J. Fac. Appl. Biol. Sci.,
Hiroshima Univ. (1980), **19**: 121 – 132

Studies on the Cooking-rate Equations of Udon, Somen, Soba and Chuka Soba

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Received: August 27, 1980
(Figs. 1–13, Tables 1, 2)

INTRODUCTION

In order to design and to control automatically various cooking apparatuses, it is necessary to determine first the cooking-rate equation from experimental data. In previous papers, we have already studied the cooking-rate equations for rice[1–5], beans[6,7], root vegetables[8,9], spagetti and hiyamugi[10].

In this paper, we studied the cooking-rate equations of udon, somen, soba and Chuka soba which in Japan are very popular elements of food. For the measuring of the cooking rates, we used a weighing method, because the degrees of cooking of low water content foods such as rice, beans, dry noodles and so on may be represented by a water soaking phenomenon. The cooking-rate equations were postulated as a simple empirical rate equation and as a semi-theoretical one based on the water-soaking-shell model which was also used in the previous papers[1–4,6,10,11].

EXPERIMENTAL

1. Samples

The noodles used as sample were bought in the market. The commercial names of udon, somen, soba and Chuka soba (Japanese wheat noodle, finely-spun wheat noodle, buckwheat noodle and Chinese vermicell) used in this studies are Special Udon (Takahashi Seimen Co., Fukuyama), Somen (Yokoyama Seimen Co., Okayama), Hiruzen Soba (Hiryu Co., Okayama), Fukushima Ramen (Ezaki Seimen Co., Fukuyama), respectively.

The weight, length and diameter of one piece of udon, somen, soba and Chuka soba were 1.280g, 25.2cm, 0.219cm; 0.235g, 19.0cm, 0.106cm; 0.605g, 28.5cm, 0.142cm; 0.331g, 18.6cm, 0.131cm, respectively. As samples, we used 20.0cm length noodles which were cut with a razor knife.

2. Cooking procedure

The samples of 10.0 cm were put into a sample basket made of stainless wire net (20 mesh), and were put into hot water and cooked at a given temperature for a fixed time. The temperature of the hot water for the cooking was 70, 80 and 90°C. It was controlled in a water bath by an electric heater, and a covered pot was used for the cooking temperature of 99.5°C.

The cooked noodles were poured out quickly into water of 20°C for 0.5 minutes in order to stop the cooking process.

In each experiment, we used 5 samples for udon and 10 samples for other noodles, respectively. The observed values used in this paper are average values.

3. Measuring method

The surfaces of the cooked samples were wiped quickly by a filter paper, and then were transfused into a weighing tube. After this, the samples were weighed with a chemical balance. The weight of the completely dryed state of the cooked samples was estimated as being the values of 10 hours drying at 130°C in a dryer. The values of the moisture content of the samples at the initial state were 14.2, 12.2, 13.6 and 13.1% (W.B.) for udon, somen, soba and Chuka soba, respectively.

The length and density of the samples were measured by means of a bamboo ruler and a specific gravity bottle at 30°C.

The values of radius of the samples were calculated by using the observed values of the weight, length and density assuming the samples had cylindrical shape.

RATE EQUATION

1. Rate equation

The cooking ratio $x(-)$ can be expressed by the following equation from the weight of the sample:

$$x = (w - w_0)/(w_e - w_0) \qquad (1)$$

where, w(g) is the cooking weight of the sample at any given cooking time θ (min). The subscripts of 0 and e give the values at the initial and equilibrium states, respectively.

As types of cooking-rate equations, we can consider two types. One is an empirical formula [12–14]. This one is useful, unless the cooking mechanism can be analyzed and their transforming model can be postulated approximately. The other type is a theoretical or a semi-theoretical rate equation based on the water-soaking-shell model and so on.

The relationships of x vs. θ do not show a S-shape curve. The empirical rate equation can be postulated as follows:

$$dx/d\theta = k_n(1 - x)^n \qquad (2)$$

where, k_n (min^{-1}) and $n(-)$ are the rate parameters which can be obtained from the experimental data of x vs. θ.

The other semi-theoretical rate equation based on the water-soaking-shell model[1–4,6,10,11] can be used for the cooking of the noodles by assuming that the unsoaked core and the soaked shell occuring in the cooking process were cleary divided by the internal plane. The rate equation for long-cylinder becomes as follows:

$$\frac{dx}{d\theta}=\frac{2\pi r_c L(C_e-C_0)/(w_e-w_0)}{\dfrac{r_c\ln(R/r_c)}{k_m}+\dfrac{1}{k_r}} \tag{3}$$

$$R=\left(R_e^2-((R_e/R_0)^2-1)(1-x)R_0^2\right)^{0.5} \tag{4}$$

$$r_c=(1-x)^{0.5}R_0 \tag{5}$$

where, R(cm), L(cm) and C(g-H_2O/cm^3) are the radius, length and water concentration of the sample, and r_c is the radius of the soaked core which can be calculated by Eq. (5). k_m (cm^2/min) is the diffusion parameter of water through the soaked layer, and k_r (cm/min) is the reaction parameter of the noodle's component with the diffused water at internal plane. These rate parameters can be obtained from the experimental data of x vs. θ. If, from the experimental data obtained, the values of L were not constant values, then we can assume the follows equation[10]:

$$L=L_e-((L_e/L_0)-1)(1-x)L_0 \tag{6}$$

This equation is same to the one dimensional increasion of the thickness on the infinite-slab shape of the water-soaking-shell model[1].

2. Calculation method of the parameters

The experimental data on the cooking of noodles can be obtained as relationships of x vs. θ, as shown below. As the data were scattered, we could not obtain reliably the differentiated values of $dx/d\theta$ from the data of x vs. θ by a differential analysis. Therefore, we had to calculate the cooking-rate parameters in Eq.(2) or (3) with a non-linear least square method[15] using a digital computer. The cooking-rate equations were integrated numerically using the Runge-Kutta-Gill method. The programs for the calculation are nealy the same as in the previous paper[1,14].

The values of the following standard deviation σ (—) were minimized.

$$\sigma=\left(\sum_{i=1}^{N}(x_{obs}-x_{cal})_i^2/N\right)^{0.5} \tag{7}$$

where, N is the number of data, and the subscripts of obs and cal give the observed and calculated values, respectively.

The initial values of the rate parameters in Eq.(2) were given as n=1.0, and the initial values of k_n were estimated by the following integral equation obtained from Eq.(2).

$$k_{n=1}=-\ln(1-x)/\theta \tag{8}$$

The initial values of k_m and k_r in Eq. (3) were calculated by the following integral equations which were obtained for the cases of only a partly control of diffusion or reaction rate, respectively.

$$\begin{aligned} k_m=&((R_0^2R_e^2-(R_e^2-R_0^2)r_c^2)\ln(R_e^2(R_0^2-r_c^2)+R_0^2r_c^2)\\ &+2(R_e^2-R_0^2)r_c^2\ln r_c-(4R_0^2R_e^2-2(R_e^2-R_0^2)r_c^2)\ln R_0)\\ &(w_e-w_0)/(4(R_e^2-R_0^2)(C_e-C_0)V_0\theta) \end{aligned} \tag{9}$$

$$k_r=R_0(1-(r_c/R_0))(w_e-w_0)/((C_e-C_0)V_0\theta) \tag{10}$$

where, V(cm^3) is the volume of samples.

From the experimental data, we could not obtain the values of w_e. Therefore, we assumed the value of w_e as one of the rate parameter as shown in the previous paper[10].

The FACOM M-200 digital computer of the Computation Center in Nagoya Univ. was used for these calculations.

RESULTS AND DISCUSSION

1. Experimental results

Each noodle was cooked at a temperature of 70, 80, 90 and 99.5°C. The relationship between weight w(g) and density ρ (g/cm^3) of the samples with the cooking time θ(min) are shown in Figs. 1~4. In Figs. 1~4, the curves of w vs. θ at a cooking temperature below 90°C and/or 99.5°C are monotonous, but the curves for udon at 99.5°C are not monotonous and have maximum states. The reason may be perhaps that the dissoluted weight of cooked noodles is more than the soaked weight of water. The values of the equilibrium weight w_e can not be obtained from these experimental data.

The relationships between the length L(cm) and the radius R(cm) of samples with the cooking time θ(min) are shown in Figs.5~8. In Fig.5, the curves of L vs. θ show characteristic S-shape's curves as the previous experimental results of spagetti (R=1.90 cm) and hiyamugi (medium-spun wheat noodle: R=0.135cm). This S-shape's tendency is less or not obtained in Figs. 6~8. The reason may be perhaps that the expansion of the axis is difficult for the larger and harder noodles, before the softening at the center parts is induced by the cooking.

From the S-shape's curves of L vs. θ , we can considere two parts in the inner

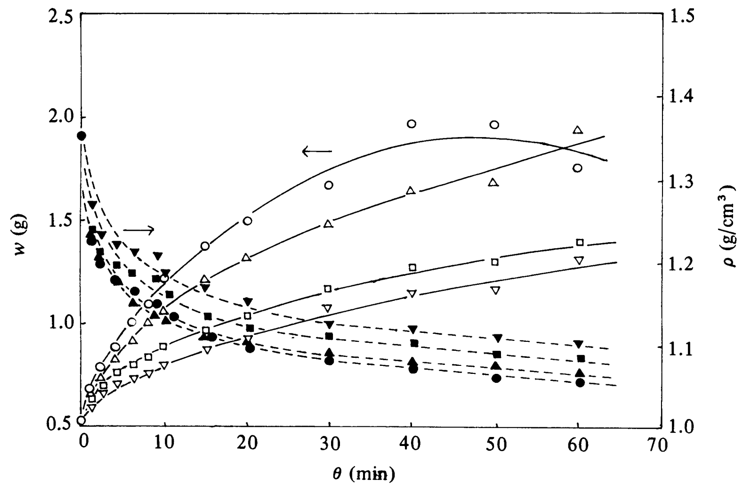

Fig. 1. Relationships between the weight w or density ρ and the cooking time θ on the cooking of udon.
Cooking temp. : 99.5 90 80 70 °C
○ △ □ ▽

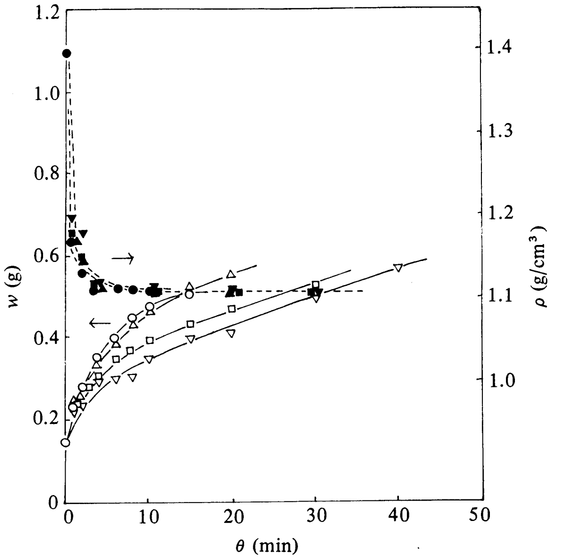

Fig. 2. Relationships between the weight w or density ρ and the cooking time θ on the cooking of somen.
Cooking temp.: 99.5 90 80 70 °C
○ △ □ ▽

components; a softer shell and a harder core. Accordingly, the water-soaking-shell model mentioned in Eq.(3) can be applied approximately in the cooking of the larger and harder noodles at these states.

2. Calculated results

The rate parameters in Eq.(2) or (3) can be calculated from the relationships of w vs. θ shown in Figs. 1~4. The initial values w_0 were used as the weight of samples soaked instantly and wiped quickly by a filter paper.

$$w_0 = \alpha w^* \tag{11}$$

where, w^* is the weight of undoaked samples. The values of α were 1.051, 1.158, 1.138 and 1.129, and the values of w_0 were 0.535, 0.144, 0.242 and 0.201 g for udon, somen, soba and Chuka soba, respectively.

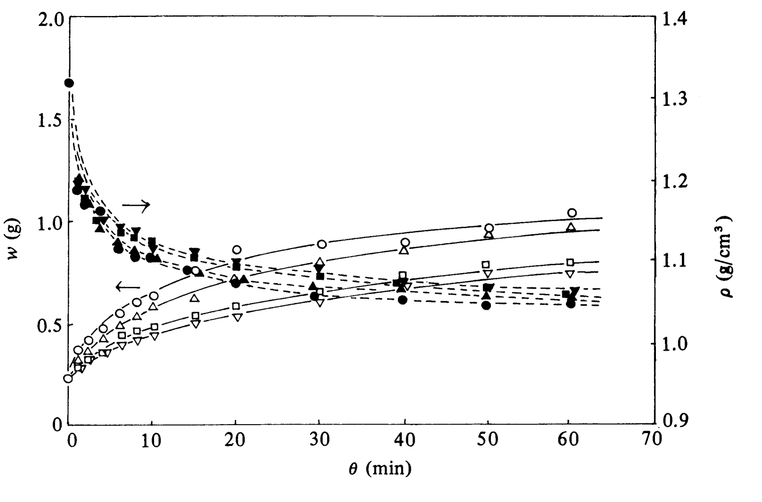

Fig. 3. Relationships between the weight w or density ρ and the cooking time θ on the cooking of soba.
Cooking temp.: 99.5 90 80 70 °C
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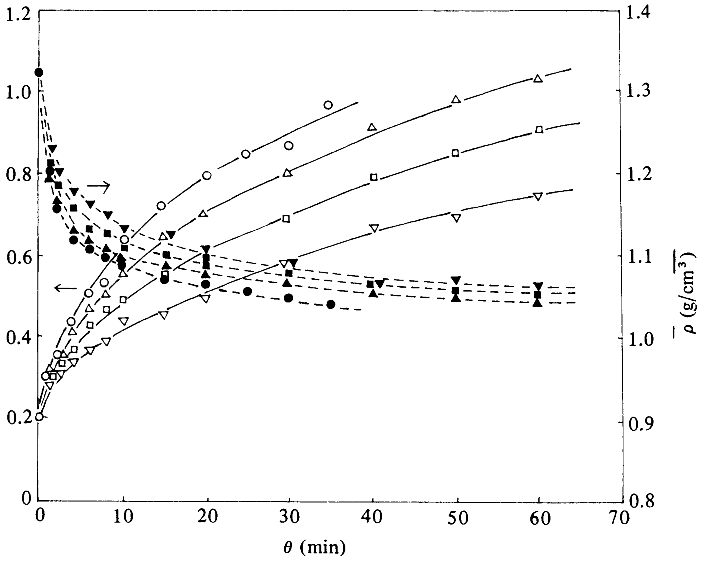

Fig. 4. Relationships between the weight w or density ρ and the cooking time θ on the cooking of Chuka soba.
Cooking temp.: 99.5 90 80 70 °C
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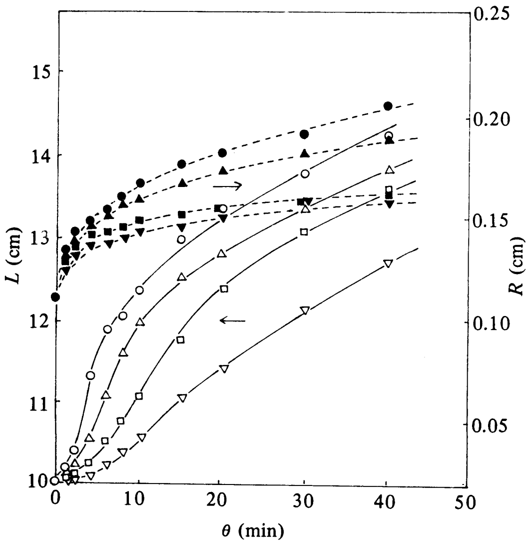

Fig. 5. Relationships between the length L or radius R and the cooking time θ on the cooking of udon.
Cooking temp.: 99.5 90 80 70 °C
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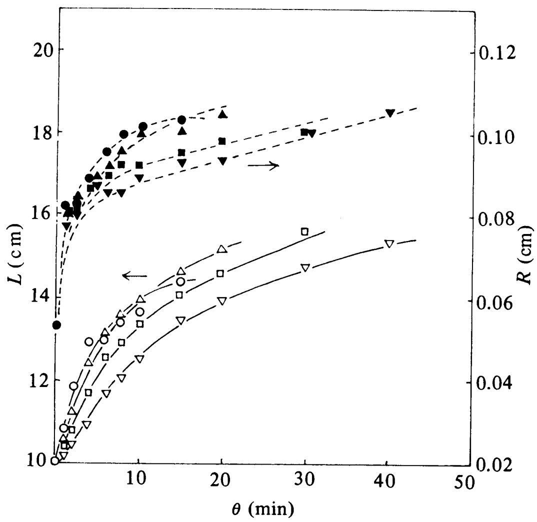

Fig. 6. Relationships between the length L or radius R and the cooking time θ on the cooking of somen.
Cooking temp.: 99.5 90 80 70 °C
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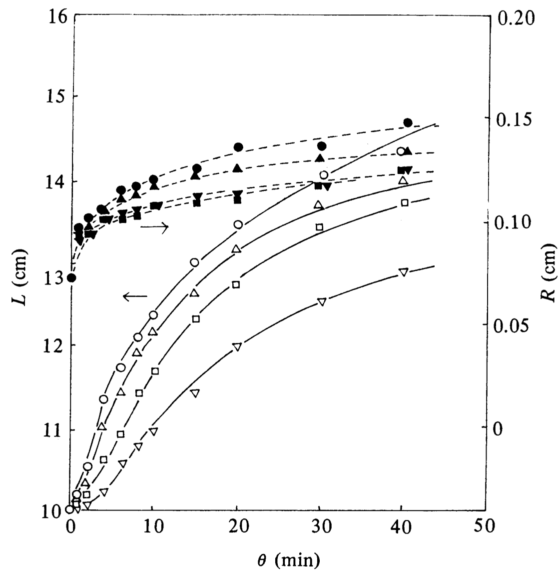

Fig. 7. Relationships between the length L or radius R and the cooking time θ on the cooking of soba.
Cooking temp.: 99.5 90 80 70 °C
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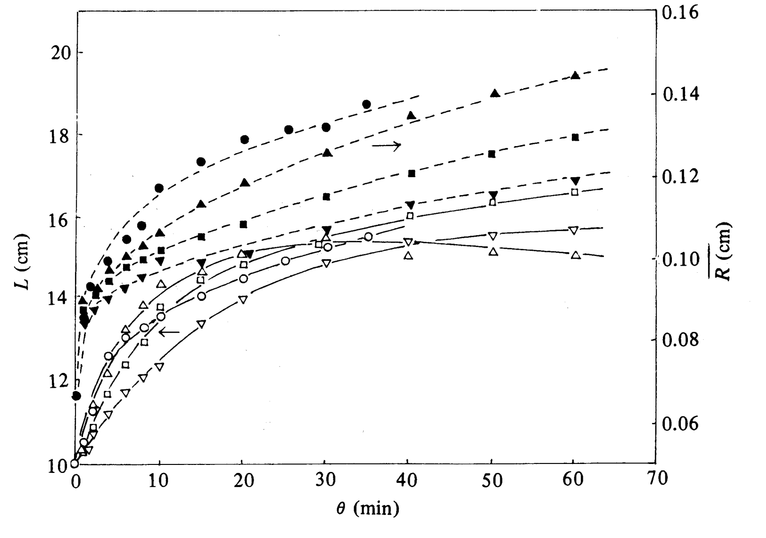

Fig. 8. Relationships between the length L or radius R and the cooking time θ on the cooking of Chuka soba.
Cooking temp.: 99.5 90 80 70 °C
○ △ □ ▽

The equilibrium values w_e can not be obtained from the experimental data of Figs. 1~4. Therefore, we assumed the value as one of the parameter with the other parameters of n and k_n using the same method shown in the previous paper[10].

The data for the longer cooking times are very complicated, since there are soaking and dissoluting phenomena. Then, we used only the data for ealier cooking times to calculate the rate parameters; up to 20, 30, 40, 40 min for udon, 6, 8, 10, 15 min for somen, 20, 30, 40, 40 min for soba and 10, 15, 20, 30 min for Chuka soba at 99.5, 90, 80, 70°C, respectively. The relations between the cooking ratio $x(-)$ and the cooking time θ(min) used for the calculation of the rate parameters are shown in Figs. 9~12.

The calculated values of the rate parameter in Eq.(2) and the standard deviation are listed in Table 1. The values of the equilibrium values w_e were 2.095, 0.574, 0.971 and 0.987 g for udon, somen, soba and Chuka soba, respectively. The values of n are found to be from 2 to 4, so the values are unified as n=2.0 as shown in the previous paper[10]. The solid curves in Figs. 9~12 show the calculated results used the rate parameters obtained n=2.0 in Eq. (2). The accordances for the lower cooking temperature region are not better than the ones for the higher region. The reason is that the lower region has a higher value of n than the used value of 2.0.

The values of logalithm of $k_{n=2.0}$ are plotted in Fig. 13 against the reciprocal of the absolute temperature. Nealy straight lines are obtained. The Arrhenius equations are obtained as follows:

For udon;

$$k_{n=2} = 3.79 \times 10^6 \exp(-1.31 \times 10^4 / R_g T)$$

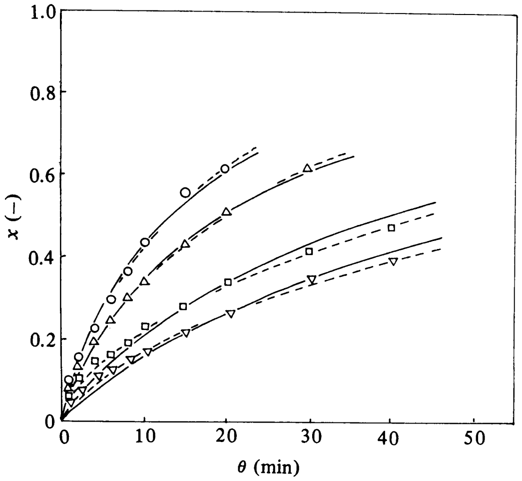

Fig. 9. Relationships between the cooking ratio x and the cooking time θ on the cooking of udon.
Cooking temp.: 99.5 90 80 70 °C
○ △ □ ▽
Calculated results : Eq. (2) ——
Eq. (3) - - -

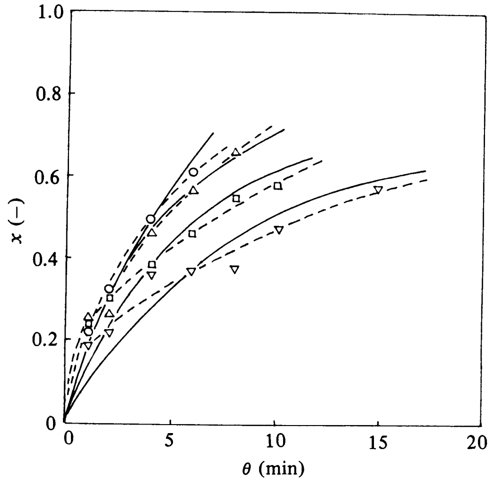

Fig. 10. Relationships between the cooking ratio x and the cooking time θ on the cooking of somen.
Cooking temp.: 99.5 90 80 70 °C
○ △ □ ▽
Calculated results : Eq. (2) ——
Eq. (3) - - - -

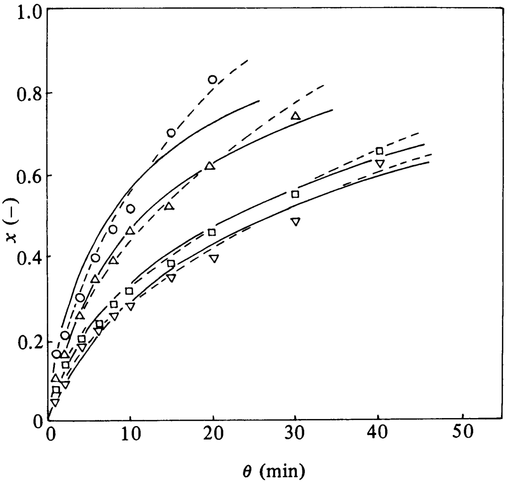

Fig. 11. Relationships between the cooking ratio x and the cooking time θ on the cooking of Soba.
Cooking temp.: 99.5 90 80 70 °C
○ △ □ ▽
Calcualted results: Eq. (2) ——
Eq. (3) ----

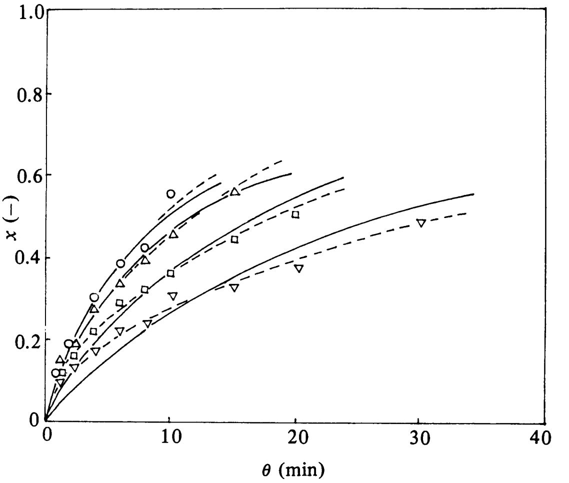

Fig. 12. Relationships between the cooking ratio x and the cooking time θ on the cooking of Chuka soba.
Cooking temp.: 99.5 90 80 70 °C
○ △ □ ▽
Calculated results : Eq. (2) ——
Eq. (3) -----

Table 1. Rate parameters in the cooking-rate equation of Eq. (2).

Cooking temp. (°C)	Udon $k_{n=2}$ (min^{-1})	Udon σ (–)	Somen $k_{n=2}$ (min^{-1})	Somen σ (–)	Soba $k_{n=2}$ (min^{-1})	Soba σ (–)	Chuka soba $k_{n=2}$ (min^{-1})	Chuka soba σ (–)
99.5	7.73×10^{-2}	0.0178	2.48×10^{-3}	0.0137	12.5×10^{-2}	0.0530	10.8×10^{-2}	0.0235
90	5.32 〃	0.0190	2.25 〃	0.0391	8.37 〃	0.0190	8.86 〃	0.0345
80	2.61 〃	0.0323	1.65 〃	0.0521	4.55 〃	0.0309	5.95 〃	0.0385
70	1.84 〃	0.0262	1.02 〃	0.0576	3.83 〃	0.0374	3.64 〃	0.0449

For somen;

$$k_{n=2} = 1.17 \times 10^4 \exp(-7.90 \times 10^3/R_g T)$$

For soba;

$$k_{n=2} = 2.68 \times 10^5 \exp(-1.09 \times 10^4/R_g T)$$

For Chuka soba;

$$k_{n=2} = 5.34 \times 10^4 \exp(-9.66 \times 10^3/R_g T)$$

where, T(°K) is the cooking temperature, and R_g=1.987 cal/g-mol·°K is the gas constant. The values of the apparent activation energy for the cooking of udon, somen, soba and Chuka soba are in the same order as the values of 8.72 and 10.5 kcal/g-mol obtained respectively from the cooking of spagetti and hiyamugi in the previous paper[10).

The calculated values of the rate parameter in Eq. (3) and the standard deviation are listed in Table 2. The broken curves in Fig. 9~12 show the calculated results used the

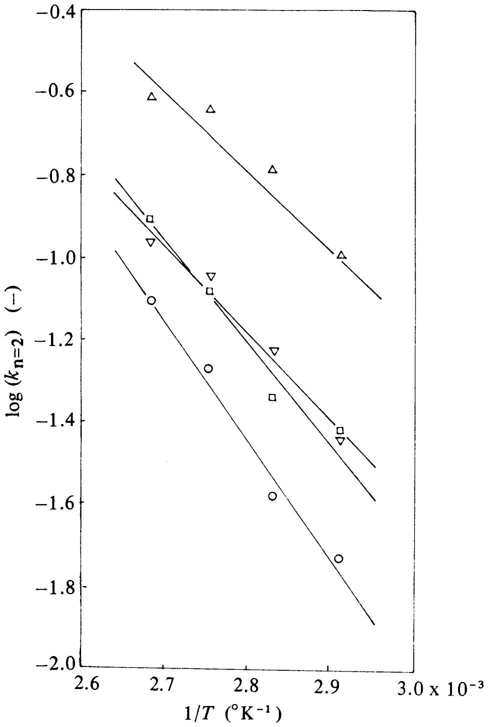

Fig.13. Arrhenius plots of the cooking of udon, somen, soba and Chuka soba.
Udon ○ Somen △ Soba □ Chuka soba ▽

rate parameters obtained in Table 2. The calculated results for the reaction controlling only differ too much from the experimental data as same to the results in the previous paper[10], then, we may deduce that the cooking rates of noodles consist perhaps both of the diffusion and reaction rates.

It is difficult to find a certain relation between the values of k_r and those of the cooking temperature in Table 2. This is due to the interrelation of k_r and k_m, and the cooking rates of noodles consist perhaps mainly in the diffusion rates.

The values of the apparent activation energy of the reaction region on the cooking of rice[2] and the one on the gelatinization of rice starch[16]; are much larger than the values of about 10 kcal/g-mol obtained for noodles in this and in the previous[10] papers. Thus, we may infer that the cooking rate of noodles is perhaps limited by the diffusion rate of

Table 2. Rate parameters in the cooking-rate equation of Eq. (3).

Cooking temp. (°C)	Udon			Somen		
	k_r(cm/min)	k_m(cm²/min)	σ (−)	k_r(cm/min)	k_m(cm²/min)	σ (−)
99.5	6.69×10^{-2}	7.19×10^{-4}	0.0110	4.25×10^{-1}	6.58×10^{-4}	0.0053
90	9.87 ″	4.08 ″	0.0076	11.3 ″	5.28 ″	0.0282
80	10.7 ″	1.80 ″	0.0056	18.7 ″	3.13 ″	0.0117
70	3.32 ″	1.36 ″	0.0094	9.36 ″	2.12 ″	0.0306

Soba			Chuka soba		
k_r(cm/min)	k_m(cm²/min)	σ (−)	k_r(cm/min)	k_m(cm²/min)	σ (−)
9.65×10^{-2}	6.13×10^{-4}	0.0181	8.10×10^{-2}	6.57×10^{-4}	0.0175
20.7 ″	3.29 ″	0.0211	74.6 ″	3.63 ″	0.0023
15.2 ″	1.80 ″	0.0066	56.1 ″	2.36 ″	0.0099
14.0 ″	1.53 ″	0.0141	34.3 ″	1.41 ″	0.0143

water, and the chemical reaction rate of starch components with water is perhaps negligible.

As the accordances of the broken curves with the data in Figs. 9~12 are better than the one of solid curves for the lower cooking ratio region, the model equation of Eq. (3) is better than the simple empirical rate equation of Eq. (2). However, the values of standard deviation for the higher cooking temperature region in Tables 1 and 2 are not too much different, so the simple empirical rate equation of Eq. (2) is more useful than the equation of Eq. (3) for designing and so on in the higher cooking temperature region.

SUMMARY

In order to design and to control automatically various cooking apparatuses, it is necessary to determine the cooking-rate equations. In previous papers, we have studied the cooking rate equations of rice[1–5] and so on [6–10].

In the present paper, we took up the cooking-rate equations of udon, somen, soba and Chuka soba following the one of spagetti and hiyamugi[10]. The cooking rates of noodles were obtained by the weighing method at the cooking temperature of 70~99.5°C.

The cooking-rate equations were postulated in two types; one type is a n-th order empirical rate equation and the other is a semi-theoritical rate equation based on the water-soaking-shell model. The activation energy for the former rate equation was about 13, 8, 11 and 10 kcal/g-mol on the cooking of udon, somen, soba and Chuka soba, respectively. These values are very similar to the values of 9 and 11 kcal/g-mol obtained for spagetti and hiyamugi in the previous paper[10]. From the results, we may deduce that the cooking rate of noodles is perhaps limited by the diffusion rate of water, and the chemical reaction rate of starch components with water is perhaps negligible.

NOTATIONS

C	:	concentration of water in sample, (g-H_2O/cm^3)
k_m	:	diffusion rate parameter of water in noodle's component, (cm^2/min)
k_n	:	rate parameter of n-th order empirical rate equation, (min^{-1})
k_r	:	reaction rate parameter of noodle's component with water, (cm/min)
L	:	length of sample, (cm)
N	:	number of data, (–)
n	:	order of n-th order empirical rate equation, (–)
R and r_c	:	radius of sample and uncooked core, (cm)
T and t	:	cooking temperature, (°K) and (°C)
V	:	volume of sample, (cm^3)
w	:	weight of sample, (g)
x	:	cooking ratio by Eq. (1), (–)
θ	:	cooking time, (min)
σ	:	standard deviation, (–)

Subscripts ;

0 and e : initial and equilibrium states
obs and cal : observed and calculated values

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うどん，そーめん，そばおよび中華そばのクッキング速度式に関する研究

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各種のクッキング装置を，設計，制御化をしていくためにクッキング速度式の設定が必要である。前報において，米[1~5]，その他[6~10]に対し，クッキング速度式に関する研究を行なってきた。

本報では，前報のスパゲティとひやむぎ[10]に引続き，うどん，そーめん，そばおよび中華そばのクッキング速度式に関する研究を行なった。これらのめん類のクッキング速度を，クッキング温度 70～99.5℃において，重量測定法により求めることができた。

クッキング速度式は，2種の形で表わされた。一つの形は，n次の経験的速度式，もう一つの形は，殼状吸水モデルに基づいた半理論的速度式である。前者の速度式に対する活性化エネルギーの値は，うどん，そーめん，そばおよび中華そばに対し，それぞれ約13，8，11および 10 kcal／g−mol となった。これらの値は，前報において，スパゲティとひやむぎに対し得られた値 9 と 11 kacl／g−mol によく似た値である。以上の結果より，めん類のクッキング速度は，おそらく水の拡散速度に律速され，デンプン成分と水の化学的反応速度が無視できるのではないかと推察される。