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

Research article

Establishment of Optimized Manufacturing Conditions for Cooked Rice -Part II- Moisture Transfer Kinetics of Cooked Rice when Drying and Soaking in Water

YOSHIKI MURAMATSU*
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan
Email: y-murama@nodai.ac.jp

MASANORI HASHIGUCHI
Keisoku Engineering System Co., Ltd., Tokyo, Japan

DAHAI MI
Keisoku Engineering System Co., Ltd., Tokyo, Japan

SOKLY SORM
Graduate School of Agriculture, Tokyo University of Agriculture, Tokyo, Japan

EIICHIRO SAKAGUCHI
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

SHOTARO KAWAKAMI
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

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

Abstract The thin-layer drying characteristics of cooked milled rice during hot air drying were measured at four temperatures (30, 40, 50, and 60 °C) and at a relative humidity of 40%. The hot air-drying process of the sample was composed of the first falling rate, and the exponential model was applied to predict the changes in moisture content of the sample at each temperature. The drying rate constant of the sample increased as temperature increased and was expressed as an Arrhenius-type equation. The water absorption characteristics of dried cooked milled rice when soaking in water were examined at four temperatures (70, 80, 90, and 98 °C). The ratios of the changes in moisture content from 8 to 150% (d.b.) were converted from the data of changes in moisture content. The first-order reaction rate equation could be applied to explain the water absorption process of samples. The water absorption rate constant had a tendency to increase with increasing soaking temperature and was expressed as a function of soaking temperature by an Arrhenius-type equation.

Keywords cooked milled rice, hot air drying, dried milled rice, water absorption, exponential model, first-order rate constant

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. We had reported the equilibrium moisture content and the latent heat of vaporization of water in part I (Muramatsu et al., 2021). 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. The moisture transfer kinetics was reported in this Part II. The equilibrium moisture content data reported in Part I was used in the analysis of the moisture transfer kinetics during drying.

Ramesh and Rao (1996) examined the drying of cooked rice (high amylose variety rice) with a vibro-fluidized bed drier. Luangmalawat et al. (2008) reported on the effect of temperature on the drying characteristics and quality of cooked rice (Jasmin rice: long grain rice, indica rice). Jiao et al. (2014) used convective hot air, microwave, and combined microwave-hot air drying techniques for the drying of cooked rice (hybrid indica rice) and evaluated the efficacy of these techniques. Jiao et al. (2014) also investigated the effect of microwave power and air temperature on the drying and rehydration kinetics of dried cooked rice and examined the changes in the color values of the product after drying. Koide et al. (2016) measured the changes in the moisture content of cooked rice during hot air drying and changes in the moisture content of dried cooked rice during water adsorption. Almost all previous papers have reported the drying characteristics of indica rice. Additionally, the drying characteristics of many kinds of food have been measured, and many mathematical models, are used to describe the drying process of food. Optimum drying and water absorption models including the values of parameters, are particularly useful for easily predicting the changes in the moisture content of materials. Therefore, knowing the optimum model is important for practical use.

In this study, we examined the thin-layer hot air-drying characteristics of cooked milled rice (short grain rice, japonica) at four different temperatures. In addition, the water absorption (rehydration) characteristics of dried cooked milled rice were also measured at four different temperatures.

OBJECTIVE

The objectives of this study were 1) to examine the hot air-drying and the water absorption characteristics at several temperatures, 2) to derive a suitable mathematical drying and water absorption models to describe changes in moisture content, and 3) to evaluate the relationship between the drying rate constant or the water absorption rate constant and temperature.

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.

Cooked milled rice was used for measuring the drying characteristics. Dried cooked milled rice was used as a sample for the water absorption test. For the preparation of this dried milled rice, cooked milled rice was dried at a temperature of 40 °C and a drying time of 6 h with a commercial hot air dryer (LH-103D, Satake Co., Ltd.).

Hot Air Drying Test

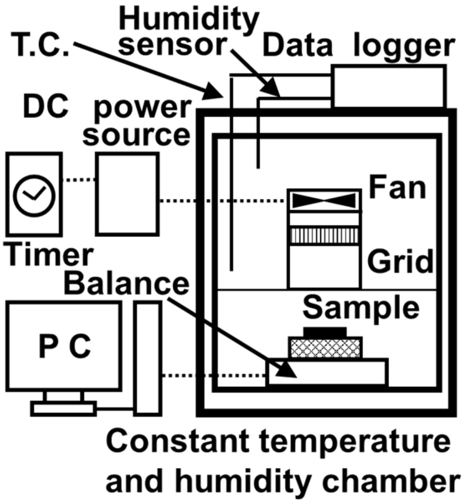

Fig. 1 Schematic of the hot air-drying apparatus

The changes in the moisture content of the cooked rice using the hot air-drying method were measured at four temperatures (30, 40, 50, and 60 °C) and at a relative humidity of 40 %. Fig. 1 shows a schematic of the hot air-drying apparatus used in this study. The apparatus consisted of three units: a drying chamber at constant temperature and humidity, a ventilation unit, and a recording unit. A constant temperature and humidity chamber (IG420, Yamato Scientific Co., Ltd.) was used as the drying chamber. The drying chamber dimensions were a width of 500 mm, a length of 390 mm, and a height of 600 mm. The temperature and relative humidity in the drying chamber were measured with a T-type thermocouple and a relative humidity sensor, and recorded with a data logger (GL200, GRAPHTEC Co., Ltd.). The airflow rate in the chamber was adjusted to 2.0 m/s by a fan (CUDC 12B4, Japan Servo Co., Ltd.) using a DC power source (model 526, Metronix Co., Ltd.). The DC power source was controlled with a timer (ELT-3, AS ONE Co., Ltd.), and the airflow was stopped when the sample mass was measured. A grid screen was fitted below the fan to straighten the air velocity pattern. Changes in mass, i.e., the changes in moisture content, when drying were measured using a digital balance (EK-300i, A&D Co., Ltd.), and the changes in sample mass were automatically recorded on a personal computer. A stainless steel basket with a diameter of 100 mm, a height of 15 mm, and a 3.0 mm aperture, was utilized as a sample tray.

The sample (approximately 10 g) was placed on the tray. The drying test was terminated when the moisture content of the sample was approximately 15 %, on a dry basis (d.b.). The final moisture content of the sample was determined using a forced hot air oven (DX-600, Yamato Scientific Co., Ltd.) at 135 °C for 24 h. Through the use of measured values of final moisture content, the changes in mass when drying were converted to the moisture content of the sample.

Measurement of Water Absorption Characteristics

Moisture content changes of the dried cooked rice when soaking in water were measured at four water temperatures (70, 80, 90, and 98 °C). Approximately 5 g of sample was put into a sample net after weighing the sample mass with a digital balance (FX-300, A&D Co., Ltd.), and soaked in a water bath (SH-12, TAITEC Co., Ltd.). The sample net was removed from the water bath at each preset soaking time (1.0, 2.0, and 5 min intervals), and the surface of the sample was wiped with Kimwipes® (S-200, Nippon Paper Crecia Co., Ltd.) to remove residual liquid. The sample was then reweighed. The increase in sample mass when soaking in water was considered to be an increase in the moisture content of the sample. The moisture content of the sample after soaking was determined from the values of the initial moisture content of the dried cooked rice and the mass changes data when soaking in water.

RESULTS AND DISCUSSION

Hot Air-Drying Characteristics

The moisture content of cooked rice decreased over elapsed time and exhibited a gentle downward curve from the beginning of the drying process at each temperature. The changes in the moisture content of the sample at four different temperatures (30-60°C) and at a relative humidity of 40% are shown in Fig. 2. The drying rate (% (d.b.)/h) of the sample was obtained by numerical differentiation (Gregory-Newton forward method) using the moisture content measurements. The drying rate of the sample increased with an increase in temperature. The linear relationship between the drying rate and the free moisture content ($|M\text{-}M_e|$) was found at each temperature. The above result indicates that the hot air-drying process of the sample comprises the first falling rate drying period.

Therefore, the measured drying data were fitted to the following exponential model (Eq. (1)) (Koide et al., 2016) using the least squares method, and the values of the drying rate constant (k_1) were determined at each temperature.

$$\frac{M - M_e}{M_0 - M_e} = \exp\left(-k_1 t\right) \tag{1}$$

Where M: the moisture content at each preset time (% (d.b.)), M_0: the initial moisture content (% (d.b.)), M_e: the equilibrium moisture content (% (d.b.)), k_1: the drying rate constant (h^{-1}), and t: the time (h). The values of M_e in Eq. (1) was also calculated from following the equation (Muramatsu et al., 2021). at each measurement condition.

$$rh = \exp\left\{-50.61T^{-0.3675}\exp\left(-2.577\times10^{-7}T^{2.326}M_e\right)\right\} \tag{2}$$

The values of k_1 and the root mean squared error (RMSE) of Eq. (1) are given in Table 1. The solid line in Fig. 2 shows the results calculated from Eq. (1). As shown in Fig. 2, the measured results matched well with the calculated results. Under all measurement conditions, the changes in the moisture content of all samples caused by hot air drying could be estimated by Eq. (1).

The temperature dependency of k_1 for grain (Murata, 1982) and beans (Muramatsu et al., 2007) was expressed by the following Arrhenius-type equation:

$$k_1 = a_1 \cdot \exp\left(-\frac{b_1}{T}\right) \tag{3}$$

where a_1 and b_1 are parameters. Eq. (3) shows that the relationship between k_1 and the reciprocal of absolute temperature ($1/T$) is approximately linear in a semilogarithmic plot. The values of k_1 shown in Table 1 were fitted by the least squares method to Eq. (3). The values of the parameters and the RMSE of Eq. (3) were: a_1 = 772.5, b_1 = 1838, and RMSE = 9.081×10^{-2}. Eq. (3) was applicable for examining the relationship between the drying rate constant and the temperature of the sample.

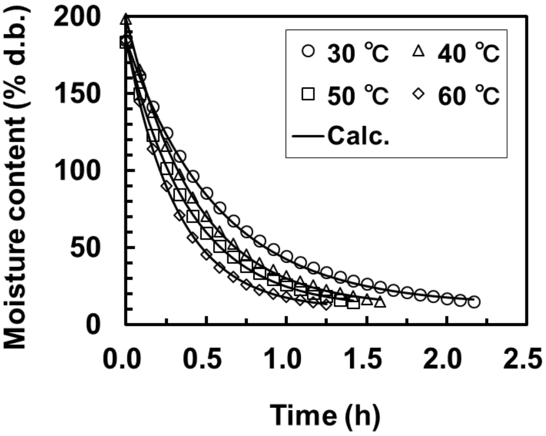

Fig. 2 Changes in the moisture content of the sample with drying

Table 1 Parameters in Eq. (1)

Temperature (°C)	M_0 (% (d.b.))	M_e (% (d.b.))	k_1 (h^{-1})	RMSE (% (d.b.))
30	184.4	12.5	1.746	1.338
40	198.5	11.6	2.311	0.8995
50	183.5	10.7	2.506	1.052
60	184.6	9.89	3.115	0.6286

Water Absorption Characteristics

The initial moisture contents of the dried cooked rice were approximately 8 % (d.b.). The water absorption curves of the sample are shown in Fig. 3. The moisture content of the sample increased over time, exhibiting a gentle upward curve from the beginning of soaking, and did not approach equilibrium under these measurement conditions. The water absorption rate of the sample increased with an increase in soaking water temperature and on the other hand decreased with an increase in soaking time at each soaking temperature.

The moisture content of cooked rice (nonglutinous japonica rice) is usually approximately 65 % (w.b.), i.e., 150 % (d.b.). In this study, to evaluate the water absorption characteristics of the sample, the ratios of the change in moisture content (Kubota, 1990) from 8 to 150 % (d.b.) (x) were calculated from Eq. (4).

$$x = \frac{M - M_0}{M_T - M_0} = \frac{M - 8}{150 - 8} \tag{4}$$

Where x: the ratios of the change in moisture content from 8 to 150 % (d.b.), and M_T: the target or final moisture content (% (d.b.)). The values of x change from 0 to 1, and when “x = 1”, the moisture content of the sample has reached 150 % (d.b.).

The tendency of the changes in the values of x had the same with changes in the water absorption rate. The values of x for the sample increased exponentially with an increase in soaking time.

Therefore, the following first-order reaction rate equation (Kubota, 1990) was applied for analyzing the water absorption characteristics of the sample.

$$\frac{\mathrm{d}x}{\mathrm{d}t} = k_2\left(1 - x\right) \tag{5}$$

Where k_2 is the water absorption rate constant (min^{-1}). The unit of time (t) in Eq. (5) is "min". The values of k_2 determined by the least squares method and the RMSE of Eq. (5) for each temperature are shown in Table 2. From the RMSE values, it was confirmed that the measured values agreed well with those calculated from Eq. (5); thus, the ratios of changes in the moisture content of the sample between 8 and 150 % (d.b.) could be estimated by Eq. (5).

The values of k_2 shown in Table 2 increased with an increase in soaking temperature. The values of k_2 were expressed as a function of temperature by using the following Arrhenius-type equation (RMSE = 0.04288).

$$k_2 = 681.0 \cdot \exp\left(-\frac{2606}{T}\right) \tag{6}$$

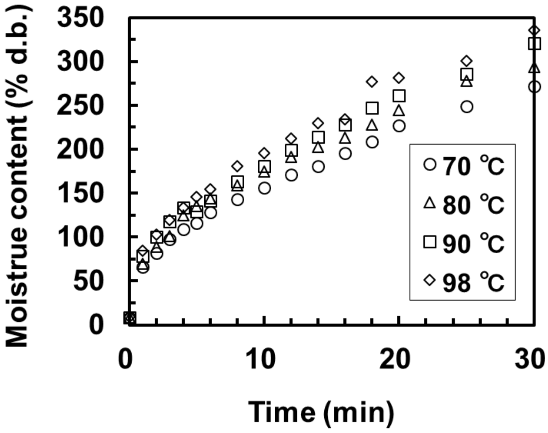

Fig. 3 Changes in the moisture content of the sample during water absorption

Table 2 Parameters in Eq. (4)

Temperature (°C)	k_2 (min^{-1})	RMSE (-)
70	0.3340	0.05893
80	0.4650	0.05416
90	0.4663	0.06033
98	0.6374	0.05380

CONCLUSION

The thin-layer drying characteristics during hot air drying of cooked rice were measured at several temperatures and relative humidity levels. The hot air-drying process of the sample was composed of the first falling rate, and the exponential model was applicable to predict the changes in moisture content of the sample at each temperature. The drying rate constant of the sample increased as temperature increased and was related to temperature by an Arrhenius-type equation.

The water absorption characteristics of dried cooked rice when soaking in water were measured at four temperatures. The first-order reaction rate equation could be applied to explain the water absorption process of samples. The water absorption rate constant was expressed as a function of soaking temperature by an Arrhenius-type equation.

The changes in moisture content of the cooked rice during drying and the dried cooked rice during water absorption can be easily predicted by using the drying model and the water absorption model, respectively. These models will be useful in the determination of the endpoints or treatment time for drying or water absorption. This information saves the input energy and the treatment time and would lead to the establishment of optimized manufacturing conditions for cooked rice.

REFERENCES

Jiao, A., Xu, X. and Jin, Z. 2014. Modelling of dehydration-rehydration of instant rice incombined microwave-hot air drying. Food and Bioproducts Processing, 92 (3), 259-265.

Koide, S., Orikasa, T., Koide, F., Muramatsu, Y. and Tagawa, A. 2016. Moisture content prediction of dried cooked rice during drying, preservation, and water absorption. J. Japan Assoc. Food Preservation Scientists, 42 (2), 59-64.

Kubota, K. 1990. Kinetics of quality conversion. In Reaction Engineering for Food, Kubota, K., Uno, J. and Kobayashi, T. (Eds.), Tokyo, 1-45.

Luangmalawat, P., Prachayawarakorn, S., Nathakaranakule, A. and Soponronnarit, S. 2008. Effect of temperature on drying characteristics and quality of cooked rice. LWT-Food Sci. Tech., 41 (4), 716-723.

Muramatsu, Y., Hashiguchi, M., Mi, D., Sorm, S., Sakaguchi, E. and Kawakami, S. 2021. Establishment of optimizing manufacturing condition for cooked rice -Part I-, Equilibrium moisture content and latent heat of vaporization of cooked rice. Int. J. Environmental and Rural Development, 12 (1), 130-135.

Muramatsu, Y., Tagawa, A., Sakaguchi, E. and Kasai, T. 2007. Prediction of moisture content changes of kidney beans during drying. J. Japan Assoc. Food Preservation Scientists, 33 (6), 295-302.

Murata, S. 1982. Characteristics of grain and estimation of drying rate. J. Japanese Soc. Agric. Machinery, 44 (3), 517-523.

Ramesh, M.N. and Rao, S.P.N. 1996. Drying studies of cooked rice in a vibrofluidised bed drier. J. Food Eng., 27 (4), 389-396.