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Studies on the Flow Behaviour in the Low Flow Region of Soy Sauce (Shoyu) and Worcester Sauce

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(Fig. 1–5; Table 1–5)

For a clear understanding of the pertinent transport processes in operations, proper design of equipment and operation of unit processes at optimum conditions, the knowledge of rheological properties of fluid foods and the relevant viscosity functions as well as their dependence on the temperature is unquestionably essential[1,2,3,4]. This laboratory has already undertaken in the past the study of the flow porperties of certain products such as starch solutions[5–7], milk solutions[8], vegetable oils[9], tomato products and others[10,11,12].

Soy sauce (Shoyu) and Worcester sauce (Sauce) are both very popular products in Japan. There is a large range of these sauces which vary from one company to another as well as within one factory itself. However, everywhere the principles of production are basically the same, only a minor variation in the details makes them different. Common as this products may be, not much literature is available in connection with their most important physical parameters[13,14,15].

For this paper we have taken one typical sample of each product from the market shelves and have determined the variation of density in respect to the temperature. Further on, the flow behaviour of these products was investigated at the low flow region with the objective to establish the viscosity function at the different temperatures.

MATERIALS AND METHODS

1. Materials

The shoyu sample was taken from a 1000 ml bottle on sale at the market. The manufacture's description of the product as explained on the label was as follows:

"Koikuchi Shoyu" : raw materials (soy beans, wheat flour, salt, defatted processed soy beans, alcohol).

The sauce sample sold in bottles of 900 ml had the following description on the label:

"Usuta Sousu": raw materials (vegetables, fruits, vinager, saccharoids, sugar, glucose, salt, spice, caramel, chemical seasoning).

The determination of the solids for Shoyu and Sauce gave results of 32.5% and 39.2% respectively, on the avarage.

In the use of these samples, both for the density determination as well as for the flow behaviour, no special manipulation were applied at all, apart from simple mixing in order to ensure the homegeneity of the sample.

2. Density determination

This was done in the normal way making use of the pycnometer. The only extra care taken was to make sure that the sample stayed in a water-bath of relevant temperature for a period of not less than 30 minutes in order to obtain temperature equilibration.

3. Flow behaviour investigation

The design of the apparatus used for the investigation of the flow behaviour of these products is the same as the one used in the previous papers[5] and is given in Fig. 1. It consists essentially of two reservours connected by a capillary tube, these two are in turn connected to a vacuum pump.

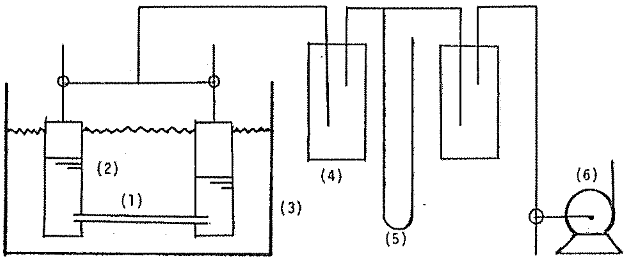

Fig.1

Experimental apparatus used for determination of viscosity of Shoyu and Sauce.
1. Capillary tube 2. Sample chamber
3. Water-bath 4. Buffer container
5. Mercury manometer 6. Vacuum pump

All the experimentations were performed by means of a carefully calibrated glass capillary tube, the inside diameter of which was determined by filling it with mercury. From the mass of the mercury that could thoroughly fill the tube, the inside diameter could be ascertained by calculation. In this case the capillary used had an inside diameter of 1.492 cm with a lenght of 26.23 cm. The two cylindrical chambers used as sample feeders had a capacity of 500 cm^3 each.

The driving force in this experiment, namely the pressure difference between the sample feeders was introduced by means of a vacuum pump and the extent of the pressure developed was measured by a mercury manometer.

The assemblage of the sample feeder and the capillary tube were placed in a water-bath which would be manipulated to maintain the desired temperature for investigation. In order to ensure the temperature equibrium between the sample and the bath an allowance of 30 minutes was made before the start of the experiment.

For temperatures ranging from 5°C to 50°C, the volumetric rates were determined by observing the time it takes to deliver a fixed quantity of the sample fluid.

Each time, the ambient temperatures were recorded in order correct the manometric presure recordings.

FLOW EQUATION

The flow equation for many non-Newtownian fluid foods can be expressed as follows:

$$\gamma = (1/K)(g_c\tau - g_c\tau_y)^n \quad (1)$$

where, γ and τ are the shear rate (sec^{-1}) and shear stress (g_f/cm^2); g_c is the gravitational factor ($g \cdot cm/g_f \cdot sec^2$); K, τ_y and n are parameters that can be obtained from flow behaviour experiments.

In a circular tube of a radius r_w (cm) and a length L (cm), Eq. (1) is reduced down to Eq. (2) through the analysis below:

$$Q = \left\{2\pi g_c^n r_w^3 (\tau_w - \tau_Y)^{n+1} / K\tau_w^3\right\} \left\{(\tau_0 - \tau_Y)^2 / 2(n+3) + \tau_Y(\tau_w - \tau_Y)/(n+2) + \tau_Y^2/2(n+1)\right\} \quad (2)$$

$$\tau_w = r_w \Delta P / 2L \quad (3)$$

where, Q and τ_w are the volumetric flow rate of the sample fluid (cm^3/sec) and the shear stress at the wall (g_f/cm^2) respectively, and ΔP is the pressure difference in the tube (g_f/cm^2).

In respect to power-law fluid in which $\tau_y = 0$ and for Newtonian fluids where $n = 1$ and $\tau_y = 0$, Eq. (1) can be expressed respectively as below:

$$Q = \pi g_c^n r_w^3 \tau_w^n / (n+3) K \quad (4)$$

$$Q = \pi g_c r_w^3 \tau_w / 4K \quad (5)$$

In Eq. (4), the flow types given by $n > 1$ and $n < 1$ are usually called pseudoplastic and dilatant fluids respectively.

The pressure difference ΔP in Eq.(3) is the final value obtained after the observed manometric pressure reading has been corrected using the equation given here.

$$\Delta P = \Delta P_m - m_p \rho \bar{u}^2 / g_c \quad (6)$$

where, ΔP_m is the pressure difference (g_f/cm^2) in the manometer, $\bar{u}$ and ρ are the mean velocity (cm/sec) and density (g/cm^3) of the flowing fluid.

The correction method mentioned above is usually called Hargenbach correction. m_p is the Hargenbach coefficient (–). The correction is applied in order to compensate for pressure drop losses resulting from contraction and enlargement effects at the sample feeder and the capiliary tube assembly. The value of this factor can be ascertained by using standard fluids of known viscosity. In our case, water and water-glycerin solutions were used.

The parameters n, τ_y and K in Eq.(2), (4) and (5) were calculated by means of non-linear least square method[16]) using the experimental data that pertain to the relationship between Q and τ_w, the latter information is obtained by application of Eq. (3). The computer program used is the same as the one described in the previous paper of this laboratory[5]). The following standard deviation δ (–) is minimised:

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

where, Q_{obs} and Q_{cal} are the observed and calculated volumetric flow rates of the sample fluids and N is the number of experimental points. In this paper, the digital computer of the computation center in Hiroshima University, HITAC M-180 was used.

RESULTS AND DISCUSSION

1. Date for the density

The values of the density of Shoyu and Sauce at temperatures of 3° ~ 50°C were examined and density ρ(g/cm^3) versus temperature t(°C) plotted as in Fig. 2. The mathematical results corresponding to these graphs will be shown later.

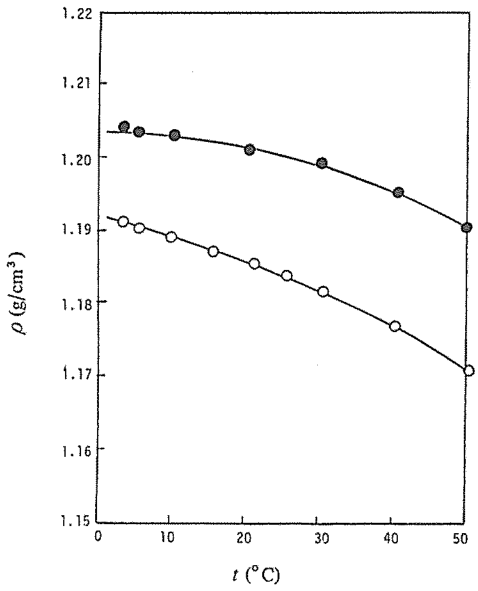

Fig.2 Density-temperature functions for Shoyu and Sauce.
Observed value: Shoyu ○
Sauce ●
Calculated value: Eq. (9) ———

2. Equation of the density in respect to the temperature.

The values of the density of gases can be calculated usually from the equation of ideal gas. However, the densities of liquids are not as easily obtainable and hence one has to resort to tables and plots for liquids that such information is available. In the case of the samples analysed, such data is not easily obtainable therefore as in the previous papers[9] we tried to determine an equation that could be applied for prediction of the density of the samples in question.

$$\rho = a + bT + cT^2 + dT^3 \tag{8}$$

$$\rho = a + bT + cT^2 \tag{9}$$

$$\rho = a + bT \tag{10}$$

$$\rho = aT^m + b \tag{11}$$

Where, T is the temperature of samples (°K), and a, b, c, and m are parameters obtainable from the data in Fig. 2.

The parameters in Eqs. (8) ~ (10) were calculated from the data using the linear least square method whereas the parameters in Eq. (11) were calculated by the non-liner least square method[16], again using the same digital computer and minimising the standard deviation δ (—) as below:

$$\delta = \left\{ \sum_{i=1}^{N} (\rho_{obs} - \rho_{cal})_i^2 / N \right\}^{1/2} \tag{12}$$

where ρ_{obs} and ρ_{cal} are the observed and calculated density of the samples. The values of the parameters in Eqs. (8) ~ (11) could be determined just as the values of the standard deviations for the density, which are give in Table 1. A careful scrutiny of the

Table 1. Standard deviation of Eqs. (8) ~ (11) for the density data of Shoyu and Sauce.

Sample	Eq. (8)	Eq. (9)	Eq. (10)	Eq. (11)
Shoyu	1.41×10^{-4}	1.90×10^{-4}	9.15×10^{-4}	8.83×10^{-4}
Sauce	3.41×10^{-4}	3.43×10^{-4}	1.11×10^{-3}	1.09×10^{-3}

table just mentioned, points to the fact that the results for Eqs. (8) and (9) are more satisfactory than those for Eqs.(10) and (11), considering that these values (the former) fall within close range. Further on the values of the parameters for the two Eqs. (8) and (9), are given in Table 2.

Table 2. Parameters of Eqs. (8) and (9) for the desity data of Shoyu and Sauce.

Sample	Equation	$a \times 10$	$b \times 10^3$	$c \times 10^6$	$d \times 10^9$
Shoyu	Eq. (8)	9.01	2.50	−5.89	2.26
	Eq. (9)	9.91	1.70	−3.54	—
Sauce	Eq. (8)	9.23	1.95	−2.83	−1.97
	Eq. (9)	8.70	2.48	−4.59	—

From various considerations, we made up the opinion that between these two equations (8) and (9), the latter, which is a simpler equation in any case, would be the best model to predict the density variation with respect to temperature for these products, other conditions but far most else, the consititution of the products, being equal. The solid curves in Fig. 2 represent the calculated values for Eq. (9).

3. Data for the flow behaviour

Already mention has been made of the correction necessary for the pressure drop and of the important correction factor, Hargenbach, obtained by using standard solutions of glycerin-water mixtures[7]. As dealt with in the previous paper, this correction factor was found to obey the same relationships as before[8] at low viscosity region and the corresponding Reynolyds numbers; at high viscosity region and Reynolds numbers of the order 500 to 2100[12], a constant value was observed for this factor and for our experimental region this stood at m_p = 1.1. Having executed the experiments for Shoyu and Sauce at temperatures 3 to 50°C, the data for the volumetric flow rate Q (cm^3/sec) versus the shear stress at the wall τ_w (g_f/cm^2) for the laminar flow region were plotted in Figs. 3 and 4. The lines in these figures represent the values of the calculated results shown later.

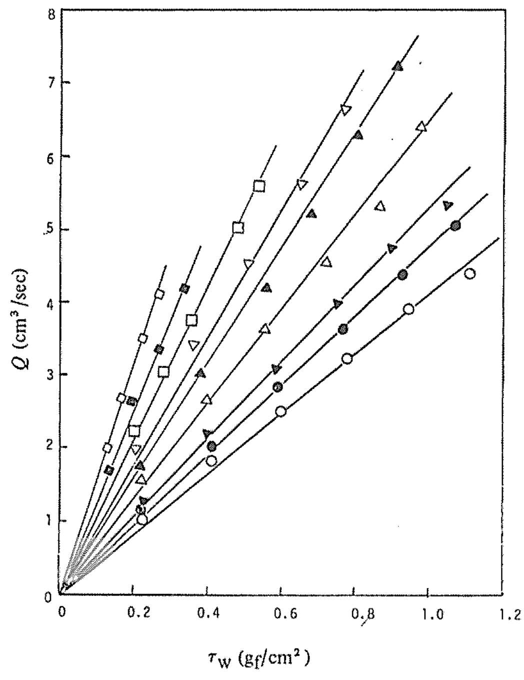

Fig.3. Relationship between the volumetric flow rate Q and the shear stress at the wall τ_W for Shoyu.
Observed value: t(°C) = 3 5 9 15 21 / ○ ● ▲ ▽ ▼ / 25 30 40 50 / △ □ ■ □
Calculated value: Eq. (5) ———

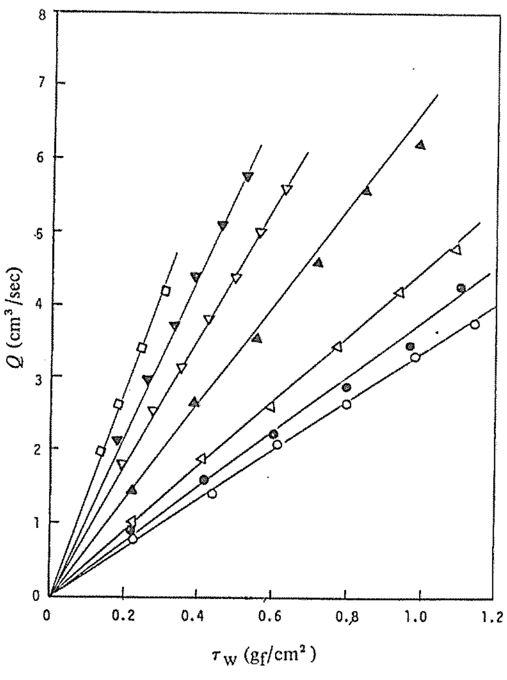

Fig.4 Relationship between the volumetric flow rate Q and the shear stress at the wall τ_W for Sauce.
Observed value: t(°C) = 3 5 10 20 / ○ ● ▽ ▼ / 30 40 50 / △ ▲ □
Calculated value: Eq. (5) ———

4. Parameters in the flow equations

The parameters in Eq. (2) were obtained by using the non-linear least square method, the values being listed in Table 3. From this table the results for τ_y are negligible, and could be unnoticed and thus taking the value of this factor as zero (τ_y = 0) in Eq. (1). Under this conditions, the parameters in Eq. (4) were obtained and are shown in Table 3.

The results show that n lies somewhere between 0.9 and 1.0 implying a Newtownian flow behaviour and consequently making Eq. (5) applicable, with τ_y = 0 and n = 1; in these circumstances K could be called by its usual name, viscosity.

Table 3. Parameters of Eqs. (2) and (4) for the flow behaviour data of Shoyu and Sauce.

Sample	T(°K)	Eq. (2)			Eq. (4)	
		n	$\tau_y \times 10^2$	$K \times 10^2$	n	$K \times 10^2$
Shoyu	276	0.96	−1.09	6.21	0.94	5.23
	278	0.98	−0.37	6.10	0.97	5.71
	282	0.95	−0.83	4.36	0.93	3.79
	288	1.04	−4.75	7.14	0.93	3.23
	294	1.13	−5.80	9.98	0.98	3.56
	298	0.96	−1.99	3.02	0.90	2.01
	303	1.00	−2.37	3.37	0.92	1.92
	313	0.96	−1.11	2.11	0.89	1.38
	323	0.97	−0.12	1.74	0.95	1.59
Sauce	276	1.02	−1.30	10.9	0.99	8.82
	278	1.13	−5.45	22.0	1.01	9.40
	283	1.05	−1.97	10.2	1.00	7.27
	293	0.97	−0.49	4.27	0.96	3.92
	303	1.00	−0.99	3.80	0.97	3.03
	313	1.01	−0.94	3.80	0.97	3.03
	323	0.98	−2.20	2.37	0.86	1.10

The values for the viscosity, K (g/cm·sec) for Shoyu and Sauce at temperatures 3 ~ 50°C are plotted in Fig. 5 and in the same plot the curves representing the results of calculated values as shown later are given.

5. Equations of viscosity with respect to temperature.

The relationships between viscosity and temperature have been expressed in the usual way by application of the Andrade or Arrhenius type of equation thus:

$$K = a\exp(b/T) \tag{13}$$

where, a and b are parameters obtainable from Fig. 5, in these experiments. However, this equation does not give accurate information for water in a wide range of temperatures and therefore a modified form must to be used.

$$K = a\exp(b/T^{m}) \tag{14}$$

where, again a, b and m are parameters that can be obtained from given data.

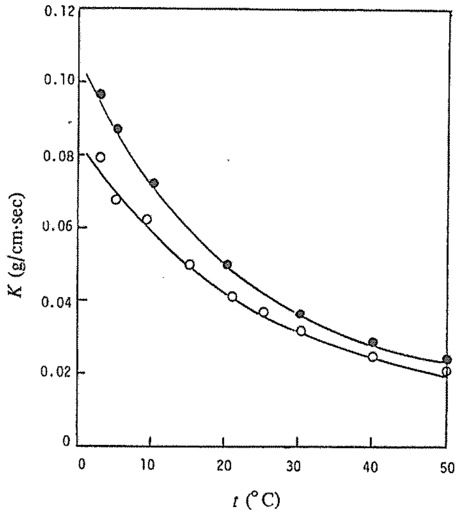

Fig.5 Viscosity-temperature functions for Shoyu and Sauce.
Observed value : Shoyu ○
Sauce ●
Calculated value: Eq. (14) for $m = 3$ ——

The main objective in the analysis here was to establish the values of this constants for application to the samples in question.

The parameters in Eq. (13) were calculated using the linear least square method but those in Eq. (14) were obtained by the non-linear least square method [16] as has been dealt with previously. The following standard deviation is minimised:

$$\delta = \left\{ \sum_{i=1}^{N} (K_{obs} - K_{cal})_i^2 / N \right\}^{1/2} \tag{15}$$

where, K_{obs} and K_{cal} are the observed and the calculated viscosities of the fluids.

For the viscosity too, the equations applicable for the density were tried for a possible application. The results point to the consideration that in some situations Eqs. (8) and (9) could be used without too much loss of accuracy.

The values of the parameters in Eqs. (13) and (14) and also for Eqs. (8) ~ (10) were determined and the standard deviations of both groups are shown in Table 4. In this table, the standard deviations for the values obtained when $m = 3$ in Eq. (14) are the smallest. Further, in Table 5 listed are the values of the parameters of Eq. (13) and Eq. (14) with $m = 3$.

The solid curves in Fig. 4 are the calculated values for Eq. (14) with $m = 3$ for the case of the samples in question currently.

Table 4. Standard deviations of the parameters in Eqs. (13), (14); Eqs. (8), (9) and (10) for the viscosity data of Shoyu and Sauce.

Sample	Eq. (13)	Eq. (14) (m=2; m=3)	Eq. (8)	Eq. (9)	Eq. (10)
			(K subsituted for ρ)		
Shoyu	1.63×10^{-3}	1.45×10^{-3} ; 1.33×10^{-3}	1.71×10^{-3}	1.79×10^{-3}	5.67×10^{-3}
Sauce	1.54×10^{-3}	1.12×10^{-3} ; 7.42×10^{-4}	1.71×10^{-3}	1.71×10^{-3}	7.48×10^{-3}

Table 5. Parameters of Eqs. (13) and (14) for which $m = 3$ (fixed) in regard to the viscosity of Shoyu and Sauce.

Sample	Equation	a	b
Shoyu	Eq. (13)	4.30×10^{-6}	2.70×10^{3}
	Eq. (14) for m=3	2.03×10^{-3}	7.63×10^{7}
Sauce	Eq. (13)	2.73×10^{-6}	2.89×10^{3}
	Eq. (14) for m=3	1.94×10^{-3}	8.20×10^{7}

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SUMMARY

The flow equations of liquid foods are important for designing the equipment and controlling the various processes. In this investigation, the flow behaviour of two popular products namely Shoyu and Sauce have been analysed at 276 ~ 323°K for low Reynolds numbers. For measuring the flow behaviour a capillary tube viscometer operated under various pressures was used.

The results indicate that the flow behaviour of these products, under relevant conditions of the experiment, is Newtonian. The variation of the viscosity of these products as a function of temperature was investigated and an equation proposed(**) for the exponential curves thereof. Along similar lines, the variation of density with temperature was analysed and visualised as hyperbolic curves(***).

(**)

$$K = a \exp (b/T^{m}) \qquad \text{(g/cm·sec)}$$

For Shoyu:

$a = 2.03 \times 10^{-3}$, $b = 7.63 \times 10^{7}$, $m = 3$

For Sauce:

$a = 1.94 \times 10^{-3}$, $b = 8.20 \times 10^{7}$, $m = 3$

(***)

$$\rho = a + bT + cT^2 \qquad (\mathrm{g/cm^3})$$

For Shoyu:

$a = 0.991$, $b = 1.70 \times 10^{-3}$, $c = -3.45 \times 10^{-6}$

For Sauce:

$a = 0.870$, $b = 2.48 \times 10^{-3}$, $c = -4.59 \times 10^{-6}$

NOTATIONS

a, b, c, d and m: parameters in various equations

g_c : gravitational conversion factor ($\mathrm{g \cdot cm/g_f \cdot sec^2}$)

K : fluid consistency index ($\mathrm{g^n/cm^n \cdot sec^{2n-1}}$) or viscosity of fluids (g/cm·sec)

L : length of capillary tube (cm)

m_p : Hargenbach coefficient (–)

N : number of experimental points (–)

n : flow behaviour index (–)

ΔP and ΔP_m : pressure difference and the observed manometric pressure reading ($\mathrm{g_f/cm^2}$)

Q : volumetric flow rate of the sample ($\mathrm{cm^3/sec}$)

r_w : radius of the capilary tube (cm)

T and t : temperature of the sample (°K) and (°C)

$\bar{u}$: average velocity of the sample (cm/sec)

γ : shear rate (sec)

δ : standard deviation in various equations

ρ : density of the sample ($\mathrm{g/cm^3}$)

τ and τ_w : shear stress and shear stress at the wall ($\mathrm{g_f/cm^2}$)

τ_y : yield stress ($\mathrm{g_f/cm^2}$)

subcripts: :

obs and cal : observed and calculated

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しょう油とウスターソースの低流速域における流動特性に関する研究

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液状食品に関する流動方程式は，各種装置を設計，制御をしていく場合に必要となる。

本研究では，しょう油とウスターソースの低流速域における流動特性に関する研究を，温度 $T = 276 \sim 323$ °K において行った。

流動特性の測定には，圧力を変化させて操作できる毛管形粘度計を使用した。いずれもニュートン流動を示した。粘度の温度関係式として次式が得られた。

$K = a \exp(b / T^m)$　〔g/cm・sec〕

しょう油：$a = 2.03 \times 10^{-3}$，　$b = 7.63 \times 10^{7}$，　$m = 3$

ウスターソース：$a = 1.94 \times 10^{-3}$，　$b = 8.20 \times 10^{7}$，　$m = 3$

また，密度の温度関係式として次式が得られた。

$\rho = a + bT + cT^2$　〔g/cm³〕

しょう油：$a = 0.991$，$b = 1.70 \times 10^{-3}$，$c = -3.54 \times 10^{-6}$，

ウスターソース：$a = 0.870$，$b = 2.48 \times 10^{-3}$，$c = -4.59 \times 10^{-6}$，