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Magnetic resonance imaging and microscopic evaluation of the effect of flow on water migration during noodle cooking

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ABSTRACT

To clarify the effect of flow on water migration during the noodle cooking process, two types of cooking experiment were conducted using a stainless stockpot and a professional gas stove, in conditions that may be described as "with flow" and "without flow" of the cooking water. The quality of the cooked noodles was evaluated using a combination of magnetic resonance imaging (MRI) and microscopic observation. The MRI results showed clear differences between the water distributions obtained with and without water flow. In the case of the "without flow" condition, there was a dramatic increase in the water content of the noodle surface, although in the interior region, the initial water content value was maintained. In the presence of water flow, the water reached the core of the noodle due to a suppression of this significant increase in the water content of the surface region. Microscopic observations combined with computer vision system (CVS) showed that the size of the region in which the starch granule gelatinized completely and dispersed in the noodle was reduced in the case for which flow was allowed.

Keywords: CVS, flow, macro-molecular dispersion, MRI, noodle cooking, starch gelatinization

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INTRODUCTION

Noodles, including pasta products such as spaghetti, are a starch-based food that requires thermal treatment with hot water to gelatinize starch granules and make them fit for human consumption and digestion. The process of water penetration into the noodle interior is rather long, while the penetration of water and the gelatinization reaction proceeds easily at the surface region of the noodle that is in contact with a large amount of water. Therefore, boiling noodles requires a large amount of hot water, while lengthy cooking times lead to a high level of energy consumption. This has wide implications in terms of the potential for energy consumption reduction if cooking times could be reduced.

Various attempts to reduce the cooking time of noodles have been reported. Xie et al. (2008) used microwave heating to produce a partially gelatinized, yet not fully dried noodle. Basman et al. (2011) studied infrared heating for use in producing a quick-drying noodle, and Thammathongchat et al. (2005) proposed an innovative quick-boiling dried noodle which was fully pre-gelatinized at the noodle center. Along with these practical attempts, it is essential to clarify the starch gelatinization and water penetration phenomena and to highlight the mechanisms by which noodles can be cooked quickly and efficiently.

The study of the starch gelatinization and water penetration phenomena with regards to noodle cooking may be divided into two approaches. One is to focus on the microstructure and water distribution. In particular, it is possible to show the moisture distribution inside cooked noodles nondestructively using magnetic resonance imaging (MRI), as reported in several previous studies (Horigane et al., 2009; Horigane et al., 2006; Kojima et al., 2004; McCarthy et al., 2002). Several researchers have recently studied both the water distribution and the microstructure within cooked noodles using MRI and microscopic observation techniques such as polarizing microscopy, fluorescence microscopy, and light microscopy with staining (Steglich et al., 2014; Bernin et al., 2014; Sekiyama et al., 2012).

Another approach is to employ kinetic analysis using a mathematical model to describe water migration and starch gelatinization during cooking.

Regarding starch-based foods, the ceiling moisture content model (Fukuoka et al., 2000), the water demand model (Watanabe et al., 2001), and the relative moisture content model (Watanabe et al., 2006) have been proposed. Del Nobile et al. (2003, 2005), presented a description of the hydration kinetics of spaghetti during the cooking process based on a water diffusion model that included the macromolecular matrix relaxation. These models are an extension of Fick's law of diffusion. Among these studies, Watanabe et al. (2006) presented an innovative model suggesting that water penetration is affected by water holding capacity, which is determined by the degree of starch gelatinization. Gomi et al. (1998) showed that the gelatinization reaction is extremely rapid and not a rate-limiting step; starch gelatinization may be completed in less than a minute in cases for which the starch granule is heated in a large amount of water at over 80 ℃.

As mentioned above, there have been many studies that focused on the cooking of starchy foods, but studies focusing on the flow behavior of boiled water in the cooking system are scarce. It is generally agreed that appropriate water flow in the pot is necessary for noodle cooking. Although the flow of hot water might affect water penetration in noodles, there has been no reported investigation into the flow of boiling water during the cooking process.

The objective of this study is to clarify the effects of water flow on the penetration of water into noodles, given that heat and water are necessary for the cooking process. Water flow conditions were quantified using the video shooting method, and the quality of the cooked noodles was evaluated using a combination of MRI and microscopic observation. Determining the key factors affecting noodle cooking in this manner may allow us to suggest a method for reducing energy consumption in boiled cooking.

MATERIALS AND METHODS

Samples and cooking experiment

Japanese noodles (raw wheat flour noodles, *Miyatake Sanuki Seimensho* Co., 0.261 g water/g solid of water content) were used in this study.

Cooking experiments were conducted using a stainless stockpot (φ 240 mm × H 240 mm) and a professional gas stove under "with flow" and "without flow" conditions.

"With flow" indicates that the noodles were boiled in a stockpot with 15 L of water at the maximum thermal power. "Without flow" indicates that the noodles were boiled in a 1 L beaker within a stockpot to minimize vigorous flow. After cooking, the water content of each sample was measured by oven drying at 100 °C for 24 h.

Determination of the flow condition in the stockpot

A digital camera (SONY Co., Ltd., Cyber-shot DSC-T 700, Japan) was placed in a waterproof bag near the side of the pot and at half the height of the water level.

The camera started shooting at the beginning of cooking. Still pictures were taken from the video data every 0.5s, and the position of the noodle in two-dimensional coordinates (x, y) was determined, where x was the radial direction of the pan and y-axis was the vertical depth in the pan.

The moving distance was calculated using the same coordinate system (⊿X, ⊿Y). The scale of the center of the pot was previously examined to calculate the size of 1 pixel in the image. For 1 pixel, the average speed V_{xy} was determined by Eq.(1)

$$v_{xy} = \sqrt{v_x^2 + v_y^2} \tag{1}$$

MRI measurement

In order to investigate the moisture profile of the noodle, ^{1}H MRI was performed using an NMR spectrometer (AVANCE400, BrukerBioSpin Inc., Germany) equipped with a standard micro-imaging accessory in a magnetic field of 9.4 T.

Each sample was placed in an NMR tube (outside diameter of 30 mm), which was inserted into the imaging radiofrequency (RF) coil (inside diameter of 30 mm) for MRI measurement.

A multi-echo sequence was used to produce proton transverse relaxation time (T_2) maps (Sharifudin et al., 2006; Horigane et al., 2006). T_2 images were fitted to the corresponding exponential decay curve for T_2 given by Eq. (2),

$$M_{xy} = M_0 \exp\left(-\frac{TE}{T_2}\right) \tag{2}$$

Where M_{xy} is the magnetization for a particular pixel, M_0 is the equilibrium magnetization, and TE is the echo time. The repetition time was 3.0 s, the echo time was 4.476 ms, the number of echoes was 16, the image matrix size was 256 × 256, and the slice thickness was 1 mm. Consequently, the spatial resolution was 78 × 78 × 1000 μm^3, the number of summations was 2, and the total scan time was 25.6 min.

Determination of MRI T_2 value vs. water content calibration curve

As the MRI data does not represent the moisture profile directly, it is necessary to determine the calibration curve for the MRI T_2 value vs moisture content in advance. The sample noodle was placed in the test tube (φ 15 mm) with distilled water and held in the hot water bath at a fixed temperature (20.0, 55.0, 57.5, 60.0, 62.5, 65.0, 70.0, 75.0, 80.0 and 85.0 °C) until the moisture profile of the noodle became homogeneous. The uniformity of the internal moisture profile of the noodle was confirmed using MRI. Noodle moisture content was measured by drying the samples at 105°C for 24 h. The T_2 measurements were then obtained by MRI using the sample with the known homogeneous moisture content.

Cooking loss measurement

Once removed from the pot, samples were rapidly cooled using iced water for 30 s, then the remaining surface water was wiped away. The solid weight of the noodles was then measured using the gravimetric method (it was dried in an oven at 105 ℃ for 18 h). Using these values, the cooking loss was calculated using the following equation.

$$\text{Cooking loss}(\text{-}) = \frac{W_0 - W_t}{W_0} \qquad (3)$$

Where W_0 was the solid weight of the noodle before cooking and W_t was the solid weight of the cooked noodle.

Microscope observation and dyeing method

Polarization microscopy and light microscopy with dying were also conducted. The noodle samples were embedded in Tissue-Tek O.C.T. Compound (Sakura Finetek Japan Co. Japan) and rapidly cooled in a Shock Freezer (KogaSangyo Co., Ltd, Japan) at -30°C for 15min. The sectioning of 10 μm sized areas was performed in a cryostat (CM1500, Leica Microsystems, Germany) at -20 ℃. For the light microscope observation, starch granules were stained with 1.0×10^{-3} mol/L iodine solution (diluted 0.05 mol/L iodine solution (Wako Pure Chemical Industries Ltd., Japan)) for 3 min (Cunin et al., 1997). All the sections were observed using a light microscope (BX50F4, Olympus Co., Japan) equipped with polarizing filters connected to a digital camera (Digital sight DS-5M, Nikon Co. Japan). A shutter speed of 1/2 for polarizing image and 1/250 for stained image were used respectively.

Conversion of the RGB image to CIE $L^*a^*b^*$

Several studies have been reported that extract food color from digital images using the computer vision system (CVS). CVS can be an effective tool for determining the color of food surfaces (Brosnan and Sun 2004; Leon et al. 2006; Mendoza et al. 2006; Liave et al., 2017; Liave et al., 2018). We obtained the digital image in $L^*a^*b^*$ color space from the RGB image using the Gamma model (Larrain, 2008). The sRGB images were converted to CIE $L^*a^*b^*$ color space using the following procedural steps,

s*RGB*→CIE*RGB*

sRGB values were linearized through division by 255 and the application of a decoding exponent of 2.2, as shown in Eq. (4) (Larraín et al., 2008). The decoding exponent of 2.2 corresponds to $1/\gamma$ which was calculated using the encoding gamma factor (γ) of 0.45.

$$R = \left(\frac{R_s}{255}\right)^{2.2}, G = \left(\frac{G_s}{255}\right)^{2.2}, B = \left(\frac{B_s}{255}\right)^{2.2} \qquad (4)$$

CIE*RGB*→XYZ_{D65}

CIE*RGB* images were converted to XYZ_{D65} using Eq. (5) (Pascale, 2003), as the D_{65} light source (the standard light source commonly used in food research) was used .

$$\begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} = \begin{bmatrix} 0.4125 & 0.3576 & 0.1804 \\ 0.2127 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9503 \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (5)$$

Using the Bradford matrix transformation (Eq.6), XYZ_{D65} values were then converted into the CIE*XYZ* system (Konica, 1998).

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} = \begin{bmatrix} 1.0098 & 0.007 & 0.0128 \\ 0.0123 & 0.9847 & 0.0033 \\ 0.0038 & -0.0072 & 1.0892 \end{bmatrix} \times \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} \qquad (6)$$

Finally, L^*, $a^*$and b^* is defined as follows:

$$\begin{aligned} L^* &= 116 \times f_y - 16 \\ a^* &= 500 \times \left(f_x - f_y\right) \\ b^* &= 200 \times \left(f_y - f_z\right) \end{aligned} \qquad (7)$$

Where

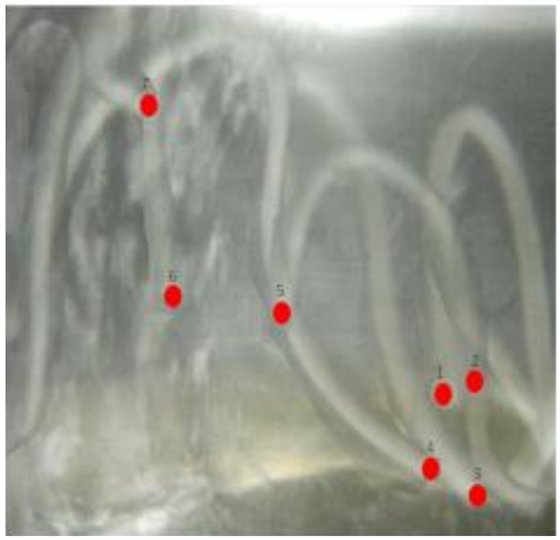

Figure 1: Observation of the noodle movement during cooking via video shooting method.

$$f_x = \begin{cases} \left(X_C / X_n\right)^{1/3} & \text{at } X_C/X_n > 0.008856 \\ 7.787 \times \left(X_C / X_n\right) + 16/116 & \text{at } X_C/X_n \leq 0.008856 \end{cases}$$

$$f_y = \begin{cases} \left(Y_C / Y_n\right)^{1/3} & \text{at } Y_C/Y_n > 0.008856 \\ 7.787 \times \left(Y_C / Y_n\right) + 16/116 & \text{at } Y_C/Y_n \leq 0.008856 \end{cases} \quad (8)$$

$$f_z = \begin{cases} \left(Z_C / Z_n\right)^{1/3} & \text{at } Z_C/Z_n > 0.008856 \\ 7.787 \times \left(Z_C / Z_n\right) + 16/116 & \text{at } Z_C/Z_n \leq 0.008856 \end{cases}$$

X_n, Y_n, and Z_n are the tristimulus values (0.973, 1.000, and 1.161, respectively) for the standard illuminant, D_{65} (Konica, 1998).

RESULTS AND DISCUSSION

Cooking experiment "with flow" and "without flow"

The moving rate of the noodles during the cooking experiment under "with flow" conditions was determined via a video shooting method. Figure 1 shows one example of the noodle movement during cooking. The still pictures acquired from moving images obtained using a video camera set inside the pan were used to calculate the average velocity of the noodle movement from Eq. (1).

The velocity of the noodles during the cooking experiment under "with flow" conditions was 8.705 cm/s (SD 0.796). The velocity of the noodles under "without flow" conditions was almost 0 cm/s, because the noodles were stationary during the cooking experiment.

Changes in average water content

Figure 2 shows the comparison of water migration into the noodles under the two conditions: "with the flow" and "without flow." The average water content of the noodles rose with increased cooking time in both cases, although the water migration rates of the two cases were very different. The rate of water migration for the "with flow" condition was much larger than that of the "without flow" condition. Moreover, in the case of the "without flow" condition, it was confirmed that the water migration rate gradually decreased with increased cooking time.

MRI measurement of water distribution

Figure 3(A) shows the 2D MRI of a noodle sample. The high brightness regions indicate high signal intensity and the dark regions show low signal intensity. With the progress of the water migration, the bright region in the outer area spreads, and the dark region formed in the noodle core becomes smaller. Furthermore, the area of the entire cross-section of the noodle was increased by swelling caused by water adsorption. These phenomena were clearly observed in the "with flow" case. Figure 3(A) shows images acquired at different echo times, and it does not represent the water content profile directly. To convert the image from signal intensity to water content profile, a calibration curve which represents the relationship between water content and the transverse NMR relaxation time (T_2) was determined, employing Eq. (9).

$$\text{Water content (g water/g solid)} = 59.92 \times 10^{-3} T_2 - 0.01 \ (r^2 = 0.9762) \quad (9)$$

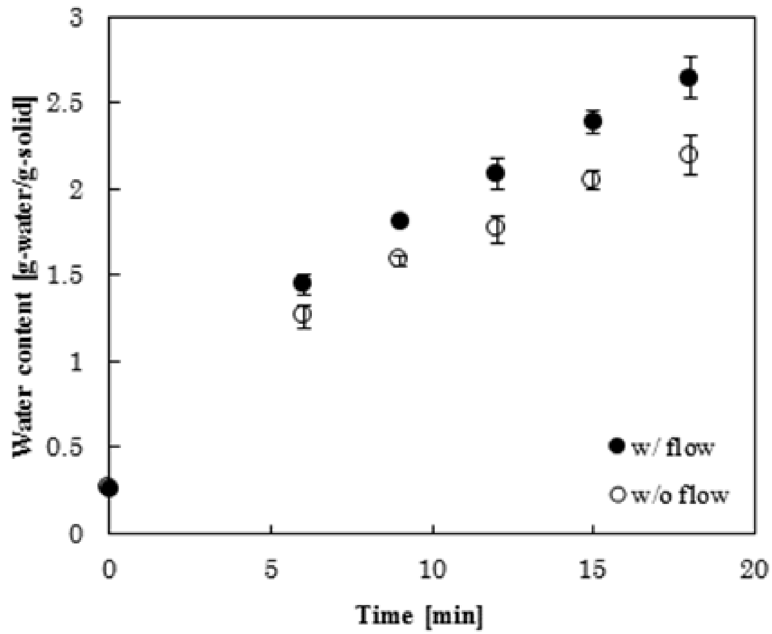

Figure 2: Changes in water content of noodle during cooking. (●; *with* "flow", ○; *without* "flow") (n=12).

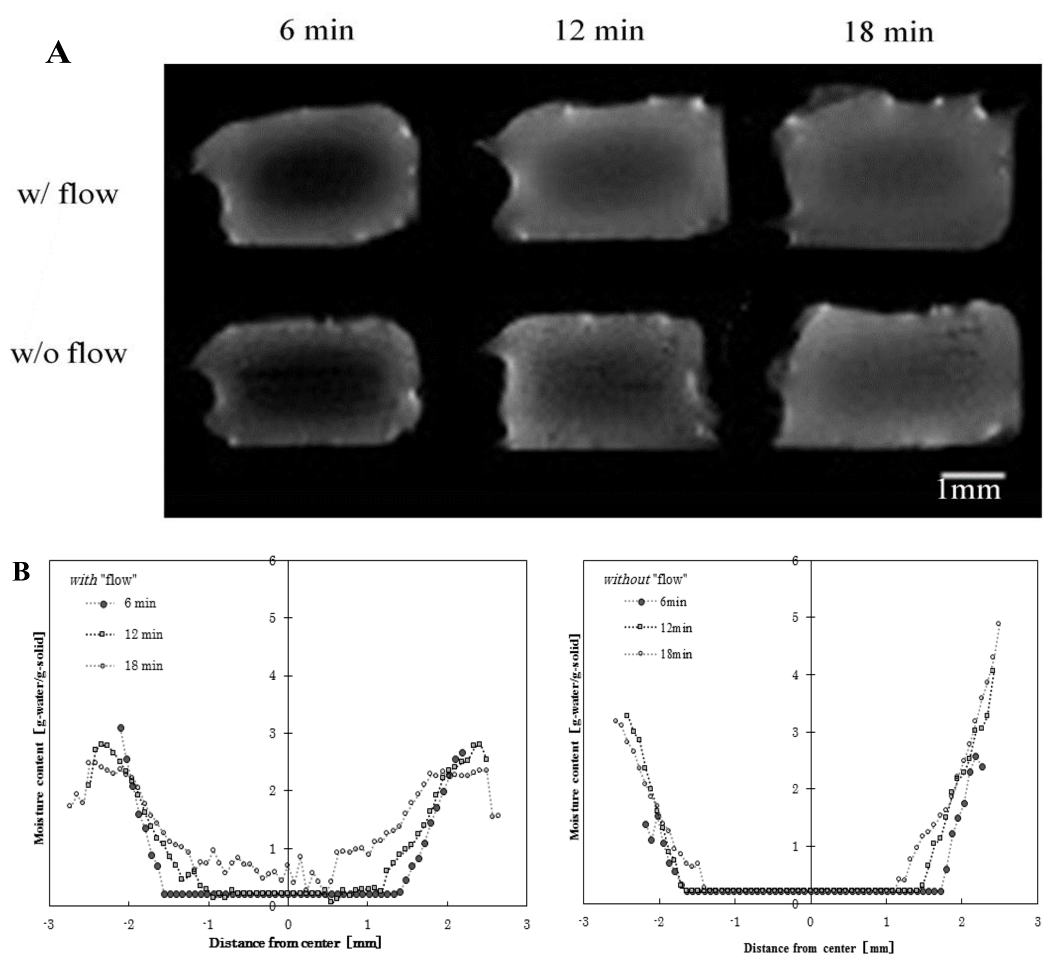

Figure 3: MRI of cooked noodle with varied cooking time: **(A)** 2D MRI and **(B)** 1D profile of noodle.

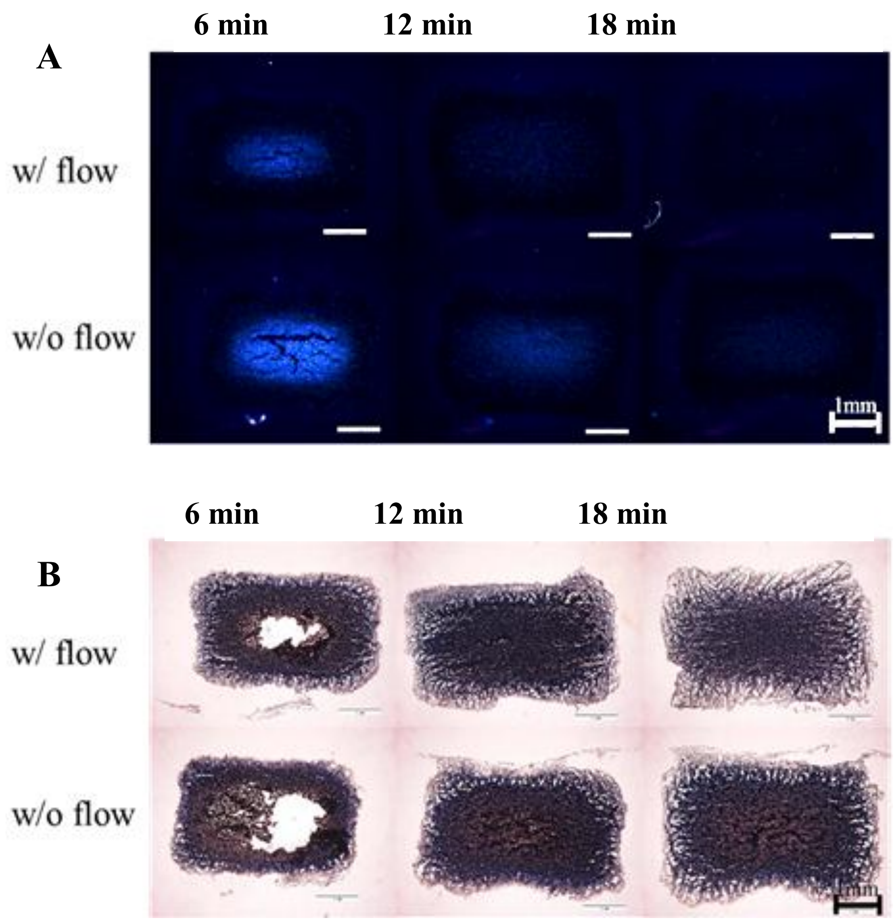

Figure 4: Microscopic observation: (**A**) polarization microscopy (**B**) light microscopy with dyeing method.

Using Eq. (9), we obtained the one-dimensional profile at the center of the two-dimensional image (Figure 3 (A)), as shown in Figure 3(B). The MRI data clearly showed that the water distribution under "with flow" conditions were different from that under "without flow" conditions. Under "without flow" conditions, the water content of the noodles dramatically increased at the surface, while that of the interior maintained its initial value. Under "with flow" conditions, the water reached the core of the noodles because the increase in water content at the surface was comparatively insignificant. Bernin et al. (2014) showed that the water ingress rate was neither dependent on pasta composition nor the presence of salt in the cooking media. On the other hand, reports are showing that the water absorption rate during cooking differs depending on the ingredients of the noodles. Maeda et al. (2009) presented the moisture distribution within two kinds of buckwheat noodles and one kind of wheat noodle during boiling by using MRI, and showed the diffusion coefficients of water in buckwheat noodles during boiling were higher than those in wheat noodles. In both reports, we cannot simply compare because the type of noodles and the manufacturing method are largely different. However, looking at the comparison result of the diffusion coefficient of buckwheat noodles, it cannot be said that there is a big difference. Compared with these results, the water transfer to the interior of the noodle shown in this research shows a big difference, and it can be said that the state of flow in the pot has a large influence on the moisture movement into the noodle. Particularly, when there is no flow, it is characteristic that the surface absorbs excessively on the surface of the noodle. Focusing on such a phenomenon, we have not found any research.

Microscopic observation

Figure 4 shows the results of microscopic observation; polarization microscopy (A) and light microscopy using the dyeing method (B). In observation with a polarization microscope, the region with high brightness is due to the birefringence of starch particles with a crystal structure.

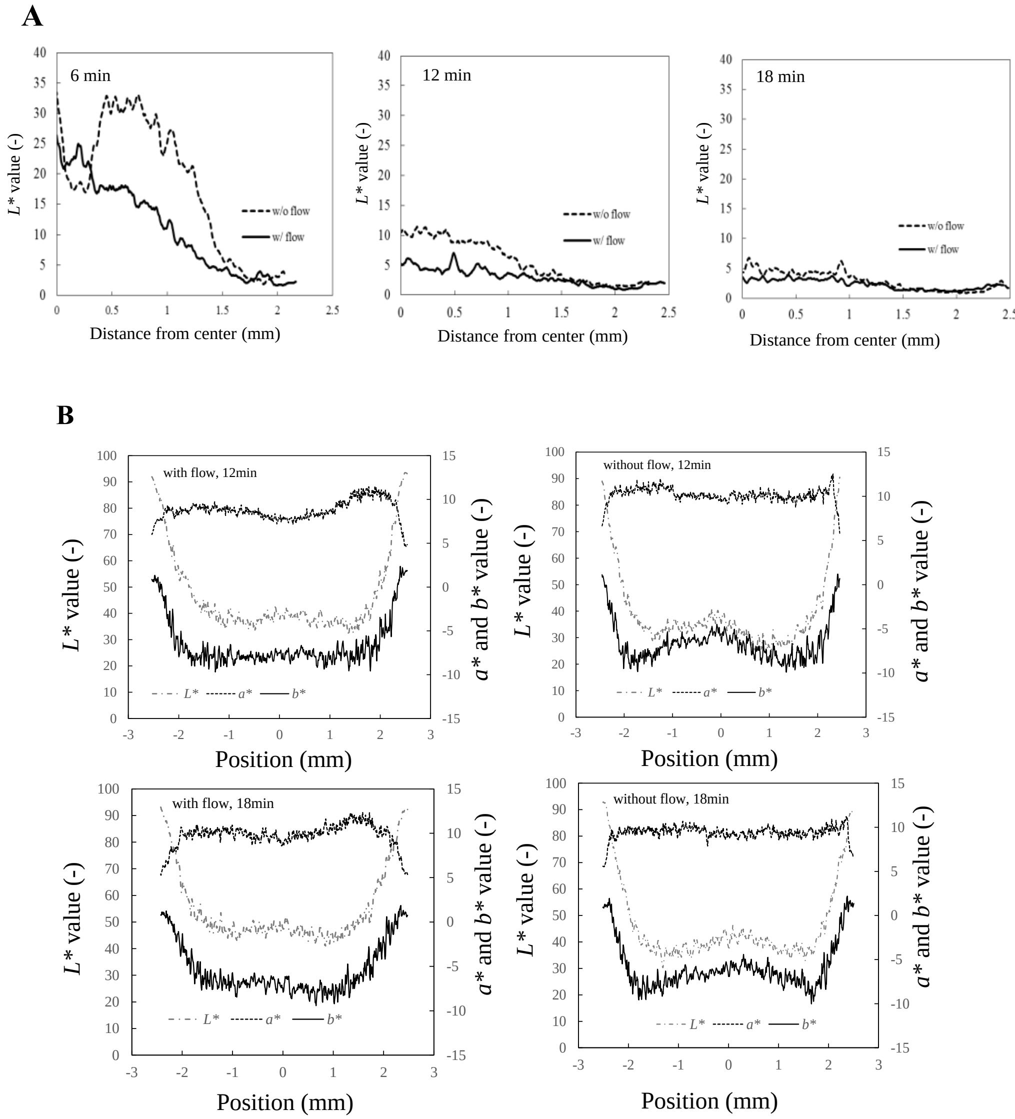

Figure 5: Color analysis of microscopic observation: **(A)** *L** value profile from the polarization microscope image **(B)** *L*, a* and b** value from the light microscopy with dyeing method.

This kind of study has already been carried out on cross sections of cooked spaghetti by monitoring of the loss of birefringence over time with a polarizing microscope (Grzybowski and Donnelly, 1977). It has been shown to be effective as a method for visually understanding the progress of the degree of gelatinization. When birefringence is lost due to the disappearance of the crystal structure, a dark area is observed, and this becomes an index of starch gelatinization. At a boiling time of 6 min, there is a region with high brightness in the central part of the noodle under both "with flow" and without flow" conditions, indicating that starch gelatinization did not occur. It can be observed that gelatinization is delayed under the "without flow" condition compared to that of the "without flow" condition, because it shows a wider region of high brightness. Furthermore, at a boiling time of 12 min, under the "with flow" condition, almost no regions with high brightness are observed in the entire noodle, and it can be observed that gelatinization progresses inside the noodle. In the case of the "without flow" condition, there are dark internal regions, even at a boiling time of 18 minutes, where non-gelatinized regions remain.

In order to quantitatively evaluate the above results, the RGB values of each pixel were converted to the CIE *L*a*b** color system and expressed by an *L** value as shown in Figure 5A. Color evaluation which is important as one of food quality is generally expressed by the CIE-*L*a*b** color system, and the single point measurement using a colorimeter is common. However, it is difficult to obtain the color distribution of the whole object using a colorimeter. For this reason, Leon et al., (2006) presented a computational solution that allows the obtaining of digital images in *L*a*b** color units for each pixel of the digital RGB image. Since *L ** value is an indicator of lightness, it is suitable for expressing how the brightness of an image decreases due to the disappearance of birefringence. As a result of this process, the degree of gelatinization progress could be clearly evaluated. Under the "with flow" condition, the *L** value is already almost zero at 12 min and clearly gelatinization is complete. On the other hand, under the "without flow" condition, it was shown that gelatinization was not completed internally because the *L** value was high, except for the region approximately 10 mm from the surface. Even at 18 min, the obtained *L** value was slightly higher than that of the "with flow" case; the degree of gelatinization in the "without flow" case was still lower.

The above results were consistent with the water distribution results measured using MRI. The non-gelatinized region confirmed by polarizing microscopy clearly agreed with the region where the water content remained at its initial value. It could be stated that water migration proceeds through the disappearance of birefringence, that is, starch gelatinization through the disappearance of the crystal structure. In boiling cooked noodles, while the flow condition in the pan was an important factor in promoting the movement of water to the interior of the noodle, and has become clear that starch gelatinization in the noodle also has a large influence on the noodle water content profile.

Consider the marked rise in water content on the noodle surface observed in the "without flow" case, the accompanying water migration to the interior and the delay in the gelatinization reaction. The state of a starch granule was divided into four stages; non-gelatinization (S1), early stage of gelatinization (S2), after gelatinization (S3), and initiated macromolecular dispersion (S4). Hermasson and Svegmark (1996) showed those characteristic starch granule structures formed in the noodle using microscopic techniques. The early stage in gelatinization (S2) corresponds to a loss of crystalline structure related to birefringence. (S3) and (S4) correspond to the later stage in gelatinization, and can be observed using a light microscopic method with staining. This observation method involving staining the entire cross-section of the noodles has been reported by Cunin et al. (1995). Light green (SF yellowish, Fluka, Buchs, Switzerland) was used for staining the protein, which was gluten, and Lugol's solution (Fluka, Buchs, Switzerland) was allowed to stain the starch. As the present work requires staining only of the starch granule, iodine solution was adopted. If the starch is in contact with the iodine solution, depending on the length of its amylose chain, it will be stained in different colors (Ophardt, 2010). Figure 4B shows the light microscope observations performed using iodine dyeing. At all of the boiling times, the center portion of the noodle has a dense, dark coloring, while the surface has a thinner layer of color. A gradation of color was observed, from dense blue-violet at the central region to light blue-violet at the middle region, and from the thin layer of bluish purple at the middle region to a thin layer of pink on the surface.

These stained images were converted to *L*a*b** color from digital RGB image shown in Figure 5B. In Figure 5B, only the results of 12 min and 18 min were shown, except for the image with a boiling time of 6 min where the loss region in the section was large. Focusing from the surface of the noodle to the inside, it can be seen that *L** value and b* value are greatly changed compared to *a** value. Ronoubigouwa et al. (2011) succeeded in quantifying the amylose content in rice grains from *L*, a* and b** values using a method based on the iodine-starch reaction. In their study, the correlation coefficient between the *b** value and the amylose content is higher than those of *L** and *a**, indicating that the *b** value decreases with decreasing amylose content. The *b** value sharply declined from the surface to the inside of the noodle and showed an increase or a constant value with a particular region as the boundary. Since it may be confirmed using images that the inflection point in the *b** value is in the continuous phase in which the shape of each starch particle is unclear, it may be assumed that gelatinization proceeds and macromolecular dispersion occur. The *b** value increased from the inflection point on the surface due to the appearance of a thin pink layer and the decoloration of the starch granule increased. As the inflection point in the "with flow" case advanced from the surface to the internal position, compared to that of the "without flow" case, it can be inferred that macromolecular dispersion is proceeding.

With the cooking loss shown in Figure 6, the elution of the solid content increased with increasing boiling time. A comparison between the "with flow" and "without flow" cases up to approximately 6 minutes of boiling time shows almost identical behavior in terms of cooking loss. However, significant elution of the solids was observed under the "with flow" condition as cooking time progressed. From this result, it is considered that the dispersed polymer fragments eluted from the surface of the noodle into the hot water. Cooking loss is related to the surfaces structurer of noodle or pasta, during which the soluble solids are eluted from the surface into the cooking water. Several studies have been reported that cooking loss is affected by the type of noodles (Kang et al., 2017, Lucisano et al., 2012; Park and Bail, 2009) and the cooking water composition (Malcolmson and Matsuo; 1993). From these studies, it can be said that the elution of solids is important as a factor determining the quality of noodles, and reducing this is important for quality improvement. In this study, however, it was shown that when the elution of the polymer is small, moisture migration to the inside is delayed, the cooking time of the

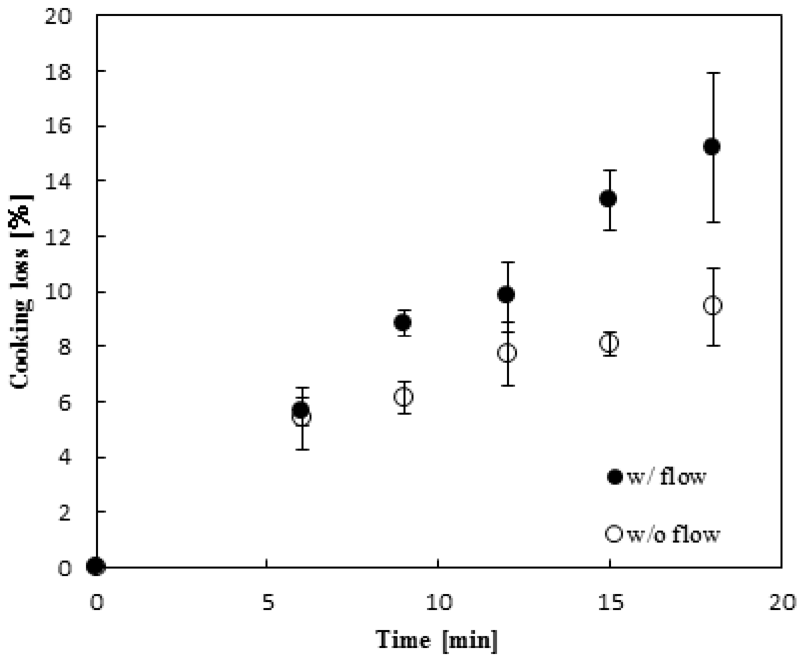

Figure 6: Changes in cooking loss of noodle with the progress of boiling time. (●; *with* “flow”, ○; *without* “flow”) (n=12).

noodles is prolonged, and as a result, unfavorable influence might be exerted on quality.

From the above results, it was shown that starch gelatinization, dispersion, and elution in the noodle were influenced by in the state of flow in the pot and that these were promoted by water flow during the cooking process. In the “without flow” system, dispersion and elution after gelatinization were suppressed, and as a result, the water holding capacity on the noodle surface dramatically increased, indicating high water content. On the other hand, in the case for which water flow was allowed, it may be considered that elution of the polymer fragments on the noodle surface progressed, and water migration to the interior was promoted as the water holding capacity decreased. Results from this study supported the findings of a previous report (Watanabe et al., 2001; Watanabe et al., 2006), which stated that starch gelatinization and the accompanying increase in water holding capacity affect water migration in starchy foods during cooking. We aim to describe the water migration observed in this study in more detailed future studies on this system.

Conclusion

The effect of flow on water migration during noodle cooking has been investigated in conditions both “with flow” and “without flow” of the water in the cooking pot. The cooked noodles were evaluated using MRI and microscopic observation. Starch gelatinization, macromolecular dispersion, and elution in the noodle cooking process were influenced by the state of water flow in the pot and promoted water migration in the noodle during cooking.

MRI observations were used to determine the water content profile of noodle samples during the cooking process; in the case of the “without flow” condition, the noodle water content dramatically increased in the surface region, although the water content in the interior region remained at the initial value. In the case of the “with flow” condition, water reached the core of the noodle because the increase in water content at its surface was comparatively insignificant.

Microscopic observations showed that the size of the region in which the starch granule gelatinized completely and dispersed in the noodle was reduced in the case for which flow was allowed.

These observations indicate that flow conditions in the cooking pot have a clear impact on the noodle water content profile and may be further investigated to develop more efficient methods for cooking foods such as noodles. A possible reduction in the boiling time for such a widely used food has significant implications for home energy consumption.

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