Food Sci. Biotechnol. Vol. 18, No. 1, pp. 202 ~ 206 (2009)

Food Science
and
Biotechnology

Drying Characteristics of Korean-type Rehmannia (*Jiwhang*) Noodle

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Abstract Drying characteristics of fresh Korean-type rehmannia (*jiwhang*) noodle was investigated to determine drying kinetic parameters under the experimental conditions of 5 temperatures (30, 40, 60, 80, and 90°C). Drying curve of the noodle showed a biphasic pattern of decrease in drying rate with initial rapid drying followed by slow dehydration as the progress in drying. In all drying conditions, only falling drying rate period was observed and the drying rate of the noodle was greatly influenced by the drying temperature. The effective diffusion coefficients (D_{eff}) were determined by the diffusion model and their temperature dependency was determined using an Arrhenius equation. The activation energy (E_a) values for the drying of the noodle were 19.94 and 21.09 kJ/mol at the initial and the latter stage of dehydration, which were comparable to those of pasta or Japanese *udong* dehydration.

Keywords: noodle, rehmannia, drying, kinetics, diffusion

Introduction

Noodle is one of the most popular traditional foods made from wheat flour in Asian countries (1). Oriental noodles differ widely from Western pasta or spaghetti in many aspects such as raw material, preparation method, texture, color, and product shape (2). Pasta is usually manufactured using coarse and strong flour like durum semolina flour (*Triticum durum*) by an extrusion process (3-5). On the other hand, Oriental noodles are manufactured using soft and fine flour of medium protein content (*Triticum aestivum*), which involves sheeting and cutting into strips using a series of rolls (2,6,7). As one of the Oriental noodles, Korean noodle is a typical white salted noodle like Japanese noodle (*udong*), which is white or creamy white in appearance and have a soft and elastic texture, being usually made from a mixture of flour (100 parts), water (32-35 parts), and salt (2-3 parts).

In processing of any type of noodles, drying is the most difficult and critical step, where the moisture level of the formed fresh noodles decreases from about 40% to less than 12.5% without damage to the finished product. Since quality of the noodles is usually determined during the drying process, drying method should be optimized through the control of the temperature and humidity of the drying air (5-8). For example, extremely slow drying of noodle is subjected to mold growth; on the other hand extremely rapid drying may cause checking or cracking. Research on drying behavior of noodles has been focused mainly on pasta (4,5,8,9) and Japanese *udong* (6,7,10). Most of drying data of noodles (pasta and *udong*) have been analyzed using the diffusion model (4-7,9-11) and the effect of temperature on moisture diffusivity was represented by the Arrhenius equation.

Recently, as an advent of increased interest for well-being foods, there has been a renewed interest on the colored noodles prepared with flour blended with dietary fiber-based materials or natural ingredients with functional properties. They are mainly intended to exploit a low glycemic effect of dietary fiber through slow digestion of the carbohydrates or functional properties (i.e., antioxidation, prevention of obesity, or specific disease) of the natural ingredients obtained from natural resources such as herbs, mushrooms, or other plants (12-18). Little attention has been paid to the drying characteristics of Korean noodles.

Therefore, the objective of this research was to test the drying characteristics of rehmannia noodle to determine the kinetic parameters for drying Korean-type noodle.

Materials and Methods

Materials Fresh rehmannia samples obtained from a local farm at Jangheung were freeze-dried using a freeze-drier (Eyela vacuum freeze dryer, FDU-1100; Tokyo Rikakikai Co., Ltd., Tokyo, Japan) at −40°C, 760 mmHg vacuum for 2 days and powdered using a high-speed hammer mill (Myungsung Machine Co., Ltd., Seoul, Korea) with passing through a 160-mesh sieve, and then packed in a airtight polyethylene bag and stored in a refrigerator until used. High quality patent flour was obtained from Korea Flour Mills Co., Ltd. (Mokpo, Korea) and commercially available refined salt with 99% purity was used for the preparation of noodles. Flour blend was prepared by mixing 3 wt% of the rehmannia powder with flour just before manufacturing of noodles.

Preparation of noodles Experimental noodles were prepared according to the method of Toyokawa *et al.* (18). Three-hundred g of the premixed flour blend, 100 mL of water, and 6 g of salt were mixed with a flat paddle in a Hobart mixer for 6 min on slow speed, to distribute water evenly throughout the flour particles. The resulting crumbly dough was sheeted between steel rolls (180-mm diameter, 5-mm gap) of a Yamato (Tokyo, Japan) laboratory-type noodle machine; it was then folded end-to-end and put

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Received July 14, 2008; Revised September 22, 2008
Accepted Septembet 22, 2008

through the sheeting rolls, then folded and sheeted again. The sheet was rested for 1 hr in a plastic bag to allow gluten development and then put through the sheeting rolls 9 times at progressively smaller gap settings from 5.0 to 1.0 mm to reduce the sheet to a final thickness of 1.0 mm. The sheet was then cut with a cutting roll (Okuba 1.0 m/m A30) into strips with 1.0×1.0 mm cross sections. The strips of noodles were used for the drying test.

Drying experiments The batch drying experiments were performed following the procedure as Rhim *et al.* (19) in a bench-top drying chamber (HB-502 M; Hanback Co., Yongin, Korea) equipped with a temperature controller (sensitivity $\pm0.5^{\circ}C$). A digital balance (Range 400 g, precision 0.1 mg, Satorius AG, Göttingen, Germany) was placed externally on top of the drying chamber. The sample holder was connected to the balance and suspended in the dryer as shown schematically in Fig. 1. Five temperatures were used in the range of 30-90°C. This temperature range included both the conventional and the high-temperature drying conditions used in the noodle industry (20,21). Twenty strips of fresh noodle sample (30 cm length/strip, about 26 g) were placed into the sample holder in the same arrangement as that of the industrial drier and its weight was continuously monitored with 1 or 5 min of intervals for 1-2.5 hr depending on the drying temperature and weight data were collected using a PC-based data acquisition system (SartoConnect, ver 3.5.2, Satorius AG). The moisture content of the dry samples was determined using an oven drying method (105°C, 24 hr). The weight of noodles collected during drying tests was converted into moisture content in dry basis (m, g water/g dry solid). Equilibrium moisture content (m_e) at each drying temperature was determined by monitoring the weight change for extended drying for 4-40 hr depending to drying temperature until it remained constant.

Analysis of drying data The moisture ratio (MR) and drying rate of the noodle samples were calculated using following equations (19):

$$MR=\frac{m-m_e}{m_o-m_e} \qquad (1)$$

$$Drying\ Rate=\frac{dm}{dt}=\frac{m_{t+dt}-m_t}{dt} \qquad (2)$$

where m, m_o, m_e are the moisture content at any time, initial moisture content, equilibrium moisture content, and m_t and m_{t+dt} are moisture content at time t and $t+dt$ (g water/g dry solid), respectively, t is drying time (min). The noodle drying data were analyzed using the diffusion model (3,6), which is based on an internal moisture transfer driven by the moisture gradient and interpreted mathematically by the Fick's second law of diffusion.

$$\frac{\partial m}{\partial t}=D_{eff}\frac{\partial^2 m}{\partial x^2} \qquad (3)$$

where D_{eff} is the effective diffusion coefficient (m^2/sec) and x is characteristic dimension of the product. For the application of the Fick's law, following assumptions were made: (i) the transfer of mass is unidirectional, (ii) the sample has an uniform initial moisture content, and (iii) the internal moisture movement is its main resistance to moisture transfer. The shape of the noodles was assumed to be an infinite cylinder and the corresponding solution of Fick's law was used to obtain the effective diffusion coefficient (D_{eff}).

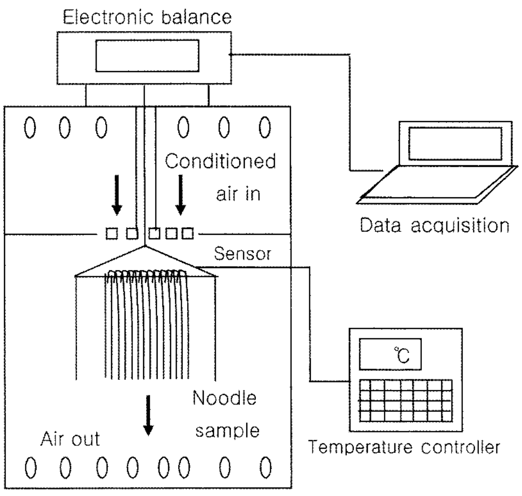

Fig. 1. Schematic diagram of the experimental drying apparatus.

The solution of Fick's law for a cylinder is as follows (22):

$$MR=\frac{m-m_e}{m_o-m_e}=\sum_{n=1}^{\infty}\frac{4}{\beta_n^2}exp\left(-\beta_n^2\frac{D_{eff}t}{R_c^2}\right) \qquad (4)$$

where β_n^2 is the Bessel function roots of the first kind and zero order, and R_c is the radius of cylinder (0.5×10^{-3} m in the present study). The effective diffusion coefficient was determined from the slope of a linear line obtained by plotting experimental drying data in terms of ln(MR) vs. drying time based on the first term of the series as shown below using the method described by Inazu *et al.* (6).

$$\ln(MR)=\ln\frac{4}{\beta_1^2}-\frac{\beta_1^2 D_{eff}}{R_c^2}t \qquad (5)$$

Temperature dependency of the effective diffusion coefficient (D_{eff}) was tested using the Arrhenius equation.

$$D_{eff}=D_{eff\,o}\exp(-E_a/RT) \qquad (6)$$

where $D_{eff\,o}$ is the pre-exponential factor, E_a is the activation energy (J/mol), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K).

Results and Discussion

Drying characteristics The moisture contents of the noodle samples as a function of drying time at different drying temperatures are shown in Fig. 2. The initial mean moisture content was between 0.48 and 0.51 g/g dry solid. The moisture content of noodle samples dried at each temperature decreased exponentially with increase in drying time. All the drying curves showed biphasic pattern of

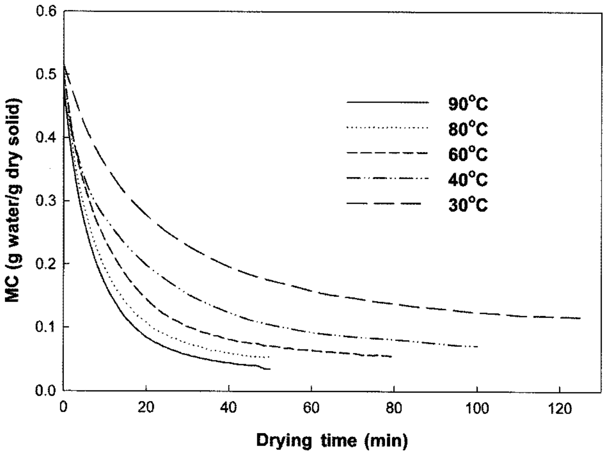

Fig. 2. Change in the moisture content (MC) of fresh rehmannia (*jiwhang*) noodle at the drying temperature of 30, 40, 60, 80, and 90°C.

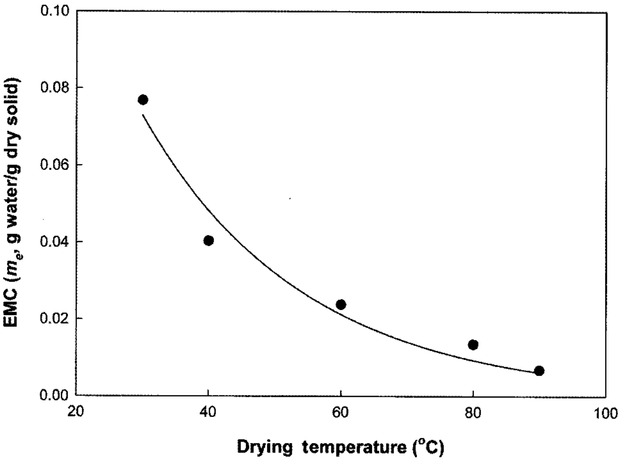

Fig. 3. Equilibrium moisture content (EMC) of rehmannia (*jiwhang*) noodle at the drying temperature of 30, 40, 60, 80, and 90°C.

drying, i.e., the moisture content of noodles decreased rapidly at the initial stage of drying then decreased slowly at the latter stage of drying to reach the final equilibrium drying state. Such a biphasic drying curves were also observed in Japanese *udong* (6,7,10) and spaghetti (3) dehydration tests. As expected, drying rate was dependent on the drying temperature, i.e., the drying rate increased with the drying temperature. This is probably due to the increase in the moisture diffusivity with temperature in the noodle. The drying times to reach the equilibrium moisture content (m_e) decreased significantly with increase in drying temperature. They were 38.7, 19.5, 22.6, 5.0, and 4.1 hr at the drying temperature of 30, 40, 60, 80, and 90°C, respectively. The equilibrium moisture content (m_e) at each drying condition was determined at these extended drying times and the equilibrium moisture content (m_e) attained at each drying condition was also dependent on the drying temperature. They decreased exponentially (m_e=0.2103$e^{-0.0366T}$; R^2= 0.97) with increase in drying temperature as shown in Fig. 3. Though m_e is usually determined using the desorption isotherms test (23), a direct measurement of the m_e at extended drying like present study is more convenient. The temperature dependence of drying rate was more clearly observed in Fig. 4, which shows a relationship between the drying rate and moisture content. Figure 4 also shows that dehydration of the noodles was occurred exclusively at a falling rate period of dehydration without experiencing a constant rate period. This is mainly attributable to the low initial moisture content of the noodles, indicating that diffusion-controlled process is dominant in noodle dehydration. In another word, the rate of moisture removal is controlled by diffusion of moisture from inside to the surface of the noodle (24).

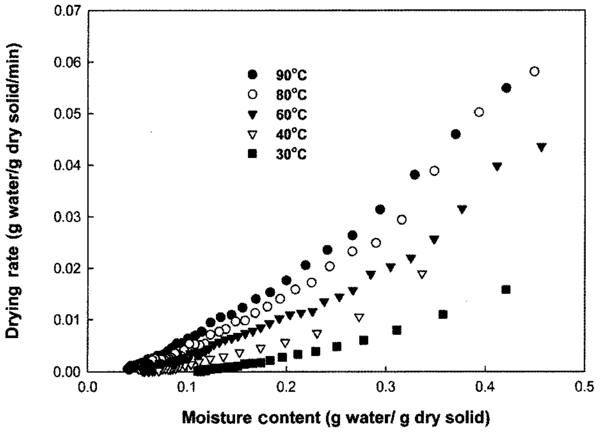

Fig. 4. Change in the drying rate of rehmannia (*jiwhang*) noodle at the drying temperature of 30, 40, 60, 80, and 90°C.

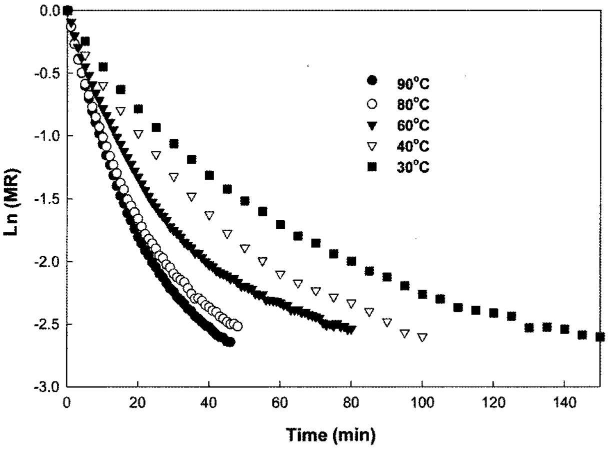

Fig. 5. Relationship between the moisture ratio (*MR*) and drying time of rehmannia (*jiwhang*) noodle at the drying temperature of 30, 40, 60, 80, and 90°C.

Dehydration kinetics Moisture ratio (*MR*) was calculated from the experimental drying curve using Eq. 1 and plotted ln(*MR*) vs. drying time as suggested by the Eq. 5 as shown in Fig. 5. The drying curve is not presented as a single straight line. There are 2 drying zones with initial rapid decrease in *MR* followed by the slow decrease, which indicates that the drying rate is not constant but decreasing as progress in dehydration. The breaking points have been observed at *MR* of −1.67, −1.51, −1.56, −1.77, and −1.62, which correspond to the moisture content of 0.096, 0.124, 0.118, 0.112, and 0.166 g water/g dry solid, at the drying

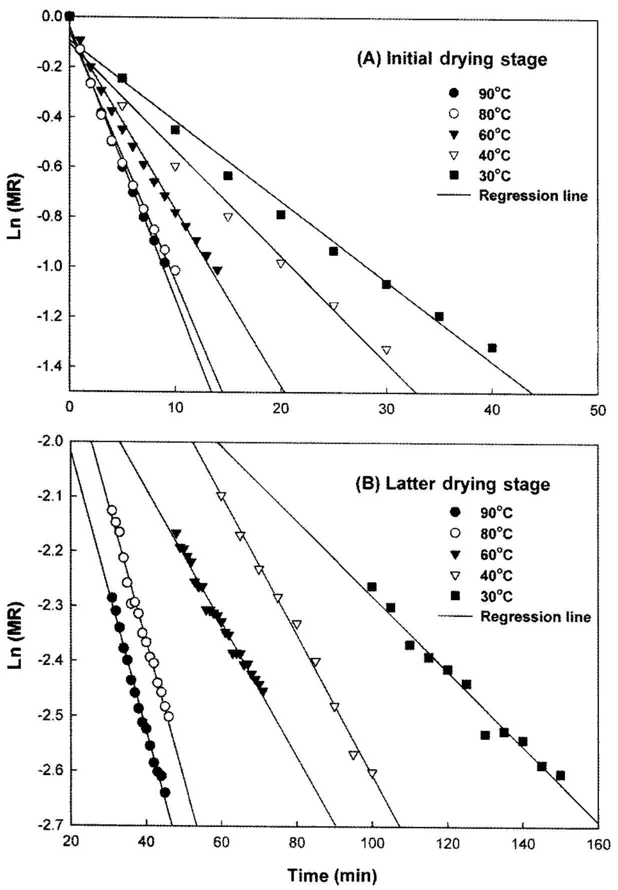

Fig. 6. Relationship between the moisture ratio (*MR*) and drying time of rehmannia (*jiwhang*) noodle at (A) the initial drying and (B) the latter drying stage.

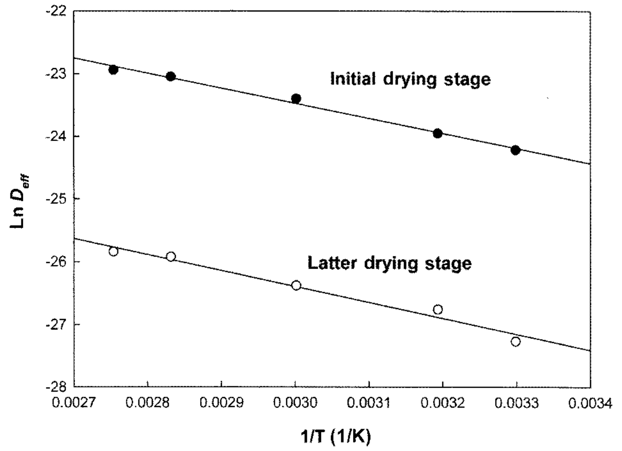

Fig. 7. Temperature dependency of the effective diffusion coefficient (D_{eff}) of rehmannia (*jiwhang*) noodle.

temperature of 30, 40, 60, 80, and 90°C, respectively. Similar drying curves with breaking points have been observed in the drying of the Japanese *udong* (6,7), pasta (4), and other low porosity materials such as soups, gels, gelatins, and glues (25). For the analysis of such experimental drying data with changing drying rate with progress in drying, Andriue and Stamatopoulos (4) divided a drying curve into 3 straight lines and determined the effective diffusion coefficient (D_{eff}) from individual straight line. On the other hand, Inazu *et al.* (6) ignored the moisture content less than 0.19 g water/g dry solid since the moisture content of about 19% (d.b.) corresponds to the final moisture content in the practical main drying process. In the present study, the drying curves divided into 2 regions and analyzed using a linear part of each region as shown in Fig. 6. The effective moisture diffusion coefficients (D_{eff}) were determined from the slope and intercept values obtained of the linear regression lines for the linear regions of drying curves at the initial and the latter stage of drying using Eq. 5 suggested by Inazu *et al.* (6). The D_{eff} values for the noodle dehydration were ranged from 3.05×10^{-11} to 1.09×10^{-10} m^2/sec and 1.44×10^{-12} to 5.51×10^{-12} m^2/sec at the initial and latter stage of dehydration, respectively. As expected, the D_{eff} values at the initial stage of drying were much higher than those at the latter stage of drying. These D_{eff} values are consistent with those of reported values for pasta (4) and Japanese *udong* (6,7). Andriue and Stamatopoulos (4) reported the D_{eff} values of 1.5×10^{-10}–4.1×10^{-10} m^2/sec for the drying of pasta at 60°C and Inazu *et al.* (6,7) reported 4.32×10^{-11}–1.51×10^{-10} m^2/sec for the moisture diffusion of the *udong* dehydration.

The natural logarithm of D_{eff} was plotted against the reciprocal of absolute temperature and it represented linear relationship as shown in Fig. 7, which indicates that the D_{eff} depend on the drying temperature following the Arrhenius equation (Eq. 6). The activation energy (*Ea*) and pre-exponential factor (D_{effo}) for the dehydration of noodle were 19.94 kJ/mol and 8.53×10^{-8} m^2/sec for the initial stage of drying (R^2=0.99) and 21.09 kJ/mol and 7.14×10^{-9} m^2/sec for the latter stage of drying (R^2=0.97). As a typical values for the moisture diffusion, these activation energy values for the noodle dehydration in the present study agreed well with those of pasta drying and of Japanese *udon* drying. For example, Andriue and Stamatopoulos (4) presented 24.1-26.7 kJ/mol, Litchfield and Okos (11) reported 25.94 kJ/mol for the moisture diffusion of pasta drying, and Inazu *et al.* (6) reported 17.61-18.03 kJ/mol for those of Japanese *udong* dehydration. However, in the practical point of view, determination of kinetic parameters of noodles at the latter stage of dehydration is not necessary since the industrial dehydration of noodles is not usually performed at the initial stage of drying as suggested by Inazu *et al.* (6).

Among the rehmannia (*jiwhang*) noodles dried at low temperature (30 and 40°C), medium temperature (60°C), and high temperature (80 and 90°C), no detectable changes in terms of apparent color and shape, cooking qualities of the noodles were found. This indicates high temperature drying is more advantageous than low temperature drying by reducing drying time as suggested by Dexter *et al.* (3).

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