Studies of Cooking-rate Equations of Potato and Sweet Potato Slices

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INTRODUCTION

In order to design and to control automatically various cooking apparatuses, it is necessary to determine the cooking-rate equations from the experimental data. In a previous paper [1], we have studied the cooking-rate equations of rice, *udon* and *kishimen*. 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 and so on may be represented by a water soaking phenomenon. Then, we postulated the water-soaking-shell models for a sphere, long-cylinder and infinite-slab which have two simple idealized zones, the soaking-shell and the unsoaking-core, and we obtained the cooking-rate equations of rice and so on based on these models.

The measuring of the cooking rates of foods have been followed frequently by a shear press method [2,3,4] and so on. Most of the results reported in the literature were obtained for meat and beans. There is little research concering cooking rate in fruits and vegetables.

In this paper, we studied the measuring method of the cooking rates and the cooking-rate equations of potato and sweet potato which in Japan are very important elements of the diet together with rice and beans. The cooking rates of high water content foods such as potato and so on can not be measured by the weighing method as can be done for rice and so on. The degrees of cooking of potato and sweet potato slices were obtained by measuring the firmness by means of a penetrating method with an impact-penetration tester designed by the authors, and the cooking rates at various temperatures were investigated from the changes in firmness during cooking of the samples.

EXPERIMENTAL

1. Samples

As samples, we used potato and sweet potato slices. These potatoes were bought in the market. Their specific descriptions as well as their producing districts were unknown. Only the center parts of the potatoes were used as samples. They were cut into slices

20x20xd (mm) with a razor knife, and stored for one hour in water at 30°C.

2. Cooking procedure

The sliced sample stored in water at 30°C was put into a sample basket made of a wire net, was entered into hot water and cooked at a desired temperature for a fixed time. The temperature of the hot water was controlled in a water bath by an electric heater.

The cooked sample was then taken out, and poured quickly into an other water bath which was controlled at 30°C, and stored for 1 minute in the water. The surface of the cooled sample in water was wiped by a filter paper, and the firmness of the sample was measured with an impact-penetration tester.

The length, weight and specific gravity was measured by means of a ruler, a chemical balance and a specific gravity bottle, respectively, but these values were not changed appreciably so the experimental results are not shown.

By these method the errors of the observed values remained large. Therefore, we repeated the experiment three times for each run. The observed values used in this paper are the average values.

3. Impact-penetration tester

The impact-penetration tester used in our experiments in shown in Fig.1. The cylinder was made with a stainless steel of 0.6 cm inside diameter and 44 cm length. The side holes of the cylinder can be used to fix a plunger with a inserted stopper. The diameter of the plunger is 0.4 cm, and this legnth can be changed. The 5, 10, 15, 20, 25 and 30 cm length of the plunger were used, and those weights were 14.7 g/15 cm.

(1) Cylinder
(2) Plunger
(3) Stopper
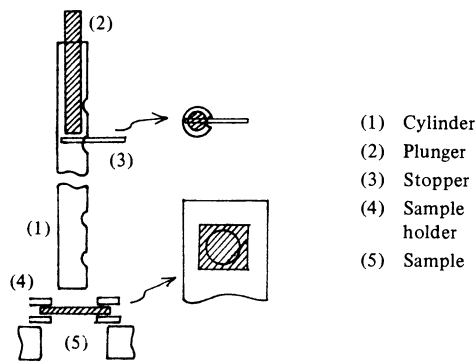(4) Sample holder
(5) Sample

Fig. 1   Impact-penetration tester.

The sample holders made of a acrylate plate of 0.32 cm thickness have respectively one hole of 1.0 cm diameter which can be pass through the plunger without touching each other. The sample is held tightly between the two sample holders.

RESULTS AND DISCUSSION

The relation between the falling height of the plunger h (cm) and the reciprocal of the plunger weight $1/m$ (g^{-1}) for the uncooked sweet potato is shown in Fig. 2. The

experimental data of up to about h=15 cm for each thickness of the sweet potato slices gave straight lines passed a origin. When the values of h were not less than 15 cm, the slopes decreased. The reason is that the frictional resistances of the falling plunger can not be neglected for the data of the longer falling height. Then, we used plungers of various weight at about h=5~15 cm.
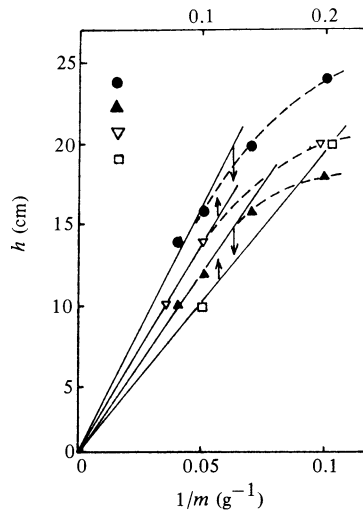

Fig. 2. Relation between the falling height of plunger h and the reciprocal of plunger weight $1/m$ for the uncooked sweet potato slices.

The slopes of the lines in Fig. 2 are proportional to the impact-penetrating energy per cross-sectional area of plunger head E^* (erg·cm^{-2}) as following equations:

$$E^*=mgh/a \qquad\qquad (1)$$
$$h=K(1/m), \qquad K=aE^*/g \qquad\qquad (2)$$

where, a (cm^2) is the cross-sectional area of plunger head, g (cm·sec^{-2}) is the acceleration due to gravity, and K(g·cm) is the impact-penetrating constant obtained from the slopes of the straight line in Fig. 2. The experimental results of the cooking of potato and sweet potato at various cooking temperatures showed a similar relationship as in Fig. 2. The shapes of the samples used for cooking at various cooking temperatures are all similar i.e. 20x20x3 mm.

The relations between the impact-penetrating constant K (g·cm) and the cooking time θ (min) for the cooking of potato and sweet potato slices at cooking temperature 80~99.5°C are shown in Figs. 3~6, respectively.

In Figs. 3~5, the values of K did not give monotonous smooth curves. The reason is that the tissue of potato and sweet potato is converted tightly at the initial time of cooking and is converted softly during the continued time. The degree of the cooking of
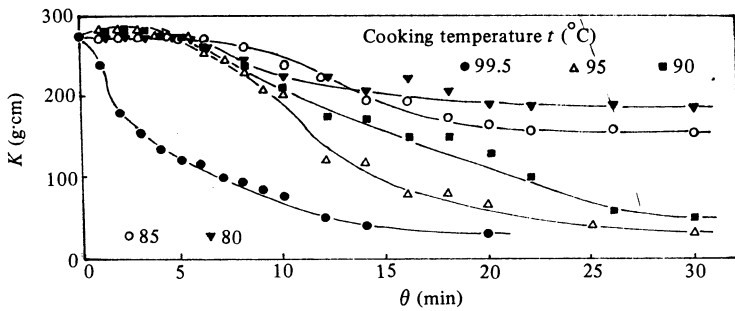
Fig. 3. Relation between the impact-penetrating constant K and the cooking time θ for the cooking of potato slices (20x20x3 mm).
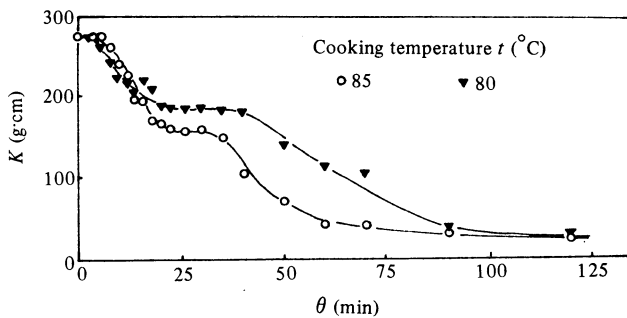

Fig. 4. Relation between the impact-penetrating constant K and the cooking time θ for the cooking of potato slices (cont.).
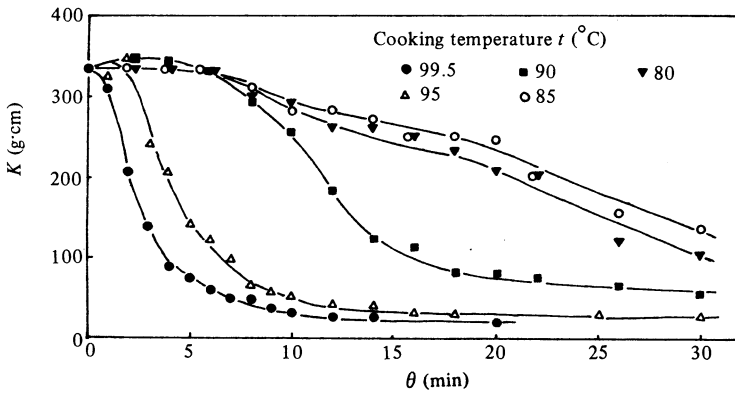

Fig. 5. Relation between the impact-penetrating constant K and the cooking time θ for the cooking of sweet potato slices (20x20x3 mm).
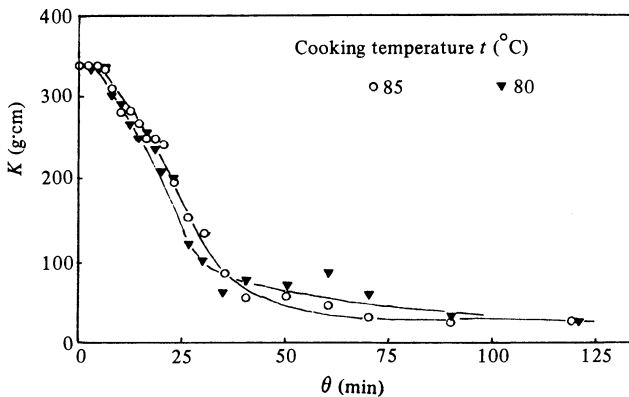
Fig. 6. Relation between the impact-penetrating constant K and the cooking time θ for the cooking of sweet potato slices (cont.).

potato and sweet potato can be correlated to the degree of physical changes as softening, rather than to that of chemical changes as gelatinizating which established faster than the physical changes in the case of the cooking of high water content foods.

The cooking-ratio x (−) can be indicated as follows:

$$x=(K_0-K)/(K_0-K_e) \tag{3}$$

where, K_0 and K_e are the impact-penetrating constants at cooking time zero and the equilibrium points, respectively.

The cooking-rate equation for the S-curve of x vs. θ used the cooking-ratio x in Eq. (3). It is expressed as follows:

$$dx/d\theta = k_{n,\alpha}(1-x)^n(x+\alpha) \tag{4}$$

where, $dx/d\theta$ (min^{-1}) is the cooking rate n (−) and α(−) are the order and the S-shape constant of the rate equations, and $k_{n,\alpha}$ (min^{-1}) is the rate parameter of nth-order and α-value's rate equation.

As the data were scattered, we could not obtain reliably the differentiated values of $dx/d\theta$ from the data x vs. θ by a differential analysis. The numerical integral analysis has to be used for the calculation of n, α and $k_{n,\alpha}$ using a digital computer. Thus, Eq. (4) is non-linear in terms of n, α and $k_{n,\alpha}$, therefore we must calculate these values with a non-linear least square method [5]. The programs for the calculation are nealy same as in the previous paper [6]. The simplified flow chart is shown in Fig. 7.

The initial values of n, α and $k_{n,\alpha}$ for the analysis were obtained by the following integrated equation calculated from Eq. (4).

$$k_{n=1,\alpha} = \frac{1}{(1+\alpha)\theta} \ln \frac{x+\alpha}{(1-x)\alpha} \tag{5}$$

The HITAC 8700−OS7 digital computer in the Computation Center of Hiroshima Univ. was used for these calculations.
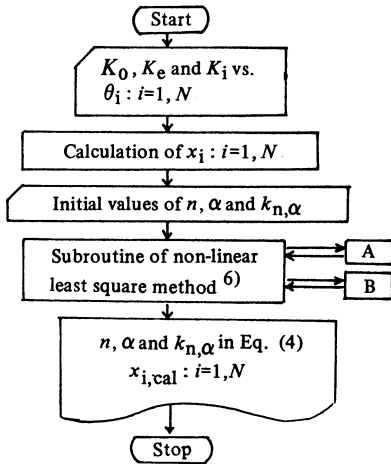
A : Subroutine for calculation of ordinary differential equations[6]

B : Subroutine for calculation of simultaneous linear equations[6]

Fig. 7. Flow chart for calculation of non-linear rate parameters.

The calculated values of α and $k_{n,\alpha}$ fixed $n=1.0$ in Eq. (4) for the cooking of potato and sweet potato slices are listed in Table 1. The calculated values of x for the obtained constants in Table 1 are illustrated by the solid lines in Figs. 8 and 9. The values of α are found to be between 0.02 and 2.5. The values of $k_{n,\alpha}$ which fixed $n=1.0$ and $\alpha=0.01$, 1.0 and 1.0 in Eq. (4) are listed in Table 2. As most of the values of standard deviation σ for fixed $\alpha=0.1$ in Table 2 are smaller in all, the calculated results fixed $\alpha=0.1$ are satisfactory. The calculated values of x for the obtained constants fixed $\alpha=0.1$ in Table 2 are illustrated by the broken lines in Figs. 8 and 9. The calculated results however are not satisfactory enough. The reason is that the potato and the sweet potato have many fibrous tissues which are not homogeneous, so the phenomenon of the cooking are not simple.
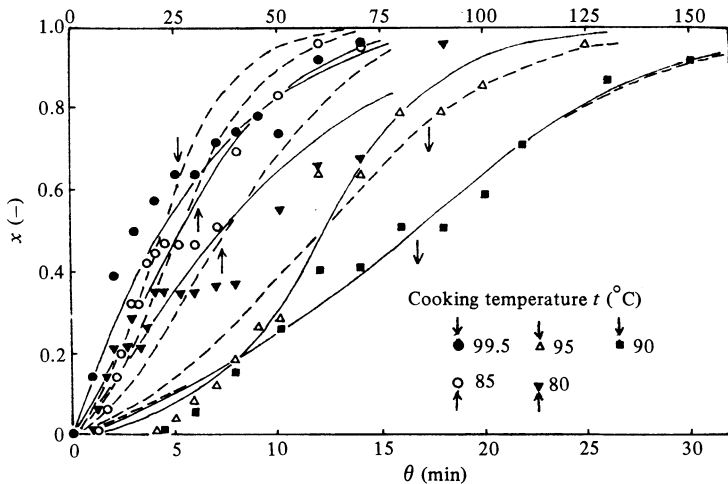

Fig. 8. Relation between the cooking-ratio x and the cooking time θ for the cooking of potato slices (20x20x3 mm)

Calculated values: ——— for $k_{n,\alpha}$ in Table 1
- - - - for $k_{n,\alpha}(\alpha=0.1$ fixed)
in Table.2.

Fig. 9. Relation between the cooking-ratio x and the cooking time θ for the cooking of sweet potato slices (20x20x3 mm)

Calculated values: ——— for $k_{n,\alpha}$ in Table 1
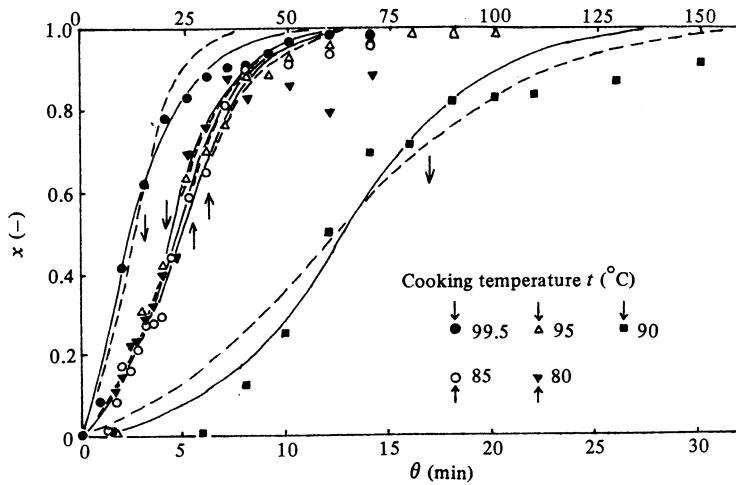- - - - for $k_{n,\alpha}$ (α =0.1 fixed) in Table 2.

Table 1. Calculated values of α and $k_{n,\alpha}$ fixed $n=1.0$ for the cooking of potato and sweet potato slices

Samples (slices)	Cooking temp. t (°C)	Initial values			Number of iteration (–)	Calculated values		
		α (–)	$k_{n,\alpha}$ (min^{-1})	σ		α (–)	$k_{n,\alpha}$ (min^{-1})	σ
Potato	80	0.1	0.05	0.110	15	0.678	0.0193	0.0723
"	85	0.1	0.08	0.0872	15	0.400	0.0400	0.0653
"	90	0.1	0.15	0.0583	13	0.0882	0.146	0.0436
"	95	0.1	0.20	0.0857	15	0.0204	0.317	0.0503
"	99.5	0.1	0.50	0.134	15	2.46	0.0575	0.0685
Sweet potato	80	0.1	0.08	0.112	15	0.0734	0.113	0.0705
"	85	0.1	0.10	0.0530	15	0.0594	0.113	0.0358
"	90	0.1	0.15	0.117	15	0.0236	0.288	0.0683
"	95	0.1	0.50	0.0550	13	0.0873	0.517	0.0542
"	99.5	0.1	0.75	0.0723	15	0.464	0.381	0.0477

where, $\sigma = \left\{ \sum_{i=1}^{n} (x_{obs} - x_{cal})_i^2 / N \right\}^{1/2}$: standard deviation

The values of logarithm of $k_{n,\alpha}$ are plotted in Fig. 10 against the reciprocal of the absolute temperature. Nearly straight lines are obtained. The Arrhenius equation is shown as follows:

$$k_{n,\alpha} = A \exp(-E/R_g T) \tag{6}$$

where, T (°K) is the cooking temperature and R_g=1.987 cal/g-mol·°K is the gas constant. A and E are the constants which are obtained from the slopes and intercepts of the

Table 2. Calculated values of $k_{n,\alpha}$ fixed $n=1.0$ for the cooking of potato and sweet potato slices

Samples (slices)	Cooking temp. t (°C)	Calculated values					
		$\alpha=0.01$ fixed		$\alpha=0.1$ fixed		$\alpha=1.0$ fixed	
		$k_{n,\alpha}(\text{min}^{-1})$	σ	$k_{n,\alpha}(\text{min}^{-1})$	σ	$k_{n,\alpha}(\text{min}^{-1})$	σ
Potato	80	0.110	0.158	0.0572	0.967	0.0144	0.0727
"	85	0.165	0.158	0.0823	0.0866	0.0208	0.0708
"	90	0.271	0.0911	0.139	0.0439	0.0360	0.0947
"	95	0.379	0.0550	0.186	0.0783	0.0452	0.143
"	99.5	1.06	0.202	0.504	0.134	0.138	0.0624
Sweet potato	80	0.205	0.0892	0.0998	0.0711	0.0241	0.0962
"	85	0.188	0.0669	0.0924	0.0405	0.0230	0.0977
"	90	0.356	0.0721	0.178	0.0829	0.0464	0.134
"	95	0.968	0.0848	0.490	0.0544	0.133	0.0931
"	99.5	1.70	0.102	0.838	0.0624	0.224	0.506

straight lines in Fig. 10. The calculated values of A and E in Eq. (6) are listed in Table 3. The values of the activation energy for the cooking of potato and sweet potato slices in Table 3 are in the same order as the values obtained from the cooking of rice[7,8]. The reason is that the cooking of rice, potato and sweet potato slices is similar in physical changes as for swelling and so on, because they are all based on the gelatinization of starch components.
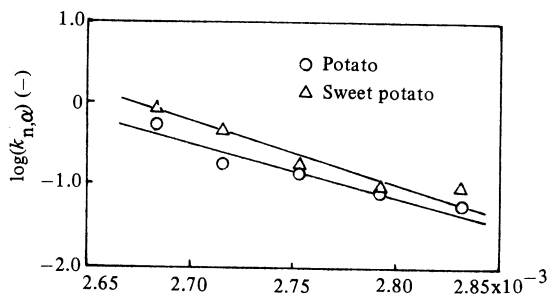
Fig. 10. Arrhenius plots of $k_{n,\alpha}$ fixed $n=1.0$ and $\alpha=0.1$ for the cooking of potato and sweet potato slices.

Table 3. Calculated values of A and E for the cooking of potato and sweet potato slices

Samples (slices)	Cooking temp. t (°C)	Constants in Eq.(6)	
		A (min^{-1})	E(cal/g-mol)
Potato	80~99.5	9.96×10^{16}	29.6×10^3
Sweet potato	80~99.5	7.33×10^{19}	34.1×10^3

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SUMMARY

In order to design and to control various cooking apparatuses, it is necessary to measure the cooking rate and to determine the cooking-rate equations. In a previous paper[1], we studied the cooking-rate equations of rice, *udon* and *kishimen* which are low water content foods using the weighing method for measuring the cooking rates.

In the present paper, we studied the measuring methods of the cooking rate and the cooking-rate equations of potato and sweet potato slices which are high water content foods. The results of this investigations are as follows.

(1) The impact-penetration method which is simple and useful for measurement the cooking-rate equations of high water content foods was used.

(2) The following cooking-rate equation postulated as simple rate equation with a S-shape constant $\alpha(-)$ was adopted with satisfaction for the cooking of potato and sweet potato slices:

$$dx/d\theta = k_{n,\alpha} (1-x)^n (x+\alpha)$$

where, x $(-)$ is the cooking-ratio, θ (min) is the cooking time, and n $(-)$, α $(-)$ and $k_{n,\alpha}$ (min) are the constants. The values of α in the equation fixed $n=1.0$ showed about 0.1 for the used samples.

NOTATIONS

A :   Arrhenius constant (min^{-1})
a :   cross-sectional area of plunger (cm^2)
E :   activation energy (cal/g-mol)
E^* :   impact-penetrating energy (erg/cm^2)
g :   acceleration due to gravity (cm/sec^2)
h :   falling height of plunger (cm)
K :   impact-penetrating constant (g·cm)
$k_{n,\alpha}$:   rate parameter of nth-order and α-value's rate equation (min^{-1})
m :   weight of plunger (g)
n :   order of rate equation $(-)$
R_g :   gas constant (cal/g-mol·°K)
T and t :   cooking temperature (°K) and (°C)
x :   cooking - ratio $(-)$, $dx/d\theta$: cooking rate (min^{-1})
α :   S-shape constant of rate equation $(-)$
θ :   cooking time (min)
Subscripts:
0 and e : initial and equilibrium states

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ジャガイモおよびサツマイモ薄片の
蒸煮速度式に関する研究

久保田清・大下恵子・細川嘉彦・鈴木寛一・保坂秀明

　各種食品の蒸煮装置を設計し，制御化などを行なっていくためには，蒸煮速度を測定し，簡単な速度式を設定していくことが必要である。既報[1]において，低含水率の食品である米，うどんおよびきしめんの蒸煮速度を重量法により求め，蒸煮速度式の設定に関する研究を行なってきた。

　本研究は，ジャガイモおよびサツマイモを例として，高含水率の食品の場合の蒸煮速度の測定法ならびに速度式の設定に関する研究を行なったものである。

　(1)　高含水率の食品の蒸煮速度の測定に有用な衝撃貫通試験法を提案した。

　(2)　S型形状係数を含む簡単な速度式として提出した次に示す蒸煮速度式が，ジャガイモおよびサツマイモ薄片の蒸煮に対して利用できた。$dx/d\theta = k_{n,\alpha}(1-x)^n(x+\alpha)$　ここで，x（一）は蒸煮率，θ（min）は蒸煮時間であり，n（一），α（一）および$k_{n,\alpha}$（min^{-1}）は定数である。上式において$n=1.0$とした場合のαの値は，本実験試料に対してほぼ0.1となった。