JOURNAL OF FOOD PROCESS ENGINEERING

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COEDITORS

FOOD & NUTRITION PRESS, INC.

VOLUME 20, NUMBER 4 SEPTEMBER 1997

JOURNAL OF FOOD PROCESS ENGINEERING

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One volume of six issues will be published annually. The price for Volume 20 is $164.00, which includes postage to U.S., Canada, and Mexico. Subscriptions to other countries are $187.00 per year via surface mail, and $198.00 per year via airmail.

Subscriptions for individuals for their own personal use are $134.00 for Volume 20, which includes postage to U.S., Canada and Mexico. Personal subscriptions to other countries are $157.00 per year via surface mail, and $168.00 per year via airmail. Subscriptions for individuals should be sent directly to the publisher and marked for personal use.

The *Journal of Food Process Engineering* is listed in *Current Contents/Agriculture, Biology & Environmental Sciences (CC/AB)*, and SciSearch, and Research Alert.

The *Journal of Food Process Engineering* (ISSN:0145-8876) is published (February, April, June, August, October and December) by Food & Nutrition Press, Inc.—Office of Publication is 6527 Main Street, P.O. Box 374, Trumbull, Connecticut 06611 USA.

Second class postage paid at Bridgeport, CT 06602.

POSTMASTER: Send address changes to Food & Nutrition Press, Inc., 6527 Main Street, P.O. Box 374, Trumbull, Connecticut 06611 USA.

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FOOD & NUTRITION PRESS, INC.
TRUMBULL, CONNECTICUT 06611 USA

ISSN 0145-8876

Printed in the United States of America

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HEAT TRANSFER TO PARTICLES IN CANS WITH END-OVER-END ROTATION: INFLUENCE OF PARTICLE SIZE AND CONCENTRATION (%V/V)

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Accepted for Publication August 15, 1996

ABSTRACT

The heat transfer coefficients (U and h_{fp}) associated with particulate fluids in cans were evaluated with suspended Nylon particles, during end-over-end rotation. Can rotation speed (10 to 20 rpm), particle diameter (19 to 25 mm) and particle concentration (single particle to 40% v/v) were studied as variables using fluids of two different viscosities (1.0×10^{-6} and 1×10^{-4} m^2/s). Particle transient temperatures were measured by placing a flexible thermocouple attached to the particle, allowing particle motion inside the can. Transient heat conduction equations for a spherical particle with convective boundary condition at fluid-particle interface were numerically solved to obtain h_{fp}. An overall heat balance equation was solved to obtain U. The h_{fp} values varied from 170 to 1165 $W/m^2.K$ with oil and 175 to 1550 $W/m^2.K$ with water depending upon process conditions. The U values varied from 110 to 220 $W/m^2.K$ with oil and 480 to 800 $W/m^2.K$ with water. The h_{fp} increased 10 to 60% with decreasing particle diameter from 25 to 19 mm while it increased about 3 folds as the particle concentration changed from a single particle to 30%. Further increase in particle concentration to 40% decreased the h_{fp} between 5 and 20% depending upon processing conditions. The effects of particle size and particle concentration on the U were similar to those obtained with h_{fp} with lower magnitudes.

INTRODUCTION

Heat transfer rates to canned food products such as a fluid containing discrete particles can be increased by mechanical agitation. This has permitted the use of high temperature short time concept with agitation processing.

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Journal of Food Process Engineering **20** (1997) 265–283.

Thermal processing schedule for canned foods has been traditionally established using experimental heat penetration data. In recent years, growing interest in mathematical modelling has prompted further attention to the mechanism of heat transfer in particulate food systems. Theoretical models can be used for the design, optimization and validation of these food systems. However, the usefulness of theoretical models depends upon the accuracy of input physical parameters. The overall heat transfer coefficient from the heating medium to the can fluid (U) and the fluid-to-particle heat transfer coefficient (h_{fp}) are important parameters beside thermo-physical properties of food materials. Transient temperature measurement of the moving particle during can rotation has been a major problem. In early studies, the h_{fp} was measured between a stationary particle and a moving fluid (Lenz and Lund 1978; Lekwauwa and Hayakawa 1986; Deniston *et al.* 1987; Fernandez *et al.* 1988). Recent studies have addressed this problem using different approaches while allowing some particle motion in cans during rotation. Stoforos and Merson (1990) developed a mathematical procedure requiring only the measurement of fluid temperatures to estimate the U and h_{fp}. Later Stoforos and Merson (1991) used fluid crystals to measure surface temperatures as the particle moved freely in cans during axial rotation. Weng *et al.* (1992) proposed the use of a time-temperature integrator and a mathematical model to determine the h_{fp}. Sablani and Ramaswamy (1995) developed a flexible thermocouple technique to measure the convective heat transfer coefficient in cans undergoing end-over-end rotation.

The overall heat transfer coefficient and the fluid-to-particle heat transfer coefficient in cans are influenced by various environmental conditions and physical properties of fluid and particles. It is important to quantify the effect of such parameters from the process design and quality optimization point of view. The effects of various parameters influencing the U and h_{fp} in axially rotating cans have been quantified by Lenz and Lund (1978), Deniston *et al.* (1987), Fernandez *et al.* (1988) and Stoforos and Merson (1992). Recently, Sablani and Ramaswamy (1996) quantified the effect of retort operating conditions on the U and h_{fp} in cans with end-over-end rotation.

MATHEMATICAL MODEL

In thermal processing of canned particulate food systems, heat is transferred from the heating medium to fluid and particles inside the cans. The overall heat energy balance on such systems can be used to calculate associated convective heat transfer coefficients. The governing equation for heat transfer in such systems [(Deniston *et al.* (1987); all symbols are detailed in nomenclature)] can be written as

$$U \cdot A_c \cdot (T_R - T_f) = m_f \cdot C_{pf} \cdot \frac{dT_f}{dt} + m_p \cdot C_{pp} \cdot \frac{d\langle T_p \rangle}{dt} \quad (1)$$

The following are assumed for deriving the Eq. (1): uniform initial temperature for the particle, uniform initial and transient temperatures for the fluid, constant heat transfer coefficients, constant physical and thermal properties for both fluid and particles, and no energy accumulation in can wall.

The second term on the right side of Eq. (1) is equal to the heat transferred to particles from the fluid through particle surface:

$$m_p \cdot C_{pp} \cdot \frac{d\langle T_p \rangle}{dt} = h_{fp} \cdot A_p \cdot (T_f - T_{ps}) \quad (2)$$

Using Eq. (2), the overall heat energy balance Eq. (1) can be rewritten as:

$$U \cdot A_c \cdot (T_R - T_f) = m_f \cdot C_{pf} \cdot \frac{dT_f}{dt} + h_{fp} \cdot A_p \cdot (T_f - T_{ps}) \quad (3)$$

It is also assumed that particle receives heat only from the fluid and not from the can wall when it impacts it, i.e. heat is transferred first from the can wall to fluid and then to particle. The transient heat flow in a spherical particle immersed in fluid can be described by the following partial differential equation (Ozisik 1985):

$$\frac{\partial T}{dt} = \alpha_p \cdot \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \cdot \frac{\partial T}{\partial r}\right) \quad (4)$$

The initial and boundary conditions are:

$$T(r,0) = T_i \qquad \text{at } t=0 \quad (5)$$

$$\frac{dT(0,t)}{dr} = 0 \qquad \text{at } t>0 \quad (6)$$

$$k_p \cdot \frac{dT}{dr} = h_{fp} \cdot (T_f - T_{ps}) \qquad \text{at } r=a \quad (7)$$

The objective of the present work was to use the flexible thermocouple approach reported earlier (Sablani and Ramaswamy 1995) to quantify the effect of particle size and concentration on the U and h_{fp} in cans at various rotational speeds with two different viscosity fluids during end-over-end rotation.

MATERIALS AND METHODS

Water and a high temperature bath oil (100 cst at 38C, Fisher Scientific Ltd., Montreal), giving different viscosity levels, were used as test fluids. Nylon spheres (Hoover Precision Products, Sault Ste Marie, MI) of different sizes (diameter 19, 22, 25 mm) were used as test particles. Table 1 summarizes the data on thermo-physical properties for the fluids and particle used in present study. The particle density was obtained from the volume of water displaced by a certain number of particles and their weight; specific heat was measured using a calorimetric method (Mohsenin 1980). The particle thermal diffusivity was evaluated using the heating rate index method by heating it in a steam cabinet (Singh 1982). The particle thermal conductivity was computed from the product of thermal diffusivity, density and heat capacity. The property data for water were taken from Ozisik (1989). The oil density was evaluated using a Pycnometer. The oil heat capacity was measured by comparing the heating rates of equal masses of oil and water for same power input during heating. Thermal conductivity of oil was evaluated using a thermal conductivity probe based on line heat source technique (Sweat and Haugh 1974).

Can fluid temperatures were measured at the geometric center of the cans using CNS copper-constantan needle type thermocouples (C-10, Ecklund Harrison Technologies, Inc., Cape Coral, FL). For the purpose of measuring particle transient temperatures, a thermocouple equipped particle was mounted inside the can. Details on preparation of the thermocouple equipped particle, attaching it to the can, retort preparations and data gathering are given in Sablani and Ramaswamy (1995).

TABLE 1.
THERMO-PHYSICAL PROPERTIES OF TEST MATERIALS

Material	Density (kg/m^3)	Heat Capacity (J/kg.K)	Thermal - conductivity (W/m.K)	Thermal-diffusivity (m^2/s)
Nylon	1128	2073	0.369	1.518×10^{-7}
Oil[a] (100 cst)	880	2210	0.165	-
Water[b]	1000	4180	0.597	-

[a] Kinematic viscosity = 1.0×10^{-4} m^2/s ; [b] Kinematic viscosity = 1.0×10^{-6} m^2/s

Cans of size 307 × 409 containing the test fluid and thermocouple equipped particle were processed in a batch type, rotary, full-immersion, hot-water sterilizer (Stock Rotomat-PR 900; Hermann Stock Maschinenfabrick, Germany). Processed water was preheated in the reservoir to 10C higher than process temperature (120C) to accommodate the heat loss to process vessel during its transfer. The retort come up time was short (less than 3 min) and temperature rise during the come-up period followed an exponential pattern; hence, the come-up period effectiveness was considered to be ~85%, typical of logarithmic come-up profiles. In each run, four test cans were placed equidistant from the horizontal central axis of the rotating cage, in a vertical orientation, to give an end-over-end rotation. The remaining space in the cage was filled with dummy cans containing water.

Three different particle sizes (19, 22, and 25 mm), four particle concentrations (single particle, 20, 30 and 40% volume by volume, v/v), three rotational speeds (10, 15 and 20 rpm) and two kinematic viscosities (1.0×10^{-6} and 1.0×1.0^{-4} cm^2/s) were considered as experimental variables. A can headspace of 10 mm, a radius of rotation of 19 cm and a retort temperature of 120C were used as fixed parameters. When cans were filled with particles to a concentration of 20-40% by volume, the thermocouple equipped particle was initially placed at the central point with respect to other particles. At the end of each experiment, the heating time was kept sufficiently long such that the fluid and particle temperatures equilibrated to the heating medium temperature. The equilibrated fluid and particle temperatures were corrected to match heating medium temperature. Temperature data were discarded if thermocouple breakage occurred during runs (about 15% of test cans suffered thermocouple breakage due to the use of fine wire thermocouples).

Fluid-to-particle Heat Transfer Determination

The fluid-to-particle heat transfer coefficients (h_{fp}) were determined by solving the governing partial differential equation of conduction heat transfer in spherical coordinates with associated initial and boundary conditions using a finite difference method. The inverse heat transfer approach, where surface heat flux is estimated using one or more measured temperature histories inside a heat-conducting body, was used to estimate h_{fp} values. Two different techniques, one based on minimization of temperature differences and another based on minimization of lethality difference have been used to determine h_{fp} values (Sablani and Ramaswamy 1996). In the present study, the difference between measured and calculated lethality at the particle center (slowest heating point in fluid/particulate system), F_o, was used as the objective function due to its relevance to thermal processing. The procedure involved initially comparing the calculated and measured lethality at the center of the particle based on an

assumed h_{fp} value, and then subsequently changing h_{fp}, in a sequential pattern, until the calculated and measured lethality values (Eq. 8) matched a fixed value of 10 min.

$$F_o = \int_0^t 10^{\frac{(T-121.1)}{10}} dt \tag{8}$$

The time required to achieve a lethality of 10 min at the particle center was taken as process time (t_{pt}). The calculated process time was used in U determination.

Overall Heat Transfer Coefficients Determination

In order to calculate the overall heat transfer coefficient (U), an expression was obtained by integrating the Eq. (3). The time of integration was considered to be the time, t_{pt}, obtained earlier in the determination of the h_{fp}. By integrating the Eq. (3) with respect to time we can get the following Eq. (9):

$$U \cdot A_c \int_0^{t_{pt}} (T_R - T_f) dt = m_f \cdot C_{pf} \cdot \int_0^{t_{pt}} dT_f + h_{fp} \cdot A_p \cdot \int_0^{t_{pt}} (T_f - T_{ps}) dt \tag{9}$$

To calculate the overall heat transfer coefficient from above Eq. (9), it is necessary to have transient temperatures of fluid and particle surface. For the transient temperatures of fluid, experimentally measured values were used and particle surface temperature were calculated from Eq. (4-7). The overall heat transfer coefficient was then calculated from Eq. (9).

Data Analysis

The overall heat transfer coefficient and fluid-to-particle heat transfer coefficient data were analyzed using statistical analysis. An analysis of variance (ANOVA) procedure was used to evaluate the level of significance of fluid viscosity, rotational speed, particle size and particle concentration, and interactions of these.

RESULTS AND DISCUSSION

Influence of Rotational Speed and Fluid Viscosity on Heat Transfer Coefficients

Overall Heat Transfer Coefficient (U). Table 2 summarizes the mean values and coefficients of variation of overall heat transfer coefficients for oil

TABLE 2.
MEAN OVERALL HEAT TRANSFER COEFFICIENT (U) AS INFLUENCED BY PARTICLE SIZE AND CONCENTRATION AT VARIOUS ROTATIONAL SPEEDS FOR OIL AND WATER ($n \geq 3$)

Particle size (mm)	Particle concentration (%, v/v)	Rotational speed (rpm)	Overall heat transfer coefficient ($W/(m^2.K)$)	
			Oil	Water
19.05	0.08*	10	141 (2.9)[1]	647 (3.5)
		15	162 (2.9)	734 (3.8)
		20	186 (2.6)	781 (1.4)
19.05	20	10	176 (1.3)	726 (3.0)
		15	198 (1.6)	760 (4.3)
		20	215 (1.4)	788 (3.8)
19.05	30	10	151 (1.1)	658 (2.6)
		15	168 (0.7)	666 (1.0)
		20	182 (1.3)	734 (2.1)
19.05	40	10	113 (1.0)	502 (3.2)
		15	136 (1.2)	554 (2.1)
		20	154 (3.2)	595 (2.2)
22.25	30	10	143 (0.4)	653 (0.4)
		15	157 (2.7)	656 (0.6)
		20	173 (1.6)	716 (0.2)
25	30	10	139 (3.0)	631 (3.8)
		15	151 (1.6)	639 (1.6)
		20	166 (0.8)	665 (2.3)

[1] The values in parantheses are the coefficients of variation (%)

*Single particle in the can

and water obtained at various rotational speeds. The U values ranged from 110 to 220 $W/m^2.K$ for oil and 480 to 800 $W/m^2.K$ for water. The U values increased significantly with increasing rotational speeds for both water and oil. This could be explained by the enhanced mixing resulting in a higher degree of

turbulence. The influence of rotational speed on the resulting temperature profile of can fluids is illustrated in Fig. 1a which shows that at higher rotational speeds the fluid temperature reaches the heating medium temperature relatively faster. The rapid rate of heating associated with the low viscosity fluid (water) perhaps narrowed the influence of rotation speed. The effect is more clearly visible with the high viscosity fluid (oil). On an average, the U value increased by 24% for

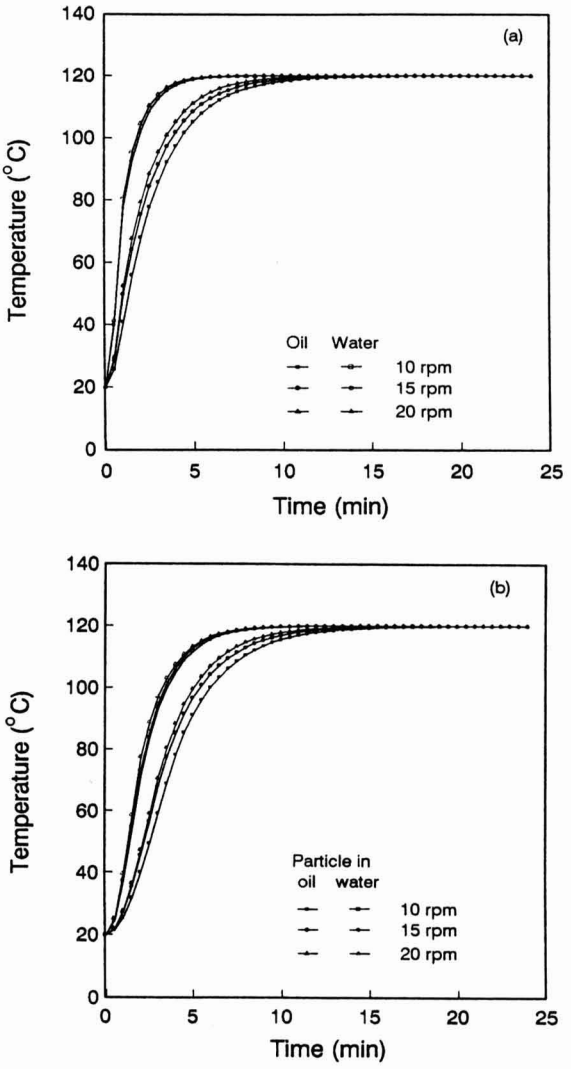

FIG. 1. TYPICAL TIME-TEMPERATURE PROFILES OF FLUID AND PARTICLE DURING END-OVER-END ROTATION SHOWING THE INFLUENCE OF FLUID VISCOSITY AND ROTATIONAL SPEED

oil and 13% for water in cans, when rotational speed increased from 10 to 20 rpm (Table 2) indicating that rotational speed effects are more pronounced with viscous fluid. Anantheswaran and Rao (1985) also reported that the end-over-end rotation was more effective for higher viscosity fluids. Rotational speed effects on the U were also more apparent in cans with a single particle than in cans with multiple particles. The influence of rotational speed on the U was lower with larger size particles (22.25 and 25.0 mm diameter) than with the smaller size particle (19.05 mm diameter). This was probably due to reduced particle mixing with increased particle size.

The U values were higher for lower viscosity fluid (water) at all the processing conditions (Table 2) as discussed earlier due to smaller thickness of the boundary layer with water. The temperature of the water reached the heating medium temperature more rapidly indicating a faster rate of heat transfer (Fig. 1a). There are two factors here which influence the temperature change in the canned fluid, one opposing the other. Higher heat transfer coefficients result in a higher temperature rise when the heat capacities of the two fluids are the same. Higher heat capacities will result in a lower temperature rise in the fluid when the associated heat transfer coefficients are the same. If one of them is changed (for example, U) by a certain margin while managing to change the other (C_p) by the same margin, then the temperature profile remains relatively unchanged (compensating effect). Changing them in any other way shifts the temperature profile in favor of the dominating factor. Figure 2 demonstrates these effects using some arbitrary values of U and C_p. At constant C_p, higher U results in a higher temperature profile (see lines 2 vs 1 or 5 vs 3 in Fig. 2). At constant U, higher C_p results in lower temperature rise (see lines 1 vs 3 or 4 vs 5). The curve for U=400 W/m^2.K and C_p=4200 J/kg.K (line 2) is identical to that for U=200 W/m^2.K and C_p=2100 J/kg.K (line 3). The curve for U=800 W/m^2.K and C_p=2100 J/kg.K (line 5) will be far above all of them and likewise the curve for U=200 W/m^2.K and C_p=4200 J/kg.K (line 1) is below all of them. In the present system, however, both C_p and U are simultaneously changed (for water and oil) and, hence, only the combined effects are seen. The U value associated with water is in the 400-800 W/m^2.K range with a heat capacity of 4180 J/kg.K. The U value associated with oil is about *one quarter* of that of water and the heat capacity is about *one half*. Thus, the influence of U (resulting from the lower viscosity) dominates over the influence of heat capacity as shown in both figures (Fig. 1a and 2).

Analysis of variance of data revealed that both fluid viscosity and rotational speed effects were highly significant ($p \leq 0.0001$) with the viscosity term explaining over 95% of total variability. Two-way interaction effects were also significant; however, their contribution compared to the main effects were small (Table 3).

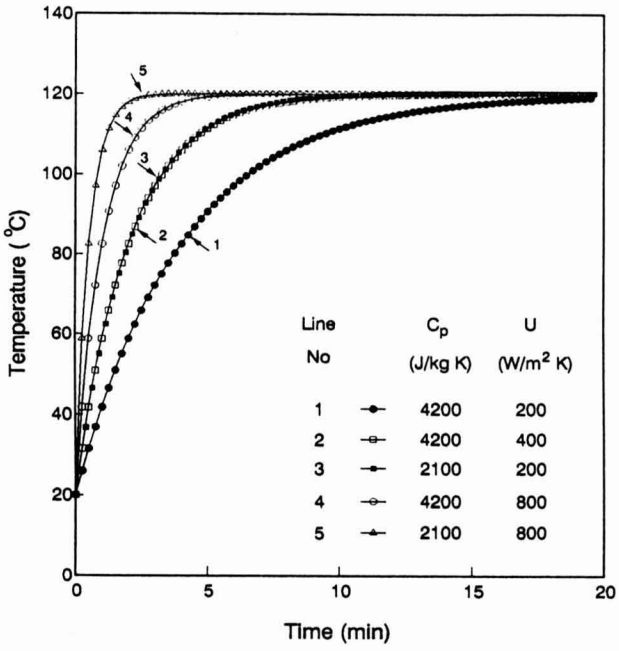

FIG. 2. INFLUENCE OF HEAT CAPACITY AND OVERALL HEAT TRANSFER COEFFICIENT ON FLUID TEMPERATURE PROFILE BASED ON SIMULATED DATA

Fluid-to-particle Heat Transfer Coefficients (h_{fp}). The associated fluid-to-particle heat transfer coefficient values in cans during agitated processing have been shown to be higher with moving particles compared to those measured with restricted particle motion (Stoforos and Merson 1992). In the present study, depending on experimental conditions, the fluid-to-particle heat transfer coefficient, h_{fp}, ranged from 170 to 1165 W/m^2.K for oil and 175 to 1550 W/m^2.K for water. Table 4 summarizes mean values and coefficients of variation of h_{fp} values for all the processing conditions. Analysis of variance showed that the viscosity and rotational speed effects were significant ($p \leq 0.0001$) with the same order of magnitude (Table 3). The increase in rotational speed improved the h_{fp} values significantly and this is illustrated in Fig. 1b. The influence of h_{fp} on particle temperature due to higher rotational speed was, again more evident with oil than with water. On an average, increasing rotational speed from 10 to 20 rpm enhanced the h_{fp} by 58% for oil and 51% for water. The h_{fp} values were lower for the high viscosity fluid (oil) presumably due to associated thicker boundary layer and higher drag forces. This is also reflected in the temperature profile of particle in oil and water shown in Fig. 1b. Particle temperature in water reached the heating medium temperature much earlier than the particle in oil. Higher particle temperatures with water were due to

TABLE 3.
ANALYSIS OF VARIANCE SHOWING THE INFLUENCE OF FLUID VISCOSITY, ROTATIONAL SPEED, PARTICLE SIZE AND PARTICLE CONCENTRATION ON U AND h_{fp}

Source	dF[a]	Sum of square (%) U	Sum of square (%) h_{fp}	dF	Sum of square (%) U	Sum of square (%) h_{fp}
Model	13	96.4*	91.3*	17	99.5*	96.6*
Fluid viscosity (FV)	1	95.6*	47.6*	1	96.2*	7.81*
Rotational speed (RS)	2	0.48*	30.7*	2	0.11*	11.7*
Particle size (PS)	2	0.16*	9.94*	-	-	-
Particle concentration (PC)	-	-	-	3	1.90*	73.2*
Interactions						
FV x RS	2	0.10*	0.03	2	0.29*	0.17
FV x PS	2	0.04**	2.14*	-	-	-
RS x PS	4	0.02	0.86	-	-	-
FV x PC	-	-	-	3	0.92*	1.99*
RS x PC	-	-	-	6	0.05***	1.69*
Residual (error)	54	3.60	8.70	151	0.50	3.40
	51 (h_{fp})			71 (h_{fp})		
Total	67			168		
	64 (h_{fp})			88 (h_{fp})		

* $p < 0.0001$

** $p < 0.0005$

*** $p < 0.005$

\- not applicable in the particular experiment set

[a] Degree of freedom

combined effect of improved U and h_{fp}. The h_{fp} values with water were nearly 20 to 80% higher than that with oil. The influence of rotational speed on the h_{fp} was also less pronounced with larger size spheres (22.25 and 25.0 mm diameter) compared to that associated with the smaller particle. This could also be

explained by the reduced particle mixing with increased particle size. Increasing rotational speed affected h_{fp} at all particle concentrations.

TABLE 4.
MEAN FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENT (h_{fp}) AS INFLUENCED BY PARTICLE SIZE AND CONCENTRATION AT VARIOUS ROTATIONAL SPEEDS FOR OIL AND WATER ($n \geq 3$)

Particle size (mm)	Particle concentration (%, v/v)	Rotational speed (rpm)	Fluid to particle heat transfer coefficient ($W/(m^2.K)$)	
			Oil	Water
19.05	0.08*	10	173 (1.8)[1]	189 (7.9)
		15	233 (8.3)	278 (9.7)
		20	279 (8.1)	365 (8.5)
19.05	20	10	583 (9.7)	853 (4.2)
		15	787 (2.2)	1090 (7.3)
		20	960 (5.0)	1160 (9.3)
19.05	30	10	682 (3.8)	1020 (13.8)
		15	967 (1.3)	1170 (1.6)
		20	1130 (2.8)	1450 (7.4)
19.05	40	10	640 (4.5)	878 (8.5)
		15	855 (4.6)	1090 (4.0)
		20	944 (8.1)	1430 (4.3)
22.25	30	10	625 (3.3)	994 (4.8)
		15	808 (4.5)	1170 (6.1)
		20	997 (5.8)	1320 (3.9)
25	30	10	501 (5.9)	910 (9.1)
		15	605 (5.4)	1120 (8.4)
		20	739 (5.0)	1280 (4.0)

[1] The values in paranthese are the coefficients of variation (%)

*Single particle in the can

Comparison with Literature Values. An absolute comparison of U and h_{fp} values from the present study with literature values is not possible due to differences in experimental conditions such as the mode of can rotation (axial vs end-over-end), transient temperature data gathering for experimental particle (fixed vs moving), physical properties of fluid and particles etc. However, the U values obtained were in the range of data published by Lenz and Lund (1978), Deniston *et al.* (1987) and Stoforos and Merson (1992). The h_{fp} values obtained in the present study were much higher compared to those determined by Lenz and Lund (1978) and Deniston *et al.* (1987). This discrepancy can be due the fact that in earlier studies the motion of the test particle was restricted by temperature measuring devices. The h_{fp} values determined in the present study were in the range reported by Stoforos and Merson (1992) who measured the particle surface temperature using fluid crystals while it moved freely in the can during axial rotation.

Influence of Particle Size on U and h_{fp}

It was found that particle size influenced ($p \leq 0.0001$) the overall heat transfer coefficient. On an average, U for oil and water were found to decrease with increasing particle diameter. Figure 3 a and b are plots illustrating the influence of size of Nylon spheres in oil and water at different rotational speeds. The U values in oil decreased by about 9% as the size increased from 19.05 to 25.0 mm diameter. The particle size reduced the U in water by about 6%. Earlier, Lenz and Lund (1978) showed that the overall heat transfer coefficient in water and 60% aqueous sucrose solutions increased with increasing particle size. With water and potato spheres, no straightforward relation was found by Deniston *et al.* (1987).

The analysis of variance showed that the particle size influence was more on h_{fp} than that on U (Table 3). Using lead particles of diameter 9.5, 20.65 and 30.15 mm immersed in water, Lenz and Lund (1978) found the h_{fp} to increase with increasing particle size. With a 60% aqueous sucrose solution, the 20.6 mm diameter particle (medium size) had the lowest h_{fp}, the 9.5 mm diameter particle (smallest size) had the highest value and the 30.15 mm diameter particle (largest size) had intermediate value. Hassan (1984) showed that h_{fp} increased with decreasing particle size from 34.9 to 22.2 mm diameter of potato spheres. Deniston *et al.* (1987) also reported a small increase in h_{fp} values with decreasing particle size from 35.0 to 22.2 mm diameter. In the present study the h_{fp} values decreased as the particle size increased (Table 4). The decrease in h_{fp} was probably due to associated thicker velocity boundary layers with larger diameter particles. The influence of particle size on h_{fp} is illustrated in Fig. 3 c and d at various rotational speeds. The fluid to particle heat transfer coefficient in oil decreased by 13% when particle diameter increased from 19.05 mm to

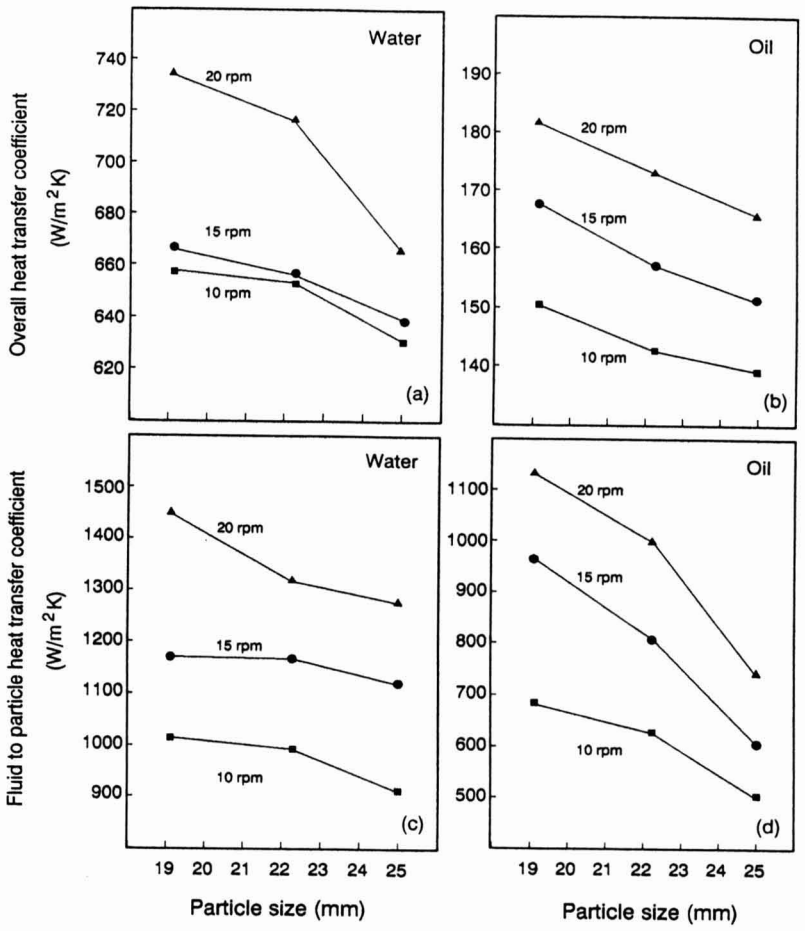

FIG. 3. INFLUENCE OF PARTICLE SIZE ON OVERALL HEAT TRANSFER COEFFICIENTS (U) AND FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENT (h_{fp}) AT DIFFERENT ROTATIONAL SPEEDS FOR OIL AND WATER

22.25 mm while a further increase in size to 25.0 mm diameter reduced the h_{fp} by 24%. The influence of particle size on the h_{fp} was less pronounced in water. With an increase in particle size from 19.05 to 25.0 mm diameter, the h_{fp} values decreased by about 9%.

Influence of Particle Concentration on U and h_{fp}

As expected, it was found that the presence of particulate matter altered the flow pattern of pure fluid during end-over-end rotation and, thus, affected the

heat transfer coefficients. The particles are expected to cause secondary agitation contributing to the mixing of can contents due to their motion. However, in the presence of high concentration of particles, velocity gradient surrounding each particle may be affected. In this case, the viscosity of mixture will be also considerably higher than that of fluid because of the interference of boundary layers around interacting solid particles, and because of the increase of drag caused by the solid particles. Thus, the magnitude of heat transfer coefficients can be expected to depend upon the particle concentration.

Figure 4 a and b are the plots showing the influence of particle concentration on the overall heat transfer coefficient (U) for oil and water at different rotational speeds. The U increased by 20% for oil and 5% for water when the particle concentration increased to 20% from a single particle. However, further increased in particle concentration to 40% decreased the overall heat transfer coefficient by 31% for oil and 27% for water. The lower particle concentration (20%) made a positive contribution to the fluid mixing and thus enhanced the overall heat transfer coefficient compared to single particle situation. However, at higher particle concentrations (30 to 40%), the secondary agitation effect due to the presences of particle was probably masked by the increased drag forces exerted by the particles on the fluid which resulted in lowering the overall heat transfer coefficient. Lenz and Lund (1978) observed that increasing the particle volume fraction by adding real food particles of different sizes to the fluid also decreased the overall heat transfer coefficient. During the processing of potato spheres in water, Deniston *et al.* (1987) found that the overall heat transfer increased with increasing particle concentration from 10.7% to 40%, but decreased at higher particle concentrations.

The fluid-to-particle heat transfer coefficient also improved significantly ($p \leq 0.0001$) with increased particle concentration. The particle concentration effect was more pronounced on h_{fp} values than U values. Analysis of variance showed that particle concentration accounted for about 75% of total variability. The influence of particle concentration on the h_{fp} is illustrated in Fig. 4 c and d. The h_{fp} increased 3 folds for oil and 3.4 folds for water when the particle concentration increased to 30% from a single particle. However, a further increase in particle concentration to 40% resulted in tight packing in the can which restricted the free particle movement and, thus, reduced the h_{fp} values by 12% and 7% for oil and water, respectively. Data from the studies of Lenz and Lund (1978) also showed that higher particle concentrations decreased h_{fp}. Hassan (1984) observed that for 2.54 cm diameter Teflon spheres h_{fp} improved with increased particle concentration from 20% to 31%. Deniston *et al.* (1987) reported slight increase in h_{fp} with increase in particle concentration from 10.7% to 40%, but decreased at higher particle concentrations (45.3% and 50.6%).

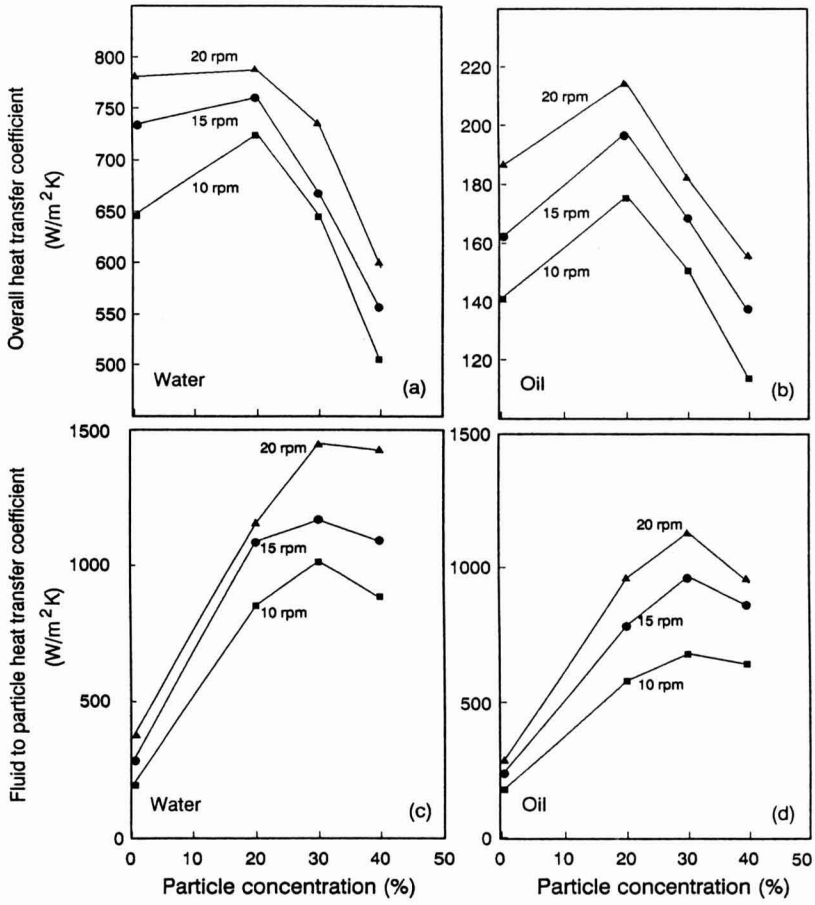

FIG. 4. INFLUENCE OF PARTICLE CONCENTRATION ON OVERALL HEAT TRANSFER COEFFICIENTS (U) AND FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENT (h_{fp}) AT DIFFERENT ROTATIONAL SPEEDS FOR OIL AND WATER

CONCLUSIONS

Overall heat transfer coefficients between retort heating medium (water) and test fluids (oil and water), and fluid-to-particle heat transfer coefficient between Nylon spheres and test fluid were influenced ($p \leq 0.0001$) by particle size and concentration at all the rotational speeds. Using a flexible thermocouple approach for temperature measurement of the moving particle, the range of h_{fp} value obtained in the present study was comparable to some previously published values. Higher U and h_{fp} values were obtained at lower fluid viscosity and higher rotational speeds. Initial increase in particle concentration from a single

particle level enhanced the U and h_{fp}; however, particle concentrations more than 20% and 30% decreased the U and h_{fp}, respectively. U and h_{fp}, followed a reciprocal relationship with particle size in oil and water at all the rotational speeds. The influence of particle size, particle concentration and rotational speed were more pronounced for the viscous fluid (oil).

ACKNOWLEDGMENTS

This research was supported by the Partnership Grant Program from Agriculture Canada, Natural Science and Engineering Research Council of Canada and Industry (Cordon Bleu Int. Ltd.).

NOMENCLATURE

a	Radius of sphere, m
A	Total external surface area, m^2
C_p	Heat capacity, J/kg.K
F_o	Process lethality, min
h_{fp}	Fluid-to-particle heat transfer coefficient, $W/m^2.K$
k	Thermal conductivity, W/m.K
m	Mass, kg
r	Radial coordinate system
T	Temperature, °C
t	Time, s
U	Overall heat transfer coefficient, $W/m^2.K$
$< >$	Volumetric average

Greek symbol

α	Thermal diffusivity, m^2/s

Subscripts

c	Can
i	Initial condition
f	Fluid
p	Particle
pt	Process time
R	Retort
s	Surface

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COAGULATION OF FISH PROTEINS FROM FROZEN FISH MINCE WASH WATER BY OHMIC HEATING

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Accepted for Publication August 15, 1996

ABSTRACT

A batch-type ohmic heating device was developed to investigate the possibility of coagulating fish proteins from frozen fish mince wash water. At constant voltage (90 VAC), the temperature of wash water samples was raised to different set points (40, 50, 60, 70, and 80C, respectively). Effect of heating on coagulation of proteins and removal of COD, TS, and TSS was investigated. When the temperature reached 70C, 33.0%, 59.3%, 33.3%, and 92.1% protein, COD, TS, and TSS, respectively, were removed from the wash water. Holding samples at constant temperatures for longer time periods did not improve solids removal, except at 40C. The highest heating temperature for effective coagulation of proteins and removal of solids is 70C. The relationship between heating temperature and heating time followed a second order polynomial model. Apparent electrical conductivity and energy consumption increased linearly with the heating temperature. At the early stage of heating, almost all electric energy was converted to heat energy. As the temperatures rose, energy efficiency began to decrease linearly with the temperature. Overall energy efficiency was above 86%.

INTRODUCTION

Heat coagulation of fish proteins from waste water is one available method that could be adopted by the seafood industry (Valle and Aguile 1990). During thermal treatment process, heat is supplied to raise the temperature of waste water and causes heat-sensitive proteins to coagulate and precipitate. In

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Journal of Food Process Engineering **20** (1997) 285–300.

principle, two distinct methods, direct or indirect heating, can be used. In direct heating, the heating medium (such as steam or hot water) is in direct contact with the materials to be heated. While in indirect heating, the heating medium is separated from the materials in different types of heat exchangers. Direct steam injection is a classical example of direct heating. Steam is directly injected and mixed with waste water, causing proteins to coagulate and precipitate at different temperatures. Although relatively high in energy efficiency, the main drawback of direct steam injection is that it increases the volume of water, often by 12% or more, due to steam condensation (Edwards and Kohler 1981). This not only increases the burden of downstream dewatering operations, but also generally requires larger fluid handling equipment to cope with increased volumes. In an indirect heating process, steam is supplied inside heat exchanging tubes or plates of a heat exchanger. As waste water flows in contact with the external walls of the heat exchanging tubes or plates, heat is transferred from the steam through the wall of the tubes or plates to the waste water, causing it to increase in temperature. As protein coagulates, a considerable amount of proteins is deposited on the surface of the heating walls, increasing the heat transfer resistance (Sandu and Singh 1991). Although scaped-surface heat exchangers can significantly reduce the coated foulants by a rotating shaft, these exchangers are generally very expensive and require higher operating and maintenance costs. In either direct or indirect heating where steam is involved, energy efficiency cannot be very high due to the large latent heat needed to generate steam, and due to energy loss in heat transfer.

Ohmic heating is a novel direct heating method which employs an alternating electric current to pass through the material to be heated. Due to the electrical resistance of the material, electric energy is directly converted to heat energy causing the temperature to rise. It is believed to be more energy efficient, and has been developed in the food industry to aseptically process liquid foods containing particulate suspensions (Stirling 1987; Biss *et al.* 1989; de Alwis and Fryer 1990; Sastry and Palaniappan 1992). Almost all research efforts have been focused on using ohmic heating to sterilize foods. Little research has been done on using ohmic heating to coagulate protein from proteinaceous liquids, particularly from surimi waste water.

Surimi is a Japanese term for mechanically deboned, minced and washed fish flesh widely used as an intermediate product for a variety of fabricated seafoods, such as imitation crab legs and flakes (Lee 1984). In industrial surimi manufacturing practices, fish mince is repeatedly washed with chilled water to remove sarcoplasmic proteins to produce a tasteless and odorless product. As a result of washing, approximately 40-50% of the minced fish solids (containing primarily soluble protein and myofibrillar protein) is lost in washing and dewatering processes (Pacheco-Aguilar *et al.* 1989; Lin *et al.* 1994; Huang *et al.* 1996). Consequently, large volumes of waste water containing mainly fish

protein, fats, and other organic materials are generated in downstream dewatering processes. Plants located inside or nearby cities may increase the burden on local waste water treatment plants by discharging waste water to local sewage systems. Those located close to bays or estuaries may discharge their waste water directly into nearby waters, thereby having negative environmental impacts. Unlike other sectors of the industry, waste water from the surimi processing industry contains 1-2% valuable protein. It is estimated that approximately 34 L of waste water would be generated to make every kg of frozen surimi from fish mince (Huang *et al.* 1996). Recovering fish protein from surimi waste water can not only reduce the negative environmental impacts and costs of waste disposal, but also may generate potential profits if the protein can be utilized (Martin 1988).

Our objectives were to investigate the heat coagulation of fish protein from frozen fish mince wash water by ohmic heating, the kinetics of coagulation process, the effectiveness of heat coagulation in waste reduction, changes of electrical conductivity as temperature rises, and the energy efficiency of ohmic heating process. Results of this research can be used in coagulating protein from surimi waste water.

MATERIALS AND METHODS

Ohmic Heating Apparatus

A batch-type ohmic heating apparatus was developed (Fig. 1). It consisted of a 500 mL beaker, two 316 stainless steel electrodes (33 mm × 120 mm × 1 mm), a variable transformer (Type 3PN116B, the Superior Electric Co., Bristol, CT), a temperature controller (Type E5CS-R1KJX-520, Omron Manufacturing, the Netherlands B.V.), and a solid state relay (Model SSR240A-C10, OMEGA Engineering, Stamford, CT). To prevent heat loss, the beaker, covered with a plastic lid, was enclosed inside a styrofoam box (wall thickness 3.8 cm). The styrofoam box was then placed on top of a magnetic stirrer (Model SP18425, Barnstead/Thermolyne, Dubuque, IA). A stirring bar was used to gently mix the sample to ensure uniform heating. Applied voltage was set at 90 VAC. The heating temperatures were controlled by the temperature controller using simple on-off mechanism. The temperature was measured by a Type C thermocouple every 5 s and recorded in a datalogger (Model CR-21X, Campbell Scientific, Inc., Logon, UT). An AC current transducer (Model OM8-2182-AFA0, OMEGA Engineering, Stamford, CT) converted the AC current in the circuit to a linear DC voltage output signal that could be recorded by the datalogger.

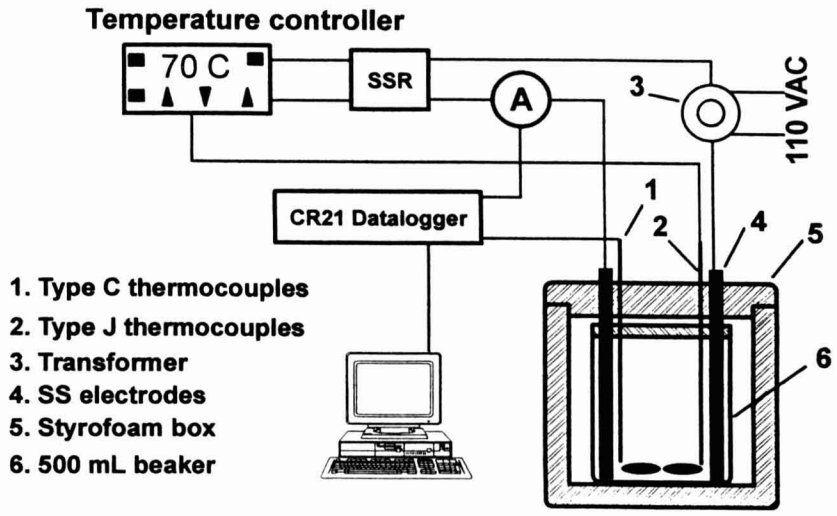

FIG. 1. THE BATCH-TYPE OHMIC HEATING APPARATUS USED IN COAGULATING FISH PROTEIN FROM FROZEN FISH WASH WATER

Sample Preparation

Pacific whiting fish mince was obtained from a local surimi processing company. Approximately 500-600 g of fish mince was vacuum-packed in a plastic bag and stored in a deep freezer (-40C) until use. Upon use, frozen fish mince was thawed in a 3-5C refrigerator overnight. The thawed fish mince was weighed and washed with distilled water (fish/water ratio = 1/3) for 3 min under a mild stirring condition. The fish mince slurry was consecutively filtered through two stainless steel strainers (hole diameters 2 mm and 1 mm, respectively) to remove coarse fish meat particles (washed mince).

Heat Coagulation

The wash water was immediately used in the heating experiments. A sample of 250 g was used in the beaker in each test. To evaluate the effect of heating upon the coagulation of fish protein, temperature of wash water samples were raised to different set points (40, 50, 60, 70, and 80C, respectively). After reaching a selected set point, the temperature was held constant for different time periods to investigate the effect of holding time varying from 0 to 9 min on protein coagulation. The electric power was cut off after the sample temperature reached the set point and was resupplied when the temperature dropped 1C below the set point. At the end of the heating experiments, the

samples were centrifuged at 1700 × g for 10 min. The supernatants were collected and analyzed for water quality. All tests were run in duplicate.

Chemical Analysis

Chemical analysis was conducted to determine total solids (TS), total suspended solids (TSS), chemical oxygen demand (COD), protein, pH, and ash. TS and TSS were measured using Standard Methods (Greenberg *et al.* 1980). Protein was analyzed using the Kjeldahl method with a conversion factor of 6.25 (AOAC, 1995). COD was measured using the method developed by Hach Chemical Co. (Gibbs 1979). Ash was measured by burning the dried samples at 525C overnight (AOAC, 1995). Sodium dodecylsulfate polyacrylamide gel electrophoresis (SDS-PAGE) was performed using the method modified from Laemmli (1970) to evaluate the effect of different heating conditions on removal of different components of protein in the frozen fish mince wash water.

Engineering Analysis of Heating Process

Kinetics of Heat Coagulation. In fish waste water, there are many different proteins, each of them having different thermal stability. During the heating process, different components of the protein mixture precipitate at different temperatures. Proteins with less thermal stability coagulate first, followed by the ones with higher stability. Therefore, coagulation approximates a continuous or pseudo-continuous process. Since the protein concentration in the samples was less than 1%, the heat of phase change during protein coagulation was minimal. The process can be regarded as a general chemical reaction without phase change.

During ohmic heating, the amount of protein coagulated from the fish mince wash water is a function of both heating temperature and heating time. The rate of protein coagulation can be expressed as

$$-\frac{dC_A}{dt} = kC_A^{\alpha}. \tag{1}$$

The reaction rate constant k is a function of temperature, and is conventionally determined by the Arrhenious equation:

$$k=\beta e^{\frac{-E_a}{RT_a}}. \tag{2}$$

Since heating is a continuous process, the rate constant k changes with both temperature T_a and heating time t. Combining Eq. (1) and (2) and transforming into the logarithmic form, we can obtain

$$\text{Ln}\left[-\frac{dC_A(t)}{dt}\right] = \text{Ln}(\beta) + \frac{-E_a}{R}\left[\frac{1}{T_a(t)}\right] + \alpha\text{Ln}(C_A(t)). \quad (3)$$

By measuring the concentration at different temperatures (T_a) and at the corresponding heating times (t), the rate of change in concentration ($-dC_A/dt$) can be calculated. Through multiple linear regression, it is possible to obtain the reaction order and activation energy of protein coagulation from the coefficients and intercept of Eq. (3).

Since the coagulation of protein is positively correlated to the removal of COD, TS, and TSS from the feed solution, the kinetics of removing these parameters can also be expressed as Eq. (3). Due to the difficulty in maintaining a constant initial concentration of the samples, relative concentration C_A/C_{AO} was used to calculate the reaction order and the activation energy (C_{AO} is the initial concentration).

Apparent Electrical Conductivity and Energy Consumption. Generally electrical conductivity of a conductive solution increases with temperature. It is a critical parameter in designing and operating an ohmic heating device (Palaniappan and Sastry 1991a,b). The apparent electrical conductivity can be calculated from

$$\sigma = \frac{I}{V}\left[\frac{L}{A}\right]. \quad (4)$$

Since electrical resistance of a material changes with temperature, if the electric voltage is kept constant during ohmic heating, the electric current I changes with temperature. Total electric energy consumption increases with heating time and can be calculated from Eq. (5)

$$E(t) = \int_0^t \frac{VI(t)}{m}dt \quad (5)$$

If the specific heat of the wash water is assumed to be the same as that of pure water, and remains constant throughout the heating process, then the energy required to raise the temperature can be expressed as

$$E_h(t) = C_p(T(t) - T_o). \quad (6)$$

Overall energy efficiency of the ohmic heating process can be calculated from

$$\eta(t) = \frac{E_h(t)}{E(t)}. \quad (7)$$

RESULTS AND DISCUSSION

The temperature of wash water increased with the heating time, as shown in Fig. 2. Under testing conditions with an initial temperature around 19C, the temperature and time relationship during ohmic heating was very reproducible, and can be modelled using a second order polynomial model ($R^2 = 0.9997$):

$$T(t) = 19.4 + 0.0948t + 0.000128t^2. \quad (8)$$

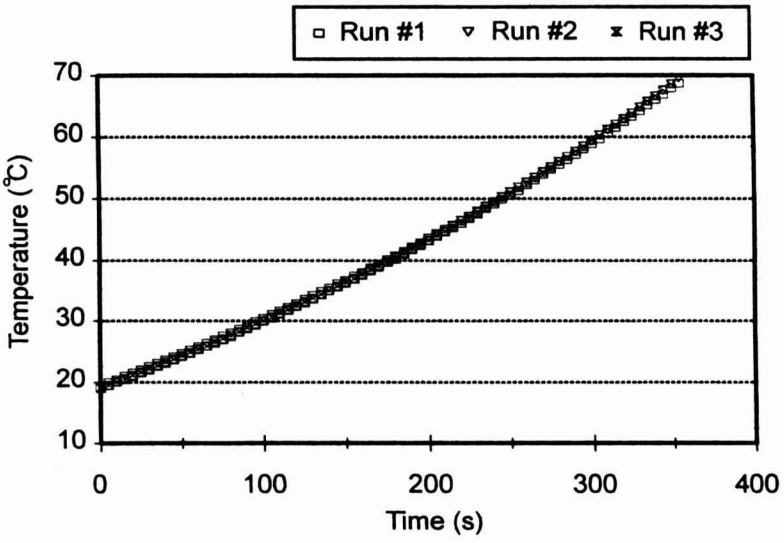

FIG. 2. TEMPERATURE INCREASED WITH THE HEATING TIME UNDER THE TEST CONDITIONS

As more electric energy was converted to heat energy, the temperature rose, and concentration of protein in the wash water samples decreased, together with COD, TS and TSS (Fig. 3). TSS of unheated sample in the 40C and 50C tests was notably lower than that of the other unheated samples (Fig. 3), which may be due to improper handling of the samples that led to proteolytic degradation of protein prior to TSS measurements (Morrissey *et al.* 1993). Positive correlation between coagulation of protein and removal of COD, TS, and TSS

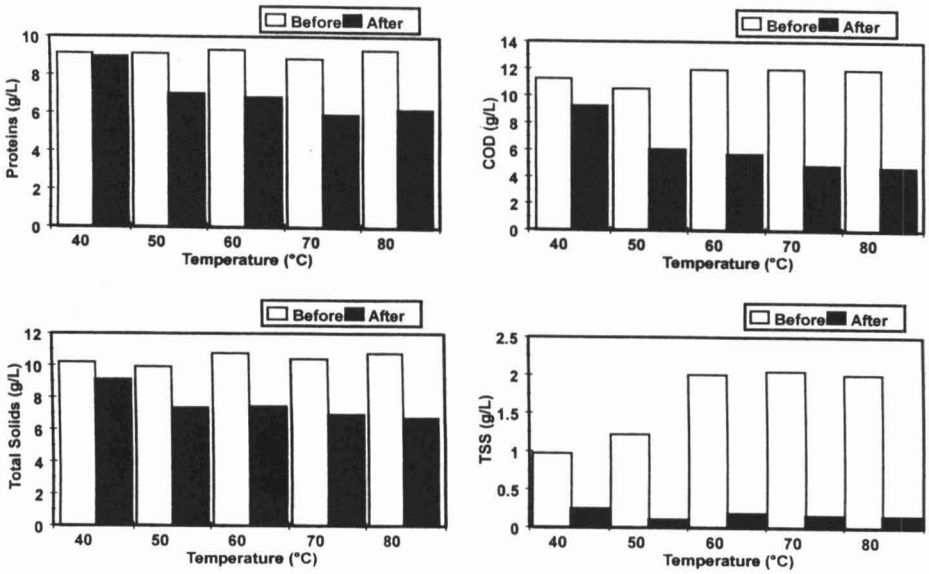

FIG. 3. EFFECT OF HEATING TEMPERATURE ON CONCENTRATION OF PROTEIN, COD, TS, AND TSS

was found (Table 1). After heating to 70C, 59.3% COD and 92.1% TSS were removed by ohmic heating, while only 33.0% protein and 33.3% TS, were removed. This indicates that the coagulated protein (33.0%) contributed to the majority of COD and TSS levels in the original wash water samples. Very little

TABLE 1.
CORRELATION BETWEEN PROTEIN REMOVAL AND REDUCTION IN COD, TS, AND TSS AS EXPRESSED AS PEARSON CORRELATION COEFFICIENT R

Solids	R	p
COD	0.993	0.0007
TS	0.988	0.0015
TSS	0.938	0.0183

improvement in solids reduction was achieved after further heating to 80C. Maximum reduction of protein, COD, TS, and TSS was achieved in temperatures above 70C (Fig. 4), indicating only heat sensitive protein can be removed from the wash water by heating methods.

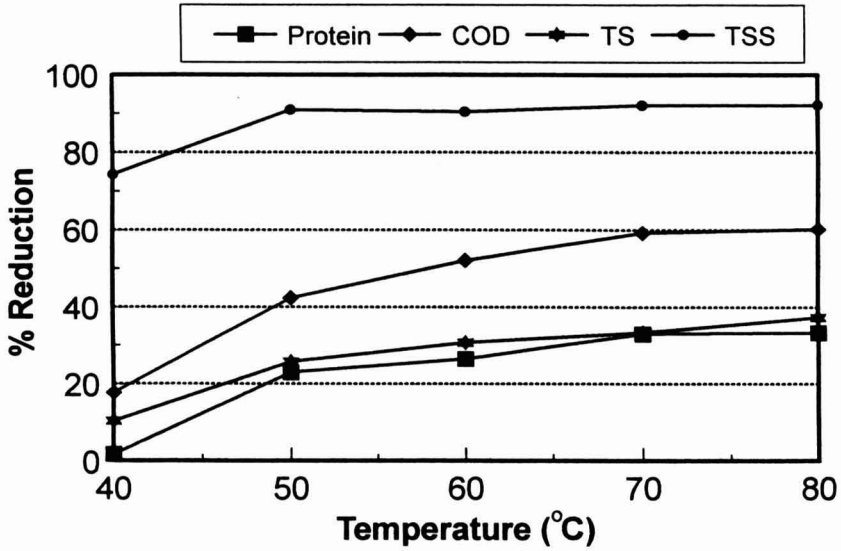

FIG. 4. EFFECT OF HEATING TEMPERATURE ON REMOVAL OF PROTEIN, COD, AND TS FROM THE WASH WATER SAMPLES

Heat stable proteins remained soluble in the wash water. This observation coincided with the results of the SDS-PAGE (Fig. 5). At low heating temperatures (40 and 50C), the pattern of protein bands were very similar to that of the control. As the temperature rose to 60C, the bands having molecular weight of around 40K began to disappear. As the temperature was increased to 60C, the protein bands between 40-45K were noticeably diminished. At heating temperatures of 70C and above, all protein bands in SDS-PAGE disappeared. This indicates that the bulk of heat sensitive proteins were effectively removed at these temperatures. However, the majority of proteins remained in solution (Fig. 4). These would be soluble proteins probably of low molecular weight ($<$ 20K) that were not well defined by SDS-PAGE. The pH and ash content of the heated wash water were not affected by ohmic heating (Fig. 6).

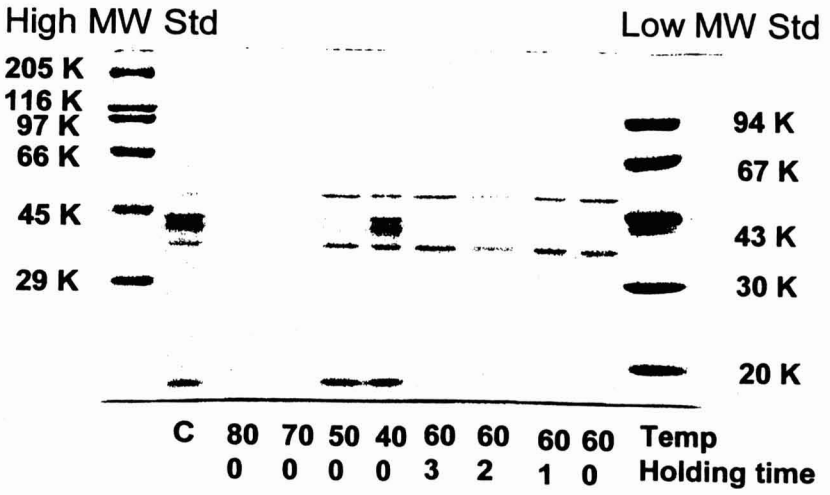

FIG. 5. SDS-PAGE OF HEAT TREATED SAMPLES
First and last lanes: high and low molecular weight standards; lane C: control; lanes 3-6: supernatant of wash water samples heated to 80, 70, 50, and 40C; lanes 7-10: supernatant of wash water samples heated to 60C with holding times at 3, 2, 1, and 0 min.

Ohmic heating was effective in removing the insoluble proteins at temperatures close to 70C. Lower temperatures may be employed in removing specific protein bands. There were few myofibrillar protein bands in the test samples. This may be due to the action of heat-activated proteolytic enzymes that are present in Pacific whiting (Morrissey *et al.* 1993). Because of seasonal constraints in surimi manufacturing, frozen mince was used for the test samples. Frozen storage will contribute to the denaturation of myofibrillar proteins in the mince that have not been stabilized by cryoprotectants. This denaturation may affect the results especially for the large molecular weight proteins. However, heat coagulation parameters should be similar to that of surimi wash water where the raw material has not been previously frozen.

As shown in Fig. 7, holding samples at constant temperatures after reaching the set points did not help further reduce the COD, except in the 40C test. This observation may indicate that raising the temperature of wash water by heating was more responsible for coagulating proteins and reducing solids. Holding the samples for a longer time at constant temperatures could not help remove more proteins at temperatures above 40C.

Kinetic analysis (Table 2) by multiple regression showed that the activation energy for coagulating proteins and reducing COD and TS was very low. Reaction orders for reduction of protein and COD are less than one with the exception of TS reduction.

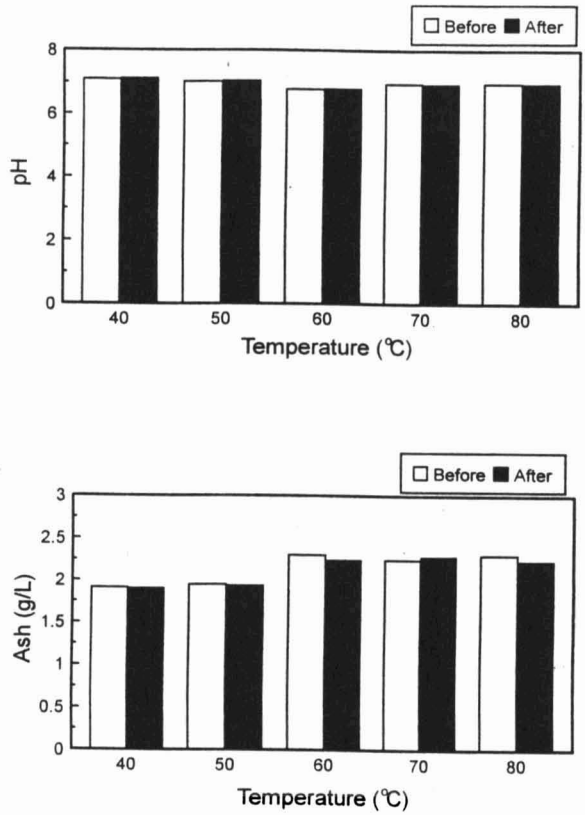

FIG. 6. EFFECT OF OHMIC HEATING ON THE pH VALUES AND THE ASH CONTENTS OF HEATED WASH WATER

Apparent electrical conductivity of wash water during the ohmic heating process increased linearly with the temperature at the rate of 0.0153 ± 0.0001 S/(m°C) (Fig. 8). Predicted apparent electrical conductivity at 0C was 0.288 ± 0.027 S/m. Electric energy consumption also increased linearly (4.606 ± 0.025 kJ/(kg °C)) with the temperature (Fig. 9). At low temperatures, nearly all electric energy was converted to heat energy. As the temperature increased, energy efficiency began to decrease at the rate of 0.244 ± 0.006 %/°C (R^2 = 0.891, Fig. 10). If the temperature was raised to 70C, at which point the majority of heat sensitive protein could be removed, the overall energy efficiency was still very high (86%). Reduced electric resistance and coagulation of protein may have contributed to decreased energy efficiency.

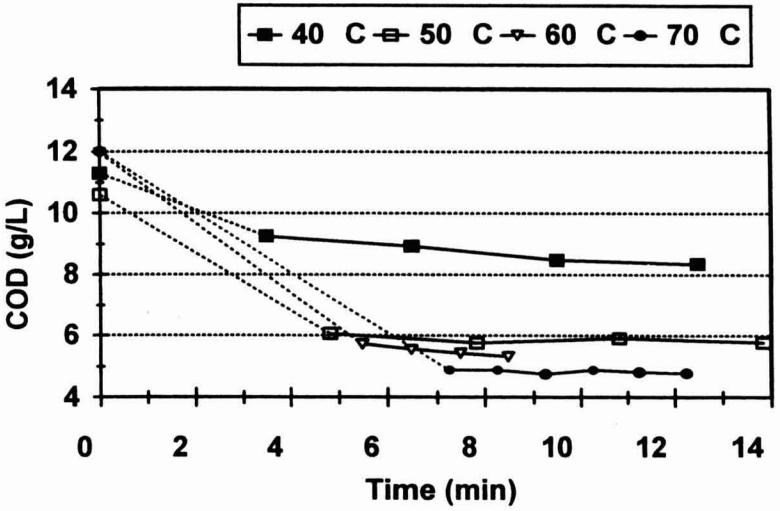

FIG. 7. EFFECT OF HOLDING TIME ON THE CONCENTRATION OF COD IN HEATED WASH WATER

TABLE 2.
KINETIC PARAMETER OF SOLIDS REMOVAL DURING OHMIC HEATING

Solids	Ln (β)	E_a (J/mol)	α	R^2
Protein	-13.1	429.9	0.655	0.9989
COD	-7.95	253.1	0.789	0.9997
TS	-8.75	259.8	1.11	0.9998

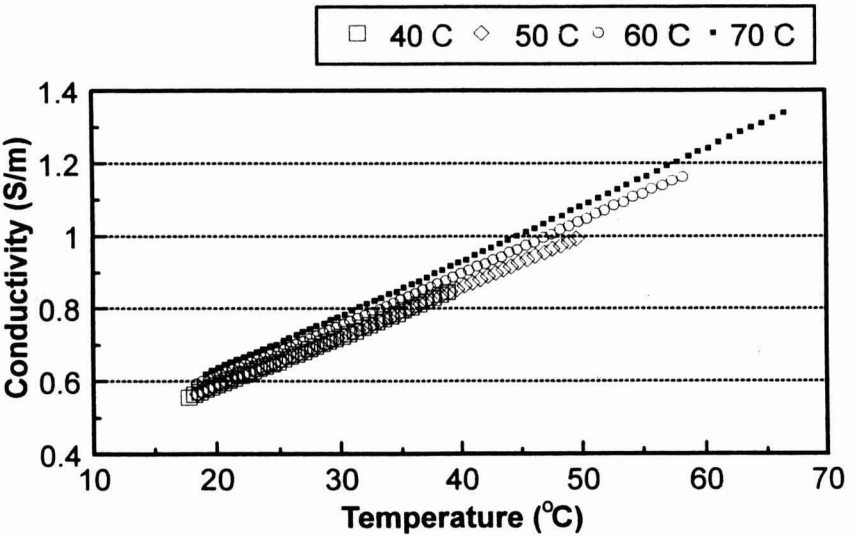

FIG. 8. THE APPARENT ELECTRICAL ACTIVITY INCREASED LINEARLY WITH HEATING TEMPERATURE

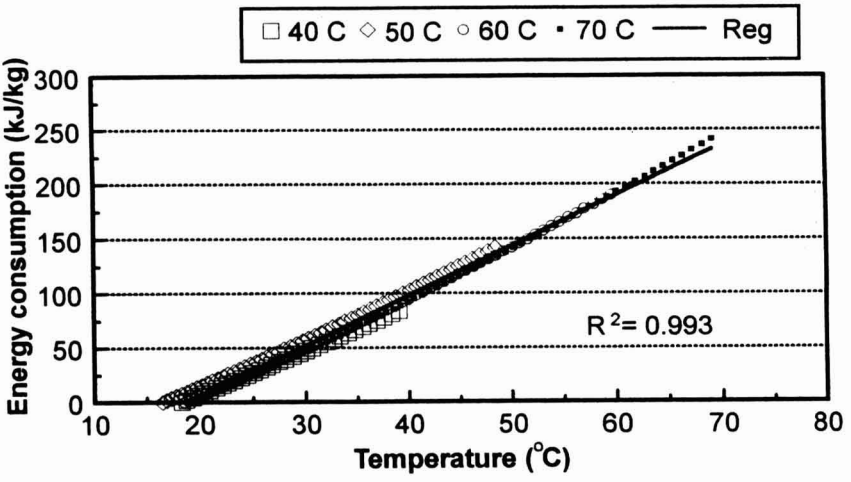

FIG. 9. THE OVERALL ENERGY CONSUMPTION INCREASED LINEARLY WITH THE SAMPLE TEMPERATURE DURING OHMIC HEATING

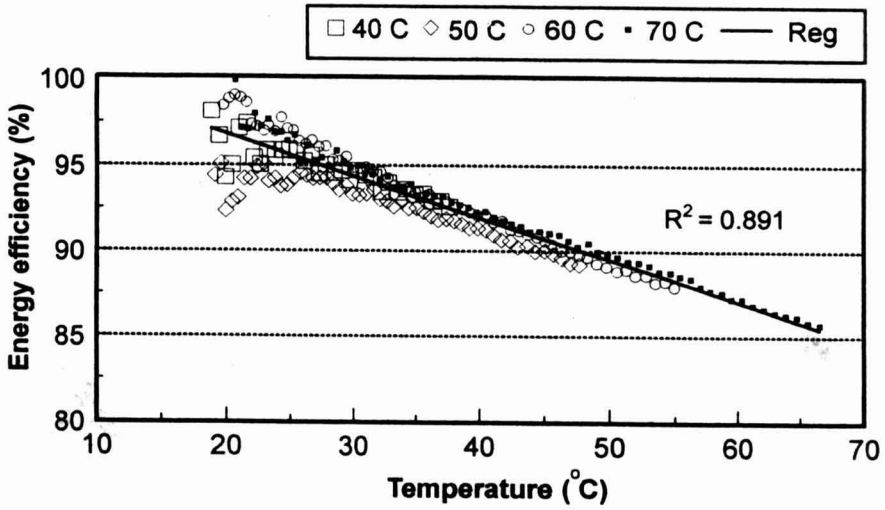

FIG. 10. THE ENERGY EFFICIENCY DECREASED LINEARLY WITH TEMPERATURE

CONCLUSIONS

Ohmic heating was an energy efficient process in coagulating proteins from wash water of frozen fish mince. The temperature changed with the heating time following a 2nd polynomial model. As temperatures rose above 70C, 33.0% of protein was coagulated from the wash water, which contributes to 59.3%, 33.3%, and 92.1% of reduction in COD, TS, and TSS, respectively. Longer holding time at constant temperatures did not improve the coagulation of protein and removal of COD, TS, and TSS, except at 40C. No significant changes in pH and ash contents were observed. Both apparent electrical conductivity and overall energy consumption increased linearly with temperature, but energy efficiency decreased linearly with the temperature. With increase in temperature, apparent electrical conductivity, overall energy consumption, and energy efficiency changed at a rate of 0.0153 $\pm$ 0.0001 S/(m°C), 4.606 $\pm$ 0.025 kJ/(kg °C), and -0.244 $\pm$ 0.006 (%/°C), respectively. Predicted apparent electrical conductivity at 0C was 0.288 $\pm$ 0.027 S/m. The highest heating temperature was recommended to be 70C. Although this research was conducted using wash water of frozen fish mince, the results may be useful in designing of an ohmic heating process to coagulate fish proteins from surimi waste water.

ACKNOWLEDGMENTS

This research was supported by grant No. NA36RG0451 (project no. R/SF-3) from the National Oceanic and Atmospheric Administration (NOAA) to the

Oregon State University Sea Grant College Program and by appropriations made by the Oregon State Legislature. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

NOMENCLATURE

A	Effective electric conducting area of the electrodes (m^2)
C_A	Protein concentration (g/L)
C_{AO}	Initial protein concentration (g/L)
E	Electric energy consumption per kg of sample (J/kg)
E_a	Activation energy (J/mol)
E_h	Heating energy required per unit kg of sample (J/kg)
I	Electric current (A)
L	Distance between two electrodes (m)
R	Gas constant, 8.314, (J/mol.K)
T	Heating temperature at time t (°C)
T_a	Absolute temperature (K)
T_o	Initial temperature (°C)
V	Electric voltage (V)
k	Reaction rate constant
m	Total mass of sample (kg)
t	Heating time (s)
α	Reaction order
β	Frequency factor
η	Energy efficiency
σ	Apparent electrical conductivity (S/m)
$-(dC_A/dt)$	Reaction rate (g/L/s)

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PUNCTURE AND STRESS RELAXATION BEHAVIOR OF BLACKGRAM (*PHASEOLUS MUNGO*) FLOUR-BASED *PAPAD* DOUGH

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Accepted for Publication October 26, 1996

ABSTRACT

Papad *is a popular traditional food adjunct in South East Asian countries. The rheology of* papad *dough is important for the purpose of sheeting and/or rolling. In the present study, two methods for testing the behavior of* papad *dough (prepared from blackgram flour) have been presented and correlated with the instrumental stickiness values. These consist of an empirical method (puncture testing) and a fundamental procedure (stress relaxation characteristics). In the former method maximum stress during compression was used as an index. In the later method, the parameters determined included the stress decaying constants* k_1 *and* k_2*, the percent relaxation and the initial compressive stress. These tests were conducted on the* papad *dough with varying moisture content (32-40%) and at different dough holding (resting) times (0-120 min). Stickiness values in the range of 141 and 148° were suitable for machining of the dough to make flat circular* papad *sheets. The corresponding moisture content was between 35 and 36% when the holding time was in the range of 0-30 min.*

INTRODUCTION

Papad is a popular traditional snack food used mainly as a food adjunct. In several South East Asian countries including India it is consumed mainly due to low cost, high shelf-life and attractive taste. In recent years, it is gaining recognition as an unique oriental contribution to international menu. India produces about 10^8 kg of *papads* per year. *Papad* exports have reached a quantity of about 7×10^6 kg in 1993-1994 (Anon 1995).

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Journal of Food Process Engineering **20** (1997) 301–316.

Papad is essentially a thin wafer-like product, usually circular in shape, and rolled from a legume flour dough. The commonly used legume for *papad* making is blackgram (*Phaseolus mungo*), although a small quantity of horsegram (*Dolichos biflorus*) *papads* are also prepared. *Papad* doughs are low moisture mixtures of water, legume flours and sometimes other cereals. Other ingredients, such as common salt, carbonates, spices and oil are also added. This dough is processed by flattening to a thin rolled sheet followed by drying to a moisture content of 14 to 15%. Finally, this sheet is deep fat fried or even toasted/baked. The toasted or baked *papad* has a low content of oil (less than 5%) such that it can be used as a low calorie tasty product even supplying a considerable amount of protein (20-22%) (Shurpalekar 1986).

Though a popular snack, only a few research investigations have been reported. The rheological characteristics of the *papad* dough affect its rolling and sheeting behavior, mixing characteristics, and hence, the finished product quality. The quality of *papad* dough in terms of rheology is determined usually by subjective assessment (by feeling with hand) and terms like soft or tough, easy or difficult to roll are used. Such terms are not suitable for use in a large-scale manufacturing sector and also for quality control. Therefore, an objective procedure for the determination of *papad* dough rheology should be useful. A preliminary study to use a Brabender Farinograph to measure the strength of *papad* has been attempted (Shurpalekar and Venkatesh 1975). But, in a recent study on the rheology of tortilla dough, Torres *et al.* (1994) have indicated that doughs can vary in their rheological behavior even though they have the same Farinograph values. As the *papad* doughs are compressed between plates or between rollers, uniaxial compression testing should be applicable. Bagley and Christianson (1986) proposed that a stress growth treatment is useful in characterizing doughs and relating such characteristics to processing behavior. Further, the surface property, particularly stickiness, has a major impact on the ability of the dough to be readily processed by handling equipments (Martin and Stewart 1991). It is felt that a simplified technique may be developed to study the *papad* dough characteristics. It is equally important to know the variation in the rheological properties of *papad* dough, with variables such as moisture addition and time of holding of the dough before rolling or sheeting. *Papad* dough properties are necessary for quality control, process modelling and for scale-up purposes.

The purpose of the present study on *papad* dough is to evaluate two rheological techniques: an empirical test (puncture behavior), and a fundamental test (stress relaxation characteristics) in relation to the effect of moisture content of dough and holding time of the same on the rheological behavior. The effect of these variables on the instrumental stickiness of the dough has also been determined.

THEORETICAL CONSIDERATIONS

Stress Relaxation

In the case of viscoelastic material, if a stress is applied quickly and the strain is kept constant, the material shows a decaying stress as a function of time. The relaxation curve has been normalized (Eq. 1) by Peleg (1979) and later modified (Eq. 2) (Peleg and Normand 1983; Purkayastha and Peleg 1986) to calculate the decaying parameters.

$$Y(t)=\frac{F_o}{F_o-F(t)} \tag{1}$$

$$\frac{F_o t}{F_o-F(t)} = k_1 + k_2 t \tag{2}$$

In Eq. (2), $1/k_1$ is the initial decay rate and $1/k_2$ denotes the asymptotic value of the relaxed portion of the initial stress. It follows that $1/k_2 \rightarrow 0$ for an elastic solid and $1/k_2 \rightarrow 1$ for a liquid. The values for the constants k_1 and k_2 can be obtained respectively, from the intercept and slope of the plot of relaxation time against $F_o t/[F_o-F(t)]$.

The initial compressive stress is obtained as:

$$\sigma_o=\frac{F_o}{A_o} \tag{3}$$

A convenient way of expressing stress relaxation is to measure the time required for the force to relax to a given percentage of its initial value (Szczesniak 1983). This is a time consuming method and the results depend on the extent of relaxation. Alternatively, a quick method for a quantitative estimation of relaxation parameter was proposed (Eq. 4) by Stanley and Emmons (1977) for cheese.

$$R_s = \frac{F_{1\ min}}{F_o} * 100 \tag{4}$$

This method was applied in the present study to determine the percent relaxation of the dough.

MATERIALS AND METHODS

Material

Blackgram (*Phaseolus mungo*) dhal (dehusked split pulse) was procured from the local market; after cleaning, they were ground in a laboratory model vertical stone grinder to obtain flour that passed through a British standard sieve of 85 mesh (180 microns).

Dough Preparation

100 parts of flour, 6 parts of powdered common salt and 1 part of 2:1 mixture of sodium carbonate and sodium bicarbonate were mixed for 2 min in a Hobart mixer. Varying quantities of water were added to attain the desired moisture content (31.9 to 39.7%, wet basis) and mixed for another 2 min in the same mixer to obtain the *papad* dough. After holding the dough for 0, 30, 60, 90 or 120 min, small spheres of about 50 mm in diameter were manually made and they were placed in a sample holder (35 mm diameter, 20 mm height) to obtain a cylindrical sample (after removing the excess portion) for further testing. Five samples were prepared and the process is replicated twice.

Stickiness of Dough

The stickiness of the dough was determined according to the method proposed by Noguchi *et al.* (1976) using the two-cycle compression with a crosshead speed of 50 mm min^{-1}. Reported stickiness values, in degrees, were the mean of five observations.

Puncture Test

Penetration of the dough with a flat bottom probe of diameter 10 mm was used to compress to an extent of 75% of the initial height of the sample. An Universal Testing machine (Model no 4301, Instron Corporation, Buckinghamshire, UK) with a crosshead speed of 200 mm/min was employed for puncture testing. Maximum puncture stress was calculated by dividing the maximum force during penetration by cross-sectional area of the probe. The number of samples tested was five and the process is replicated twice.

Stress Relaxation

In the fundamental test, stress relaxation characteristics of the lubricated (using paraffin oil) cylindrical sample (35 mm diameter, 20 mm height) was determined. The extent of compression was 25% at a compression rate of 200 mm/min. When the compression was achieved at the 25% level, the crosshead

surface (110 mm in diameter) was stopped and the dough was allowed to relax for 480 s. The force at different relaxation times was continuously monitored. Initial compressive stress and percent relaxation were calculated using Eq. (3) and (4), respectively. The constants (k_1 and k_2) were obtained from the intercept and slope, respectively from the relaxation curve by plotting relaxation time against $F_0t/[F_0-F(t)]$ according to Eq. (2). The reported results are the mean of five observations and the whole experiment was repeated twice.

Experimental Design and Data Analysis

The independent variables were the moisture content (31.9, 33.8, 35.2, 37.8 and 39.7%) and dough holding time (0, 30, 60, 90 and 120 min), such that a total of 25 combinations were possible. An additional sample of 24 h holding time was tested for the stickiness of the dough. The correlation coefficients, presented in Table 1, was based on 25 data points. The significance of the correlation coefficients was judged at a probability of 0.001.

TABLE 1.
CORRELATION COEFFICIENT (r) MATRIX BETWEEN THE RHEOLOGICAL PARAMETERS

	R_s	S	k_1	k_2	σ_p
σ_o	0.83	0.82	0.86	0.90	0.95
R_s	-	0.95	0.99	0.97	0.94
S		-	0.93	0.93	0.91
k_1			-	0.97	0.95
k_2				-	0.96

All r values are significant at p = 0.001

The experimental results or response functions (maximum puncture stress, initial stress, percent dough relaxation, k_1, k_2 and stickiness) were related to the independent variables (moisture content and holding time of dough) by a second

order polynomial using the technique of least squares (Little and Hills 1978). These polynomials were used to draw 3D response surfaces.

RESULTS

Puncture Test

The response surface in Fig. 1 shows the effect of moisture content and holding time of dough on maximum puncture stress. Increase in moisture content from 31.9 to 39.7% markedly decreased the puncture stress; it had a higher effect than that of holding time. An increase in holding time elevated the puncture stress; the extent of increase being high (>20%) at lower dough moisture content (31.9-35.2%) compared to that (<10%) at higher moistures (37.8-39.7%).

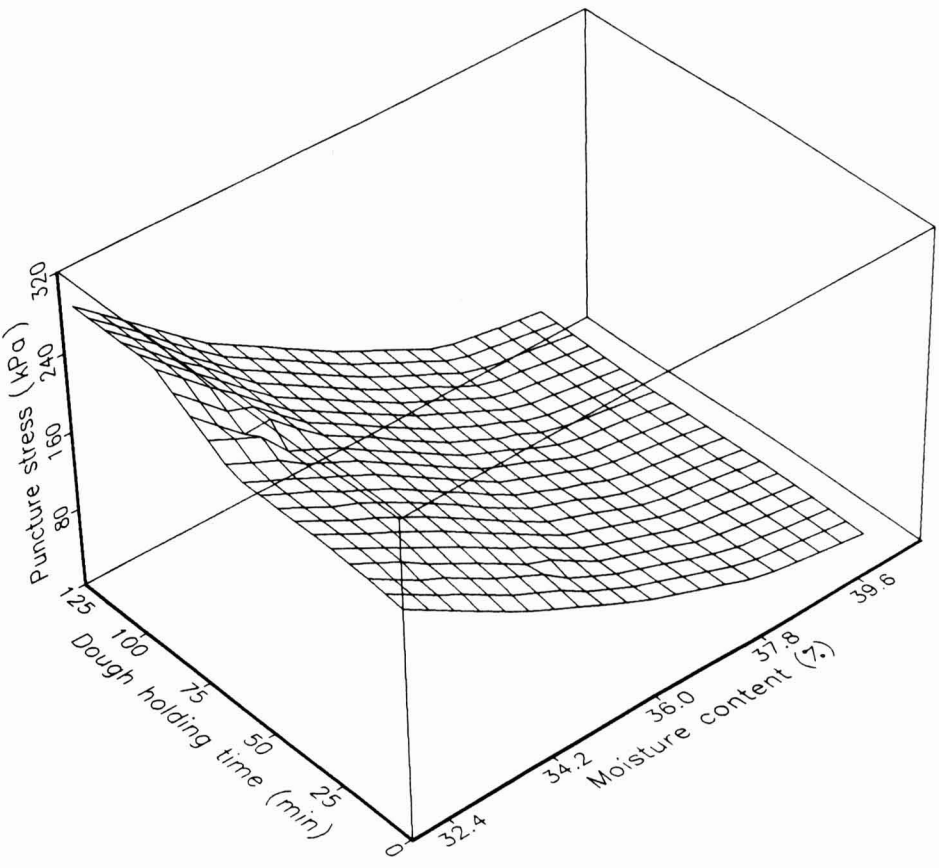

FIG. 1. RESPONSE SURFACE FOR MAXIMUM PUNCTURE STRESS OF *PAPAD* DOUGH

Stickiness

The stickiness (S) of the *papad* dough is between 103 and 177 degrees, and is represented by the response surface plot (Fig. 2). An increase in moisture content markedly increased stickiness values whereas the effect of holding time is low. A slight increase in stickiness was observed with increasing holding time only at low moisture (31.9-35.2%) contents. An increase in holding time up to 24 h showed negligible change in stickiness values (data not presented in Fig. 2). For example, stickiness values with 31.9% moisture at 2 and 24 h were 128 and 130 degrees, respectively; with 39.7% moisture content, these values were 176 and 177 degrees, respectively.

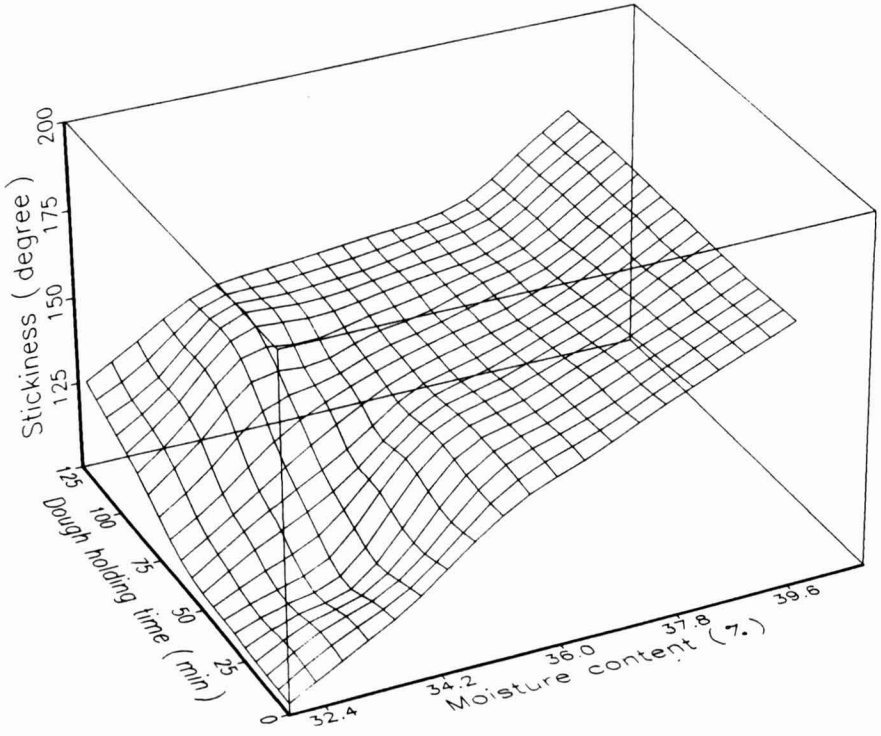

FIG. 2. STICKINESS OF *PAPAD* DOUGH AS A FUNCTION OF MOISTURE CONTENT AND HOLDING TIME

Stress Relaxation

The sample plot (Fig. 3) shows the relaxation curves (as a function of time) of *papad* doughs at different moisture contents (31.9 and 39.7%) for a holding time of zero minute. At the end of experimental time (480 s), all the relaxation curves attained fairly steady conditions or equilibrium values. The relaxation curves basically have three zones. Initially the force decreases sharply (zone 1); later, the rate of decrease is rather slow (zone 2), and finally in zone 3, dough cannot relax any further and attains an equilibrium status. As expected, low moisture dough (such as in the case of dough with 31.9% moisture) resists more than at higher moisture (39.7%) dough yielding a high value of initial stress (σ_o).

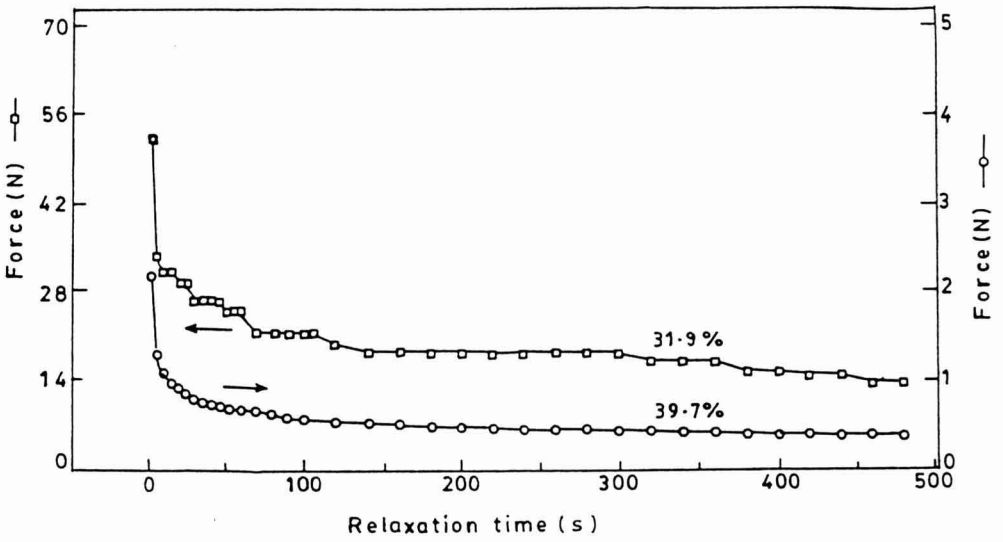

FIG. 3. RELAXATION CURVES FOR *PAPAD* DOUGH AT DIFFERENT MOISTURE CONTENTS

Figures 4 and 5, respectively, show the response surface for initial compressive stress or stress at the beginning of relaxation (σ_o) and extent of stress relaxation (R_s) at 1 min. An increase in moisture content of the dough drastically decreased the initial compressive stress (Fig. 4) and the extent of relaxation (Fig. 5). The σ_o values sharply decreased when moisture content is increased from 31.9 to 33.8%.

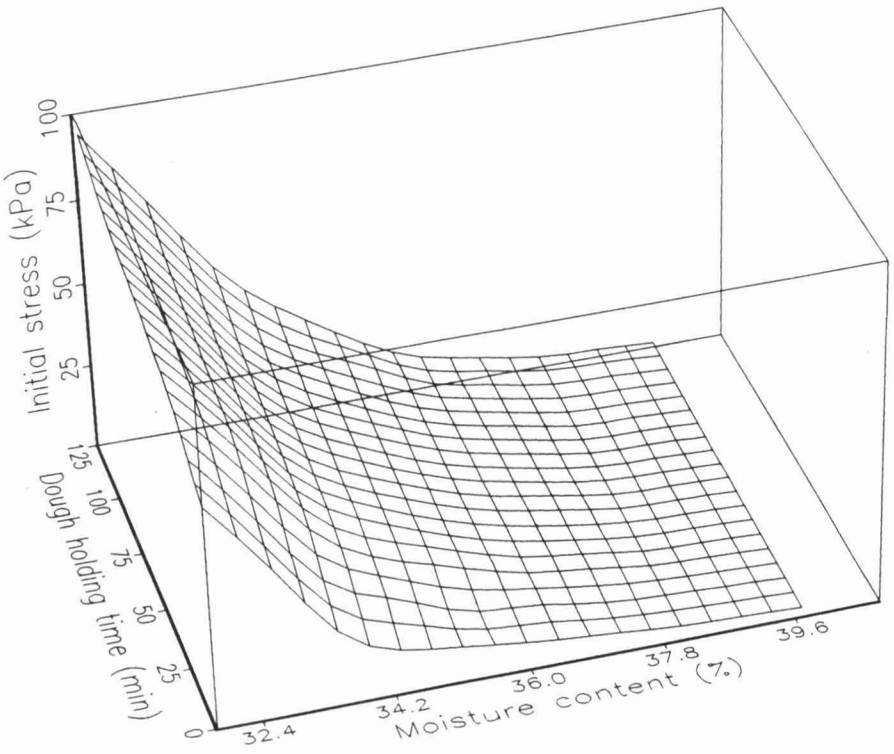

FIG. 4. RESPONSE CURVE FOR INITIAL STRESS (σ_o) AT DIFFERENT MOISTURE CONTENTS AND HOLDING TIMES

The parameter $[F_o t/\{F_o - F(t)\}]$ when plotted against relaxation time yielded straight lines ($r \geq 0.994$, $p \leq 0.01$) for *papad* doughs at all combinations of moisture content (31.9-39.7%) and dough holding times (0-120 min). The representative normalized plot at a moisture content of 35.2% (and at zero holding time) produced a straight line (Fig. 6) with a very high correlation coefficient ($r = 0.998$, $p < 0.01$).

The effect of moisture content of dough and dough holding time on the constants (k_1 and k_2) are represented by response surfaces in Fig. 7 and 8, respectively. The behavior of these variables on the constants k_1 and k_2 was similar to Fig. 5. An increase in moisture content decreased k_1 and k_2 (i.e. increased both $1/k_1$ and $1/k_2$) whereas the effect of dough holding time was negligible.

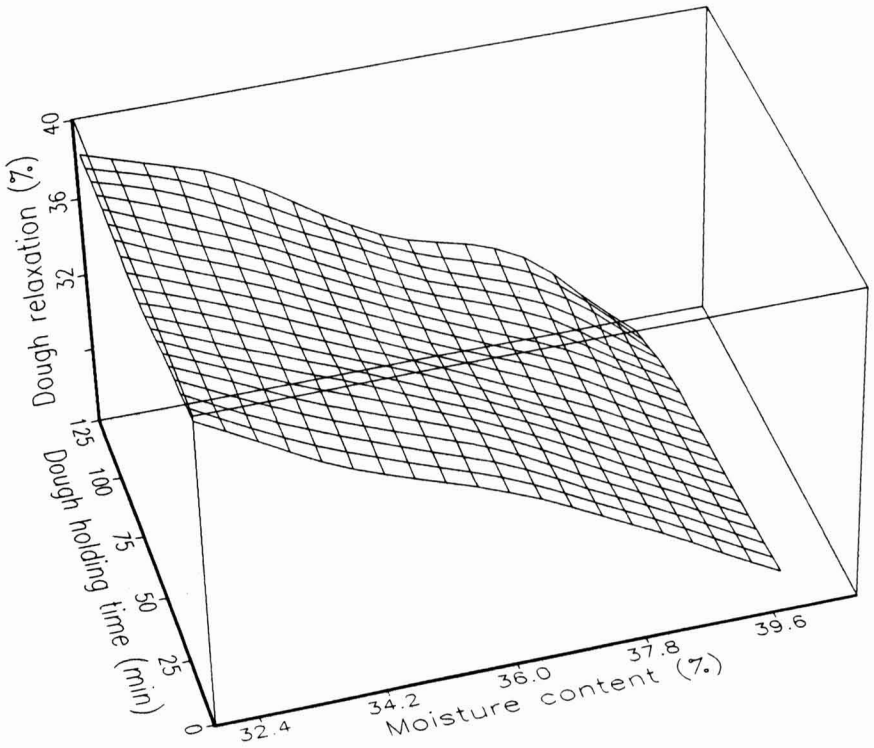

FIG. 5. PERCENT DOUGH RELAXATION AS A FUNCTION OF MOISTURE CONTENT AND HOLDING TIME

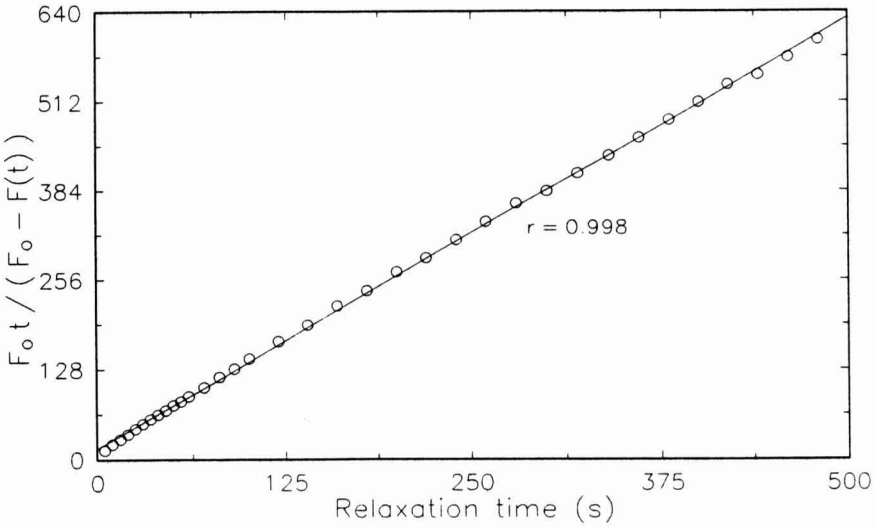

FIG. 6. NORMALIZED CURVE FOR *PAPAD* DOUGH

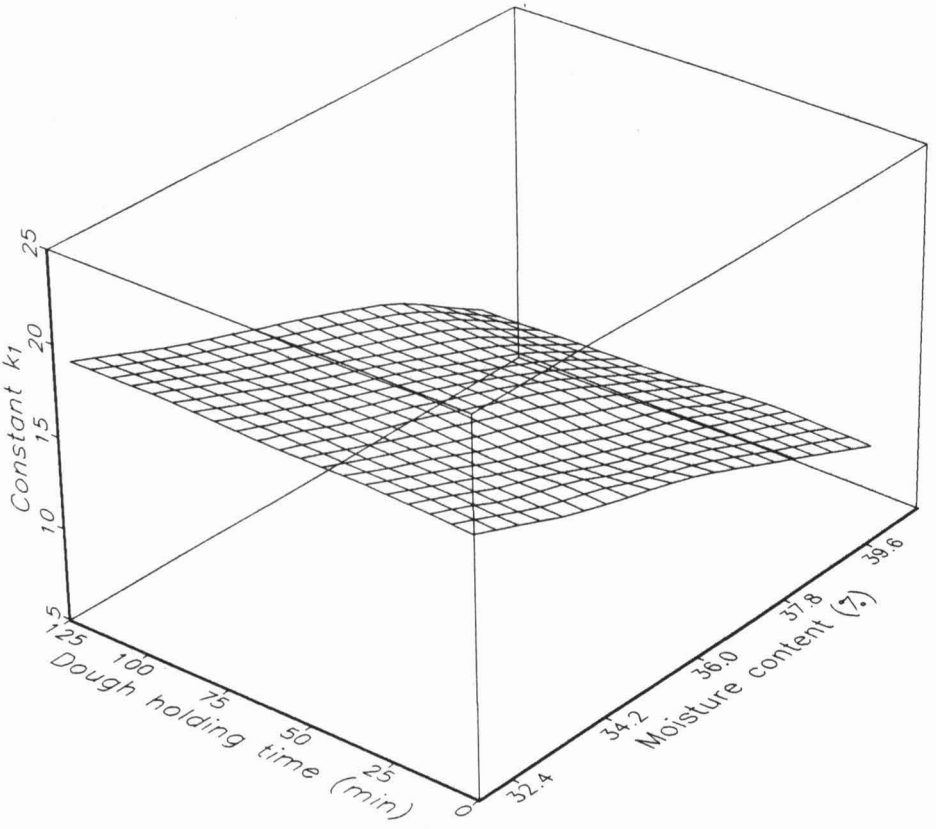

FIG. 7. EFFECT OF MOISTURE CONTENT AND HOLDING TIME ON CONSTANT k_1

Interrelationship Between the Rheological Parameters

The different parameters, obtained from puncture, stickiness and stress relaxation tests were interrelated (Table 1). Good correlations ($r \geq 0.91$, $p \leq 0.001$) were observed between puncture stress (σ_p) and all the stress relaxation parameters (σ_o, R_s, k_1 and k_2), and also between σ_p and stickiness. In addition, R_s, k_1 and k_2 were also highly interrelated ($r \geq 0.97$).

DISCUSSION

Stickiness

The stickiness of the dough plays an important role during processing. For *papad* dough, a stickiness value of above 162° gave rise to extreme difficulty

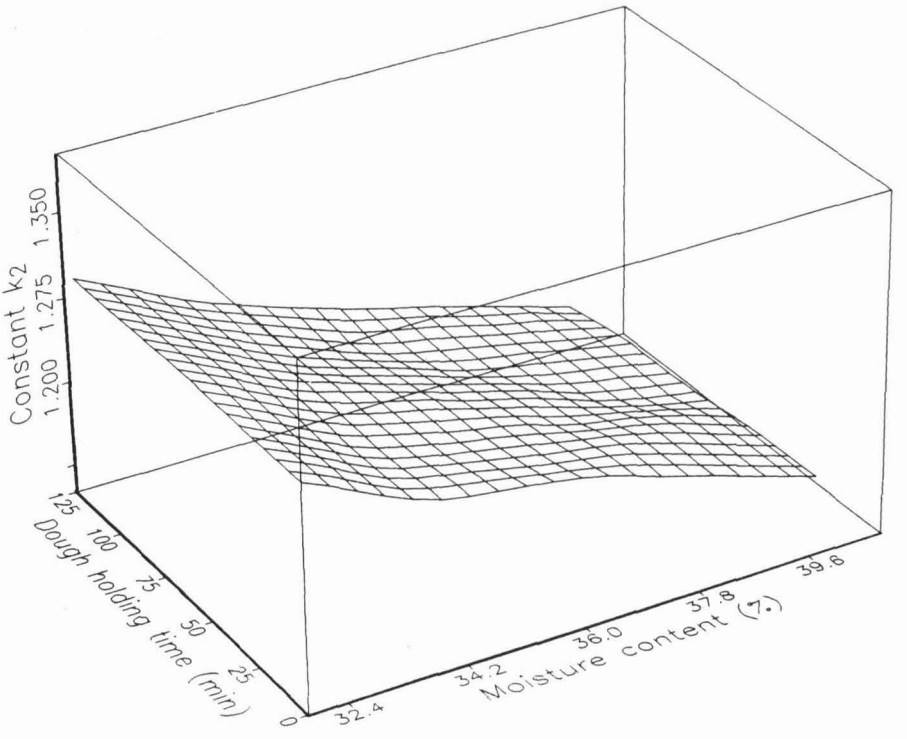

FIG. 8. VARIATION IN CONSTANT k_2 WITH MOISTURE CONTENT AND HOLDING TIME OF DOUGH

during rolling and/or flattening. Some problems of sticking to rolling/flattening surfaces were observed when stickiness was between 148 and 161°. Satisfactory machining property was obtained between 141 and 148°. The corresponding dough moisture was between 35 and 36%, and at that moisture content, negligible change in stickiness was noticed with an increase in dough holding time. Hence, a holding time of 0-30 min can be selected. It is worth mentioning here that Noguchi *et al.* (1976) reported that a stickiness value between 140 and 150° was suitable for machining of bread dough.

Puncture Test

Puncture test, though an empirical approach, represents one of the simplest and most widely used methods for the objective assessment of food texture (Hamann and MacDonald 1992) and rheology. A decrease in the puncture stress with increase in moisture content may be due to exuded moisture that reduced

the friction at the boundaries of the sample (Masi and Addeo 1986). An increase in the puncture stress of the dough (particularly at low moisture content) is possibly due to moisture absorption by major pulse components, such as, carbohydrates (mainly the nonstarchy type) and by proteins to produce a cohesive mass; this cohesive mass can offer high resistance during testing. It is worth mentioning here that blackgram contains about 23 and 60% protein and carbohydrate, respectively (Reddy *et al.* 1989), and 40% of the carbohydrate is starch; the polysaccharide present in blackgram is mainly arabinose (about 74%) (Reddy *et al.* 1990). On the other hand, at a high level of moisture (37.8-39.7%) (even after absorption of enough water by the dough), there appears to be some excess moisture in the dough. Such doughs with excess (free) moisture show fairly constant values even though the holding time was increased.

For proper machining of the *papad* dough, stickiness values in the range of 141 and 148° (corresponding to 35-36% moisture content and 0-30 min of holding time) was found suitable. The corresponding puncture stress values were in the range of 100 and 110 kPa. It is worth mentioning here that the *papad* made with 30 min holding time showed no difference from those made with traditional method (overnight holding of the dough) as long as the stickiness values were kept between 141 and 148° or the puncture stress values were between 100 and 110 kPa.

Stress Relaxation

Stress relaxation is a useful supplement to the compression test (Peleg 1977). This fundamental approach has been used for testing the rheology of food doughs, agar gel, sausage, bread, cheese, several fruits (apple, pear) and vegetable (potato) (Peleg 1979).

Papad doughs generate relaxation curves (Fig. 3) that depend mainly on the moisture content of the sample. Increase in moisture content allows the dough to relax to a high extent (and hence less resistance during relaxation) such that they turn to an elastico-viscous liquid (moisture content 39.7%, Fig. 3) from the viscoelastic solid (moisture content 31.9%, Fig. 3); these categories are made according to Peleg (1979). There may be two reasons for such behavior. Water in a dough has a plasticizing effect. Berland and Launay (1995) mentioned that in the case of wheat flour dough, water has mainly strong plasticizing effects, and it changes the values of the rheological parameters without modifying the structure. The second reason being the decrease in protein content when the dough moisture was increased. In an experiment with heat-set egg white gels, Hsieh and Regenstein (1993) found that $1/k_2$ decreases (i.e. elastic component increases) with an elevation in protein content. This implies that more protein was used to construct more cross-links (Masi and Addeo 1984) as concentration of protein increased. Adam *et al.* (1980) have found that for roll crumb, an

increase in moisture content decreased initial stress. Since legume flours are high protein foods, similar involvement of protein could be expected.

CONCLUSIONS

The instrumental methods of puncture and stress relaxation tests, and determination of dough stickiness could be applied to study the behavior of the *papad* dough. The moisture content of the dough imparted marked effect on the rheological parameters whereas dough holding time had a less effect. Stickiness values in the range of 141 and 148° give suitable machining property of the dough which corresponds to 35-36% moisture content. At this condition, the puncture stress (a simple measurement technique) values were between 100 and 110 kPa.

NOMENCLATURE

A_o	Initial cross-sectional area of the sample (m^2)
F_o	Initial force at time t=0 (N)
$F_{1\ min}$	Force at 1 min (N)
F(t)	Force at relaxation time t (N)
k_1, k_2	Constants in Eq. (2)
$1/k_1$	Initial decay rate (s^{-1})
$1/k_2$	Hypothetical asymptotic level of the relaxed portion of the stress (dimensionless)
p	Probability level (dimensionless)
r	Correlation coefficient (dimensionless)
R_s	Extent of stress relaxation at 1 min (%)
S	Stickiness of dough (degree)
t	Time of relaxation (s)
Y(t)	Decaying parameter (dimensionless)
σ_o	Initial compressive stress (kPa)
σ_p	Maximum puncture stress (kPa)

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INACTIVATION OF *ESCHERICHIA COLI* IN SKIM MILK BY HIGH INTENSITY PULSED ELECTRIC FIELDS

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Accepted for Publication December 17, 1996

ABSTRACT

The inactivation of microorganisms is the most important function in the processing of milk and dairy products. Traditionally, this purpose is realized by thermal treatment, but heat produces alterations to flavor and taste in addition to nutrient loss. The high intensity pulsed electric field (PEF) treatment should be a good alternative to heat because demonstrations have shown PEF can reduce the Escherichia coli *survival fraction in aqueous solutions and model foods. In this study, PEF treatment was found to inactivate* E. coli *in skim milk (inoculum 10^9 CFU/mL) at 15C. The microorganism inactivation satisfied Hülsheger's model following a first order kinetic for both the electric field intensity and number of pulses when skim milk inoculated with* E. coli *was treated in a static or continuous flow chamber. PEF treatment in a continuous system when the critical electric field (E_c) and minimum number of pulses (n_{min}) were 12.34 kV/cm and 2.7 at 30 kV/cm and 30 pulses (0.7–1.8 μs pulse width) inactivated more microorganisms than in a static system. It has also been proven that increasing the pulse duration increases the* E. coli *inactivation. The inactivation of* E. coli *using PEF is more limited in skim milk than in a buffer solution when exposed to similar treatment conditions of field intensity and number of pulses due to the complex composition of skim milk, its lower electrical resistivity and the presence of proteins.*

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Journal of Food Process Engineering **20** (1997) 317–336.

INTRODUCTION

As the most complete food, milk is a complex mixture of protein, carbohydrates, fat, water, vitamins, minerals and other nutrients (Ronsivalli and Vieira 1992). Skim milk, which may contain 0.5% fat or less, has been a popular beverage for many years. Most milk is produced on farms that deal primarily with the raising of dairy cattle. As drawn from the cow's udder, milk is seldom free from microorganisms (Ronsivalli and Vieira 1992). When improperly handled, raw milk, may undergo adverse changes such as becoming sour due to the growth of bacteria that produce lactic acid, or foamy from the growth of gas-producing coliform bacteria. The coliform test is one of the most commonly used in dairy microbiology for evaluating milk quality. Among coliforms, the presence of *E. coli* in dairy products is considered significant from a public health point of view (Singh *et al.* 1985). Certain strains of *E. coli* have been recognized as important emerging pathogens (Knabel 1995). The organism causes foodborne illnesses such as hemorrhagic colitis or bloody diarrhea (Griffin and Tauxe 1991; Padhye and Doyle 1992; Whittam *et al.* 1993). Recently, dairy cattle have been identified as a reservoir for *E. coli* (Vasavada and Cousin 1993; Cliver 1993).

The control of bacteria and bacterial growth is the most important function in the handling and manufacture of milk and dairy products (Ronsivalli and Vieira 1992). Currently, this control is carried out by pasteurization, in which milk must be heated to at least 63C for no less than 30 min (Potter 1986). Since pasteurized milk is not sterile, it must be quickly cooled following pasteurization to prevent multiplication of surviving bacteria. Milk may be sterilized rather than pasteurized by using more severe heat treatments such as UHT sterilization (150C, 2-3 s, Ronsivalli and Vieira 1992).

The increased consumer demand for fresh-like products without excessive loss of flavors, nutrients, and vitamins during food processing, has caused a growing interest in nonthermal processes such as pulsed electric fields (PEF) that inactivate microorganisms without adverse effects on food flavor and taste (Dunn and Pearlman 1987; Grahl *et al.* 1992; Knorr *et al.* 1994). Thermal treatment has proven to be a good method of pasteurization, but the alterations of flavor and taste in addition to loss of nutrients have led to objections on the part of the public (Jayaram *et al.* 1992). Pothakamury *et al.* (1995) compared the PEF technology to the thermal method by showing that a five log cycle reduction of *E. coli* can be achieved by heating milk at 82.2C. Similar results are observed when *E. coli* is inoculated in simulated milk ultrafiltrate (SMUF) and treated by high intensity PEF with 60 pulses of 200-300 μs at 16 kV/cm at a maintained temperature below 30C.

One of the earliest applications of electricity in food processing was the sterilization of milk. At the beginning of this century several authors found that

milk could be sterilized by passing a low-intensity alternating current through the food known as Electro-Pure Process, which resulted in microbial inactivation due to ohmic heating (Anderson and Finkelstein 1919; Beattie and Lewis 1925; Prescott 1927; Fetterman 1928; Getchell 1935). The Electro-Pure Process inactivated *Mycobacterium tuberculosis* and *E. coli* (Fetterman 1928). Moses (1938) estimated that between 1928 and 1938, at least 200 million quarts of electrically pasteurized milk were consumed without detrimental effects upon the health of consumers. However, the Electro-Pure Process fell into disfavor in the dairy industry by the 1960s because of the presence of chemical products from food electrolysis (Jayaram *et al.* 1992). More recently, Dunn and Pearlman (1987) inoculated homogenized and pasteurized milk with *E. coli* (8.1×10^6 CFU/mL) and treated it with 23 pulses of 100 μs at 28.6 - 42.8 kV. The population of *E. coli* immediately after treatment was reduced to 7.4×10^3. The temperature during treatment increased from 13C to 43C.

Microorganisms have a different behavior depending on the medium in which they exist. In an aqueous solution the behavior is different than in model foods, and both behaviors are distinct from the behaviors in real foods. The effect of high voltage on *E. coli* in buffer solutions has been well studied (Castro *et al.* 1993; Martín *et al.* 1994), and the inactivation of *E. coli* has been determined to be directly dependent on the electric field intensity and treatment time (Sale and Hamilton 1967; Zimmermann *et al.* 1974; Hülsheger *et al.* 1983; Zhang *et al.* 1994a). Sale and Hamilton (1967) and Hamilton and Sale (1967) reported a lethal effect of high voltages on *E. coli* suspended in a neutral solution of sodium chloride. Electric fields up to 25 kV/cm were applied as direct current pulses, and death of the organisms was due to an irreversible loss of the membrane function as a semipermeable barrier between the bacterial cell and its environment. Matsumoto *et al.* (1991) observed destruction of *E. coli* cells in a phosphate buffer solution after PEF treatment at 30 kV/cm using an electron microscope. The cells did not change their shape, but their size became rather small and their surface rough. Zimmerman *et al.* (1974) demonstrated that high voltage electric fields produce a dielectric breakdown of *E. coli* cell membranes, and moreover, *E. coli* cells from the logarithmic growth phase are killed in a markedly higher percentage than cells harvested from the stationary growth phase (Hülsheger *et al.* 1983). Hülsheger *et al.* (1981) described the survival rate (s) of microorganisms treated by PEF as a function of the field intensity (E) and treatment time (t):

$$\text{Ln } s = -b_E(E - E_c) \tag{1}$$

$$\text{Ln } s = -b_t \ln(t/t_c) \tag{2}$$

where b_E is a regression coefficient dependent of time treatment; E_c is the extrapolated critical value of E for $s=1$; b_t is the regression coefficient dependent of field intensity; and t_c is the extrapolated critical value of t for $s = 1$. Since the survival rate can be considered as a function of the field intensity and the treatment time, Eq. (3) was calculated from (1) and (2) (Hülsheger *et al.* 1983):

$$s = \left(\frac{t}{t_c}\right)^{\frac{-(E-E_c)}{k}} \tag{3}$$

where k is an independent constant factor.

Several authors ruled out the possibility of heating as the cause of bacteria inactivation by PEF since in most of the cases, the measurable temperature rise is less than 10C (Sale and Hamilton 1967; Hülsheger *et al.* 1981; Zimmermann *et al.* 1974). However, the temperature also affects the effectiveness of PEF treatment; an increase in treatment temperature from 7 to 20C significantly increases *E. coli* inactivation by PEF (Zhang *et al.* 1995a).

The bacteriocidal effect of electrical discharges on *E. coli* suspended in saline solutions is reduced when increasing the pH and ionic strength and consequently, the conductivity of the media (Sale and Hamilton 1967; Edebo *et al.* 1969; Hülsheger *et al.* 1981; Vega-Mercado *et al.* 1995). Electrolitically produced chlorine was shown to act as an additional toxic agent and bivalent cations were found to reduce the lethal action (Hülsheger *et al.* 1980; 1981). On the other hand, the presence of protein in the saline solution reduced the effectiveness of treatment and increased energy was required for complete sterilization. Proteins diminish the effect because they may absorb the active radicals and ions resulting from the discharges (Allen and Soike 1966; Gilliland and Speck 1967a).

Engineering aspects of PEF technology in food processing were reported by Zhang *et al.* (1994). Generation of pulsed electric fields, calculation of electric energy and pulse duration input, and the estimation of processing temperature increase per applied pulse were reviewed. For the given field intensity and pulse duration, increasing the processing temperature would significantly increase the microbial inactivation. However, the temperature should be controlled to ensure nonthermal treatment.

The purpose of all preservation methods is to initially inactivate the pathogen or spoilage microorganisms present in foods. To begin studies about the effectiveness of a potential preservation method and the particular effect of different parameters, a preliminary inactivation test must be realized in a buffer

solution and in model foods. In the development of nonthermal food pasteurization by using high intensity PEF technology, there are promising results about the inactivation of certain microorganisms such as *E. coli* inoculated in a buffer solution and model foods. At this stage of research, the knowledge of microbial inactivation in real foods is essential. This research was focused on the inactivation of *E. coli* in skim milk by high intensity PEF treatment. The main objective was to investigate the effect of PEF treatment applied using both a static and continuous flow treatment chamber at a low temperature (15C) and different field intensity, pulse duration and number of pulses.

MATERIALS AND METHODS

Microbial Preparation

Cultures of *Escherichia coli* (ATCC 11229) were obtained from American Type Culture Collection (ATCC, Rockville, MD) and bacteria were grown according to ATCC procedure. Nutrient broth (DIFCO 0003-01-6) was used as the growth medium. One milliliter of frozen culture was thawed, and inoculated in 50 mL of nutrient broth and continuously agitated in a temperature controlled shaker (Model MSB-3322A-1, GS Blue Electric, Blue Island, IL) at 37C and 135 oscillations per min for 15 h as a preculture. The 10 mL of preculture were inoculated into 500 mL of the growth medium, and incubated at 37C for 5.5 h to reach the early stationary phase. The growth of bacteria cells was followed by absorbance at 540 nm in a UV-light spectrophotometer (Koch 1981). *E. coli* cells were harvested by centrifugation at 3830 $\times$ g for 10 min at 10C using a Beckman J-21C centrifuge with a fixed-angle (JA14) rotor. *E. coli* pellets were washed with the chilled nutrient broth, centrifuged again, suspended in 0.5 mL of 20% glycerol cryoprotectant, frozen, and stored at -70C until needed for further use.

Individual frozen pellets of *E. coli* were thawed at room temperature for 5 min and then centrifuged at 4000 $\times$ g, 4C for 5 min to remove excess glycerol by decanting supernatant. The cell pellets were then resuspended in 40 mL of skim milk (Darigold Inc., Seattle, WA) for 20 min at 25C to hydrate the cells. To assess the dilution effect of skim milk on *E. coli* inactivation and to have an appropriate electrical resistance in the treatment chamber, the commercial skim milk was diluted to 1:1 and 1:2:3 with sterile water. To ensure the electrical energy received by the food, the load resistance in the treatment chamber had to be at least 2Ω in the designed PEF system.

The viable cells in inoculated milk before and after PEF treatment were assayed by counting colony-forming units (CFU) in a petri dish. Samples were plated on tryptic soy agar with violet red bile agar overlay and incubated at 37C

for 24 h as described by Richardson (1985). Dilutions for the CFU were carried out such that the number of colonies on the agar plates were between 25-250; the mean count was reported for the four plates used for each dilution.

Pulsed Electric Field Treatment Apparatus

Treatment in a Static Chamber System. A 40 kV Blumlein Pulse Forming Network (BPFN, Fig. 1) was designed and constructed to provide the high intensity short duration electric pulses. Two spools of RG-8A/U coaxial cables (152 m each) were used as the distributed capacitor-inductor units. When the switch was closed, the food in the treatment chamber was subjected to a high voltage square pulse. A typical measured pulse waveform is illustrated in Fig. 2. A matching resistance of the treatment chamber was required to obtain a meaningful waveform.

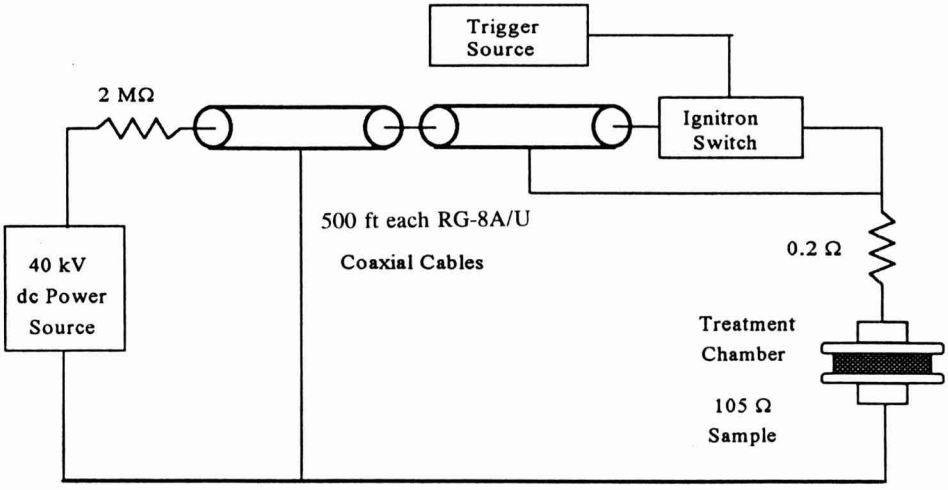

FIG. 1. CIRCUIT DIAGRAM OF A BLUMLEIN PULSE GENERATOR USING COAXIAL CABLES

A parallel plate treatment chamber (Fig. 3, Table 1) was used in all tests conducted (Zhang *et al.* 1995b). Cooling of the chamber was provided by circulating water at pre-selected temperatures through jackets built into the electrodes.

Treatment in a Continuous Chamber System. Figure 4 illustrates the circuit design which was constructed to produce exponential decay voltage

waveforms (Fig. 5). A dc power supply charged a capacitor bank in series with a charging resistor R_s, and when a trigger signal was applied to ignite the circuit, the charge stored in the capacitor flowed through the food in the treatment chamber. A parallel-plate chamber with flow-through ability was also designed and constructed (Zhang *et al.* 1995b) by adding baffles to the original static chamber (Fig. 6).

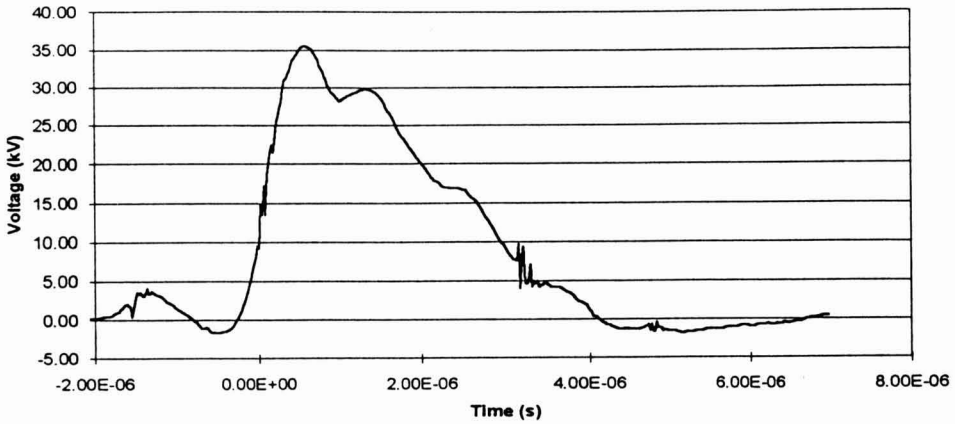

FIG. 2. MEASURED VOLTAGE OF 2 μs PULSES GENERATED BY A BLUMLEIN PULSE GENERATOR

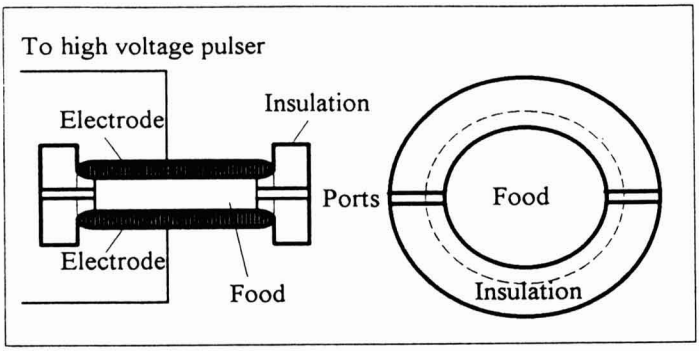

FIG. 3. SCHEMATIC DRAWING OF THE WSU STATIC TREATMENT CHAMBER USED IN THIS STUDY. ELECTRODES ARE POSITIONED HORIZONTALLY AT WORK

TABLE 1.
PARAMETERS OF PEF TREATMENT IN A STATIC CHAMBER SYSTEM

Description	Operating Condition
Electrode arrangement	Parallel, disk plates contour edge
Electrode orientation	Horizontal
Volume chamber (mL)	13.8
Electrode contact area (cm^2)	27.1
Electrode gap (cm)	0.51
Electrode material	Stainless steel
Insulator material	Plexiglas
Field uniformity	< 2%
Electrode cooling volume (mL)	14
Electrode cooling area (cm^2)	74
Cooling fluid	Water
Cooling fluid temperature (°C)	15
Cooling flow rate (mL/min)	1200

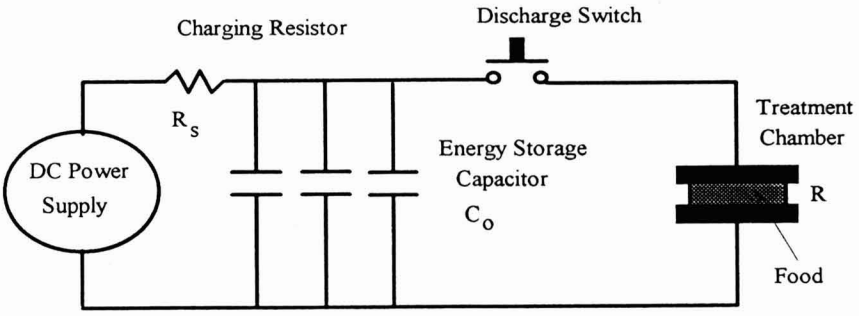

FIG. 4. LAYOUT OF AN EXPONENTIAL DECAY PULSE GENERATOR OF THREE CAPACITOR UNITS. $C_1 = C_2 = C_3 = 0.1\mu F$

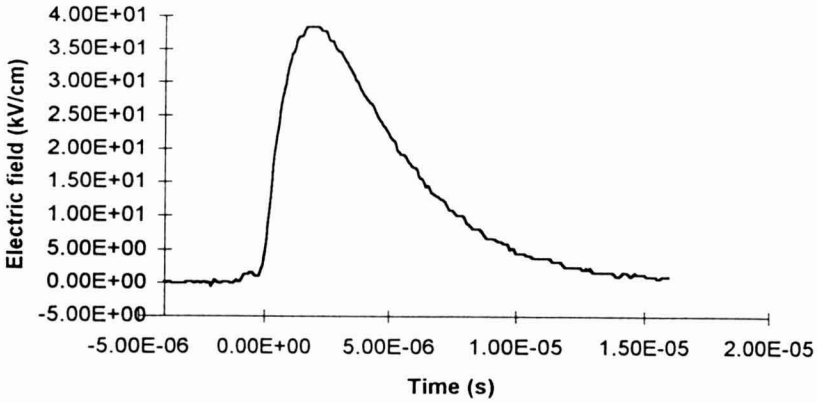

FIG. 5. TYPICAL WAVEFORM OF AN EXPONENTIAL DECAY PULSE

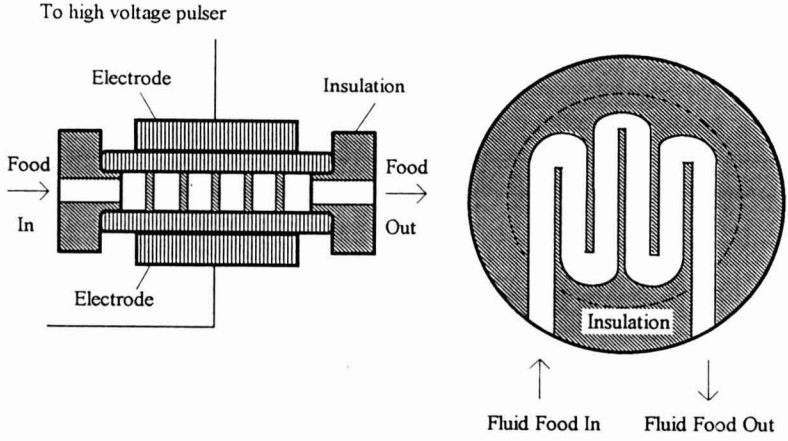

FIG. 6. SCHEMATIC DRAWING OF THE WSU CONTINUOUS-FLOW TREATMENT CHAMBER USED IN THIS STUDY
Fluid inside the chamber is baffled to avoid dead spots.

PEF Treatment Procedure

Treatment in a Static Chamber. The chamber was filled with *E. coli* inoculated skim milk (13.8 mL, 20C) for each treatment, in which gas bubbles

were completely expelled from the chamber. The temperature of the treatment chamber was controlled by circulating 15C water through the electrode, and the intervals between pulses (15-30 s) were controlled to maintain the electrode temperature within ±0.2C of the selected temperature (15C). After each treatment, the milk was removed from the chamber, which was washed with a 70% sterile alcohol solution and rinsed with sterile distilled water. The inoculated milk was subjected to a selected PEF treatment with a field intensity ranging from 20 to 45 kV/cm and a maximum of 64 applied pulses. The pulse width in the static treatment ranged from 1.8 μs to 6 μs.

Two basic types of PEF treatments were conducted in this study. A one step treatment was conducted by treating a batch of *E. coli* inoculated skim milk with a selected number of pulses not exceeding 16, with each set of data obtained by using one batch of freshly inoculated milk.

A stepwise treatment was conducted by treating the *E. coli* inoculated skim milk with 16 pulses each. Milk was recollected and retreated in batches, with only the first stepwise treatment loaded with batches of freshly inoculated milk. Consecutive stepwise treatments were loaded with milk that was treated previously. Since 1 mL of sample was needed to assay the microbial viability of *E. coli* before and after each treatment step, a sequence of six, four, and two batches of milk was treated in the first, second, third and fourth steps. In the first treatment step, six batches of freshly inoculated milk were separately treated with 16 pulses. The six batches were then collected, mixed, and divided in four batches which were treated with 16 additional pulses as the second step (32 pulses in total). The batches were collected after the second step, mixed and divided. The resulting two batches of milk were treated in a third and fourth step (32 pulses in total). Four treatment steps were conducted for each stepwise test and the averages of all the batches in each treatment step were reported.

Treatment in a Continuous Chamber. Twenty-five milliliters of *E. coli* inoculated skim milk were placed in a closed-loop system consisting of a reservoir, peristaltic pump, and chamber. Prior to the treatment 1 mL of milk was plated as the control, and 1 mL of skim milk was assayed for viability at a treatment ranging from 5–30 pulses. To maintain the same volume of milk in the circulating system, 1 mL of milk was added to the cell suspension after a 1 mL sample was taken. The experimental conditions were: processing temperature: 15C; constant flow rate: 45 mL/s; electric fields: 15-25 kV/cm; pulse duration: 0.7-1.8 μs; and pulse rate: 0.5 Hz.

RESULTS AND DISCUSSION

Treatment in a Static Chamber System

PEF treatment inactivates *E. coli* in skim milk at 15C. The principal

parameters influencing the microbial inactivation are the applied electric field intensity and treatment time, which can be expressed by the number of pulses (n) when the width of pulses is fixed (Qin *et al.* 1994c).

The *E. coli* survival fraction decreases when milk is treated with an increasing number of pulses at a constant field intensity (Fig. 7). The rate of inactivation of *E. coli* increases with an increase in the electric field intensity at a constant number of pulses (Fig. 8). Less than one log reduction in *E. coli* population was observed for PEF treatments of 20, 25 and 30 kV/cm with 64 pulses at 15C. However, PEF treatments at 45 kV/cm, 64 pulses, and 15C led to a nearly 3 log cycle reduction.

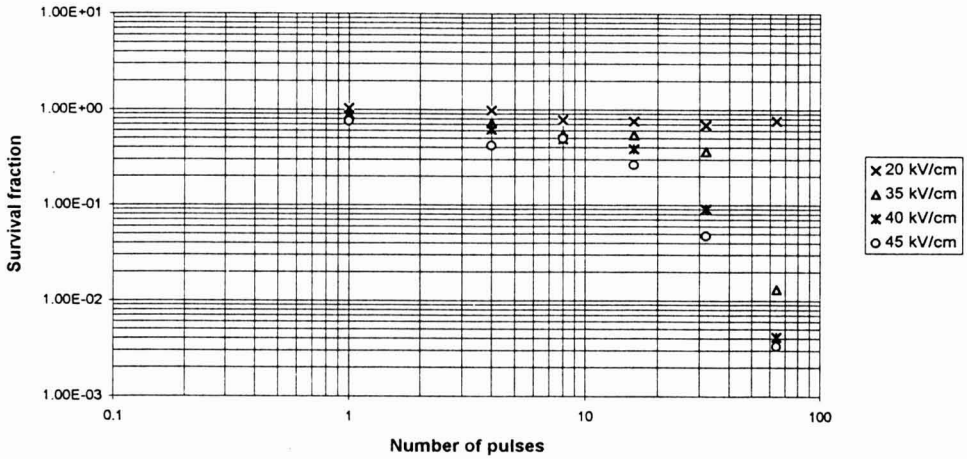

FIG. 7. INACTIVATION OF *E. COLI* IN SKIM MILK AT 15C IN A STATIC CHAMBER AT SEVERAL FIELD INTENSITIES

The obtained results are consistent with those reported by Dunn and Perlman (1987). Although the temperature increased up to 43C in the treatment applied by these authors and the treatment in this study was realized at 15C, similar *E. coli* inactivation was obtained with 20 kV/cm PEF in saline solution (Hamilton and Sale 1967). Hülsheger *et al.* (1983) reduced the population 4 log cycles by applying a PEF treatment of 20 kV/cm with 2-30 pulses and a 0.07-1.1 pulse duration for *E. coli* inoculated in phosphate buffer. Grahl *et al.* (1992) reached a nearly 5 log cycle reduction by treating *E. coli* suspended in a sodium alginate solution with 26 kV/cm PEF. The inactivation of *E. coli* in potato

dextrose agar by applying 64 pulses of 40 kV/cm at 15C resulted in a 6 log cycle reduction. Notice that PEF inactivation kinetics in semisolid products are different from the PEF inactivation kinetics in fluids because *E. coli* cells are fixed in a gel matrix which increases uniformity of inactivation (Zhang *et al.* 1994b).

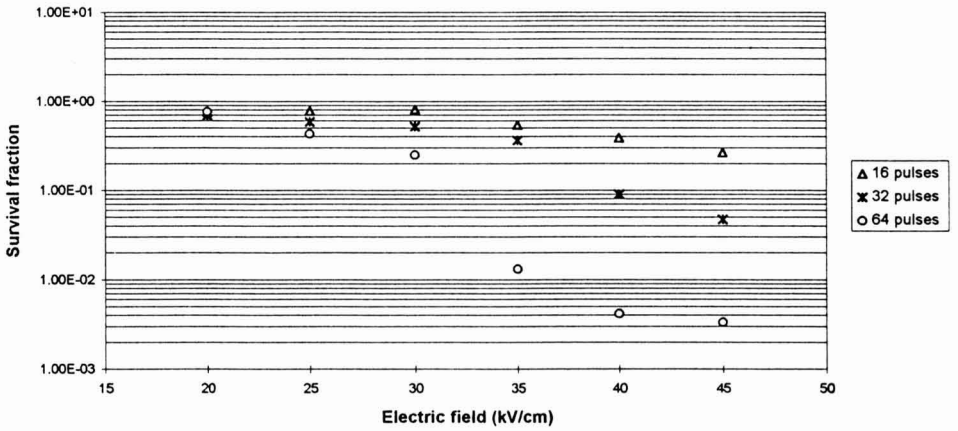

FIG. 8. INACTIVATION OF *E. COLI* IN SKIM MILK AT 15C IN A STATIC CHAMBER WITH DIFFERENT NUMBERS OF PULSES

Inactivation of *E. coli* in skim milk by PEF treatment in a static chamber satisfied Hülsheger's model (Table 2) because the destruction of this microorganism in skim milk followed a first order kinetic for both the electric field intensity and the number of pulses. The minimum number of pulses (n_{min}) necessary to inactivate the microorganism in skim milk at 45 kV/cm using a static chamber was 11 and 15 pulses at 35 kV/cm, respectively. The critical electric field (E_c) was 19.9 kV/cm with 64 pulses at 45 kV/cm. The E_c for inactivating the bacteria in milk was higher than the value reported by Grahl *et al.* (1992) for *E. coli* suspended in a sodium alginate solution (14 kV/cm). Zhang *et al.* (1994b) calculated 17.5 kV/cm E_c for *E. coli* in semisolid model foods.

It is more difficult to reduce the number of microorganisms present in skim milk than in buffer solutions and model foods because the composition of skim milk is very complex (i.e., high protein content 33-40 g/L) (Goff and Hill 1993). These substances diminish the lethal effect of PEF in microorganisms by absorbing free radicals and ions which are active in the cell breakdown (Allen and Soyke 1966; Gilliland and Speck 1967a). Moreover, the inactivation of bacteria by PEF is a function of solution resistivity, which is inversely

proportional to ionic strength. The number decreases when resistivity increases and ionic strength decreases (Hülsheger *et al.* 1981; Vega-Mercado *et al.* 1995). The measured resistivity of skim milk is 310 Ω × cm and that of buffer solutions is even higher. Since diluting milk increases the resistivity and decreases protein concentration, the effectiveness of PEF treatment is improved. The inactivation rate of *E. coli* suspended in a mixture of milk and water (1 vol. milk: 2.3 vol. water) and exposed to 40 kV/cm in a static chamber at 15C is higher than if a less diluted skim milk is used (1:1) (Fig. 9).

TABLE 2.
KINETIC CONSTANTS OF HÜLSHEGER'S MODEL FOR *E. COLI* INACTIVATION IN SKIM MILK BY PEF TREATMENT IN A STATIC CHAMBER

Electric Field Intensity (kV/cm)	Number of Pulses (n)	n_{min}	E_c (kV/cm)	k (kV/cm)	R^2
35	<64	15.2	-	5.6	82.9
40	<64	13.0	-	6.1	95.8
45	<64	11.0	-	8.0	98.5
<45	16	-	18.7	2.9	83.3
<45	32	-	20.4	3.9	86.1
<45	64	-	19.9	2.7	92.4

R^2 = correlation coefficient for regression analysis (p = 0.05)

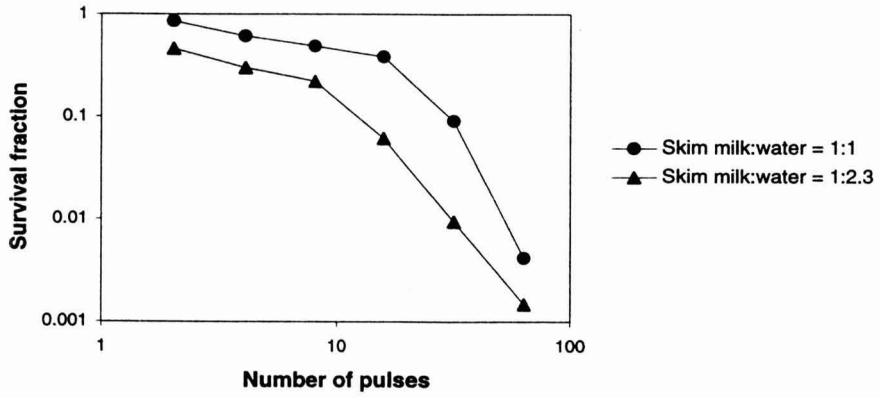

FIG. 9. EFFECT OF SKIM MILK DILUTION IN THE INACTIVATION OF *E. COLI* BY 35 kV/cm PEF TREATMENT IN A STATIC CHAMBER AT 15C

Treatment in a Continuous Chamber System

A PEF treatment in a continuous-flow chamber also inactivated *E. coli* inoculated in skim milk. An increase in field intensity or number of pulses produced a greater bacterial inactivation (Fig. 10 and 11), and the microorganisms' death followed a first order kinetics with both field intensity and number of pulses (Table 3). The E_c when the PEF treatment was carried out in a continuous system at 30 kV/cm maximum electric field intensity was between 12.34 and 14.62 kV/cm, and the n_{min} ranged from 1.9 to 5.4 pulses. The values were lower than those obtained in the same treated product using the static system.

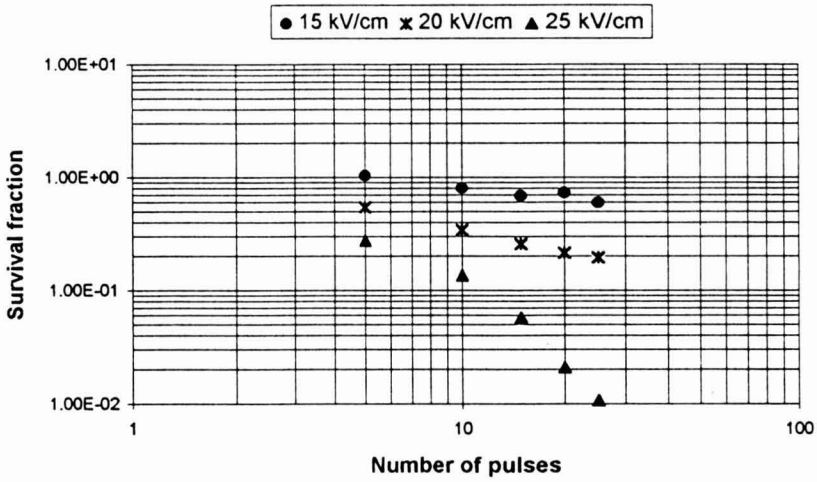

FIG. 10. INACTIVATION OF *E. COLI* IN SKIM MILK AT 15C IN A CONTINUOUS-FLOW CHAMBER AT DIFFERENT FIELD INTENSITIES

In general, PEF treatment in continuous systems is more effective in terms of microorganism inactivation than in static systems due to the greater treatment uniformity in continuous rather than static systems. Moreover, in this study, although both chambers are parallel-plate type, the treatment volume in the static chamber was 13.8 mL as opposed to 8 mL in the continuous-flow chamber. Therefore, the energy density defined as energy divided by volume is higher in continuous systems.

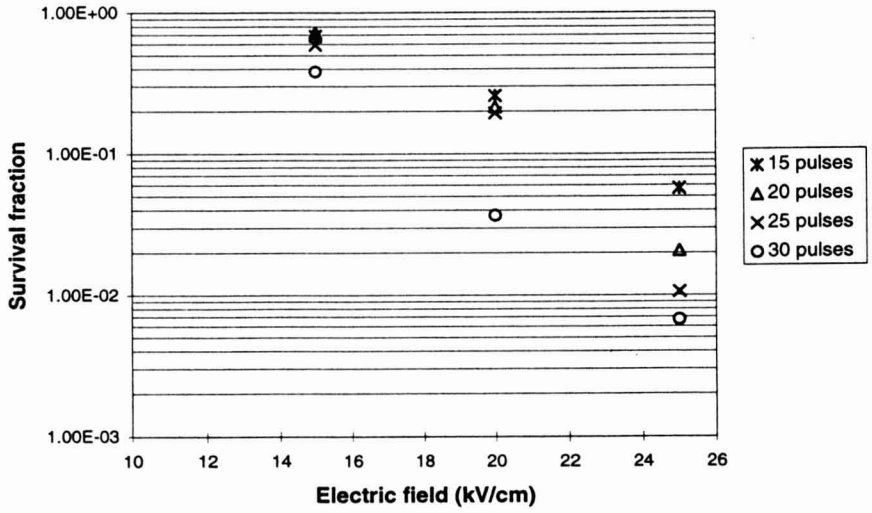

FIG. 11. INACTIVATION OF *E. COLI* IN SKIM MILK AT 15C IN A CONTINUOUS CHAMBER WITH DIFFERENT NUMBERS OF 1.8 μs PULSES

TABLE 3.
KINETIC CONSTANTS OF HÜLSHEGER'S MODEL FOR *E. COLI* INACTIVATION IN SKIM MILK BY PEF TREATMENT IN A CONTINUOUS-FLOW CHAMBER

Electric Field Intensity (kV/cm)	Number of Pulses (n)	n_{min}	E_c (kV/cm)	k (kV/cm)	R^2
15	<30	5.4	-	3.9	91.8
20	<30	1.9	-	9.5	99.7
25	<30	2.7	-	5.8	95.5
<30	15	-	13.82	4.3	98.5
<30	20	-	14.62	2.2	96.8
<30	25	-	14.44	2.2	93.8
<30	30	-	12.34	3.5	99.2

R^2 = correlation coefficient for regression analysis (p = 0.05)

The effectiveness of PEF treatment also depends on the pulse duration, which increases the *E. coli* inactivation because the energy applied in each pulse is higher. Applying 25 pulses of 0.7 μs each at 25 kV/cm in a continuous-flow chamber reduces the survival fraction of *E. coli* inoculated in skim milk less than one log cycle, but a treatment in the same chamber with the same number of pulses and field intensity and 1.8 μs duration pulse reduces the survival fraction by more than 2 log cycles (Fig. 12).

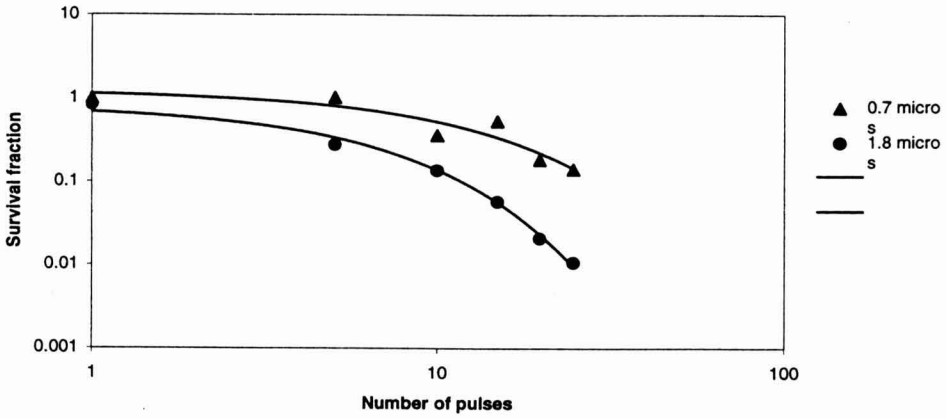

FIG. 12. EFFECT OF PULSE DURATION IN THE INACTIVATION OF *E. COLI* IN SKIM MILK BY 25 kV/cm PEF TREATMENT IN A CONTINUOUS CHAMBER

CONCLUSIONS

PEF treatment inactivated *E. coli* in skim milk. The bacterial inactivation followed a first order reaction kinetics for both the intensity of electric fields and the number of pulses. In both static and continuous chambers the reduction rate was greater when the field intensity and number of pulses were increased. Using the same field intensity and number of pulses, the inactivation of *E. coli* in skim milk was lower than when it was inoculated in buffer solutions due the complexity of skim milk composition, its lower resistivity and the presence of proteins. Pulse duration also affected the inactivation of *E. coli* in skim milk as inactivation was found to be greater with increased pulse duration.

The PEF inactivation of *E. coli* in skim milk can be improved by designing and constructing continuous systems that have the ability to withstand a greater number of pulses at uniform and higher voltage, without dielectric breakdown of the food (when food becomes conductive).

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PRODUCTION OF COWPEAS IN TOMATO SAUCE: ECONOMIC COMPARISON OF PACKAGING IN CANNING AND RETORT POUCH SYSTEMS

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Accepted for Publication February 12, 1997

ABSTRACT

The economic feasibility of using the retort pouch as an alternative to the canning system for packaging and processing of cowpeas in tomato sauce was evaluated using the Net Present Value (NPV) and Internal Rate of Return (IRR) methods assuming a uniform cash flow over a 10-year plant life. Cost estimates for the alternative packaging system were based on an equal mass flow rate of processed cowpea, i.e., 360 cans/min. The retort pouch system required a larger fixed capital investment than the canning system. The cost of cans accounted for a larger percentage of the raw material cost than the pouch. Energy costs in processing for both systems contributed very little to the total operating costs. In addition, all the variable operating costs were higher in the pouch system than in the cans for one 8-h shift operation such that the cost of producing each unit was of product higher with the pouch than in the can. Increasing the number of shifts to two increased the economic performance of both systems at the same time reducing product cost. Results of the NPV and IRR indicated that capital investment on the canning line would be more profitable than the pouch system.

INTRODUCTION

A substantial number of consumers in Nigeria have acquired a liking for baked beans — an imported, commercially-sterile ready-to-eat product canned in tomato sauce. Canned baked beans are convenient for use outside the home and can be included in several recipes. However, due to inflation, the product is no longer affordable and has become a delicacy of the elite group. It is necessary therefore, to provide a local substitute to imported baked beans. Taiwo (1996) established processing conditions for the production of commer-

Journal of Food Process Engineering **20** (1997) 337–348. *All Rights Reserved.*

cially-sterile, unfragmented cowpea seeds (*Vigna unguiculata*) using IFE-BPC variety (a hybrid of cowpea developed by the International Institute for Tropical Agriculture, Ibadan, Nigeria) in tomato sauce having acceptable canning attributes similar to those of the imported baked beans.

Appropriate packaging, in addition to its role of providing a means of delivery of the product, maintains commercial sterilization of the product, and provides a barrier to several hazards (Cabes 1985). Food processing industries are relatively energy intensive in their operation and presently use a greater amount of energy in the production process than any other sector of the food system because of the packaging materials used (Williams *et al.* 1981). Although the practice of sterilization of foods in hermetically-sealed metal containers has been in use for a long time and has been extensively studied, development of economical technologies that directly or indirectly reduce energy consumption are important to food processors. Improved packaging materials, containers, and methods are continually being developed in order to obtain thermo-stabilized products of better quality (Abou-Fadel and Miller 1983). Energy saving is one of the features of the retortable pouch that has made it a promising alternative packaging method for sterile shelf-stable products. The thin profile of the retort pouch allows for rapid heat transfer during sterilization, thereby reducing processing time by 30-40% and resulting in minimal surface overcooking. Hence, it is expected that there will be higher retention of heat labile and water-soluble nutrients in foods processed in the pouch than in the can (Lebowitz and Bhowmik 1990).

The retort pouch is cheaper to purchase and, in addition, offers savings in energy consumption during container manufacture and delivery, food processing, product transportation, and storage compared to metal cans of comparable size (Cabes 1985). The emergence of the retort pouch is a response to changes in consumer tastes and buying habits, as they demand quality, taste, and convenience in foods. The results of consumer studies suggested that there will be a growth in packages that minimize the effort of preparing and serving foods (Fox 1989). Although the retort pouch has unique advantages as a substitute package, its adoption has been related to issues of whether it can economically compete with the can. Large capital investments are necessary to begin the commercial production of products in retort pouches. Conversion of an existing canning line to a pouch processing line involves huge capital investment and this may lead to outright abandonment of some equipment and render such a line no longer usable for cans (Roop and Nelson 1981).

Presently, canning industries are few in Nigeria. The establishment of new processing industries may be based on the less energy consuming packaging line. It will be beneficial to conduct a comparative study on the economics of the two packaging systems. Williams *et al.* (1981) evaluated the economic feasibility of processing, packaging and distribution of fruits and vegetables in both the retort

pouches and the canning systems. They reported that although the cost associated with acquiring and maintaining the durable machinery for retort pouch processing was significantly higher than for either a new or an existing canning system, other operating expenditures considered were considerably lower. The aim of this study was therefore to conduct a comparative analysis on the economics of the can and pouch packaging lines in the production of commercially-sterile packaged cowpeas processed in tomato sauce.

MATERIALS AND METHODS

Economic evaluation of the can and retortable pouch packaging systems was based on the established processing conditions for IFE-BPC cowpea variety shown in Fig. 1. The basis of comparison was a constant mass flow rate of processed cowpea in 300 × 207 cans with a line speed of approximately 360 cans/min. Assuming a product weight of 225g per can and 85% plant efficiency, 33.05 metric tons of processed cowpeas in tomato sauce would be produced in an 8-h shift, i.e., 5.9 metric tons of raw cowpea per shift. Cost estimates for the alternative packaging systems were based on this level of output for an industrial plant working continuously for 330 days (Moresi 1994). A plant service life of 10 years was assumed.

The cost of purchasing new equipment (Table 1) was based on recent data from a variety of equipment manufacturers and suppliers and revised in accordance with the data given by Williams *et al.* (1981). It is assumed that the fill/form/seal machines will be equipped with liquid dispensers as in Williams *et al.* (1981) hence, no syrup dispensing units were incorporated into the pouch packaging costs. Fixed capital was estimated using the factorial method as a function of the total purchase cost of the major equipment items required for the process as described by Coulson and Richardson (1983), and Moresi (1994). This includes the costs of ancillary installations, instrumentation, piping and valves, painting, electrical plants, civil works, provision of utilities and services, design and engineering, contractor's fees and contingencies. These prices are valid for 1995 at the exchange rate of ₦85 to $1.

An estimate of the operating costs, i.e., the cost of producing the product, was evaluated from the flow sheets and this included the raw materials, service requirements, and the capital cost estimates as described in Coulson and Richardson (1983). Table 2 gives the essential materials required to manufacture the product. The quantities required were multiplied by the operating hours per annum to get the annual requirements. The current prices of the raw materials were obtained from the local market. Cost estimates of N15.62/unit were obtained for the cans (three-piece steel with tin plate) from the manufacturers (Metal Box Plc, Lagos) and ₦7.54/unit for pouches from the local user industry

(Lever Brothers Plc, Lagos). The price of the carton was estimated as ₦2.05/unit.

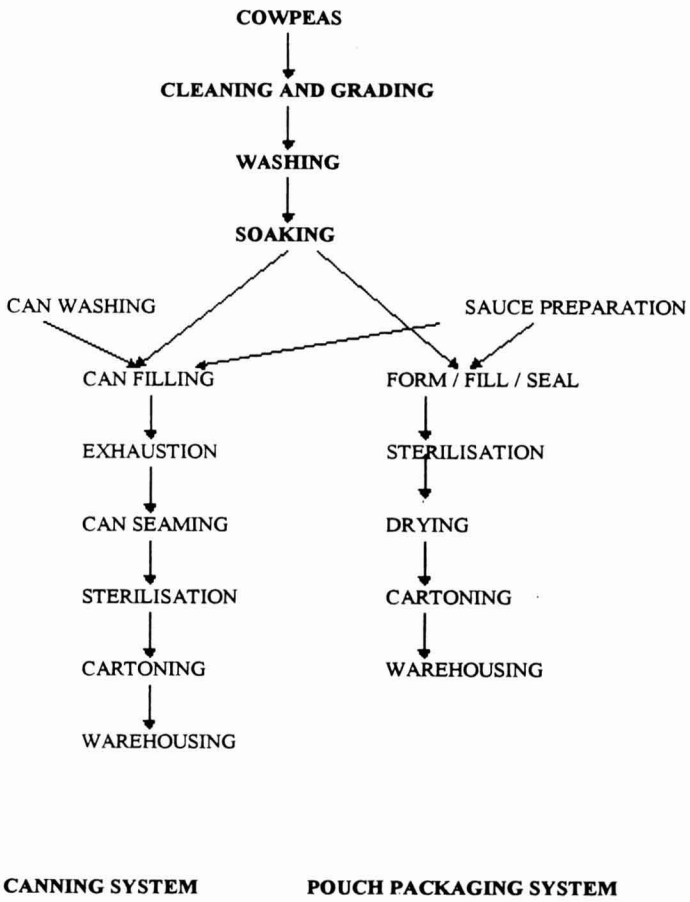

FIG. 1. FLOW DIAGRAMS SHOWING CAN AND POUCH PACKAGING LINES IN THE PRODUCTION OF COWPEAS

The term utilities include power, steam, cooling and processing water, etc. Energy consumption (kWh's per 8-h shift) for the processing alternatives is described in Table 1. Electrical energy use of the various equipment required was calculated from the electrical ratings specified by the manufacturers. Steam requirements, where necessary, were calculated from manufacturers information and expressed as kWh. The national rates for industrial users supplied by the public corporations were used (power at N4/kWh, and water at N15/m^3).

TABLE 1.
MAJOR EQUIPMENT FOR PROCESSING COWPEA IN ALTERNATIVE PACKAGING SYSTEMS
(Cost estimates, labor, and utility requirements).

	Cost estimates, labour and utilities requirements						
Equipment	**Cost ($N \times 10^6$)**	**Capacity**	**Labour /unit**	**Steam kWh / 8hr-shift**	**Electricity kWh/8-hr-shift**	**Number of units required**	
						Can	**Pouch**
Cleaning and grading	0.5	500 kg/h	1	-	2.4	2	2
Washing vat	0.4	1.0 m^3	1	-	-	3	3
Thermos-stabilised soaking vat	1.3	1.0 m^3	-	1.6	-	3	3
Steam jacketed cooker	5.2	2.0 m^3	1	16.0	-	2	2
Can filler	6.0	360 cans/min	1	-	6.0	1	-
Exhaust chamber	2.1	360 cans/min	-	100.0	-	1	-
Can seamier	8.1	360 cans/min	1	-	8.0	1	-
Continuos retort	30.2	180 cans/min	1	11790.0	-	2	-
Sauce dispenser	9.0	180 cans/min	1	-	6.0	2	-
Batch retort	21.6	90 P/min	4	5895.0	-	-	4
form/fill/ seal	40.1	45 P/min	1	267.0	160.0	-	8
Dryer	1.0	60 P/min	-	-	45.0	-	6
Cartoner	20.0	180 P/min	1	-	27.0	-	2
Can washer	5.6	360 cans/min	1	4.0	8.0	1	-
Packaging table	0.1	8 m^2	2	-	-	1	-
Steam boiler	3.5	1.0 m^3	1	-	100.0	1	1

Estimated in July 1995 . Exchange rate N85 to $1 P = Pouch

The labor costs were evaluated based on labor requirements, qualification, experience with similar processes and current wage levels (Ilori *et al.* 1996). The number of operating labor was estimated as 1.5 times the calculated number from Table 1 to take care of emergencies and operating supervision was 20%

TABLE 2.
COST OF RAW MATERIALS IN THE PRODUCTION OF PROCESSED COWPEA IN TOMATO SAUCE

Material	g/225g pack	cost (N/kg)
Tomato	14.00	250.0
Flour	1.32	70.0
Sugar	3.72	50.0
Salt	0.81	20.0
Vinegar	0.14	400.0
Spices	0.31	500.0
Water	164.70	15.0
Cowpea	40.00	25.0

Exchange rate ₦85 to $1

of the operating labor (Coulson and Richardson 1983). The average wage rates including allowances in the Nigerian food industries (as of 1995) were ₦4000/month for the factory worker and ₦6000/month per supervisor. The number of factory operators required per unit of equipment has been indicated in Table 1. Maintenance cost per annum was evaluated as 7.5% and 13.0% of the fixed capital for the single and double shifts, respectively, while straight line depreciation was used to calculate plant depreciation expense over a 10-year period (Williams *et al.* 1981; Moresi 1994). Zero salvage value was assumed for the equipment at the end of their life. In addition to the above operating costs, other general expenses including taxes, insurance, capital charges, royalties, sales expenses, general overheads, etc. were taken into consideration. Estimation of these costs are described in Coulson and Richardson (1983). The bank interest rates for lending and savings were 21% and 15%, respectively (Ilori *et al.* 1996).

The economic feasibility of processing cowpea in tomato sauce in the alternative packages, was evaluated using the net present value (NPV) and the internal rate of return (IRR) using the procedures described by DeGarmo *et al.* (1979) and Barry *et al.* (1983). These methods were chosen for they directly account for the time value of money and are hence considered superior methods (Barry *et al.* 1983). In the analysis, cash flows were assumed to be uniform throughout the plant life. The minimum attractive rate of return (M.A.R.R.) was taken as the minimum bank interest rates of 15%. The bank interests rates in the country vary between 11-15% depending on the bank policy. NPV was estimated using Eq. (1) for a uniform series of payments

$$NPV = -Inv + A[USPV_{i,N}] + \frac{V_N}{(1+i)^N} \quad (1)$$

where Inv = Initial investment, A = Annual cash flow, i = interest rate or discount rate, USPV = Uniform series of payment value, N = Plant life, V_N = Salvage value of equipment. Since the salvage value for the equipment is zero, then Eq. (1) becomes

$$NPV = -Inv + A[USPV_{i,N}] \quad (2)$$

USPV is found by using the appropriate uniform series table at the desired interest rate (Tables E-1 to E-20 in DeGarmo *et al.* 1979). The internal rate of return (IRR) is that rate of interest which equates the NPV of the projected series of cash flow payments to zero. To find IRR for an investment, NPV was set equal to zero, and then solved for i, i.e.,

$$0 = -Inv + A[USPV_{i,N}] \quad (3)$$

Trial and error approach was used to determine i where the interest rate i was greater than 50% (DeGarmo *et al.*1979). The current market price of imported baked beans is in the range ₦90-110/225g pack. The selling price of the processed product was estimated as cost price plus 30% profit. This profit margin was chosen to enable the product to have a good market performance. Expected annual sales was obtained by multiplying the selling price with the number of units produced. The price of a unit product was obtained by dividing the total operating cost by the number of units produced per annum.

RESULTS AND DISCUSSION

A summary of the economic analysis for the different packaging lines is presented in Table 3. Out of the fixed capital cost, the cost of purchasing the major equipment is ₦47.32 $\times$ 10^7 for the pouch system which is higher than N12.03 $\times$ 10^7 for the can. By the analytical method employed, since fixed capital is a function of the cost of the major equipment, hence, the fixed capital required for investment for the pouch system was much larger than that required for the can. This indicates that large capital investments are required in the commercial production of products using retort pouches for packaging which

agrees with the report of Roop and Nelson (1981) and Williams *et al.* (1981). Investment in major equipment is not influenced by the number of shifts operated.

TABLE 3.
SUMMARY OF THE OPERATING COSTS FOR PROCESSING COWPEA IN TOMATO SAUCE PACKED IN ALTERNATIVE SYSTEMS

Parameter	Estimated costs (N)			
	Canning line		Pouch line	
	1-shift	2-shifts	1-shift	2-shifts
Fixed capital	5.31×10^8	5.31×10^8	2.10×10^9	2.10×10^9
Raw materials	10.02×10^8	20.04×10^8	61.10×10^7	12.22×10^8
(Food materials)	(2.43×10^8)	(4.86×10^8)	(2.43×10^8)	(4.86×10^8)
(Pouch/can)	(7.57×10^8)	(15.14×10^8)	(3.65×10^8)	(7.3×10^8)
(Cartons)	(2.07×10^6)	(4.14×10^6)	(2.76×10^6)	(5.52×10^6)
Utilities	11.87×10^8	23.74×10^8	11.91×10^8	23.82×10^8
(Water)	(1.16×10^9)	(2.32×10^9)	(1.16×10^9)	(2.32×10^9)
(Electrical and thermal energy)	(27.75×10^6)	(5.59×10^6)	(3.1×10^7)	(6.2×10^7)
Maintenance	39.83×10^6	69.03×10^6	15.75×10^7	27.37×10^7
Labour	15.12×10^5	30.24×10^5	32.40×10^5	64.80×10^5
Depreciation	5.31×10^7	5.31×10^7	2.10×10^8	2.10×10^8
General expenses	61.44×10^7	10.62×10^8	10.43×10^8	14.43×10^8
Operating costs	28.45×10^8	55.12×10^8	30.06×10^8	53.26×10^8
Product cost per 225g pack	58.69	56.86	62.01	54.95

Exchange rate N85 to $1

The two systems have equal production rate hence equal costs for food materials. Under raw materials, the price of cans doubled that for pouches while cartons cost more in the pouch system. The difference in carton costs for the two alternatives may be attributed to the need for more cartons in the pouch system because fewer number of units of the 225g packs can be packed in a carton compared to the cans. The raw materials cost revealed that the food materials constitute 24.25% while the cans and cartons make up 75.55% and 0.20%, respectively, of the total cost of raw materials. In the pouch system, the food materials constituted 39.79%, while the pouch and cartons were 59.76 and 0.45%, respectively, of the total raw material cost. This result is similar to those of Williams *et al.* (1981) that indicate that package costs are the largest components of the variable costs for operating the packaging systems. In this study, cans and cartons account for a larger percentage (75.75%) of the raw material cost of the canning system than in the pouch packaging (60.21%) system. The lower percentage of packaging costs in the pouch system is

advantageous in view of the fact that pouch costs increase less rapidly than the rate at which can costs increase (Williams *et al.* 1981). In addition, retort pouch processing and packaging systems are reportedly less energy intensive than a canning system (Williams *et al.* 1981). Therefore, as energy prices increase, it is expected that the difference between the total costs associated with canning i.e. processing and packaging systems and the retort pouch packaging systems get larger. Furthermore, the advantage of retort pouch processing becomes greater the faster energy prices increase (Steffe *et al.* 1980).

The cost of energy used in processing accounted for a small (approximately 1.0%) proportion of the total operating costs. It is generally presumed that the thermal energy requirements for retorting pouches is significantly less than that required for comparable cans. This is due to the fact that the pouch has a geometry which is more favorable to heat transfer than the can. Because of the uncertainty surrounding the extent of energy savings, a more conservative energy consumption estimate for pouch retorting was used for the economic analysis as suggested by Williams *et al.* (1981). This report agrees with the report of Williams *et al.*(1981) that any interest in retort pouch packaging as an alternative to can packaging because of its potential energy saving advantage in the retorting process appears to be commercially unwarranted when compared with how other items effect the cost of retort pouch packaging system. Cost of processing water accounted for a large percentage (94.5%) of the total utility costs. This is so because of the large volumes of water required for processing and cooling. It was estimated that 40kg of water would be used for every 1kg of cowpea processed (Taiwo 1996). Labor, maintenance, and total operating costs were higher in the retort pouch system (Table 3) than in the canning systems which agree with the work of Williams *et al.* (1981).

The sensitivity of product price as a function of the number of operating shifts/day was tested. The results in Table 3 indicate that the fixed capital and some variable operating costs which are a function of the fixed capital did not change while costs such as raw materials, labor, maintenance, utilities etc. increased as the number of shifts increased. The total operating costs for the pouch was lower than that for the can. Production costs of cowpeas in alternative packaging systems when two 8-h shifts/day are operated are presented in Table 3. The cost price of canned cowpea is slightly less than that processed and packaged in the retort pouch (having equal weight of 225g/pack) for one 8-h-shift production schedule for the year. The unit cost of production/225g pack for the two-shift pouch system was lower than that in the two-shift canning system by approximately 3.4%. Increasing the number of shifts from one to two reduced the cost price of the product by 3.12% in the can system and 11.4% in the pouch system. This may be attributed to the substantial reduction in raw material cost. This did not necessarily make the system more profitable as the cash flow played a significant role in the calculations.

Details of the economic analysis for the alternative packaging systems at 85% operating plant efficiency using a selling price of cost price + 30% profit margin are given in Table 4. Since all the net present values are positive, it indicates that all the alternatives are profitable investments and the higher the value, the better the performance of the investment. The canning systems appear to be more acceptable than the pouch lines either on the single or double shifts basis. This implies that the canning lines will break even with greater surplus than the pouch systems at 15% interest rate which was the MARR used in the analysis. This is also supported by the interest rates obtained from the IRR tests. The high IRR for the canning line suggests that the system is more robust and will be profitable even at higher interest rates. Increasing percentage profit increased the selling price (Table 5), but the values were less than the current price of imported canned beans.

TABLE 4.
PROFITABILITY ANALYSIS OF COWPEA PROCESSING IN ALTERNATIVE PACKAGING SYSTEMS

	Packaging systems (Values in ₦)			
Parameters	Canning line		Pouch line	
	1-shift	2 shifts	1-shift	2 shifts
a) Sales	36.99×10^8	71.66×10^8	39.08×10^8	69.24×10^8
b) Operating costs	28.45×10^8	55.12×10^8	30.06×10^8	53.26×10^8
c) Before tax earning (a-b)	8.54×10^8	16.54×10^8	9.02×10^8	15.98×10^8
d) Depreciation	5.31×10^7	5.31×10^7	2.1×10^8	2.1×10^8
e)Taxable income (c-d)	8.00×10^8	16.01×10^8	6.96×10^8	13.88×10^8
f) Tax (45% of e)	3.60×10^8	7.20×10^8	3.11×10^8	6.25×10^8
g) Cash flow (c-f)	4.94×10^8	9.34×10^8	5.91×10^8	9.73×10^8
Net Present Value	19.48×10^8	41.57×10^8	8.66×10^8	27.83×10^8
Internal Rate of Return %	64	72	25	47

Exchange rate N85 to $1

TABLE 5.
MARKET PRICE OF PROCESSED COWPEAS AT DIFFERENT PROFIT MARGINS

Profit margin	**Selling price (₦) / 225g pack**			
Cost price + % profit	**Canning line**		**Pouch line**	
	1 shift	**2 shifts**	**1 shift**	**2 shifts**
30	76.31	73.92	80.61	71.44
40	82.17	79.60	86.81	76.93
50	88.04	85.29	93.02	82.43

Exchange rate N85 to $1

CONCLUSION

This study evaluated the economic performance of the canning and pouch packaging systems assuming a uniform cash flow over the 10-year plant service life having zero salvage value. The cash flow of the pouch system is very similar to the cans while the capital costs are considerably higher. An NPV of N1.57 $\times$ 10^8 was obtained for the 2-shift canning line and N19.48 $\times$ 10^8 for the single canning line. Those for pouch lines were ₦27.83 $\times$ 10^8 and ₦8.66 $\times$ 10^8 for double and single shifts, respectively. The large NPV estimated for the canning line could serve as an incentive to entrepreneurs who wish to invest in cowpea processing.

ACKNOWLEDGEMENT

The authors acknowledge Obafemi Awlowo University Research Committee sponsorship of the project through research grant 1425pp.

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(Required by 39 USC 3685)

1. Publication Title	2. Publication Number	3. Filing Date
JOURNAL OF FOOD PROCESS ENGINEERING	0 1 4 5 - 6 4 9 0	OCTOBER 1, 1997
4. Issue Frequency	**5. Number of Issues Published Annually**	**6. Annual Subscription Price**
QUARTERLY	4	$164.00

7. Complete Mailing Address of Known Office of Publication *(Not printer) (Street, city, county, state, and ZIP+4)*	Contact Person / Telephone
6527 MAIN STREET, TRUMBULL, FAIRFIELD, CONNECTICUT 06611	JOHN J. O'NEIL (203) 261-8587

8. Complete Mailing Address of Headquarters or General Business Office of Publisher *(Not printer)*

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JOURNAL OF FOOD PROCESS ENGINEERING	07/30/97,06/11/97,02/28/97,12/27/96

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