. (5) can be expanded into Eq. (6) and (7) when applying to vaporization processes of moisture in the grains

Table 1 Estimated regression coefficients and root mean square error for modified Henderson model

	Regression coefficients			RMSE		R^2	
	K	C	N	EMC	RH	EMC	RH
Rough rice	0.00007836	13.058	2.1581	0.0037	0.0188	0.9935	0.9940
Brown rice	0.00005224	12.844	2.2788	0.0030	0.0151	0.9956	0.9962
White rice	0.00002076	11.3595	2.3437	0.0036	0.0187	0.9937	0.9941
Rice hull	0.000196	5.1966	1.9680	0.0046	0.0250	0.9895	0.9894

and free moisture, respectively.

$$\frac{1}{h'_{fg}}\frac{dP_v}{P_v}=\frac{dT}{RT^2} \tag{6}$$

$$\frac{1}{h_{fg}}\frac{dP_s}{P_s}=\frac{dT}{RT^2} \tag{7}$$

where, h'_{fg} : latent heat of vaporization of moisture in rice (kJ/kg)

P_v : vapor pressure of water in rice (kPa)

P_s : saturation vapor pressure of free water (kPa)

Eq. (6) and (7) can be combined as follows.

$$\frac{dP_v}{P_v}=\frac{h'_{fg}}{h_{fg}}\frac{dP_s}{P_s} \tag{8}$$

The calculated values of P_v and P_s at the same equilibrium moisture contents were then plotted on logarithmic scales. The slopes of the resulting straight lines were determined to give the latent heat of vaporization ratio.

$$\ln P_v=\frac{h'_{fg}}{h_{fg}}\ln P_s+C \tag{9}$$

where, C : constant of integration

The vapor pressure of moisture in rice at each moisture content was calculated as:

$$P_v=P_s\times ERH \tag{10}$$

where, ERH : equilibrium relative humidity (dec.)

To determine the latent heat of vaporization of moisture present in the rough rice, brown rice, milled rice and rice hull, an equilibrium relative humidity data was generated within a moisture content.

$$\frac{h'_{fg}}{h_{fg}}=1+a\exp(-bM) \tag{11}$$

where, M : Moisture content (dec., d.b.)

3. RESULT AND DISCUSSION

Figures 1 and 2 show the results of the prediction for

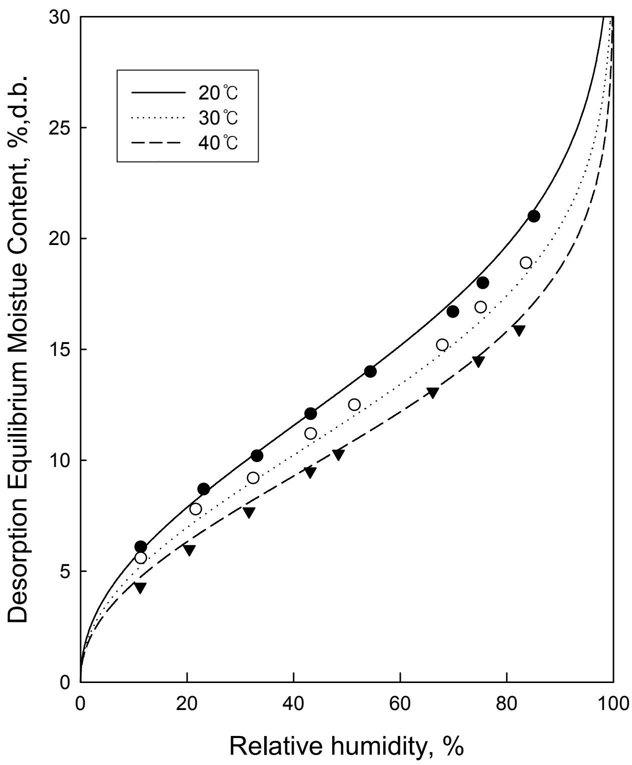

Fig. 1 Comparison of measured data and the predicted desorption equilibrium moisture content of temperatures using modified-Henderson equation for rough rice.

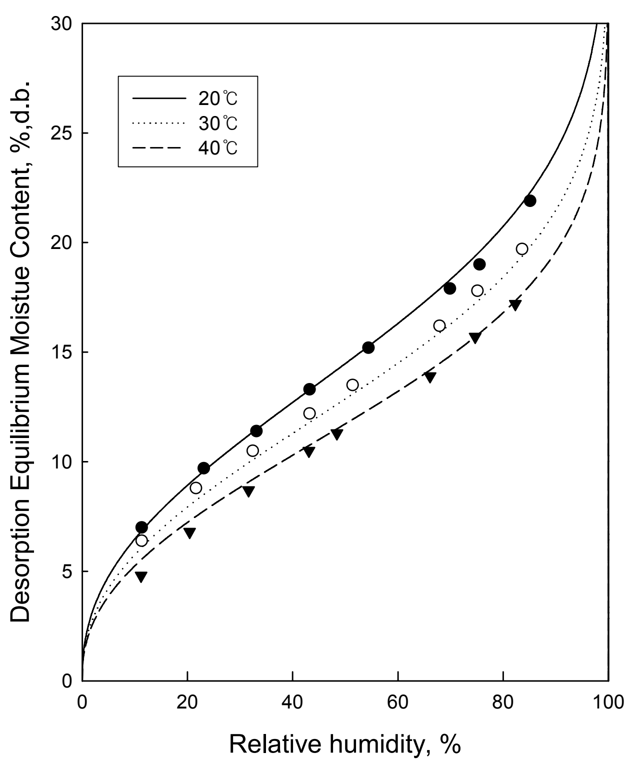

Fig. 2 Comparison of measured data and the predicted desorption equilibrium moisture content of temperatures using modified-Henderson equation for white rice.

equilibrium moisture contents of rough rice and white rice at three temperature levels along with relative humidity ranges from 11.2% to 85.0% by using Keum's equilibrium moisture content model. As shown in Figures 1 and 2, prediction by equilibrium moisture content model agrees well with the experimental data on rough rice and white rice. Similar results were observed on brown rice and rice hull. Standard deviation of difference between the prediction and experimental data were ranging from 0.0030 to 0.0046% indicating stability of the model. It was found that the equilibrium moisture content beame smaller as temperature increased and that the equilibrium moisture content became greater as the relative humidity increased. The equilibrium moisture content of white rice showed the greatest value, followed by those of brown rice, rough rice, and rice hull.

The equilibrium relative humidity were obtained in the moisture content range of 10~36% (d.b.) and temperature range of 10~50℃. Using those values, pressures of water vapor (P_v) for each temperature and moisture content condition were calculated with the saturation pressures of water vapor (P_s) in rough rice, brown rice, white rice, and rice hull.

Figure 3 shows the latent heat of vaporization at the temperatures of 20, 30, and 40℃ as the moisture content of rough rice changes. At 40℃, the latent heat of vaporization for free moisture is 2,407 kJ/kg while the latent heat of vaporization for rough rice is 2,589.5 kJ/kg at 22% (d.b.) of the moisture content and 2,890.9 kJ/kg at 16% (d.b.) of the moisture content indicating that it requires more energy to vaporize moisture in grains than to vaporize free moisture. Also, the latent heat of vaporization tends to increase at smaller moisture content and lower temperature.

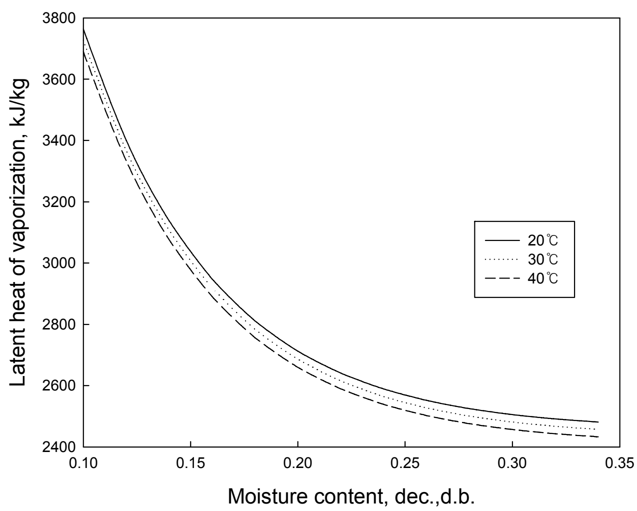

Fig. 3 Comparison of latent heat of vaporization at various temperatures and moisture contents of rough rice.

Figure 4 shows the saturation pressure and pressure of water vapor at each temperature level for rough rice with 14% (d.b.) of moisture content illustrating that the saturation pressure of water vapor was greater than the pressure of water vapor was. Similar results were observed on brown rice, white rice, and rice hull.

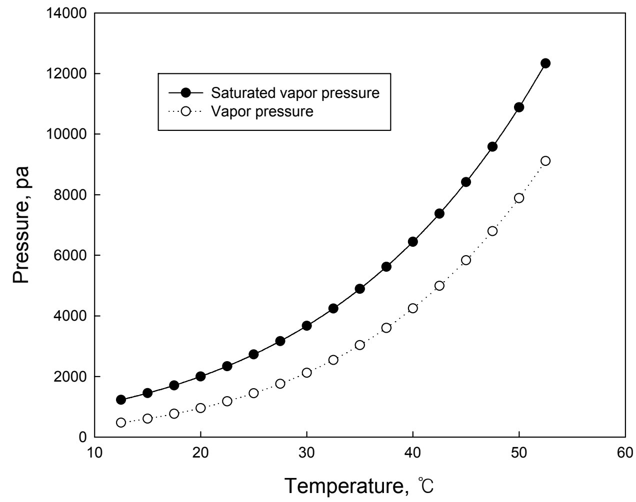

Fig. 4 Comparison of saturated vapor pressure and vapor pressure of rough rice at moisture content 14% (d.b.).

Using the calculated saturation vapor pressure of free water and the vapor pressure of water in rice, $\ln P_v$ and $\ln P_s$ were calculated for each temperature and moisture content level, and the latent heat of vaporization ratio $(\frac{h'_{fg}}{h_{fg}})$ is obtained. The constant of the latent heat of vaporization Eq. (11) is determined by non-linear regression using SAS.

Table 2 shows the constants a and b and coefficient of determination for rough rice, brown rice, white rice, and rice hull. Coefficients of determination are 0.9968, 0.9962, 0.9996, and 0.9973 for rough rice, brown rice, white rice,

Table 2 Constants of regression equation and coefficients of determination for latent heat of vaporization

	a	b	R^2
Rough rice	2.7093	16.2564	0.9968
Brown rice	3.0643	16.6721	0.9962
White rice	1.1121	7.6143	0.9996
Rice hull	2.4322	14.7936	0.9973

and rice hull, respectively indicating that the regression equation is statistically significant.

Figure 5 illustrates the latent heat of vaporization ratio for rough rice, brown rice, white rice, and rice hull at each moisture content level. The latent heat of vaporization ratio for white rice was the greatest followed by rice hull. The ratio for rough rice and brown rice showed very little difference while the ratio for the rice hull was slightly greater than rough rice and brown rice.

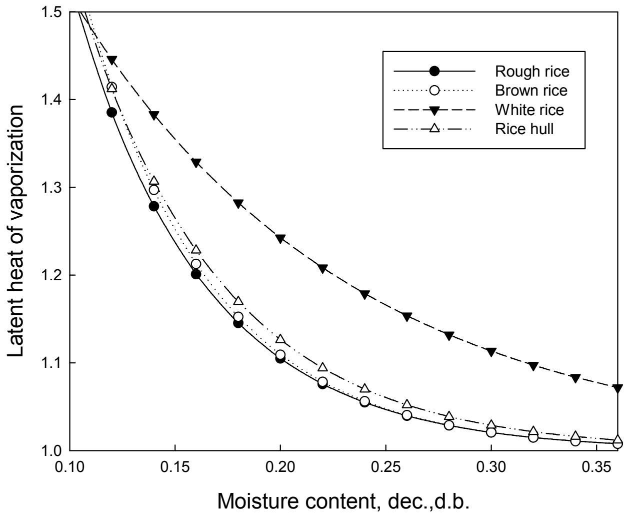

Fig. 5 Comparison of latent heat of vaporization ratio ($\frac{h'_{fg}}{h_{fg}}$) for rough rice, brown rice, white rice and rice hull.

4. CONCLUSIONS

A latent heat of vaporization experimental model was developed and evaluated by the equilibrium moisture content model and Clausius-Clapeyron equation for rough rice, brown rice, white rice, and rice hull. At 40℃, the latent heat of vaporization was 2,407, 2,589.5, 2890.9 kJ/kg for free moisture, rough rice with 22% (d.b.) of moisture content, and rough rice with 16% (d.b.) of moisture content, respectively. The results indicates that the latent heat of vaporization becomes greater as the temperature and moisture content become lower.

The coefficients of determination of the non-linear regression equation for the latent heat of vaporization experimental model were 0.9968, 0.9962, 0.9996, and 0.9973 for rough rice, brown rice, white rice, and rice hull, respectively, confirming that the model is statistically significant. The latent heat of vaporization ratio of white rice was the highest compared to those of rough rice, brown rice, and rice hull; those of rough rice and brown rice were similar; and that of rice hull was a slightly greater than those of rough rice and brown rice.

REFERENCES

1. Choi, B. M., J. H. Lee., S. J. Park., C. S. Kim and J. Y. Rhee. 1992. Equilibrium moisture content of korean ginseng. Journal of Biosystems Engineering 17(3):247-259.
2. Duc, L. A and J. W. Han. 2009. The effects of drying conditions on the germination properties of rapeseed. Journal of Biosystems Engineering 34(1):30-36.
3. Gallaher, G. L. 1951. A method of determining the latent heat of agricultural crops. Agricultural Engineering 32(1):34-38.
4. Han, J. W., D. H. Keum., W. Kim., L. A. Duc., S. H. Cho and H. Kim. 2010. Circulating concurrent-flow drying simulation of rapeseed. Journal of Biosystems Engineering 35(6):401-407.
5. Henderson, S. M. 1952. A basic concept of equilibrium moisture. Agricultural Engineering 33(1):29-32.
6. Kaleemullah, S and R. Kaliappan. 2005. Latent heat of vaporization of moisture from red chillies. International Journal of Food Properties 8(2):199-205.
7. Kato, H. 1979. Overall studies on the physical properties and the measurement of agricultural products. Japanese Society of Agricultural Machinery. 2(3):117-122.
8. Keum, D. H. 1986. Data and equations for the analysis of rough rice drying. Journal of Biosystems Engineering 11(2): 92-102.
9. Keum, D. H., H. Kim and Y. K. Cho. 2000. Desorption equilibrium moisture content of rough rice, brown rice, white rice and rice hull. Journal of Biosystems Engineering 25(1): 47-54.
10. Keum, D. H., H. Kim and N. U. Hong. 2002. Equilibrium moisture contents and thin layer drying equations of cereal grains and mushrooms(2). Journal of Biosystems Engineering 27(3):219-226.
11. Kim, H and J. W. Han. 2009. Low temperature drying simulation of rough rice. Journal of Biosystems Engineering 34(5):351-357.
12. Kim, Y. H., J. W. Han and D. H. Keum. 2008. Desorption EMC models for rapeseed. Journal of Biosystems Engineering 32(6):403-407.
13. Kuwairi, B and R. N. Maddox. 1984. Generalized method for calculating latent heat of vaporization. Chemical Engineering Communications 29(1):337-351.

14. Murata, S., A. Tagawa and S. Ishibashi. 1988. An equation for calculating the latent heat of vaporization. Japanese Society of Agricultural Machinery 50(3):85-93.
15. Othmer, D. E. 1940. Correlating vapor pressure and latent heat data -a new plot-. Industrial and Engineering Chemistry 32(6):841-856.
16. Strohman, R. D and R. R. Yoeger. 1967. A new equilibrium moisture content equation. Transactions of the ASABE. 10(4):675-677.
17. Tagawa, A., S. Murata and H. Hayashi. 1993. Latent heat of vaporization in buckwheat using the data of equilibrium moisture content. Transactions of the ASABE. 36(1):113-118.