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Studies on the Rheological Properties of Wheat Flour Paste and Cooked Udon

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(Figs. 1—9, Tables 1—2)

INTRODUCTION

In order to design and to control automatically various cooking apparatuses, it is necessary to determine the physical properties such as rheological values and cooking-rate equations from experimental data.

In previous papers, we have studied the rheological equations by using a capillary tube viscometer for fluid foods such as starch solutions[1-4], skim milk solutions[5,6] and so on[7-10]. Furthermore, we have studied a simple, convenient rheological instrument for the measurement of the rheological properties of solid foods such as cooked vegetables[11-13], agar contained model gel foods[14], cooked soybean[15] and so on.

In the present paper, we studied the simple convenient textual instrument for the measurement of the rheological properties of wheat flour paste and the paste foods.

The degrees of cooking for noodles such as udon, soba[16], spaghetti, hiyamugi[17,18], soybean[19], red bean[20] and so on have been measured by means of the weighing method, because the degree of cooking of low water content foods can be represented as a water soaking phenomenon. The degree of cooking of root vegetables such as potatoes[11,13], radish, carrot[12] and so on which are foods with a high water content could not be measured by the weighing method, so we had to use the rheological method.

The values of order n in the nth-order rate equation[21,22] on the soaking and cooking of soybean by the weighing method are nearly one, but the rheological method they are nearly five[15]. From these results, we can induce that the cooking equation of noodles by the rheological data differs from the one obtained by the weighing data[16-18]. Therefore, in this paper, we studied the cooking-rate equations of udon, which is a most popular food element in Japan by using the simple convenient textual instrument[15]. The cooking-rate equation obtained from the rheological data could not be postulated as a simple empirical rate equation, however the optimum cooking time could be obtained from these data.

TUBULAR TYPE INSTRUMENT FOR PASTE FOODS

1. Apparatus

Rheological properties of fluid and paste food have been evaluated, usually by a capillary tube viscometer and so on[1-4,7,23,24]. In previous papers, we studies a simple convenient and cheap rheological instrument. However, this instrument can be used for measuring the rheological data of fluid foods only. Therefore, we had to design a new tubular type instrument which that could be used for paste foods. This rheological instrument is shown in Fig. 1.

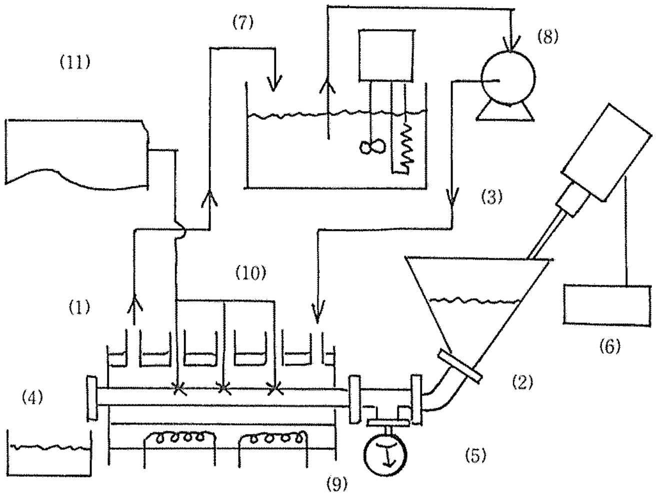

Fig. 1 Tubular type instrument for paste foods
(1) tube, (2) Mohono pump, (3) sample hopper, (4) receiver, (5) diaphragmatic pressure gauge, (5) rotation indicator, (7) thermo-heated water bath, (8) pump, (9) heater, (10) thermocouple, (11) voltage recorder

The rheological and textual properties can be obtained by using a General Foods Texturometer[25], The Instron Universal Testing Machine[26], Rheometer[27] and so on. These instruments are very useful for obtaining the data of the textural properties such as compression, extension and so on, but they are very expensive when we want to obtain the rough parameters which are operating properties in the transforming process of foods such as extrusion cooking and so on[28-31].

The new tubular type instrument used in our experiments is shown in Fig. 1. This apparatus is useful for the measuring of the rheological data of sol, gel, paste, and soft solid foods and for the cooking data of paste and so on.

All the experiments were made with a copper tube of 0.7 cm inside diameter, 0.9 cm outside diameter and 75.0 cm length. At the inlet side of the tube, the raw materials of wheat paste can be put in by using a Mohono pump (Type: 3NVL06, Heishin Soubi Co. Ltd., Japan) connected to a sample hopper. The pressure at the inlet side can be measured by using diaphragmatic pressure gauge. At the outlet side of the tube, the samples can be received with a receiver. The pressure at the outlet side was the same as the atmosphere pressure.

All measurements were made at constant flow rates by using a Mohono pump which had a rotation indicator. The flow rates of the samples were measured from the weight of received samples at constant time.

The wall surface temperature of the copper tube was held at a constant temperature by using constant temperature water from a thermo-heated water bath. The temperatures of the samples through the tube were measured by means of a chromel-alumel thermocouple which has connected to a voltage recorder (Type: 3056-22, Yokogawa Hokushin Denki Co. Ltd., Japan).

2. Material

The wheat flour paste used in these studies was prepared from wheat flour (Churikiko-Yuki, Nissin Seifun Co. Ltd., Japan) with an equivalent weight of distilled water. The paste was prepared under vigorus mixing for 10 minutes by using a paste mixer (Type: Cake Master, MK-710, Matsushita Denki Sangyo Co. Ltd., Japan). The mixed paste was used after 15 minutes preservation at room temperature.

EQUATIONS FOR TUBULAR TYPE INSTRUMENT

1. Flow and heat transfer equations of power-law flow fluid or paste are expressed as follows[1,2,32].

$$dP/dL = -(4/g_cD)\,[8(m+3)KQ/\pi D^3]^{1/m} \tag{1}$$

$$dT/dL = (\pi D/\rho C_pF)\;U\,(T_w-T) \tag{2}$$

where, $K = B\exp(C/T)$ (3)

$$U = (1.75)(\lambda/D)[\,(m+3)\rho C_pQ/4\lambda L_t]^{1/3}(J/J_w)^{0.14} \tag{4}$$

$$J = g_c[\,(m+3)K/4]^{1/m}8^{(1/m)-1} \tag{5}$$

where, P(g$_f$/cm^2(gauge)) and T(°K) are the pressure and the temperature at the length L(cm) of the tube. D(cm) and L_t(cm) are the inside diameter and the length of the tube. Q(cm^3/sec) is the flow rate of fluids or paste and U(cal/cm$^2\cdot$sec$\cdot$°C) is the over-all heat transfer coefficient. ρ(g/cm^3), C_p(cal/g$\cdot$°C), λ(cal/cm$\cdot$sec$\cdot$°C), K(g^m/cm$^m\cdot$sec^{2m-1}) and $m(-)$ are the density, the specific heat, the thermal conductivity, the fluid consistency index and the flow behavior index of fluids or pastes. g_c(g$\cdot$cm/g$_f\cdot$sec^2) is the gravitational conversion factor. Subscript of w shows the values at the wall of tube.

2. Transforming-rate equations

If the change of the value of the rheological parameter K in Eq.(3) can be observed on the heating of fluids and differs greatly from the general viscoelastic change related temperature, we may infer that the change occurred in the chemical reaction, cooking and so on. The transforming-rate equations are expressed as follows[21,22].

nth-order rate equation:

$$dx/d\theta = k\,(1-x)^n \tag{6}$$

S-shape rate equation:

$$dx/d\theta = k\,(1-x)^n(x+\alpha) \tag{7}$$

where, $x = |B - B_0| \;/\; |B_e - B_0|$ (8)

$$\theta = \pi D^2L/4Q \tag{9}$$

where, $x(-)$ and θ(sec) are the transforming ratio and the time, respectively. Subscripts 0 and e show the initial and equilibrium states. k, n and α are the rate parameters which can be obtained from the experimental data of x vs. θ.

The value of k can be indicated by using the following Arrhenius equation for the chemical reaction, cooking and so on.

$$k = A \exp(-E/R_g T) \tag{10}$$

where, T(°K) is the temperature and $R_g = 1.987$ cal/g-mol·°K is the gas constant. A and E are the frequency factor and the activation energy which can be obtained from the data.

In our experiments, we considered that wheat starch could not be gelatinized, because the temperature of the samples was not higher than that of the gelatinization start point of the starch. Therefore, we do not take in account the Eqs.(6)-(10) respecting cooking and so on, in this study. We consider the rheological properties only. The gelatinization studies of rice and potato starches were examined in a previous paper[3] where we used the Eqs.(6) and (10).

3. Calculation method of parameters.

The experimental data were generally obtained as integral data of P, T and x vs. L or θ. Therefore, the numerical integral method offers the best results when a digital electronic computer is used. The equations were integrated numerically using the Runge-Kutta-Gill method, and the parameters were calculated by a non-linear least square method[33] which was made by using the digital electronic computer of the Computation Center at Nagoya University. The values of the following standard deviation $\sigma(-)$ for the variables P and T were minimized.

$$\sigma = \left\{ \sum_{i=1}^{N} \left[(P_{obs} - P_{cal})^2 + (T_{obs} - T_{cal})^2 \right]_i / N \right\}^{0.5} \tag{11}$$

We used the digital electronic computer of the Computation Center at Hiroshima University.

TEXTURAL INSTRUMENT FOR UDON

1. Apparatus

The transforming rates, such as the soaking and the cooking rates of low water content foods have been measured by means of a weighing method. In fact the degree can be considered as a water soaking phenomenon. Therefore, the cooking rates of the noodles[16-18] were measured by means of this method. The cooking-rate equations of the noodles[16,17] were posturated in two types; one type is a nth order empirical rate equation and the other is a semi-theoretical rate equation based on the water-soaking-shell model. However, these equations and data measured by means of the weighing method could not obtained the optimal cooking time.

For the measurements of the textural properties of the noodles, the various parameters such as hardness, cohesiveness, elasticity, adhesiveness, brittleness, chewiness, gumminess and so on have been measured by means of the instruments of Rheometer[34,35], Senimeter[36,37], Texturometer[38] and so on. These, instruments are very useful to determine the various textural properties, but are very expensive if we want to obtain the rough value of the optimal operating time on the transforming process. Therefore, we used a simple textural instrument which could be used for cooked soybean[15]. In the test for the noodles, the crosshead and the sample support plate used for the hard solid foods must be changed. With the instrument shown in Figs. 2-4, we can obtain the shear properties of noodles.

The behavior of noodles under the test is one of the easiest yet most important mechanical tests for obtaining the textural properties on the transforming processes. The test requires a sample holder which can loosely set the soft sample and the suitable crosshead plate that can cut at the pressing section. If the holder and the crosshead plate are not suitable, the sample is bent by

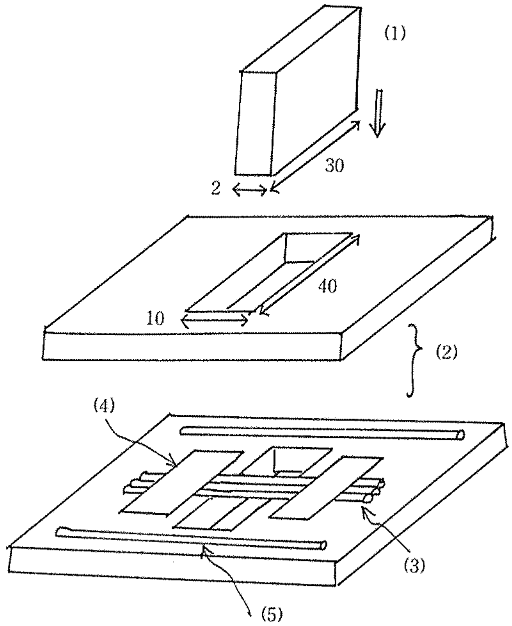

Fig. 2 Instruments for shearing test (Method A)

(1) crosshead plate, (2) sample holder, (3) sample, (4) rubbered cloth tape, (5) silicone rubber tube

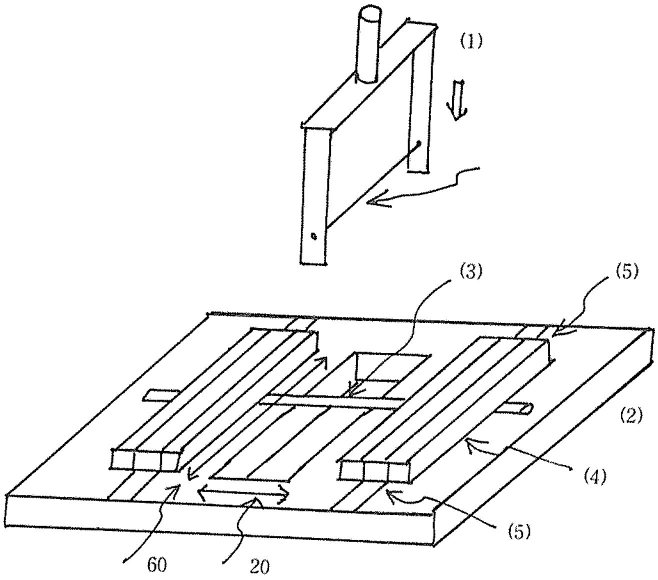

Fig. 3 Instruments for shearing test (Method B)

(1) crosshead wire, (2) sample holder, (3) sample, (4) foam polystyrol plate, (5) cellophane tape and gripper

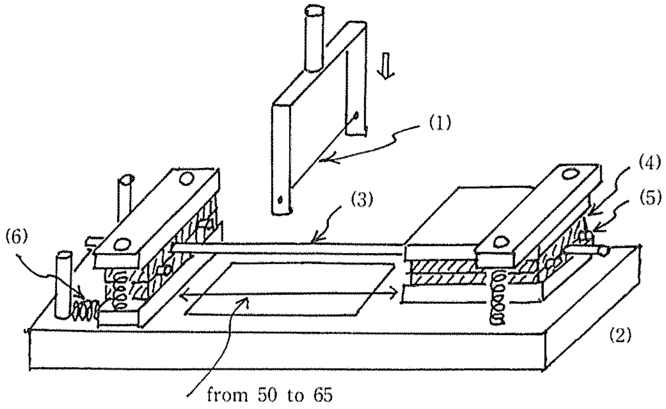

Fig. 4 Instruments for shearing test (Method C)
(1) crosshead wire, (2) sample holder, (3) sample, (4) soft sponge brush, (5) soft spring, (6) silicone rubber tube

the pressing of the crosshead plate and cut at the attach section of the holder side. Therefore, we tested various types of crosshead plates and holders for the shearing test of noodles as shown in Figs. 2-4.

A 5 kg load cell (Type: 9E01-L3, Nippon Denki Sanei Co. Ltd., Japan) was set under the holder. The load cell was connected to a dynamic strain amplifier (Type: 6M62, Nippon Denki Sanei Co. Ltd., Japan), and finally voltage recorder (Type: 3056-22, Yokogawa Hokushin Denki Co. Ltd., Japan). The force-time relationship of samples can be obtained on the recorder. The crosshead plate which could be moved at constant rate, was connected to the driving system as shown in the previous paper[15]. The crosshead speed was 2.65 cm/min.

A crosshead plate and a sample holder of Method A are shown in Fig. 2. Three noodles were set on the holder which made acrylic resin plate by using the rubbered cloth tape. Two silicon rubber tubes were used to make the interval of the two holder plates as shown in Fig. 2. When the diameter of the noodles changes, the tubes must be changed according to the diameter. In this study, we used two tubes of 2 mm inside diameter and 4 mm outside diameter. After the noodles were set on one side holder plate, the two holder plates were coupled by using two rubber thread rings.

When crosshead plates of 5 and 10 mm width were used, the sample was bent by the pressing of the plate and cut at the attach section of the holder side. That is why we had to use a plate of 2 mm width.

A crosshead wire and a sample holder of Method B are shown in Fig. 3. One noodle was set on the holder which made acrylic resin plate by using the foam polystyrol plate. The sample can be loosely set by using the foam polystyrol plate which has a frictional surface. In this study, we used a cellophane tape and a gripper that pressed the foam and resin plates.

In this study, we used a crosshead made of a stainless steel wire, as shown in Fig. 3. When wire of 1 mm diameter were used, the sample was bent by the wire and cut at the attach section of the holder side. So, we used the wire of 0.3 mm diameter. When the three noodles were used on this wire crosshead, the samples could not cut at the same time. Therefore, one noodle was set on the holder.

The sample holder using the test of Method C is shown in Fig. 4. The crosshead wire is the same to the one of Fig. 3. One noodle was set into the two soft sponge brush holders which made foam urethane resin. The sample can be loosely set by using the soft sponge brush holders which have frictional surfaces, and the soft springs which pressed two foam holders. In this study, we used two springs which loosely pulled the sample.

2. Materials

The noodles used as sample were bought in the market. The commercial names of udon (Japanese wheat noodle) used in this studies are Motohachi Sanuki Udon (Nakano Shokuhin Co., Kagawa) and Koukyumen Udon (Hata Seimen Co., Hiroshima). The weight, length and diameter of one piece of these udons were 1.066 g, 24.0 cm, 0.16:0.27 cm and 1.420 g, 24.6 cm, 0.19:0.28 cm, respectively. The suitable cooking times of these udons according to the makers remarks are pointed out at 10 and 20 minutes, respectively.

3. Cooking procedure

The noodles were put into a pot of 5000 cc boiling water for a fixed time. The temperature of the hot water for the cooking was 99.5°C. The cooked noodles were poured out quickly into water of 20°C for 0.5 minute in order to stop the cooking process. In each experiment, we used three noodles, and the observed values used in this paper are average values. The surfaces of the cooked samples were wiped quickly with a filter paper, and then were used for obtaining the rheological properties. The force-time relationships of samples were observed by using the three type instruments shown in Figs. 2-4.

RESULTS AND DISCUSSION

1. Flow of wheat flour paste

The rheological data of wheat flour paste were observed by using the instrument shown in Fig. 1. In this study, the temperature of samples was not higher than the temperature of the gelatinization start point of the starch.

The experimental data were obtained as integral data of pressure P and temperature T vs. fixed length of tube L. The data are tabulated in Table 1. Subscripts of s and t show the values at the inlet and outlet sides of the tube.

Table 1 Experimental conditions and calculated results

Run	T_w(°K)	Q(cm^3/sec)	P_s(g$_f$/cm^2 (gauge))	T_s(°K)	T_t(°K)	$(P_t)_{cal2}$	$(T_t)_{cal2}$
1	313.2	0.693	700	294	311	32	310
2	313.2	0.401	500	295	312	5	312
3	322.7	0.693	600	297	320	−25	318
4	322.7	0.401	500	296	321	36	320

where, P_t = 0.0 g$_f$/cm^2(gauge)

Table 2 Calculated parameters

Cal.	B	C(°K)	m(—)	σ(—)
1	116.0	2013	1.99	18.06
2	116.7	2003	2.0*	19.19

where, B : (g^m/cm^m·sec^{2m-1})

* : fixed value

By applying the data in Table 1, it is possible to calculate the rheological parameters B, C and m in Eqs.(1)-(5). The density of the paste was measured by using a pycnometer, and we obtained ρ = 1.155 g/cm^3. We used the values of C_p = 0.693 cal/g·°C and λ = 0.00111 cal/cm·sec·°C which were obtained from the previous data[39].

The calculated values of parameters are listed in Table 2. The values of Cal.1 are the best results in the calculated results for initial value fixed as $m=1$, 2 and 3. The values of Cal.2 are the results which fixed $m=2.0$. The calculated values by using the parameters of Cal.2 are tabulated in Table 1. The value of m is nearly by the same as in the previous papers41,42).

The value of the coefficient in Eq.(4) has been reported to be 1.7532). If this value is not known, we must obtain it from the data. When this value includes A^* in the parameters, the calculated parameters and the standard deviation are obtained as $A^*=1.41$, $B=115.2$ $\mathrm{g}^m/\mathrm{cm}^m \cdot \mathrm{sec}^{2m-1}$, $C=2010$°K, $m=1.99$ and $\sigma=18.22$. The calculated value of A^* is not different from the reported value. Thus, we may infer that the flow behavior of the paste in this study may be approximated by using Eqs.(1)-(5).

We tried a few experiments to obtain the data on the temperature at which wheat starch can be gelatinized, but the gelatinized paste flew out intermittently. From this, we may deduce that the temperature of the paste increased quickly and the gelatinized paste adhered to the inner surface of the copper tube. If we can obtain the data on the temperature at which the wheat starch gelatinizes by using this instrument, the cooking-rate equation of the wheat flour paste can be perhaps obtained by using Eq.(6) or (7).

2. Rheological properties of cooked udon

The relations between the force F(dyn) and time t(sec) of cooked udon were obtained by using the three instruments shown in Figs. 2-4. The force-deformation or the stress-strain data can be obtained easily from the relations of the compression test15), but they can not be obtained from the shearing test. Therefore, the force-time relationships were obtained. But the shearing test for raw udon was difficult to perform with our instruments, because the samples could not be cut at the same point.

The cutting energy for the force-time data can be related to the following quasi-energy variable.

$$G_c = F_c t_c \tag{12}$$

where, G_c(dyn·sec) is cutting quasi-energy.

The subscript of c show the values at the cutting point.

The experimental results by using three instruments are shown in Figs. 5-9. The values of F, t and G for Sanuki and Koukyo udon have their minimum point at nearly 10 and 20 minutes, respectively. Especially, the values of G are clear. These minimum points are the same as the cooking times by the maker. The curves for the longer cooking times are much more complicated, due to the soaking and dissoluting phenomena.

The results of Method C gave better results than the other methods, but the instrument is more complicated. Method A or B are more useful since they are much simpler method.

From these results, we may conclude that the cooking data of udon by the rheological method differ from those obtained by the weighing method which could be postulated as a simple 2nd-order rate equation16,17). While the cooking-rate equation by the rheological data can not be postulated as a simple rate equation, not only because the relations between the cutting force F_c, time t_c, quasi-energy G_c and the cooking time θ are very complicated, but especially because the values at the initial point are distinctly higher than the one at the other points. However, the optimum cooking time can be discussed from these data.

The cutting behavior of noodles is one of the important mechanical tests for researching the

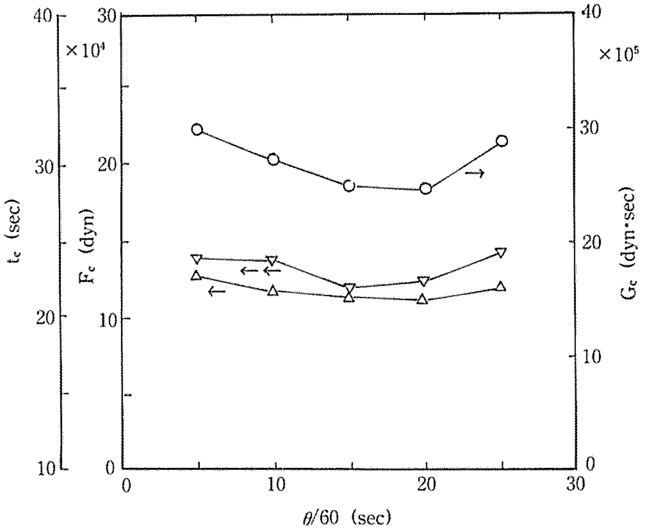

Fig. 5 Relations between the cutting force F_c, time t_c and quasi-energy G_c and the cooking time θ
Sample: Koukyu udon, Method A

textural properties on the transforming process. The cutting behavior of udon in the shearing test agreed fairly well with the cutting behavior of spaghetti in the tensile test by Hara *et al.*[37]. If these cutting behaviors can be obtained more easily by using a handy type spring-balance which can mark the point of the maximum compressed or tensiled force, this method would be economic for finding the rough value of the optimal operating time on the transforming process.

This paper was presented on the occasion of the Okayama (17, July, 1985) and Osaka (27, March, 1986) Meetings of the Society of Chemical Engineers of Japan.

This paper was partly presented on the occasion of the Kyoto symposium (9, Nov., 1985)

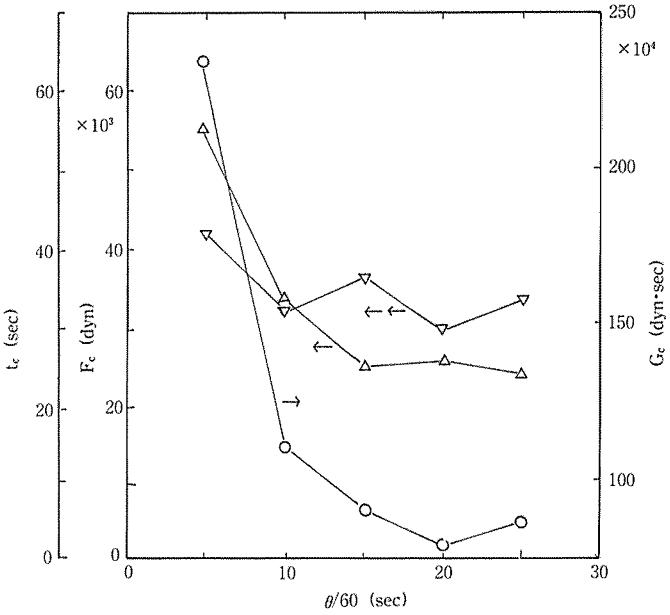

Fig. 6 Relations between the cutting force F_c, time t_c and quasi-energy G_c and the cooking time θ
Sample: Koukyu udon, Method B

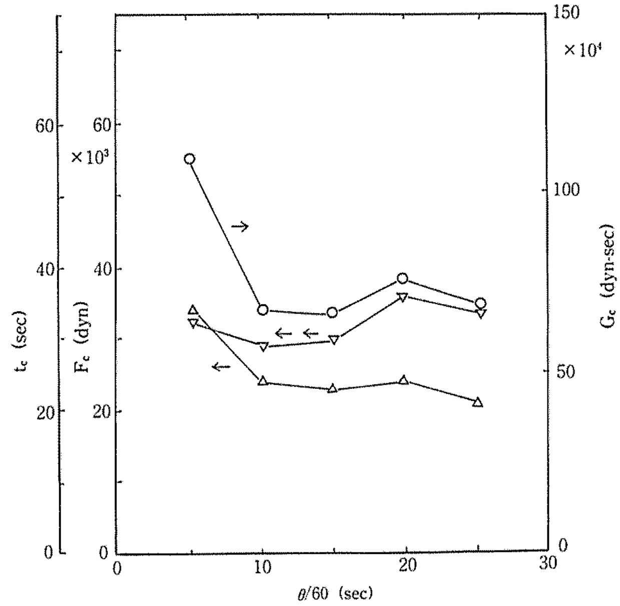

Fig. 7 Relations between the cutting force F_c, time t_c and quasi-energy G_c and the cooking time θ

Sample: Sanuki udon, Method B

together with the summary reports[42,43].

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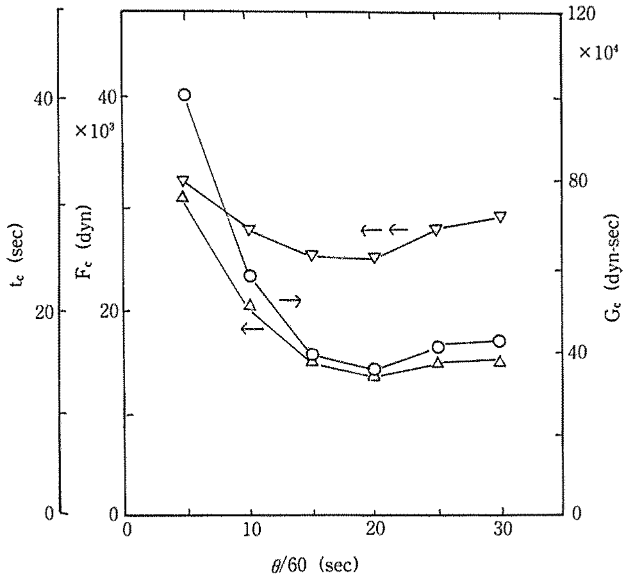

Fig. 8 Relations between the cutting force F_c, time t_c and quasi-energy G_c and the cooking time θ

Sample: Koukyu udon, Method C

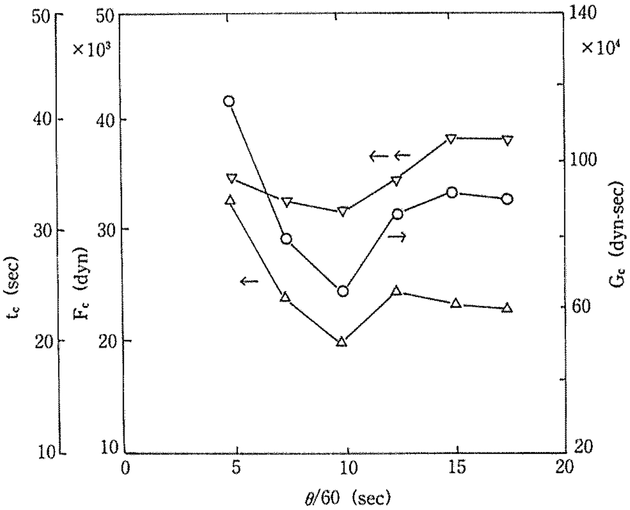

Fig. 9 Relations between the cutting force F_c, time t_c and quasi-energy G_c and the cooking time θ

Sample: Sanuki udon, Method C

SUMMARY

In order to design and to control automatically various cooking apparatuses[44] such as a batch tank, a continuous belt containing tank, a continuous tube apparatuses and so on, it is necessary to measure the rheological properties, to determine the cooking-rate equation and to obtain the optimal operating time.

In previous papers[1-10], we have studied the rheological properties of liquid foods. In this paper, we studied a tubular type instrument for paste foods, an instrument that can be used for measuring the rheological properties and for determining the cooking-rate equation. We could define the rheological equation of wheat flour paste (dough).

In previous papers[16-18], we have studied the cooking-rate equation of noodles by the weighing method. Now, in this paper, we could determine the optimal operating time in the rheological method.

NOTATION

A : frequency factor (sec^{-1})
A^* : constant 1.75 in Eq.(4)
B, C : constant in Eq.(3)
C_p : specific heat (cal/g·°C)
D : inside diameter of tube (cm)
E : activation energy (cal/g-mol)

F : cutting force of shearing test (dyn)

G : cutting quasi-energy of shearing test (dyn·sec)

g_c : gravitational conversion factor ($g \cdot cm/g_f \cdot sec$)

J : value obtained from Eq.(5)

K : fluid consistency index ($g^m/cm^m \cdot sec^{2m-1}$)

k : rate parameter of empirical rate equations (sec^{-1})

L : length of tube (cm)

m : flow behavior index (—)

N : number of data (—)

n : order of empirical rate equations (—)

P : pressure (g_f/cm^2(gauge))

Q : flow rate (cm^3/sec)

R_g : gas constant (cal/g-mol·°K)

T : temperature (°K)

t : cutting time of shearing test (sec)

U : over-all heat transfer coefficient ($cal/cm^2 \cdot sec \cdot °C$)

x : transforming ratio (—)

α : parameter in Eq.(7)

θ : time (sec)

λ : thermal conductivity (cal/cm·sec·°C)

ρ : density (g/cm^3)

σ : standard deviation (—)

Subscripts :

0 and e : initial and equilibrium states

obs and cal : observal and calculation values

s and t : inlet and outlet sides

w : at wall of tube

c : cutting point

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小麦粉ペーストおよびうどんのクッキングにおけるレオロジー特性に関する研究

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回分槽型，連続ベルト槽型，連続管型などの各種クッキング装置を，設計，制御化していくために[44]，レオロジー特性の測定，クッキング速度式の設定および最適操作時間を得ることなどの研究が必要となる。

前報[1-10]において，液状食品のレオロジー特性について研究してきた。本報では，ペースト状食品のレオロジー特性の測定とクッキング速度式の設定に対して有用となる管型装置を製作し，小麦粉ペースト（ドウ）のレオロジー特性を求めることができた。

また，前報[16-18]において，重量測定法によってめん類のクッキング速度式の設定に関する研究を行ってきた。本報では，レオロジー特性測定法によって最適操作時間を求める方法について検討を行った。