Water Sorption in Pre-heat-treated Wheat Flour Dough

Yoshiko YAHATA, Mika FUKUOKA, Takaharu SAKIYAMA, and Hisahiko WATANABE[†]

Department of Food Science and Technology Tokyo University of Marine Science and Technology, Konan 4, Minato, Tokyo 108-8477, Japan

When starchy food such as rice grains or noodle strands are boiled for a few minutes, the food body can be interpreted as becoming a multiphase system in terms of water-holding capacity because uneven starch gelatinization takes place in the food body and gelatinization seems to govern water-holding capacity. In order to describe water migration in such a multiphase system, Relative Water Content Model (Water Demand Model) is proposed. For the practical use of this model, information on water-holding capacity is required. In an attempt to measure the effect of temperature and water content on water-holding capacity, pre-heat-treated wheat flour dough packed in a cylindrical frame was immersed in water at 25°C and the time course of water content was observed. Unexpectedly, water content in the sample continued to rise for seven days even though the water content in the sample monitored by NMR imaging showed a flat profile. Since the standard water content to be used in Relative Water Content Model is not necessarily the maximum water content (ceiling water content), we defined first stage water-holding capacity as the water content when the rise of water content changed its rate after NMR imaging profile became flat. The first stage water-holding capacity collected in this way was favorably used to simulate the change of water content profile in a wheat flour dough slab that was temperature-gradient heat-treated.

Key words: water-holding capacity, starch, gelatinization, water absorption, wheat flour dough

1. Introduction

Since the water content profile in a food body sometimes has a strong influence on methods of organoleptic evaluation such as texture and mouth-feel, understanding of water migration in starchy food during cooking is of great interest to food technologists [1–5]. It is a gravimetric method that is widely used for measuring water content. In the study of soaking or drying food, weight change of food samples has been observed and its time course analyzed using a mathematical model. In these mathematical models, water migration has usually been described by Fick's molecular diffusion equation.

Unfortunately, however, gravimetric method is not suited to identifying water content difference in given positions in a food body that is small in size, such as a rice grain or a noodle strand. Consequently the change in water content profile could not be verified by experiments.

With the availability of MRI (magnetic resonance imaging) for observation of changes in water content profile in food bodies, unusual changes in water content profiles were sometimes reported in starchy foods and these changes could not be described using Fick's equation of

diffusion [6,7]. In order to describe these irregular water content profiles, some used a Case II diffusion model [8] and others proposed a Water Demand Model [9, 10].

In the water demand model, water migration is derived not only by the gradient of water content but also by the gradient of ceiling water content, which is defined as the potential maximum water-holding capacity in food when the food is immersed in pure water. Does all food show its ceiling water content when the targeted food body is immersed in pure water? The answer may be “no” for foods that contain ingredients that dissolve in water. On the other hand, the following examples strongly suggest that rice grains and spaghetti strands have a ceiling water content.

A grain of (non-gelatinized) rice absorbs water up to 30% (wet basis) only, when it is immersed in water at room temperature. On the other hand, a rice grain processed as “instant rice” absorbs water up to 60% (wet basis) [7]. This fact states that (1) a grain of rice absorbs water and has a maximum water content value when it is immersed in pure water. (2) The maximum water content values vary as the grain is thermally processed. It is also reported that a spaghetti strand purchased on the market increased in weight and reached an equilibrium value when the strand was boiled for two hours [5].

A starchy food that is initially a single phased body in

(Received 18 Oct. 2005; accepted 30 May. 2006)

[†] Fax: +81-3-5463-0497, E-mail: hisahiko@s.kaiyodai.ac.jp

terms of having unique water-holding capacity sometimes turns into a multiphase body when some part of the body is fully cooked, some part is partly cooked and some is left uncooked. This cooking process makes a heterogeneous profile of water-holding capacity in the food body. This food body may be regarded as a multiphase system.

Fick's diffusion equation is applicable to a homogeneous (single phase) system and not applicable to a heterogeneous (multiphase) system. Recently, Watanabe et al. [11] proposed the Relative Water Content Model, which could be regarded as a revision of the Water Demand Model. The Relative Water Content Model states that the Fickian diffusion equation becomes applicable to a multiphase system if relative water content (water content divided by standard water content) is substituted for water content in the Fickian diffusion equation.

The standard water content to be used in this variable conversion is not necessarily the maximum water content of water immersion. You can arbitrarily define the standard water content if a linear approximation is satisfied in the activity vs. water content relationship [11].

With the intention of demonstrating the features of a food body that is turned into multiphase by cooking, Yahata et al. [12] verified by experiment that water can be made to diffuse against the water content gradient in a starchy food body that consists of a different water-holding capacity. The outline of the experiment is as follows:

A slab (10 mm thick) of wheat flour dough (1.12 kg-water/kg-solid) was simultaneously heated to 90°C on one side and cooled to 0°C on the other side. This operation formed a linear temperature profile in the dough slab (as is shown later in Fig. 10) that made the dough partly gelatinized where it was heated above 55°C, leaving the other part un-gelatinized. This heat-treatment was intended to give an uneven water-holding capacity profile in the dough slab. After the heat-treatment, the dough slab was quenched to 25°C to prevent further gelatinization, and the change of water content profile in the dough slab was monitored for three days by NMR imaging. The change in the water content profile showed that water migrated from the un-gelatinized region to the gelatinized region against the water content gradient.

The objective of the present study is to measure the water-holding capacity of the pre-heat-treated wheat flour dough that was used in the experiment by Yahata et al. [12]. In order to find the ceiling water content, wheat flour dough samples that were evenly heat-treated at a selected temperature were immersed in pure water at 25°C, and the time course of the water content was measured.

Unfortunately, however, the ceiling water content as the equilibrium value of water content could not be obtained. Consequently, we tried to find some characteristic water content value that could be used as a standard water content value described in the Relative Water Content Model. We devoted our attention to the phenomenon that the rise of water content during water absorption changed when the monitored water content profile became flat.

2. Materials and Methods

2.1 Schematic description of the method

In the present experiment, pre-heat-treated wheat flour dough samples were packed in a glass cylinder (both ends open) and then immersed in pure water. Since it was evenly heated, the dough sample could be recognized as being single phase. In this case, water migration in the dough may be governed by Fickian diffusion, and the change of water content profile in the dough sample will be depicted as in Fig. 1A. The water content at the dough surface will rapidly rise up to an equilibrium value, m_e , while that at the center will gradually rise up and will approach this equilibrium value, m_e . It is this equilibrium value that is targeted in the present study.

However, it has often been observed that the surface of wheat flour dough swells up and expanded fragments become detached, resulting in an extraordinary increase in water content. Therefore, we estimated the change of water content in the dough sample as is shown in Fig. 1B. We guessed that the water content at the center of the

Fig. 1 The change of water content profile in the dough sample depicted schematically, with (A) stable surface, and (B) swollen and extremely expanded surface.

sample would approach the equilibrium value, m_e .

We observed the time course of water content at the center of the sample cylinder, measured the total length of the sample and monitored water content profile by NMR image. The details of the method are described in the following sections.

2.2 Materials

Wheat flour containing 8.5% weight protein (Nisshin Seifun Group Inc., Tokyo) was used as received. 60 g of flour was put into a mortar, a selected amount of distilled water was gradually added to it, and this was mixed with a pestle for a few minutes. Next, the dough was put into a plastic bag and kneaded by hand for 10 minutes. After that, the dough was wrapped in wrapping film to prevent it from drying and left to stand for 24 hours at 5°C. Wheat flour dough with three levels of water content, 0.64, 1.00, and 1.15 kg-water/kg-solid, was prepared. We also prepared samples with higher water content, 1.41, and 1.66 kg-water/kg-solid. The water content of the samples was measured by gravimetric method (oven-dried for 48 hours at 100°C).

Each of the samples with different water content was embedded in a cylindrical glass frame (diameter: 10 mm, length: 10 mm, both ends open) and vacuum-sealed in a heat-resistant plastic bag. Next, the sample was isothermally heated at a specified temperature (55°C, 60°C, 70°C, 80°C, and 90°C) for 30 minutes in a water bath and then quenched to room temperature.

2.3 Immersion

After removal from the plastic bag, the sample was immersed with the glass frame in distilled water at 25°C for a selected number of days between one day and seven days. Five samples were collected every day. First, the length of the sample was measured by caliper. Next, one of the samples was used to observe NMR images. The rest of the samples were used for measuring water content. The center of the sample was dissected into 3 mm-thick disks and its water content was measured by gravimetric method. The water, in which the samples had been immersed, was replaced with new water every day to prevent rotting. In the case of immersion of the un-gelatinized sample (the non-heated one and that heated at 55°C), a cylindrical glass frame with a bottom was used to prevent water pouring away.

2.4 NMR image

A one-dimensional proton NMR (nuclear magnetic res-

onance) image of the sample was measured along the axis of the sample with the cylindrical glass frame. Bruker AM200WB equipped with a 4.7 T magnet and an imaging accessory were used. A spin-echo-based imaging sequence was used in which the echo time and the recycling time were 14.2–19.2 ms and 3s, respectively. The signal acquisition was averaged over twenty measurements and the resolution was 0.122 mm. Proton signal intensity was calibrated by the apparent transverse relaxation time obtained from a series of six images with a selected echo time in the range between 14.2 ms and 19.2 ms.

2.5 Multiphase–Multilayer Model (illustration in Two-phase system)

In this section, the method of calculating water content profile using the Multiphase–Multilayer Model is described by applying the Multiphase–Multilayer Model to solve a simple problem: the change of water content in a two-phase system. Suppose that there are two layers, A and B, of the same size (both 5 mm thick). Both of the layers have the same initial water content (0.5 kg-water / kg-solid) but different water-holding capacity: $m_A^* = 2.0$ kg-water/kg-solid, $m_B^* = 1.0$ kg-water/kg-solid. Water diffusivity is the same in the both layers: $D = 1.0 \times 10^{-10}$ m²/s.

Suppose that the layers A and B are brought into contact at time $t = 0$, and that the external sides of the layers are sealed using plastic film to prevent drying. The partition equilibrium in place at the boundary where A and B are in contact may be represented as follows when the partition coefficient does not have concentration dependence:

$$K = m_A^* / m_B^* \quad (1)$$

The water migration in each of the layers is governed by Fick's diffusion equation:

$$\frac{\partial m}{\partial t} = \frac{\partial}{\partial x} \left\{ D \left(\frac{\partial m}{\partial x} \right) \right\} \quad (2)$$

The change in water content profile in both layers A and B can be calculated using a numerical method (an explicit method). When the central difference is used, the concentrations at the three lattice points at time step j , $m_{j,i-1}$, $m_{j,i}$, $m_{j,i+1}$, are used to calculate the concentration at position i at time step $j+1$, $m_{j+1,i}$. When all of the three lattice points, $i-1$, i , $i+1$, exist in one layer, $m_{j+1,i}$ is calculated by the following equation:

$$m_{j+1,i} = m_{j,i} + \frac{\Delta t}{(\Delta x)^2} D (m_{j,i+1} + m_{j,i-1} - 2m_{j,i}) \quad (3)$$

When lattice $i-1$ is in layer A and the other two lattices, i and $i+1$, are in layer B, $m_{j+1,i}$ is calculated by:

$$m_{j+1,i} = m_{j,i} + \frac{\Delta t}{(\Delta x)^2} \left\{ D(m_{j,i+1} - m_{j,i}) - D_{eff}^*(m_{j,i} - \frac{m_{j,i-1}}{K}) \right\} \quad (4)$$

When lattices $i-1$ and i are in layer A and lattice $i+1$ is in layer B, then

$$m_{j+1,i} = m_{j,i} + \frac{\Delta t}{(\Delta x)^2} \left\{ D_{eff}(K \cdot m_{j,i+1} - m_{j,i}) - D(m_{j,i} - m_{j,i-1}) \right\} \quad (5)$$

where

$$D_{eff} = \frac{1}{1-K} D, \quad D_{eff}^* = \frac{1}{1+K} D \quad (6)$$

D_{eff} and D_{eff}^* are used to adjust the material balance across the boundary between different phases. Using these formulas, the change in water content profile in layers A and B is calculated as shown in Fig. 2. Water content profile approaches equilibrium after five days ($m^A = 0.667$ kg-water /kg-solid; $m^B = 0.333$ kg-water /kg-solid).

Fig. 2 The change of water content profile in a two-phase system calculated using the multiphase-multilayer model.

3. Results

The time course of water content in the sample dough at its center in the cylinder frame during water sorption at 25°C for samples that were pre-heat-treated at 90°C and those that were not pre-heat-treated (designated as heat-treated at 25°C) is plotted in Fig. 3.

Samples pre-heat-treated at 90°C absorbed more water when they were pre-heat-treated at higher water content. Although the rise in water content became gradual at three days or four days of immersion, the water content at five days of immersion and later indicates that the rise was continuing. The samples immersed for more than seven days were discarded because they smelled of rotten

starch/protein.

The water content in samples that were not pre-heat-treated approached equilibrium.

The effect of heat-treatment temperature on water absorption into the dough during immersion in water at 25°C is shown in Fig. 4. The dotted line indicates the water content at which the dough was pre-heat-treated (1.00 kg-water/kg-solid).

Figure 4 showed that pre-heat-treatment at 55°C had

Fig. 3 The time course of water content at the center of the dough sample that was immersed in water at 25°C. The sample was pre-heat-treated at 90°C or non-heat-treated (designated as heat-treated at 25°C). The water content at the heat-treatment is noted in the figure.

Fig. 4 The time course of water content at the center of the dough sample that was immersed in water at 25°C. The water content of the sample when it was pre-heat-treated is 1.00 kg-water/kg-solid. The temperature with which the sample was heat-treated is noted in the figure.

little effect on water absorption. Both of the samples, pre-heat-treated at 55°C and that not pre-heat-treated, seemed to approach equilibrium. Dough samples pre-heat-treated at 90°C also seemed to approach equilibrium. On the other hand, dough samples pre-heat-treated at 60°C continued water absorption for seven days running. The time course of water content in the dough sample pre-heat-treated at 70°C and 80°C was between that of 60°C and of 90°C.

The change in the length of the sample dough (the water content at the pre-heat-treatment was 1.00 kg-water/kg-solid) is shown in Fig. 5. The dough pre-heat-treated at 60°C showed about 30% expansion after one day of immersion and reached a constant expansion (54%) after four days of immersion. On the other hand, the dough pre-heat-treated at 90°C showed about 50% expansion after one day of immersion and 80% expansion after seven days of immersion.

Figure 6 shows the proton signal intensity profiles in the sample dough monitored by NMR imaging. Since it is calibrated by the apparent transverse relaxation time, the proton signal intensity indicates water content in relative value.

The monitored images indicates that water content profile became flat after two days or three days immersion in both of the dough samples pre-heat-treated at 60°C and 90°C.

4. Discussion

4.1 Maximum water content/ water-holding capacity

It is starch and protein (gluten) that govern water absorption or water-holding capacity of starchy food. The kernel of cereal grains such as rice and wheat consists of cells in which starch granules are stored (Fig. 7A). When the kernel is cooked, the gelatinization of starch granules takes place. The gelatinized starch absorbs water from outside of the cells and tends to expand. Since the cell wall has a considerable resistive strength, however, the expansion is bal-

anced and water content reaches an upper limit (ceiling water content)[13].

Fig. 5 The change of the length of dough samples during steeping in water at 25°C. The water content of the sample when it was pre-heat-treated is 1.00 kg-water/kg-solid.

Fig. 6 One-dimensional NMR images of the dough sample during steeping in water. The sample was pre-heat-treated at (A) 90°C or (B) 60°C with its water content 1.00 kg-water/kg-solid.

Fig. 7 A schematic diagram of starchy food: (A) kernel of cereal grain, (B) wheat flour dough.

On the other hand, wheat flour dough products such as spaghetti strand, consists of gluten network in which starch granules are inlaid (Fig. 7B). When the wheat flour dough is cooked, starch gelatinization will take place and this facilitates water absorption. If the gluten network is strong enough, as in the case of spaghetti, the expanding force due to water absorption will be balanced by some resistive force due to gluten network resulting in maximum water content being reached [5].

Unfortunately, however, some of the wheat flour dough used in the present experiment did not show maximum water content. This could be because the wheat flour used in the present experiment was not for use in spaghetti but for udon (Japanese noodles); the wheat flour for udon contains lower protein (8.5% weight) than that for spaghetti (12–13% weight). This could result in the formation of less resistive networks.

Starch gelatinization is governed by water content, m [kg-water/kg-solid], and temperature, θ [°C], when the dough was heat-treated [14 – 16]. The extent of starch gelatinization, η , can be estimated by the equation proposed by Fukuoka et al. [17]:

$$\eta(m, \theta) = \frac{3.15m/(1+m) - 0.946}{1 + \exp[-0.1792(\theta - 69.1)]} \quad (0.54 \leq m \leq 1.5) \quad (7)$$

By the use of this equation, the extent of starch gelatinization is estimated to be 0.28 when the wheat starch heated at 90°C has low water content (0.64 kg-water/kg-solid). As is shown in Fig. 3, a dough sample with 28% starch gelatinization absorbed water in a similar way to a dough sample without heat-treatment. This indicates that water uptake in the flour dough is governed by the water absorbed in the protein (gluten) rather than the starch when the extent of starch gelatinization is not high.

On the other hand, the extent of starch gelatinization is estimated to be higher (0.72 and 1.00, respectively) when the dough samples are pre-heat-treated (90°C) with high-

er water content (1.15 and 1.66 kg-water/kg-solid). Water absorption seems to be governed by starch gelatinization: the higher the extent of starch gelatinization, the more water absorbed into the dough sample (Fig. 3).

Unfortunately, however, the temperature dependence on water absorption shown in Fig. 4 cannot be explained by the extent of starch gelatinization. The relationship appears to be the inverse of what it should be. The lower the temperature of heat treatment, namely resulting in the lower extent of gelatinization, the more water absorbed. When we look at the details in Fig. 4, the water content in the dough sample pre-heat-treated at 90°C is approaching a maximum value while those pre-heat-treated at 60°C continued rising. This may be explained if we postulate that “pre-heating at a higher temperature not only promotes starch gelatinization but also strengthens gluten network formation.” From this point of view, the dough sample pre-heat-treated at 60°C is assumed to have been lacking in the strength of its gluten network so that a gradual breakage of the network occurred when the dough was immersed in water for a long time.

The average time, τ , needed for a molecule to migrate over a distance, L , in one-dimensional diffusion can be roughly estimated by [18]

$$\tau = L^2 / 2D \quad (8)$$

where D is diffusion coefficient. D of water in wheat flour dough is known of the order of $10^{-10} \text{ m}^2/\text{s}$. Substituting $L=5 \text{ mm}$ into Eq. (8) gives $\tau=1.5$ days. Consequently, the water content in the central part of the cylinder is assumed to approach the equilibrium value, m_e , after two days or three days of immersion (Fig. 1A). This idea is supported by the water content profile monitored by NMR imaging, namely, the water content profile became flat after two days or three days of immersion (Fig. 6). When the time course of water content during dough immersion is examined in detail, it is found that the rise in water content could be fitted by a pair of straight lines; we witnessed an intersection at two days or four days of immersion (Fig. 8). This may be caused by the change of driving force: the flattened profile of water content loses the force to drive diffusion. In this case, something other than water content gradient, such as deformation due to expansion, might have become effective for seemingly driving water migration.

On the other hand, it is found that a linear relationship between activity and water content needs to be held for estimating partition coefficient that is independent on water content. The detail is reported elsewhere [11]. In

Fig. 8 The time course of water content in the dough sample fitted by a pair of straight lines. Pre-heat-treated at (A) 90°C or (B) 60°C. The water content value at the intersection is defined as first stage water-holding capacity.

order to satisfy this requirement, the water-holding capacity for the use of estimating the partition coefficient in Yahata's experiment [12] is preferably in a middle water content region rather than in a much high water content region such as the maximum water content, because the range of water content involved in the experiment was in the middle water content region (1.0–2.0 kg-water/kg-solid). Consequently, the water content at the intersection could provide a potential candidate for a characteristic water content value.

This value at the intersection, named as the first stage water-holding capacity, m^0 , was collected and plotted in Fig. 9 against the temperature at pre-heat-treatment. Figure 9 shows that the first stage water-holding capacity value is mainly governed by the water content with which the dough was pre-heat-treated, while the effect of pre-heat treatment temperature is not significant.

4.2 A mathematical model simulation using the first stage water-holding capacity

In this section, the first stage water-holding capacity values shown in Fig. 9 are applied to simulate the water

Fig. 9 First stage water-holding capacity of the dough sample plotted against the heat-treatment temperature.

migration experiment in the temperature-gradient heat-treated dough slab[12] that is briefly described in the Introduction of this paper. In this simulation, we used a multiphase-multilayer model, in which the dough slab was virtually sliced into a number of layers along the axis from the heated side to the cooled side. Each of the layers was considered to be a homogeneous layer with its own (different) water-holding capacity value. Inside each layer, a Fickian diffusion equation governs water migration, while at the boundary of each layer, instantaneous partition equilibrium is assumed to be reached. The partition equilibrium that takes place at the boundary where i -th phase and $(i+1)$ -th phase are in contact is represented as:

$$K = m_i^+ / m_{i+1}^+ \quad (9)$$

where m_i^+ and m_{i+1}^+ are water-holding capacity in phase i and $i+1$, respectively. In the present simulation, we used the first-stage water-holding capacity (Fig. 9) as the substitute for water-holding capacity.

The approximately linear temperature profile across the dough slab, shown in Fig. 10, was applied on the wheat flour dough slab when it was temperature-gradient heat treated [12]. Combining this temperature profile with Fig. (9), the first-stage water-holding capacity at each position across the dough slab was calculated and shown in Fig.11. Next, the partition coefficient at the boundary of adjacent phases (of virtually sliced layers in the multiphase-multilayer model) was calculated using Eq. 9. The profile of calculated partition coefficients is shown in Fig. 12. These partition coefficients were used in the present simulation.

Fig. 10 The temperature profile across the dough slab when the dough sample was temperature-gradient heat-treated [12]. The key indicates the measured temperature.

Fig. 11 The first-stage water holding capacity profile across the dough slab that was temperature-gradient heat-treated [12]. Figure 11 was estimated by combining Fig. 9 and Fig. 10.

In this simulation, the dough slab was sliced into 100 layers and each phase was divided into 5 nodes. The water diffusivity used was $10^{-10} \text{ m}^2/\text{s}$. Using the equations from Eq.(3) through Eq.(6), we calculated the water content profile (solid line) 1.5 hours after heat treatment, as well as those 1 day and 3 days after heat treatment (Fig. 13). These are compared with the measured water content profile (dotted lines). A good agreement is seen in the gelatinized side (left-hand side), while a highly scattered behavior of the measured water content profile in the un-gelatinized side (right-hand side) cannot be simulated. It is worth noting that both measured and calculated water content profiles show a wavy form 1.5 hours after heat

Fig. 12 Partition coefficient profile across the temperature-gradient heat-treated dough slab [12]. The partition coefficient is calculated as the ratio of first stage water-holding capacity in each of the layers in contact.

treatment that may be caused by water migration from the right-hand side to the left-hand side across the region near the center where first-stage water-holding capacity jumps sharply, creating a spike in the partition coefficient profile. The result of the simulation shows that the first-stage water-holding capacity is valuable for the use of simulating water migration in a situation where the water content is limited to lower levels.

Conclusion

Wheat flour dough samples that had been pre-heat-treated at a selected temperature ranging from 55°C to 90°C were immersed in distilled water at 25°C and the time course of water content was observed with the intention of obtaining the equilibrium value (ceiling water content). Unexpectedly, however, the water content of the samples pre-heat-treated at 60°C and above continued to increase even after seven days of immersion, although some of them approached equilibrium.

The rise of water content in the dough samples during immersion was accelerated when the water content at the time of heat treatment was high, although the influence of heat-treatment temperature was scarce.

The water content profile monitored by NMR imaging became flat at two or three days of immersion, even though the water content measured by gravimetric method continued rising. The continued rise of water content is supposed to be caused by a change of water-holding

capacity due to expansion. Consequently, we defined “the first stage water-holding capacity” as the water content at the time when the rise of water content changed its rate after the NMR imaging profile became flat. The first stage

water-holding capacity collected in this work was favorably used to simulate the change of water content profile in a wheat flour dough slab that was temperature-gradient heat-treated.

Fig. 13 Comparison between measured (dots) and calculated (solid lines) water content profile in the temperature-gradient heat-treated dough slab. (A) 1.5 hours, (B) 1 day, (C) 3 days after the heat-treatment.

References

- [1] R. Ruan, S. J. Schmidt, A. R. Schmidt, J. B. Litchfield; Nondestructive measurement of transient moisture profiles and the moisture diffusion coefficient in a potato during drying and absorption by NMR imaging. *J. Food Process Eng.*, **14**, 297–313 (1991).
- [2] A. K. Horigane, H. Toyoshima, H. Hemmi, W. M. H. G. Engelaar, A. Okubo, T. Nagata; Internal hollows in cooked rice grains (*Oryza sativa* cv. Koshihikari) observed by NMR micro imaging. *J. Food Sci.*, **64**, 1–5 (1999).
- [3] T. I. Kojima, A. K. Horigane, M. Yoshida, T. Nagata, A. Nagasawa; Change in the status of water in Japanese noodles during and after boiling observed by NMR micro imaging. *J. Food Sci.*, **66**, 1361–1365 (2001).
- [4] K. L. McCarthy, J. J. Gonzalez, M. J. McCarthy; Change in moisture distribution in lasagna pasta post cooking. *J. Food Sci.*, **67**, 1785–1789 (2002).
- [5] M. A. Del Nobile, G. G. Buonocore, A. Panizza, G. Gambacorta; Modeling the spaghetti hydration kinetics during cooking and overcooking. *J. Food Sci.*, **68**, 1316–1323 (2003).
- [6] A. G. F. Stapley, T. M. Hyde, L. F. Gladden, P. J. Fryer; NMR imaging of the wheat grain cooking process. *Inter. J. Food Sci. Tech.*, **32**, 355–375 (1997).
- [7] S. Takeuchi, M. Fukuoka, Y. Gomi, M. Maeda, H. Watanabe; An application of magnetic resonance imaging to the real time measurement of the change of moisture profile in a rice grain during boiling. *J. Food Eng.*, **33**, 181–192 (1997).
- [8] A. G. F. Stapley, P. J. Fryer, L. F. Gladden; Models for the processing of whole wheat grains in cereal manufacture, In R. Jowitt (Ed.), *Engineering and Food at ICEF7 (part 2, H37–H40)*. Sheffield Academic Press, Sheffield (1997).
- [9] M. Fukuoka, T. Mihori, H. Watanabe; MRI observation and mathematical model simulation of water migration in wheat flour dough during boiling. *J. Food Sci.*, **65**, 1343–1348 (2000).
- [10] H. Watanabe, M. Fukuoka, A. Tomiya, T. Mihori; A new non-Fickian diffusion model for water migration in starchy food during cooking. *J. Food Eng.*, **49**, 1–6 (2001).
- [11] H. Watanabe, Y. Yahata, M. Fukuoka, S. Sakiyama, T. Mihori; Relative water content model that describes non-Fickian diffusion in multiphase inhomogeneous systems.

- Japan J. Food Eng., (in Japanese), **7**, 129–139 (2006).
- [12] Y. Yahata, M. Fukuoka, T. Mihori, H. Watanabe; Water can be made to diffuse against the water content gradient in starchy foods. *J. Food Eng.*, **76**, 490–499 (2006).
- [13] Nihon Shokuhin Kougakukai; *Shokuhin Kougaku Handbook*, Asakura Shoten, Tokyo 2006, p. 287.
- [14] A. C. Eliasson; Effect of water content on the gelatinization of wheat starch. *Starch/Stärke*, **32**, 270–272 (1980).
- [15] Q. Liu, R. Yada, J. Arul; Characterization of thermal properties of potato dry matter–water and starch–water systems. *J. Food Sci.*, **67**, 560–566 (2002).
- [16] H. Liu, J. Lelievre; A model of starch gelatinization linking differential scanning calorimetry and birefringence measurements. *Carbohydrate Polymers*, **20**, 1–5 (1993).
- [17] M. Fukuoka, K. Ohta, H. Watanabe; Determination of the terminal extent of starch gelatinization in a limited water system by DSC. *J. Food Eng.*, **53**, 39–42 (2002).
- [18] G. B. Benedek, F.M.H. Villars; *Physics with Illustrative Examples from Medicine and Biology; Statistical Physics*, 2nd ed. Springer-Verlag, New York, 2000, pp. 113–125.

◇◇◇◇ 和文要約 ◇◇◇◇

加熱処理した小麦粉ドウの浸漬特性

八幡淑子, 福岡美香, 崎山高明, 渡辺尚彦[†]

東京海洋大学食品生産学科

米粒や麺線のようなデンプン食品を短時間ボイルすると食品の表面部分と中心部分は糊化の進行が異なるため水分保持能力が異なる状態となる。ここで加熱を中止し乾燥を防ぎながら室温で長時間放置すると、中心部は低含水率、周辺部は高含水率のまま平衡になり、均一な含水率分布は得られない。これは当初均相系（均一系）だった食品物体が平衡含水率の異なる各相からなる多相系に変化したと考えることができる。このように調理過程で多相系に転じるような食品中では Fick の拡散法則はそのままでは適用できない。このような系に適用できる拡散モデルとして著者らは相対含水率モデル (Relative Water Content model) を提案している。相対含水率モデルでは食品の吸水能力の指標となる標準含水率を適宜定義して用いる。実用的な標準含水率 (standard water content) として、食品を純水に浸漬させたときに得られる平衡含水率を食品の吸水容量 (WHC=Water Holding Capacity) と名付けて採用することができる。

本研究では小麦粉ドウの WHC の測定を試みた。小麦粉ドウは加熱処理時の温度や含水率によって WHC が変化すると考えられるので、加熱処理条件の異なるドウを調整した後、円筒状のガラス棒に詰め水 (25℃) に浸漬してドウ円筒中心部の含水率の時間変化を重量法で測定した。同時にドウの円筒軸方向の含水率分布を磁気共鳴画像法でモニタした。ドウ円筒中心部の含水率は、一部で平衡に近づくものもあったが、予想に

反して平衡値に達することなく、浸漬した7日間にわたって上昇を続けるものが多かった。

一般に小麦粉ドウはグルテンの作る網目の中にデンプン顆粒が埋め込まれた構造をしており、糊化したデンプン顆粒が吸水して膨張しようとする力と、伸びたグルテンの網目によって発生する抵抗力とがバランスして平衡が保たれると考えられる。ところが本研究で用いた小麦粉はうどんの製造に使われる中力粉であってタンパク含量が少ないためグルテンの網目が吸水したデンプンの膨張力によって少しずつ破壊されて平衡値が変化した可能性がある。

一方、磁気共鳴画像法によりモニタした含水率分布は浸漬後、2日ないし3日たつとフラットな含水率分布を示した。この含水率分布がフラットになるのと同じ時期にドウ中心部の含水率上昇の速さが変化することがわかった。そこでこの時期の含水率上昇を2本の直線で近似し、直線が交差する点での含水率を first stage water-holding capacity と名付け、実用的な標準含水率の候補とした。種々の加熱処理条件により作成した小麦粉ドウ試料を水へ浸漬させた実験により first stage water-holding capacity を測定し、first stage water-holding capacity に対する加熱処理時の含水率、加熱温度の影響をグラフにまとめた。さらにその値を用いて、温度勾配熱処理を施した小麦粉ドウ中の水分移動のシミュレーションを、多相多層モデルを用いて行なった。

(受付 2005 年 10 月 18 日, 受理 2006 年 5 月 30 日)

〒 108-8477 東京都港区港南 4-5-7

[†] Fax: 03-5463-0497, E-mail: hisahiko@s.kaiyodai.ac.jp