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Original paper

Water Sorption Kinetics of Wheat Noodle with Different Diameters

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The water sorption properties of udon-like wheat noodle were measured at different temperatures to estimate changes in the moisture content and loss of mass; transient changes in these properties could be expressed by hyperbolic and exponential empirical equations, respectively. The maximum moisture content changed stepwise with temperature near the gelatinization temperature of wheat flour; however, the initial sorption rate with temperature obeyed the Arrhenius equation. These processes were also measured for wheat noodle with different initial diameters at 100℃. Changes in the moisture content could be expressed by a hyperbolic equation as a function of time divided by the square of the initial diameter. The loss of wheat noodle mass was proportional to the specific surface area, and the loss per specific surface area could be expressed solely as a function of time.

Keywords: udon-like wheat noodle, water sorption, kinetics, gelatinization, loss of mass

Introduction

Udon is a traditional Japanese noodle made of wheat flour that is extensively consumed in Japan. The palatability of udon is ascribed to its texture, in which the structure of gluten plays an important role. Scanning electron microscope observations have indicated that the gluten network is developed by repeated rolling and does not change during boiling (Dexter *et al.*, 1979). Hand-stretched udon has a fibrous gluten structure, whereas machine-made udon has no regular structure (Kojima *et al.*, 1992). Addition of salt affects the microstructure and rheological properties of udon (Kojima *et al.*, 1995). Gelatinization of starch also affects the texture of udon as well as the structure of the gluten (Toyokawa *et al.*, 1989a). The effects of the amylose content of starch on the water sorption capacity and rheological properties have been reported (Toyokawa *et al.*, 1989b).

Many studies have been performed on changes in udon texture before and after boiling at or near 100℃. However, the kinetics of water sorption has not yet been sufficiently investigated, although moisture distribution in udon during and after boiling has been observed using magnetic resonance imaging (Kojima *et al.*, 2001; Maeda *et al.*, 2009). We previously reported the water sorption kinetics of spaghetti (Ogawa *et al.*, 2011; Ogawa and Adachi, 2013; Aimoto *et al.*, 2013; Yoshino *et al.*, 2013). However, the diameter or thickness of udon is generally larger than that of spaghetti. Thicker noodles take longer to boil and loss of noodle mass becomes more significant for thicker noodles. Udon is consumed in a variety of diameters; therefore, it is necessary to determine the kinetics of water sorption and loss of mass for udon with different diameters. In addition, we expected that gelatinization would affect the kinetics.

Therefore, we measured the moisture content and loss of mass of udon-like wheat noodle during the water sorption process at various temperatures. The water sorption processes of wheat noodle having different initial diameters were also measured. The effects of temperature and initial diameter of the wheat noodle on these processes were kinetically evaluated.

Materials and Methods

Materials Wheat flour, the protein and ash contents of which were respectively 8.6 and 0.35 wt% on a wet basis, suitable for the preparation of udon was supplied by Nisshin Flour Milling Inc. (Tokyo, Japan).

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Preparation of udon-like wheat noodle Tubular udon is usually prepared by a lamination method. However, an udon-like wheat noodle of cylindrical shape was, in this study, prepared by an extrusion method without the addition of salt in order to obtain udon-like wheat noodles of the same quality in every preparation. Wheat flour (300 g) and tap water (90 g) were mixed using a stand mixer (KitchenAid KSM150 FMI; St. Joseph, MI, USA) for 10 min. The wheat dough was placed in an electric pasta machine (Magica; Bottene, Marano Vicentino, Italy) and extruded through a Teflon die under reduced pressure (41.3 kPa) using a diaphragm vacuum pump (DTC-60; Ulvac Kiko Inc., Miyazaki, Japan). The diameter of the Teflon die hole was 0.80 (No. 1), 1.50 (No. 4), 2.25 (No. 7), or 3.00 (No. 10) mm.

Water sorption of the udon-like wheat noodle A conical tube (2.8 cm inner diameter, 12 cm length) containing about 50 mL of water was placed in a water bath (SD Thermominder and Personal-11; Taitec, Saitama, Japan) or a stainless steel pan heated with a digital hot stirrer (DP-1S; As One, Osaka, Japan) and maintained at temperatures ranging from 20 to 100℃. The wheat noodle was cut into pieces 8-cm in length and the weight of an individual sample, W_1, was measured using an electric balance (AUX320; Shimadzu, Kyoto, Japan). The wheat noodle samples were photographed using a digital camera (EOS40; Canon, Tokyo, Japan) and printed images were used to measure the diameter of the sample, d_0, using a Vernier caliper (CD-S15C; Mitsutoyo, Kanagawa, Japan). The diameter was measured at three different points and averaged. An 8-cm piece of wheat noodle was placed in the conical tube. After a given period, the sample was removed from the tube and immediately blotted with paper (Kimwipes S-200; Nippon Paper Crecia, Tokyo, Japan) to remove any superficial water. The new weight, W_2, and diameter, d_t, were measured as described above. The sample was dried at 135℃ for 5 h in a convection-drying oven (DN400; Yamato Scientific, Tokyo, Japan) to measure its bone-dry weight, W_3. The initial moisture content, X_0, and the content at time t, X_t, were determined using Eqs. 1 and 2, respectively:

$$X_0 = (W_1 - W_0) / W_0 \qquad \cdots\cdots\text{Eq. 1}$$

$$X_t = (W_2 - W_3) / W_3 \qquad \cdots\cdots\text{Eq. 2}$$

where W_0 is the initial weight of the bone-dry wheat noodle. The loss of wheat noodle mass during water sorption was calculated as follows:

$$M_t = (W_0 - W_3 + W_4) / W_0 \qquad \cdots\cdots\text{Eq. 3}$$

where W_4 is the weight of the dry mass adhering to the Kimwipe paper, estimated from the weight of a fresh Kimwipe, w_0, and of the Kimwipe with the wheat noodle adhering, w_1:

$$W_4 = w_0 - w_0 \qquad \cdots\cdots\text{Eq. 4}$$

Apparent density of the udon-like wheat noodle The apparent density of the cooked udon-like wheat noodle was determined pycnometrically at 25℃ using dodecane (Wako Pure Chemical Industries, Osaka, Japan), assuming no penetration of the dodecane into the wheat noodle.

Differential scanning colorimetric measurement The udon-like wheat noodle was ground using a mortar and pestle. Three milligrams of the ground wheat noodle was precisely weighed and placed in a chromate-treated aluminum cell (Hitachi High-Tech Science Corp., Tokyo, Japan) and distilled water of 1.44 times the weight of the dried flour was added to the cell. After the cell was tightly sealed using a sealer (Hitachi High-Tech Science Corp.), the cell was held at 4℃ for at least 3 h. Differential scanning colorimetric (DSC) measurement was conducted while raising the temperature from 5 to 130℃ at a rate of 5℃/min with a differential scanning colorimeter (DSC7020; Hitachi High-Tech Science Corp.) to detect the starting, peak, and concluding temperatures, T_s, T_p, and T_c, for gelatinization of the flour. Alumina with the same weight as the dry flour was placed in the reference cell. Each measurement was repeated twice.

Results and Discussion

Water sorption at various temperatures Figure 1 shows water sorption by udon-like wheat noodle prepared with a 2.25-mm die at various temperatures. Water sorption at each temperature conformed to the following hyperbolic equation:

$$X_t = \frac{a \times (t / d_0^2)}{b + (t / d_0^2)} + X_0 \qquad \cdots\cdots\text{Eq. 5}$$

The parameters a and b were estimated to best fit the calculated X_t values to the experimental values using Solver in Microsoft Excel®. The curves in Fig. 1 were drawn using the estimated values of a and b. The curves fit the experimental points well, with a coefficient of determination $R^2 \geq 0.985$. We have previously used Eq. 5 to describe water sorption by dried spaghetti (Ogawa *et al.*, 2011; Ogawa and Adachi, 2013; Aimoto *et al.*, 2013; Yoshino *et al.*, 2013) and the present results indicate that this equation also applies to water sorption by wheat noodle.

Because X_0 is much smaller than a, the latter can be approximated by the moisture content at maximum, X_e, which is defined as the X_t value at $t \to \infty$:

$$X_e = \lim_{t \to \infty} X_t \approx a \qquad \cdots\cdots\text{Eq. 6}$$

The initial water sorption rate, v_0, is given by the following equation:

$$v_0 = d_0^2 dX_t / dt \,|_{t=0} = a / b \qquad \cdots\cdots\text{Eq. 7}$$

Figure 2 shows the temperature dependence of a (or X_e) and a/b (or v_0). T_s, T_p, and T_c for gelatinization of the flour were 44.1, 60.6, and 82.1℃, respectively. The temperature dependence of a changed at a temperature between T_s and T_p, but otherwise obeyed the van't Hoff equation in both the high- and low-temperature

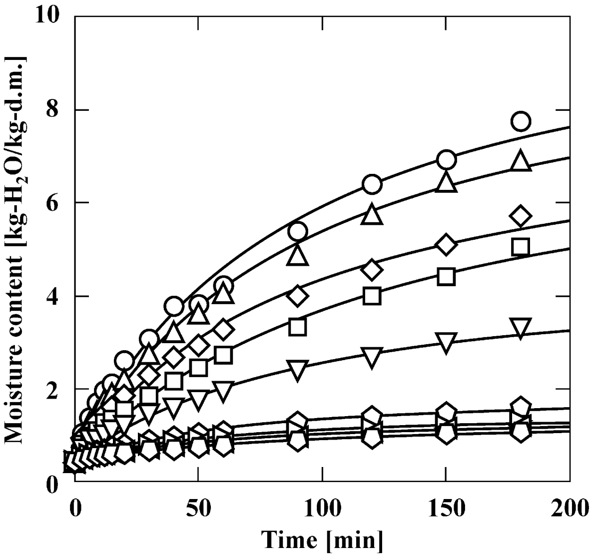

Fig. 1. Water sorption by udon-like wheat noodle with a diameter of 2.25 mm at (⬡) 20℃, (◁) 30℃, (▷) 40℃, (⬠) 50℃, (▽) 60℃, (□) 70℃, (◇) 80℃, (△) 90℃, and (○) 100℃.

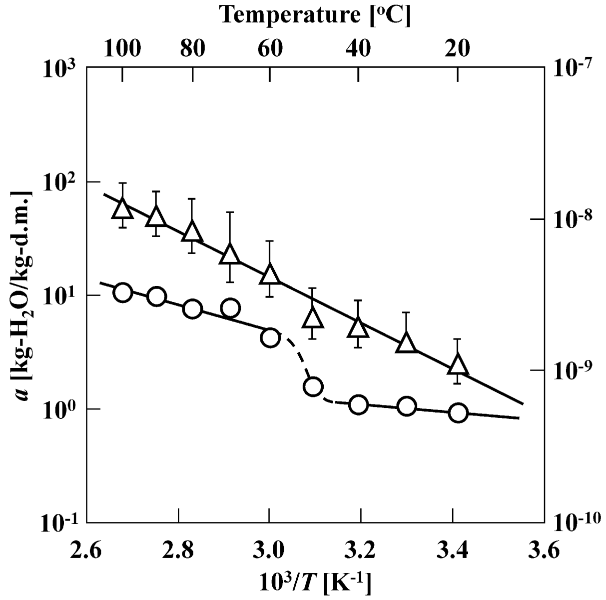

Fig. 2. Temperature dependence of (○) the maximum moisture content a and (△) the initial rate of water sorption a/b. Bars indicate the accidental error of the coefficient evaluated with a confidence level of 95% ($p < 0.05$) by linearization (Miller and Miller, 1988).

regions:

$$d \ln a / d (1/T) = -\Delta H / R \qquad \cdots\cdots \text{Eq. 8}$$

where T is the absolute temperature, ΔH is the change in the enthalpy of water sorption, and R is the gas constant. The ΔH values for the low- and high-temperature regions were determined to be 6.28 and 21.5 kJ/mol, respectively. The ΔH values for spaghetti made from durum semolina for the temperature regions lower and higher than the gelatinization temperature were 1.44 and 25.1 kJ/mol, respectively (Ogawa *et al.*, 2011). Although the wheat variety used to make udon-like wheat noodle is different from that for spaghetti, there was not a large difference in the ΔH values between the two types of noodles. Amorphous starch granules hold water reversibly at temperatures lower than T_s, but irreversible changes in the structure of the granules occur at temperatures higher than the gelatinization temperature. These processes account for the small and large ΔH values in the low- and high-temperature regions, respectively.

The plots of a/b vs. $1/T$ were linear over the entire tested range of temperatures, indicating that the temperature dependence of v_0 can be expressed by the Arrhenius equation:

$$v_0 = a / b = A_0 \exp(-E / RT) \qquad \cdots\cdots \text{Eq. 9}$$

where A_0 and E are the frequency factor and the activation energy, and were determined to be 1.41×10^{-4} m^2·kg-H$_2$O/(s·kg-d.m.) and 28.9 kJ/mol, respectively. The E value for wheat noodle was nearly the same as that for spaghetti (Ogawa *et al.*, 2011). The E value reflects the energy barrier for water diffusion into wheat noodle or spaghetti. Udon-like wheat noodle and spaghetti are both made by mixing wheat flours with water, although the variety of wheat and the particle size are different. Therefore, they have similar E values.

Swelling of udon-like wheat noodle during cooking The inset of Fig. 3 shows changes over time in the diameter, d_t, normalized to the initial diameter, d_0, of udon-like wheat noodle cooked at various temperatures. Wheat noodle swelled more at higher temperatures. Particularly large swelling occurred at temperatures higher than the gelatinization temperature. The moisture content is plotted against $(d_t/d_0)^3$ in Fig. 3. Except the later portion of the plot for 100℃, all of the plots were linear. Therefore, a constant ratio of radial expansion to longitudinal expansion was generally maintained during cooking.

To identify the reason for the deviation from linearity of the plot at 100℃ in the late stage, the change over time in the specific volume of the wheat noodle cooked at 100℃ was plotted (inset of Fig. 4). The moisture content and specific volume exhibited a linear correlation (Fig. 4) ($R^2 = 0.999$) with a slope of 1.01×10^{-3} kg-H$_2$O/m^3-total, approximately the same as the density of water, during the entire cooking period. Therefore, the deviation in Fig. 3 is due to the decrease in the expansion coefficient in a longitudinal direction compared with that in the radial direction during the late stage of cooking.

Water sorption by udon-like wheat noodle with different diameters Figure 5 shows water sorption by udon-like wheat noodle with different diameters. The x-axis represents the cooking time divided by the square of the initial diameter. All of the plots lie on a consistent curve, indicating that Eq. 5 effectively describes water sorption by wheat noodle of any diameter. These results suggest that diffusion of water into wheat noodle plays an important role during cooking, like in spaghetti (Ogawa *et al.*,

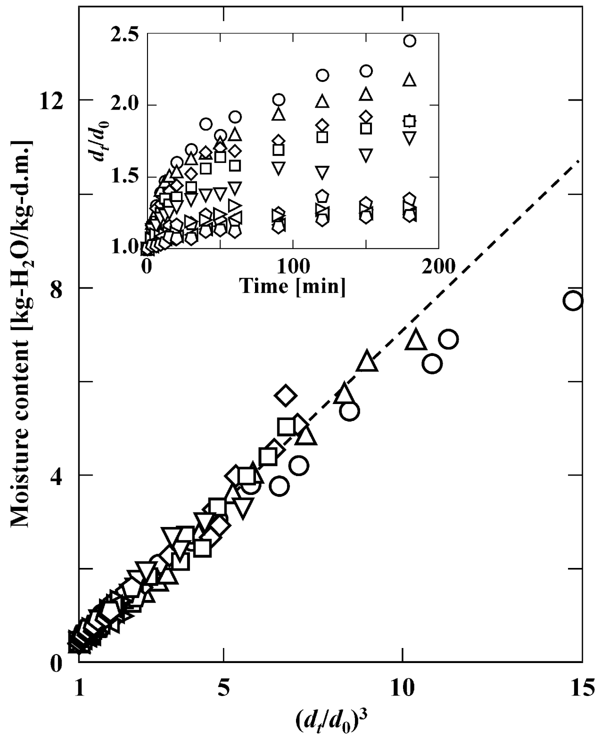

Fig. 3. Relationship between the moisture content and swelling of udon-like wheat noodle. Swelling was represented by the cube of the ratio of the diameter of swollen wheat noodle to that of the initial diameter, $(d_t/d_0)^3$. Inset: Change in d_t/d_0 with time. Symbols are the same as in Fig. 1.

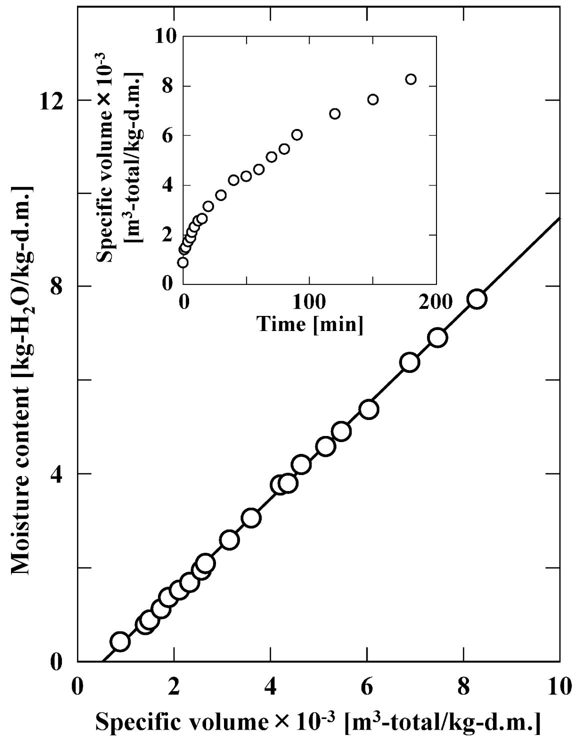

Fig. 4. Relationship between the moisture content and specific volume of udon-like wheat noodle cooked at 100℃. Inset: Change in the specific volume of the wheat noodle with time.

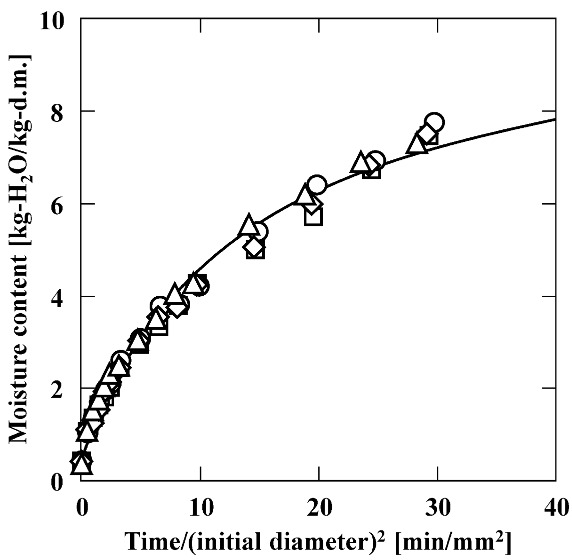

Fig. 5. Change in the moisture content at 100℃ of udon-like wheat noodle with initial diameters of (△) 0.80 mm, (◇) 1.50 mm, (○) 2.25 mm, and (□) 3.00 mm.

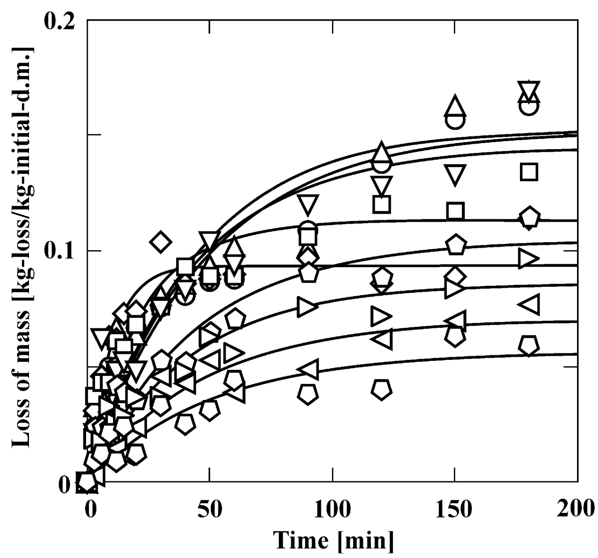

Fig. 6. Loss of udon-like wheat noodle mass during water sorption by wheat noodle with an initial diameter of 2.25 mm at various temperatures. Symbols are the same as in Fig. 1.

2011).

Loss of udon-like wheat noodle mass during cooking Figure 6 shows the loss of udon-like wheat noodle mass during cooking at various temperatures, using wheat noodle prepared with a 2.25-mm die. The loss increased at higher cooking temperatures. In our previous study on water sorption by spaghetti (Ogawa *et al.*, 2011), we found that the loss could be represented as follows:

$$M_t = M_e[1 - \exp(-kt)] \quad \cdots\cdots \text{Eq. 10}$$

where M_t is the loss at time t, M_e is the maximum loss of wheat noodle mass, and k is the rate constant. The M_e and k values were estimated to best fit the calculated values to the experimental ones using Solver in Microsoft Excel® for each temperature.

The temperature dependence of the M_e and k values are shown

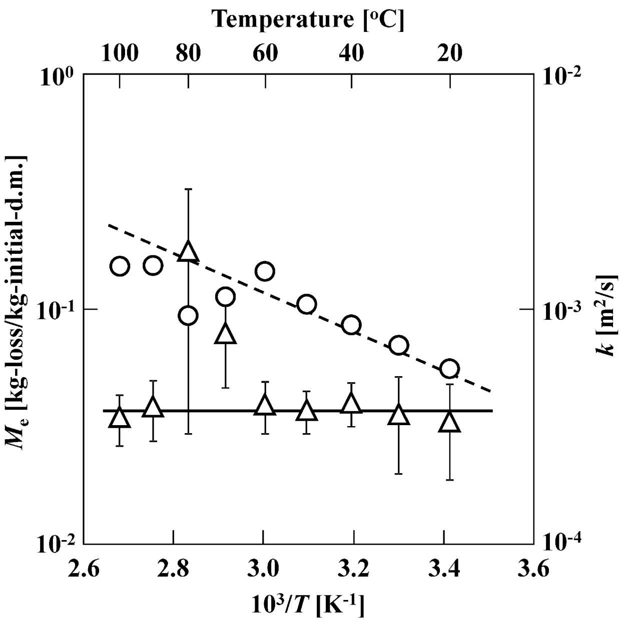

Fig. 7. Temperature dependence of (◯) the maximum loss M_e and (△) the rate constant k for udon-like wheat noodle. Bars for the k values indicate the accidental error of the coefficient evaluated with a confidence level of 95% ($p < 0.05$) by linearization (Miller and Miller, 1988).

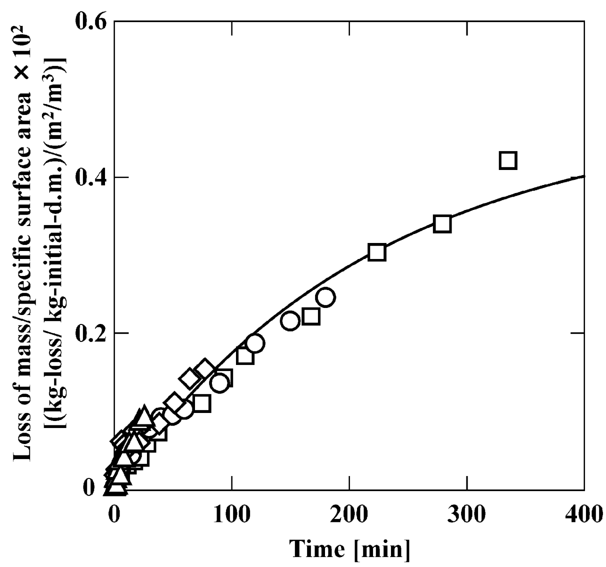

Fig. 8. Change over time in the loss of mass divided by the specific surface area of udon-like wheat noodle with various diameters. Symbols are the same as in Fig. 5.

in Fig. 7. Although there were large deviations due to the experimental difficulty in measuring the loss, the relationships appear to be linear. The M_e value was larger at higher temperatures, whereas the rate constant was only slightly dependent on temperature. The latter suggests that the loss of wheat noodle mass is due to the mechanical detachment of mass.

The loss of wheat noodle mass was also measured at 100℃ for wheat noodle with different initial diameters. The loss divided by the specific surface area of the wheat noodle, M_t/α_t, is plotted against cooking time in Fig. 8. All of the plots for wheat noodle with different diameters lie on a consistent curve. Similar to Eq. 10, M_t/α_t can be represented by the following equation:

$$M_t / \alpha_t = M'_e [1 - \exp(-k't)] \quad \cdots\cdots \text{Eq. 11}$$

where α_t (= d_t^2/d_t^3) is the specific surface area at time t, M'_e is the maximum loss per specific surface area, and k' is the rate constant. The parameters M'_e and k' were estimated to best fit the calculated curve to the experimental points with a correlation coefficient of 0.959, and were estimated to be 4.77×10^{-3} kg-udon mass/kg-initial d.m./(m^2/m^3) and 7.67×10^{-5} 1/s, respectively. Therefore, the loss of wheat noodle mass was proportional to the surface area, indicating that mechanical detachment of wheat noodle from the surface is the primary mechanism in the loss of wheat noodle mass.

Conclusions

Both the moisture content and loss of mass of the udon-like wheat noodle at a specific temperature considerably increased in the early stages of sorption and then reached maximum levels. The change in moisture content with time could be expressed by an empirical hyperbolic equation, whereas the change in the loss of wheat noodle mass could be expressed by an empirical exponential equation. By measuring water sorption of wheat noodle with different initial diameters, we inferred that the process could be expressed as a function of sorption time divided by the square of the initial diameter and that the loss of wheat noodle mass was proportional to the specific surface area of the wheat noodle.

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