IJERD – International Journal of Environmental and Rural Development (2021) 12-2

Research article

Establishment of Optimized Manufacturing Conditions for Cooked Rice -Part I- Equilibrium Moisture Content and Latent Heat of Vaporization of Cooked Rice

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Received 6 November 2020 Accepted 15 October 2021 (*Corresponding Author)

Abstract The equilibrium moisture contents of cooked milled rice in the desorption process were measured at several temperatures (20-60°C) and relative humidity levels (10-86%) by a static method. The equilibrium moisture content of the sample increased with increasing equilibrium relative humidity at a constant temperature and increased with a decrease in temperature at any given equilibrium relative humidity. The Chen-Clayton equation, which is a sorption isotherm, was used to express the relationship between the equilibrium moisture content of the sample, equilibrium relative humidity, and absolute temperature. The latent heat of vaporization of water for the cooked rice was calculated by using the Chen-Clayton equation and thermodynamic theory (Clapeyron equation). At a moisture content of 15-30% (d.b.) (d.b.: the amount of water per unit mass of dry matter present in the material), the latent heat of vaporization of the sample decreased almost exponentially with an increase in moisture content. For samples at a moisture content above 50% (d.b.), the values of latent heat of vaporization sufficiently approached that of free water.

Keywords equilibrium moisture content, sorption isotherms, latent heat of vaporization, Chen-Clayton equation, Clapeyron equation, cooked milled rice

INTRODUCTION

The development of processed food made from rice at production location is expected to lead to regional revitalization and increased income for farmers. A simply processed food made from rice is dried cooked rice or pregelatinized rice. A general manufacturing process of dried cooked rice is as follows: 1) washing raw rice, 2) soaking the washed rice in water, 3) cooking or steaming the rice (the raw rice starch is changed to pregelatinized starch), 4) separating the rice kernel from the mass of cooked rice to a single cooked rice, and 5) drying the cooked rice. The dried cooked rice is usually rehydrated with water or hot water and then eaten.

Recently, food that can be kept in case of emergency has been developed and manufactured in Japan to prevent food shortage in the case of natural disasters and infectious diseases. The interest in dried cooked rice has increased as it can be used in preserved food, portable ration food, and emergency provisions. In addition, dried cooked rice has been used as a material in instant food products, for example, an instant pot dried rice similar to an instant pot noodle; thus, the market of dried cooked rice products has continued to increase. The data of the drying characteristics, equilibrium moisture content, latent heat of vaporization for cooked rice, and water absorption (rehydration) characteristics of dried cooked rice are required for optimizing processing operations, designing equipment, and ensuring high quality.

We measured the equilibrium moisture content of the cooked rice, the hot air-drying characteristics of the cooked rice, and the water absorption characteristics of the dried cooked rice. This basic information is needed to establish the optimized manufacturing conditions for cooked rice. The latent heat of vaporization of water for cooked rice was calculated based on the thermodynamic theory by using the equilibrium moisture content data. The moisture transfer kinetics during the drying and the water absorption was analyzed based on the drying theory of the first falling rate period or the first-order reaction rate theory. The equilibrium moisture contents are needed to analyze the hot air-drying characteristics in addition to examining food preservation. Because the changes in moisture content occur during the drying and the water absorption process, kinetic analysis to predict the changes in moisture content are required to optimize the processing conditions. We reported the equilibrium moisture content and the latent heat of vaporization of water in this part I and will report the moisture transfer kinetics in next part II.

To determine the storage conditions and analyze the drying process, it is necessary to know the relationship between the equilibrium moisture content (EMC) in the foodstuffs and the equilibrium relative humidity (ERH) of the drying air or aeration air at a given temperature. This relationship is described by sorption isotherm equations (Sun and Woods, 1993). Knowledge of the moisture sorption isotherms of foodstuffs is valuable in solving food processing and engineering problems such as equipment design, drying, and storage processes as well as predicting shelf life (Arogba, 2001). The latent heat of vaporization (LHV) of water in foodstuffs is important for the design of drying equipment (Chen, 2006). The LHV is neither constant nor equal to the heat of pure water evaporation because the LHV is a function of temperature and moisture content, i.e., the LHV varies throughout the drying process (Rückolda et al., 2003). The LHV can be calculated by using the sorption isotherm equations and Clapeyron thermodynamic theory (Murata et al., 1988; Tagawa et al., 1993). Koide et al. (2016) reported the EMCs for dried cooked rice in the absorption process. However, little research has been reported on the EMC and LHV for cooked rice.

In this study, the EMCs of cooked rice (short grain rice, japonica) in the desorption process were measured at several temperatures and relative humidity levels, and the LHV of water for the cooked rice was calculated by using the measured results of EMC and thermodynamic theory.

OBJECTIVE

The objectives of this study were 1) to evaluate the relationship between the EMC, ERH, and temperature and 2) to estimate the LHV of water by using the thermodynamic theory.

METHODOLOGY

Sample

Non-glutinous rough rice (cv. “Hoshinoyume”) was purchased from a Japanese agricultural cooperative in Tohma, Hokkaido, Japan (JA Tohma) and was stored in a refrigerator at approximately 5°C until the test. The “Hoshinoyume” was widely cultivated in Hokkaido when we conducted this research because this rice had a good eating quality or tasty. This non-glutinous rough rice was first hulled with a roll-type rice huller (THU35B, Satake Co., Ltd.). Brown rice (800 g) was put into an abrasive-type (stir-type) rice-milling machine (SKM-5B (1), Satake Co., Ltd.) and milled for 5.0 min to produce milled rice. The degree of milling (or milling yield) was adjusted to be approximately 92%.

The milled rice was cooked with commercial rice cookers (NP-FB10, Zojirushi Co., Ltd.) in accordance with the operation manual of the rice cooker. To uniformly gelatinize the rice, the rice was soaked in tap water at room temperature for 1 h before cooking. The cooking time was 45-60 min and the maximum temperature in the rice cooker was around 104°C. To obtain a single grain of cooked rice from the mass of cooked rice, the cooked rice was rinsed with tap water for 3 s, and the excess water was drained. After the rinse, the surface of the cooked rice was wiped with Kimwipes® (S-200, Nippon Paper Crecia Co., Ltd.) to remove excess water.

Equilibrium Moisture Content (EMC)

The EMCs of the cooked rice in the desorption process were measured by a static method (Murata et al., 1988; Tagawa et al., 1993) at three temperatures (20, 40, and 60°C) and ten relative humidity levels ranging from 10% to 86%. The temperature was controlled with an incubator (IN802, Yamato Scientific Co., Ltd.). Ten kinds of saturated salt solutions (NaOH, LiCl, CH_3COOK, $MgCl_2$, K_2CO_3, NaBr, $NaNO_2$, $NaNO_3$, NaCl, KCl) were used to maintain the particular relative humidity in each vessel. Each saturated salt solution presents different vapor pressure or relative humidity at each temperature in a closed container. The relative humidity ranges for each saturated salt solution were 4-7% for NaOH, 10-12% for LiCl, 19-24% for CH_3COOK, 29-34% for $MgCl_2$, 42-45% for K_2CO_3, 49-60% for NaBr, 58-66% for $NaNO_2$, 67-76% for $NaNO_3$, 74-76% for NaCl, and 80-86% for KCl. The relative humidity data of these saturated salt solutions are shown in the references (Arai et al., 1976; Tagawa et al., 1993; Tanaka, 1998). Approximately 10 g of the sample was suspended in a 1 L wide-mouth bottle containing a selected saturated salt solution to maintain a constant humidity at a constant temperature. The sample was weighed on a digital balance (ER-182A, A&D Co., Ltd.) at intervals of 2 or 3 days. Equilibrium was considered to be reached when the change in weight was less than 0.2 mg between two successive measurements. In this method, it took approximately 30 days for a sample to reach the EMC. The EMC of the sample was determined using a forced hot air oven (DX-600, Yamato Scientific Co., Ltd.) at 135°C for 24 h.

RESULTS AND DISCUSSION

Relationship among the Equilibrium Moisture Content (EMC), Equilibrium Relative Humidity (ERH), and Temperature in the Desorption Process

The relationship between the EMC and ERH is usually expressed by means of a sorption isotherm. The moisture desorption isotherms of the sample at three different temperatures are presented in Fig. 1. As shown in Fig. 1, the EMC increased with increasing ERH at a constant temperature and increased with a decrease in temperature at any given ERH.

Several mathematical descriptions of the sorption data have been developed for different ranges of ERH in regard to different agricultural products (Chakraverty & Singh, 2014). The Chen-Clayton equation (Chen & Clayton, 1971), which is a sorption isotherm, closely fit measured EMC data of the six kinds of grains (Murata et al., 1988; Tagawa et al., 1993). The Chen-Clayton equation is as follows:

$$rh = \exp\left\{-f_1 T^{g_1} \exp\left(-f_2 T^{g_2} M_e\right)\right\} \tag{1}$$

where rh: equilibrium relative humidity (-), T: absolute temperature (K), M_e: equilibrium moisture content (% (d.b.), d.b.: the amount of water per unit mass of dry matter present in the material), and f_1, f_2, g_1, and g_2: parameters.

The measured EMC data of the sample were fitted to Eq. (1) using a nonlinear least squares method (false position method). The goodness of fit was evaluated by the values of the root mean squared error (RMSE). The values of the parameters in Eq. (1) were: $f_1 = 50.61$, $f_2 = 2.577\times10^{-7}$, $g_1 = -0.3675$, and $g_2 = 2.326$. The solid lines in Fig. 1 are the results calculated from Eq. (1). As is evident from Fig. 1, the agreement between the experimental and predicted values of Eq. (1) was found to be satisfactory (RMSE = 0.022). The relationship between the EMC of the sample in the desorption process, ERH, and absolute temperature was expressed by Eq. (1).

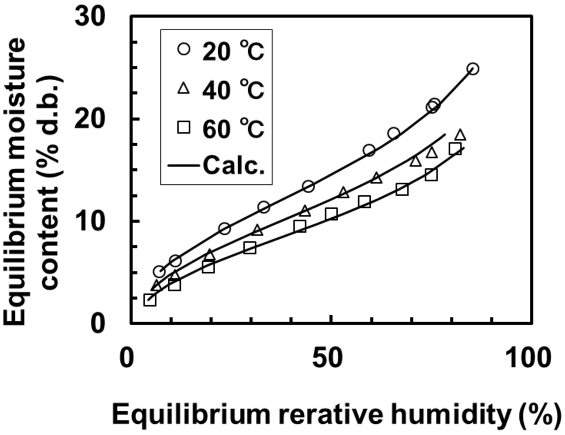

Fig. 1 Moisture desorption isotherms of the sample at three different temperatures

Latent heat of Vaporization (LHV) of Water

Because Eq. (1) satisfactorily correlated the experimental sorption data of the sample within the range of measurement conditions, Eq. (1) was used to calculate the LHV of water for the sample. The LHV was determined by the same method as Murata et al. (1988) and Tagawa et al. (1993). The Clapeyron equation for vapor-liquid equilibrium is written as follows:

$$\frac{\mathrm{d}p_{st}}{\mathrm{d}T} = \frac{\Delta h_v}{T\left(v_g - v_l\right)} \tag{2}$$

where p_{st}: the water vapor pressure in the sample (Pa), Δh_v: the latent heat of vaporization (J/kg), v_g: the specific volume of water vapor (m^3/kg), and v_l: the specific volume of liquid water (m^3/kg).
To calculate the LHV (Δh_v), Eq. (3) was rewritten from Eq. (2).

$$\Delta h_v = \left(v_g - v_l\right) \times T \times \frac{\mathrm{d}p_{st}}{\mathrm{d}T} \tag{3}$$

In Eq. (3), the vapor pressure of the moisture in the sample at a given psychrometric condition (p_{st}) was determined from Eqs. (1) and (4).

$$p_{st} = rh \times p_s \tag{4}$$

Where p_{st}: the water vapor pressure in the sample (Pa) and p_s: the saturated vapor pressure (Pa). The saturated vapor pressure (p_s) in Eq. (4) is a function of temperature only. The saturated vapor pressure (p_s) in Eq. (4), along with the specific volume of water vapor (v_g) and specific volume of liquid water (v_l) in Eq. (3) were calculated by using the IFC formulation for industrial use (The Japan Society of Mechanical Engineers, 1980) and the equilibrium relative humidity (rh) in Eq. (4) was determined by Eq. (1). The values of $\mathrm{d}p_{st}/\mathrm{d}T$ in Eq. (3) was obtained by differentiating p_{st} in Eq. (4) with respect to the absolute temperature (T).

$$\frac{\mathrm{d}p_{st}}{\mathrm{d}T} = \frac{\mathrm{d}rh}{\mathrm{d}T} p_s + \frac{\mathrm{d}p_s}{\mathrm{d}T} rh \tag{5}$$

The $\mathrm{d}rh/\mathrm{d}T$ value in Eq. (5) was obtained by differentiating rh in Eq. (1) with respect to T as shown by Eq. (6).

$$\frac{\mathrm{d}rh}{\mathrm{d}T} = -rh \times \exp\left(-f_2 T^{g_2} M_e\right) \times \left(f_1 g_1 T^{g_1-1} - f_1 f_2 g_2 T^{g_1+g_2-1} M_e\right) \tag{6}$$

In addition, the dp_s/dT value in Eq. (5) was calculated by differentiating p_s with respect to T, where p_s was obtained from the IFC formulation (The Japan Society of Mechanical Engineers, 1980).

The LHV isotherms of the sample are shown in Fig. 2, and the LHV values calculated from Eq. (3) for three temperatures is plotted against the moisture content. Though these isotherms were obtained by extrapolating the data at moisture contents above 25% (d.b.), they showed that the LHV decreased as temperature increased. At a moisture content of 15-30% (d.b.), the LHV of the sample decreased almost exponentially with an increase in moisture content, and at a moisture content above 50% (d.b.), the LHV sufficiently approached that of free water. This tendency of LHV versus moisture content is in agreement with the results of Murata et al. (1988) and Tagawa et al. (1993) for grains. The values of LHV for cooked rice were almost the same degree with the grains and beans reported by Murata et al. (1988) and Tagawa et al. (1993). For the sample with a moisture content above 50% (d.b.), it seemed reasonable to assume that the LHV of the sample was equal to that of free water. Since the LHV is the amount of energy required to remove water from a solid, the higher the LHV, the more tightly bound the water is. The LHV was a function of both temperature and moisture content, i.e., the values varied throughout the drying process. Through the utilization of Eqs. (1) and (2), the LHV of the sample could be estimated as a function of both temperature and moisture content. The LHV of water is the amount of energy (enthalpy) that must be added to a liquid substance, to transform a given quantity of the substance into gas. The energy necessary to add to the drying process can be estimated based on the values of the LHV. This energy calculation leads to the optimization of the manufacturing condition for the cooked rice.

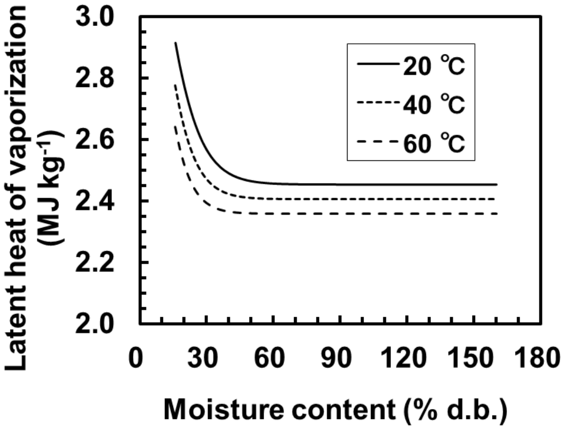

Fig. 2 Latent heat of vaporization of water for the sample calculated from Eq. (3)

CONCLUSION

The equilibrium moisture contents (EMCs) of the cooked rice in the desorption process were measured by a static method at three temperatures (20, 40, and 60 °C) and ten relative humidity levels ranging from 10-86 %. The Chen-Clayton equation was used to express the relationship among the EMC of the sample in the desorption process, equilibrium relative humidity, and absolute temperature. Using the measured results of the EMC, the latent heat of vaporization of water in the sample (LHV) was calculated5 by the Clapeyron thermodynamic theory. The values of LHV decreased almost exponentially with an increase in moisture content from 15-30 % (d.b.) and sufficiently approached that of free water at a moisture content above 50 % (d.b.).

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