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MODELING THE SOLUBILIZATION PROCESS DURING COFFEE BREWING

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ABSTRACT

Two different processes may be considered in coffee brewing: (1) solubilization of some compounds from the grind into the water, and (2) filtration of the extract through the grind.

These two processes have been dissociated in our experimental studies. The results obtained for the first of them, solubilization, will be reported here.

Variations in soluble content as a function of time, temperature, proportion of coffee to water were interpreted in relation to a model based on the general equation of diffusion and assuming the grind to be spherical particles suspended in a homogeneous system.

Qualitative variations in the chemical composition of the extract have also been determined by some physico-chemical measurements: optical density, titrable acidity, viscosity, caffein content.

INTRODUCTION

Coffee drink preparation and its analysis are complex. In all cases, two physical processes occur successively:
(1) dissolution (brewing), and
(2) separation of grounds and extract.

According to Loncin (1961) *brewing* includes:
(1) water penetrating to the pores of the coffee granules and displacing gas between the particles;
(2) soluble elements (from coffee, either preexisting or resulting from hydrolysis) dissolve into water in the pores of the coffee granules;
(3) these elements diffuse through the water in the pores to the spherical surface of the granules; and
(4) there is mass transfer by convection from the surface to the bulk of the water surrounding the granules.

The equilibrium state is characterized by a concentration in soluble elements almost equal in the free solvent and that imbibed by the solid.

Separation, usually achieved by filtration, consists of separating free solution, enriched in the soluble elements of coffee, from the grind. Filtration time depends on filter porosity and grounds characteristics.

Data concerning the influence of extraction conditions are available (reported by Sivetz 1963, and by the Coffee Brewing Institute). However, the experimental conditions in which they were obtained are not well-known. The present study was designed in order to dissociate, as far as possible, the two phenomena of brewing and separation. Studies on the brewing process, only, will be reported here.

The influence of the grind/water proportion, granule size, water temperature and water-grind contact time on the physico-chemical properties of the extract has been studied. The properties examined are solid content, extraction ratio, pH, acidity, optical density, viscosity and electrical conductance.

MATERIALS AND METHODS

Raw Materials

Pure Arabica coffee was used (80% coming from Cameroon, 20% from Haiti and Columbia). It was roasted at 150—180°C for 12 to 15 min. It was ground in a Mahlkonig mill yielding a grind of constant characteristics. The grind was then sieved; only particles between 0.2 and 0.8 mm were retained (Table 1). Mineral water was used (Volvic). It contains ions (Table 2), and its conductance is 0.36 m Mho at 60°C and pH is neutral.

Table 1. Granule size distribution in the grind used

Mesh of the Sieve (mm) Passes Through	Retained On	Fraction Total (%)
0.800	0.630	22.0
0.630	0.500	37.5
0.500	0.315	34.5
0.315	0.200	6.0

Coffee-Drink Preparation

One hundred ml of Volvic water was poured into the main cylinder of the apparatus (Fig. 1). When the selected temperature was reached, the

Table 2. Composition of mineral water

Anions	mg/liter	Cations	mg/liter
Cl^-	7.5	Ca^{++}	10.4
NO_2^-	0	Mg^{++}	6
NO_3^-	2	Na^+	8
SO_4^-	6.7	K^+	5.4
CO_3H^-	64	Fe^{++}	Traces

(Institut d'hydrologie de l'université de Clermont-Ferrand Faculté de médecine et pharmacie-France)

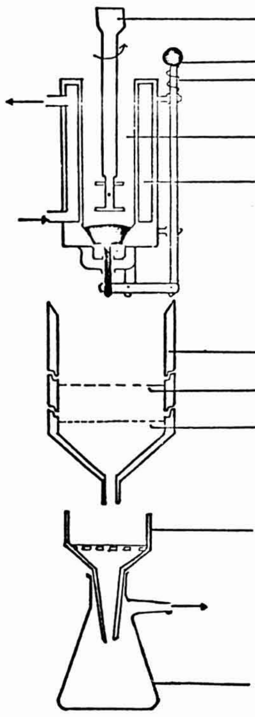

FIG. 1. EXTRACTION APPARATUS FOR COFFEE

grind was added and the water/grind contact time, as well as stirring rate, was fixed. Filtration was performed in a very short time (about 10 s).

Physico-Chemical Analysis

It was verified that the amount of insoluble solids was negligible. For this purpose, the coffee-drink was refiltered on Whatman 115 paper. The drink was regarded as acceptable and did not need to be refiltered before the physico-chemical analyses.

Solids content (S) is the concentration of soluble elements in the extract expressed in grams per 100 ml coffee-drink. It was measured by drying samples at 102°C for four hours.

Solubles Yield (SY) is defined in % as the ratio of solids weight to the weight of coffee-grind originally added to the extractor.

$$SY\ (\%) = \frac{S \times \text{volume of coffee-drink} \times 100}{\text{weight of coffee-grind}}$$

Optical density (OD) of coffee-drink diluted at 1/20, was measured at 430 nm with the help of a Pye Unicam UV-Visible spectrophotometer. The measurement of optical density at this wave length gives an idea of the coffee color (Sivetz 1963).

Viscosity was measured with a Rheomat 15 (Contraves — Zurich) with coaxial cylinders (Epprecht type). As reported by Sivetz (1963), coffee-drink is a Newtonian fluid.

Electrical Conductance, according to Heiss (1969) and Czechoskva (1976), is closely related to the solid content of the extract. Measurements were made using a Metrohm (EA 608-08) cell, with a constant equal to 0.82 cm^{-1}, connected to a Universal Bridge B 221 conductivity meter (Wayne-Kerr). Measurement sensitivity was about 0.01%.

Acidity was measured by neutralizing a coffee-drink sample with NaOH (N/100). It is expressed in H_2SO_4 milliequivalents per 100 ml.

Caffein was analyzed by gas phase chromatography following the technique of Vitzthum *et al.* (1974).

RESULTS AND DISCUSSION

The extraction parameters investigated were the following:

brewing time = 0.5 to 20 min,
water temperature = 70 and 85°C,
grind/water proportion = 7.5 g, 10 g, 12 g and 14 g/100 ml.

With the grind granule size between 0.200 and 0.800 mm two series of trials were made with a granule size range of 0.315 and 0.500 and 0.630—0.800 mm at temperature of 70 and 85°C, and grind/water proportions of 12 and 10/100, respectively. All experimental measurements were repeated three times and the variation coefficient was 5%.

All physico-chemical measurements were made except in the study of granule size influence where only the value of solid contents will be given.

Variation of Solid Content Versus Operating Conditions

Influence of Brewing Time. Coffee-drink solids content (S) increases rapidly during the first minutes of brewing and then stabilizes (Fig. 2). The solubles yield (SY) reaches 90% of its final value within about 1 min (Fig. 3).

Influence of Granule Size. The finer grinds produced higher concentrations of solids in the coffee drink for all operating conditions tested (Fig. 4). This phenomenon was also observed by Natarajan (1965) and Heiss (1969).

Influence of Grind/Water Proportion. When the proportion of grind to water was increased by 7.5 to 14%, S increased while SY decreased (Fig. 2, 3). As can be verified if a mass-balance is made, the decrease of SY is

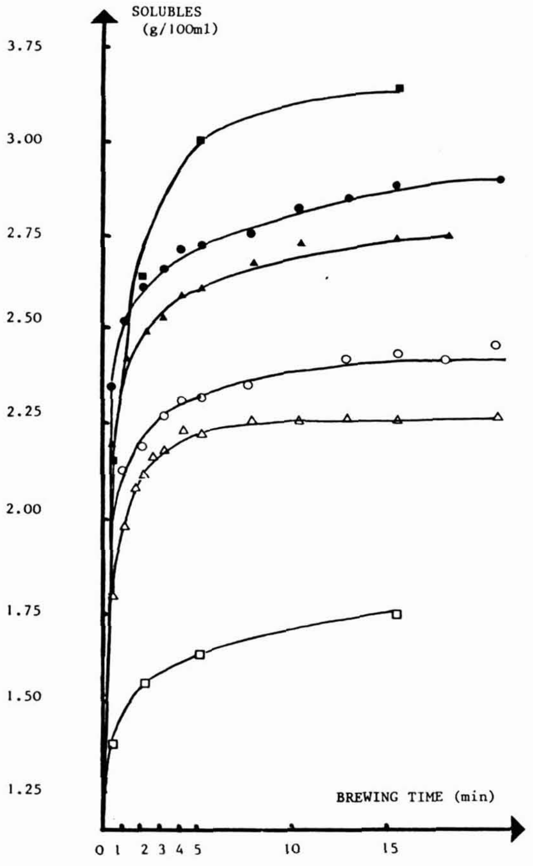

FIG. 2. SOLUBLES EXTRACTED AT DIFFERENT TEMPERATURES AND GRIND/WATER PROPORTIONS AS A FUNCTION OF BREWING TIME

grind/water proportion	temperature (°C)
□ 7.5/100	70
△ 10/100	70
○ 10/100	85
▲ 12/100	70
● 12/100	85
■ 14/100	70

explained by the fact that the amount of extract retained by the grounds increases with the grind/water proportion.

Influence of Water Temperature. A temperature increase caused solids content, final solubles yield and dissolution rate to increase (Fig. 2 and 3). The rate of extractive process increased with the temperature.

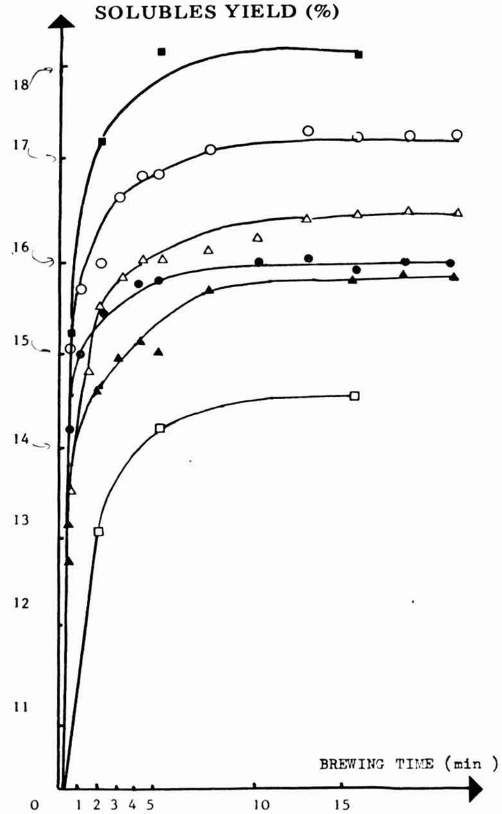

FIG. 3. SOLUBLES YIELD AT DIFFERENT TEMPERATURES AND GRIND/WATER PROPORTIONS AS A FUNCTION OF BREWING TIME

(symbols as in Figure 2).

Physico-Chemical Study of Extract

Some qualitative variation of extract versus time or operating conditions is shown by various physico-chemical measurements. Optical density at 430 nm, conductance, viscosity, acidity and caffeine increase with water/grind contact time, grind/water proportion and water temperature. Merritt (1959), and Lockhart (1957), showed that extraction rate of various chemical components is influenced by water temperature.

The above increase is not merely the consequence of the increase in the solid content of the extract. We give here two examples of this phenomena. As shown in Fig. 5, it is verified that dilution of the extract results in a linear variation of optical density. On the contrary, when the solid content increases as a result of increasing brewing time, optical

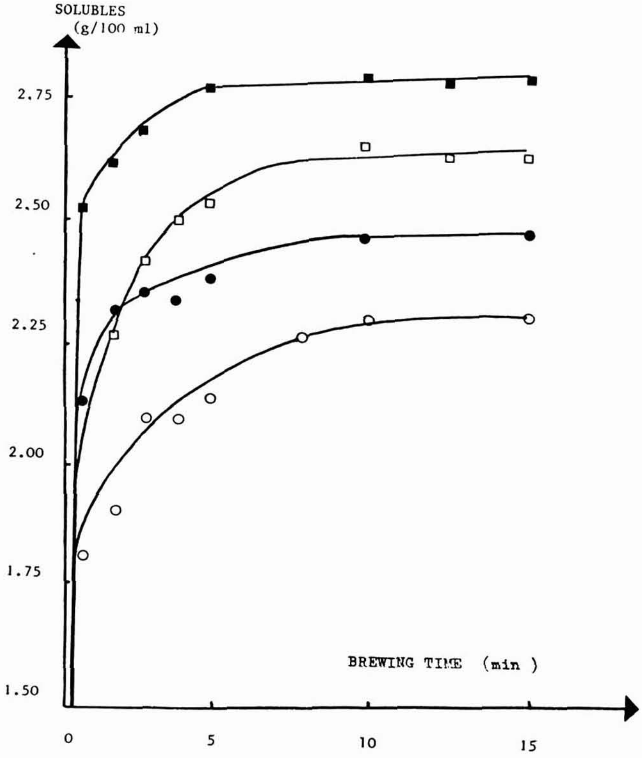

FIG. 4. SOLUBLES EXTRACTED FROM GRANULES OF DIFFERENT SIZE, AS A FUNCTION OF BREWING TIME

grind/water proportion	temperature (°C)	granule size
○ 10/100	85	0.630—0.800
● 10/100	85	0.315—0.500
□ 12/100	70	0.630—0.800
■ 12/100	70	0.315—0.500

density increases more rapidly than the solid content. This is due to the variation of the composition of the extract: the difference between the curves means that differing solids that contribute more to the optical density diffuse more slowly. Moreover, the relationship between optical density and solids content depends on the operating conditions.

We observe also the same kind of behavior with viscosity: the varying composition during concentration and the constant ratio of components during dilution.

On the other hand, titrable acidity is a linear function of solid content in all the operating conditions tested (Fig. 6). The ratio of caffeine to solids content remains approximately constant (Fig. 7) during brewing,

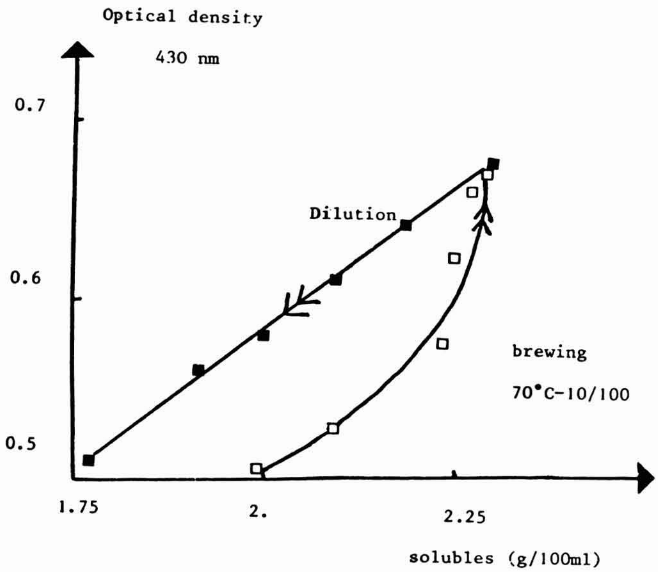

FIG. 5. OPTICAL DENSITY AT 430 nm AS A FUNCTION OF SOLUBLES

but may undergo some variations with temperature or grind/water proportion. Conductance appears to be a linear function of solids content for the operating conditions tested (Fig. 8); for longer brewing times, however, it increases slightly less rapidly than solids content.

It is, thus, certain that the extract composition undergoes qualitative changes during the brewing process and is effected by brewing conditions. These changes may result from differential solubilization, hydrolysis or even chemical reactions.

Extraction Rate of Soluble Substances

It seems possible to describe globally the extraction process of soluble substances versus operating conditions using the diffusion equation of a single component in a sphere as given by Crank (1975). It must be assumed that:

(1) the grind grains are spheres,
(2) diffusion is radial, isotropic and the diffusion coefficient is independent of the concentration, and
(3) at time zero, soluble substances are uniformly distributed in the grind grain and concentration in the water is homogeneous.

The boundary conditions assume that the rate at which the solute leaves

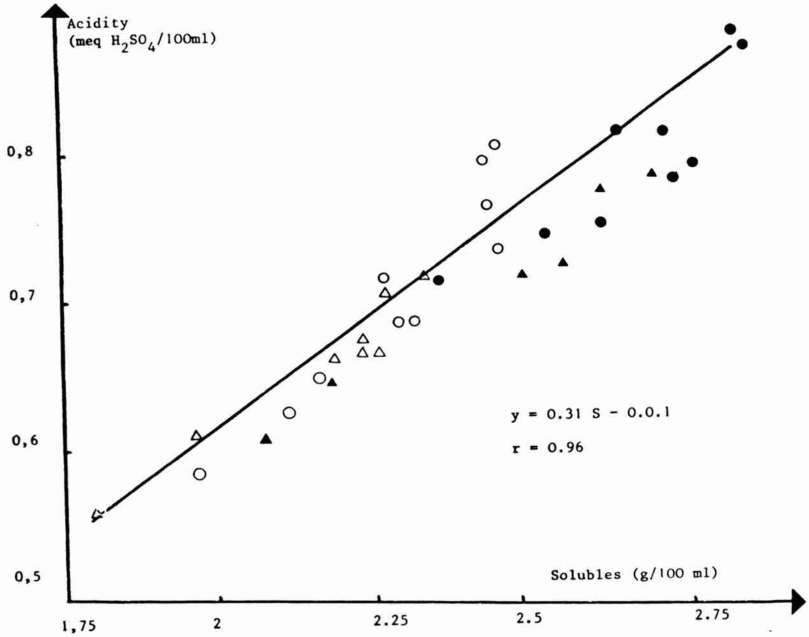

FIG. 6. TITRATABLE ACIDITY AS A FUNCTION OF SOLUBLES

grind/water proportion	temperature (°C)
○ 10/100	85
△ 10/100	70
● 12/100	85
▲ 12/100	70

the grain through the sphere surface is equal to that at which it enters the solution.

Under these conditions, we can write that the ratio of the mass of solids which have diffused into the water after a time t to that at an infinite time (mean of the last values) equals:

$$\frac{Mt}{M_\infty} = 1 - \sum_{n=1}^{\infty} \frac{6\,\alpha\,(\alpha + 1)\exp(-D\,q_n^2\,t/a^2)}{9 + 9\alpha + q_n^2\,\alpha^2}$$

where q_n are roots of the equation:

$$\tan q_n = \frac{3\,q_n}{3 + \alpha q_n^2} \quad \text{with n from 1 to 6.}$$

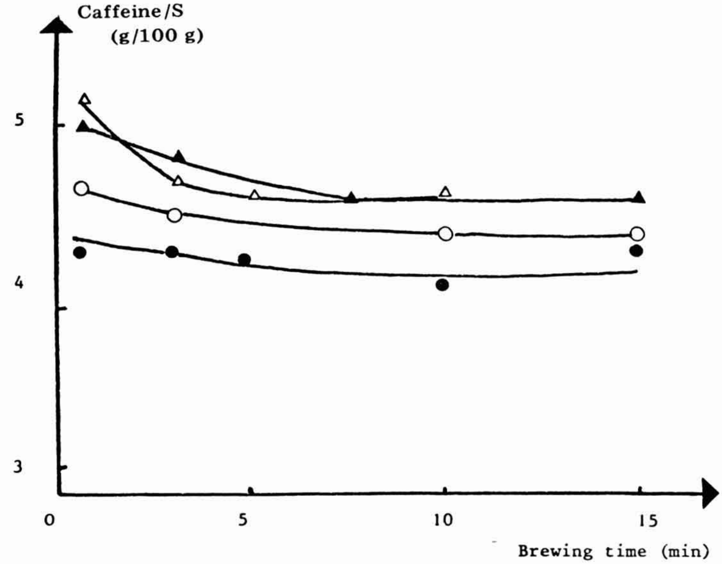

FIG. 7. RATIO OF CAFFEINE CONCENTRATION TO SOLUBLE SOLIDS CONCENTRATION AS A FUNCTION OF BREWING TIME

Symbols explained in Fig. 6

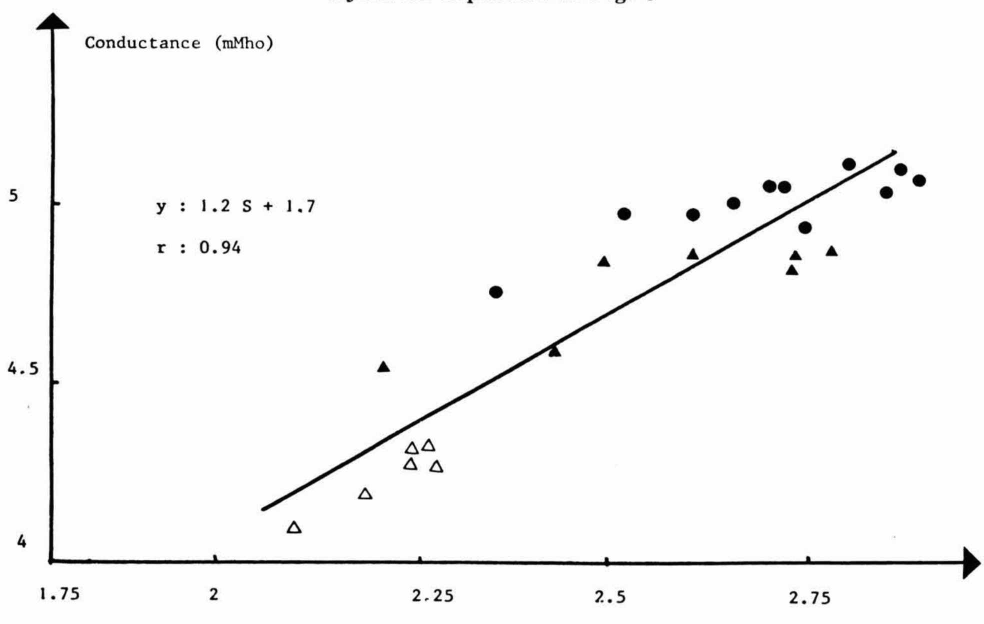

FIG. 8. CONDUCTANCE AS A FUNCTION OF SOLUBLES

Symbols explained in Fig. 6.

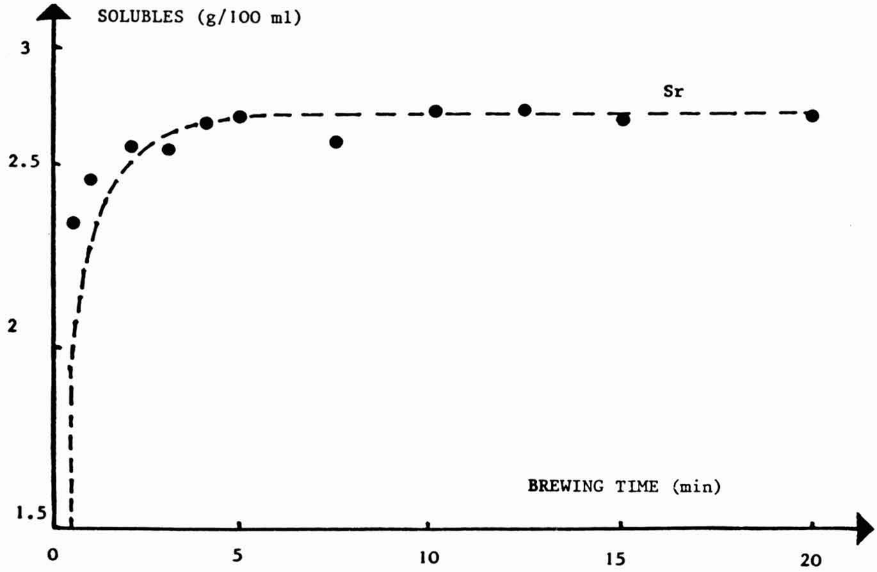

FIG. 9. CALCULATED AND EXPERIMENTAL SOLUBLE SOLIDS CONCENTRATIONS AS A FUNCTION OF BREWING TIME AT 85°C AND FOR 12/100 GRIND/WATER PROPORTION

D = diffusion coefficient of all solubles solids ($m^2 \times s^{-1}$).
a = mean diameter of grind particle

$$\alpha = \frac{\text{water amount per particle}}{\text{particle volume}}$$

D is the only unknown and is determined by minimization of the mean square error. The results obtained are listed in Tables 3 and 4. Figure 9 shows the general profile of the extraction process of soluble substances versus brewing time, when the first six terms are retained. The theoretical curve (with a step change in solids concentration with exterior solution) corresponds to diffusion only. The difference between the theoretical and the experimental curves should be explained by the superimposition of various other processes, with lower rates, onto the diffusion process: soaking the grind in water, dissolution of solubles, hydrolysis. The corrected curve (S_r — Fig. 9), however, taking into account evaporation during brewing, is closer to the theoretical curve for diffusion. We notice, however, that the points at time less than one minute seem to be higher than the model predicts; perhaps this is caused by soluble solids that are washed off the outer surface of the granules in addition to diffusion. The diffusion model used, thus, seems to describe the brewing process quite satisfactorily.

Table 3. Variation of experimental (Sa) and calculated (Sc) soluble solids concentrations versus extraction conditions at 85°C

Water Temperature (°C)	85		85		85		85 (Fig 9)		85	
Grind/Water Proportion	10/100		10/100		10/100		12/100		12/100	
Grind Mean Diameter (m)$\cdot 10^3$	0.500		0.715		0.4075		0.500		0.715	
Apparent Density of Dry Grind	0.350		0.438		0.337		0.350		0.438	
Time (s)	(Sa)	(Sc)	(Sa)	(Sc)	(Sa)	(Sc)	(Sa)	(Sc)	(Sa)	(Sc)
0	0	0	0	0	0	0	0	0	0	0
30	1.97	1.58	1.69	1.05	—	1.86	.2.35	1.92	1.02	1.28
60	2.12	1.99	1.81	1.43	2.15	2.22	2.52	2.40	2.18	1.73
90	—	2.19	—	1.66	—	2.36	—	2.63	2.12	2.00
120	2.16	2.30	1.90	1.82	2.32	2.42	2.62	2.75	2.20	2.19
150	—	2.36	—	1.93	—	2.44	—	2.82	—	2.32
180	2.26	2.39	2.10	2.01	2.34	2.45	2.67	2.85	2.34	2.42
240	2.31	2.42	2.09	2.12	2.35	2.46	2.71	2.88	2.48	2.54
300	2.29	2.42	2.12	2.18	2.38	2.46	2.73	2.89	2.46	2.61
450	2.33	2.43	—	2.24	—	2.46	2.76	2.89	—	2.68
600	2.37	2.43	2.30	2.26	2.54	2.46	2.82	2.89	2.50	2.69
750	2.46	2.43	—	2.26	—	2.46	2.85	2.89	2.56	2.70
900	2.44	2.43	2.26	2.26	2.44	2.46	2.88	2.89	2.60	2.70
1050	2.42	2.43	—	2.26	—	2.46	2.92	2.90	—	2.70
1200	2.43	2.43	2.26	2.26	2.46	2.46	2.90	2.90	2.70	2.70
α Calculated		3.5		4.38		3.37		2.92		3.65
D Approached ($m^2 \cdot s^{-1}$)	1.1×10^{-10}		1.1×10^{-10}		1.1×10^{-10}		1.1×10^{-10}		1.1×10^{-10}	

Table 4. Variation of experimental (Sa) and calculated (Sc) soluble solids concentrations versus extraction conditions at 70°C

Water Temperature (°C)	70		70		70		70	
Grind/Water Proportion	10/100		12/100		12/100		12/100	
Grind Mean Diameter (m)· 10^3	0.500		0.500		0.500		0.500	
Apparent Density of Dry Grind	0.350		0.350		0.438		0.337	
Time (s)	(Sa)	(Sc)	(Sa)	(Sc)	(Sa)	(Sc)	(Sa)	(Sc)
0	0	0	0	0	0	0	0	0
30	1.77	1.48	2.19	1.82	1.68	1.26	2.32	1.92
60	1.97	1.86	2.43	2.28	1.74	1.70	2.52	2.38
90	2.06	2.04	—	2.50	2.07	1.97	2.50	2.59
120	2.08	2.14	2.49	2.61	2.27	2.15	2.62	2.69
150	2.16	2.20	—	2.67	—	2.28	—	2.75
180	2.18	2.23	2.55	2.71	2.42	2.37	2.67	2.77
240	2.24	2.25	2.59	2.74	2.49	2.49	2.67	2.79
300	2.24	2.26	2.61	2.74	2.54	2.56	2.76	2.80
450	2.24	2.27	2.68	2.75	—	2.63	—	2.80
600	2.26	2.27	2.74	2.75	2.66	2.64	2.78	2.80
750	2.25	2.27	—	2.75	2.61	2.64	2.76	2.80
900	2.27	2.27	2.74	2.75	2.61	2.65	2.77	2.80
1050	—	2.27	2.75	2.75	—	2.65	—	2.80
1200	2.27	2.27	2.79	2.75	2.71	2.65	2.80	2.80
α Calculated		3.5		2.92		3.65		2.80
D Approached ($m^2 \cdot s^{-1}$)	1.1×10^{-10}		1.1×10^{-10}		1.1×10^{-10}		0.8×10^{-10}	

It should be expected that water temperature and also granule size would influence the diffusion rate. This could not be observed, however, with the two temperatures tested.

CONCLUSION

During coffee brewing, the variations of the total solids content of the extract are rather well described by means of the diffusion equation in a sphere after taking account of the boundary conditions.

The study of some physico-chemical characteristics of the extract, on the other hand, shows that its qualitative composition undergoes changes versus time and other operating conditions of brewing. The different types of substances do not have the same behavior during brewing-process.

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EFFECTS OF SCREW RESTRICTIONS ON THE PERFORMANCE OF AN AUTOGENOUS EXTRUDER

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ABSTRACT

The Brady Crop Cooker is a low-cost autogenous extruder capable of manufacturing products suitable for human consumption in less developed countries (LDC). Versatility is achieved by the design of the extruder which directly affects its operation. One such design aspect is the inclusion of internal screw channel restrictions. The effects of location and number of restrictions on operation and product quality were studied. Results indicated that restrictions affected the location of the mechanical energy input and therefore temperature profiles along the screw. Increasing the number of restrictions also promoted cleavage of starch molecules due to the resulting higher shear in the screw channel.

INTRODUCTION

Single screw extruders are an efficient and versatile food processing tool which are used to cook, shape and texturize food products. Extruders have been used to fabricate or "engineer" a variety of foods including breakfast cereals, beverage powders, pasta products, infant foods and texturized vegetable proteins. In addition, extruders have been ex-

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[1] Former graduate research assistant, Department of Agricultural and Chemical Engineering, Colorado State University.
[2] Name and address to whom correspondence should be sent.

tensively used to process pet foods (dry and semi-moist) and to precook animal feeds.

Harper (1978) and Rossen and Miller (1973) have described the working parts of single screw extruders used for food extrusion and their operating characteristics. Single screw extruders have four basic components: a barrel equipped with a feed hopper, a rotating screw or flighted rotor, a die restriction at the extruder discharge, and a drive motor. Food extruders can be divided into two broad categories: forming or cooking extruders. The forming extruders are commonly operated at low temperatures and shape food materials (pasta products, candies). The latter are used to cook and shape a wide variety of foods.

The beneficial application of extruders to thermally process oil seeds or mixtures of oil seeds with cereals have been described by Smith (1976), Clark (1969) and Mustakes *et al.* (1964, 1970). The use of relatively simple autogenous extruders, which have the entire energy input from the viscous dissipation of the mechanical energy or friction, have been investigated by Harper and Jansen (1976) and Wilson and Tribelhorn (1980).

The autogenous extruder has been used as an appropriate processing technology for less developed countries (LDCs) to thermally process cereal/oil seed blends into precooked nutritious foods. The versatility of the autogenous extruder is restricted, however, because of a limited ability to vary and control processing conditions since moisture content ranges between 15—20%.

In an autogenous extruder, the processing conditions can be changed by altering the extruder die configuration. The Brady extruder, Model 206, (Fig. 1) uses a variable discharge annulus as a die to control the active or filled length of the screw and consequently the quantity of mechanical energy input dissipated in the form of heat changing the extrudate temperature. Altering dough moisture is another way to control operations with higher moistures reducing the amount of mechanical energy dissipated.

Another potential control parameter in an autogenous extruder is the use of internal restrictions along the screw to vary the position and intensity of the viscous dissipation of the mechanical energy input. In the case of the Brady extruder, cross channel dams exist near the discharge of the screw.

To increase the versatility and flexibility of the Brady extruder, a study was undertaken to determine the effect of screw speed and screw restrictions on extrusion operation and product. Specifically, the operating variables of energy input, extrusion rate, temperature profiles along the barrel and the overall performance of the extruder were measured.

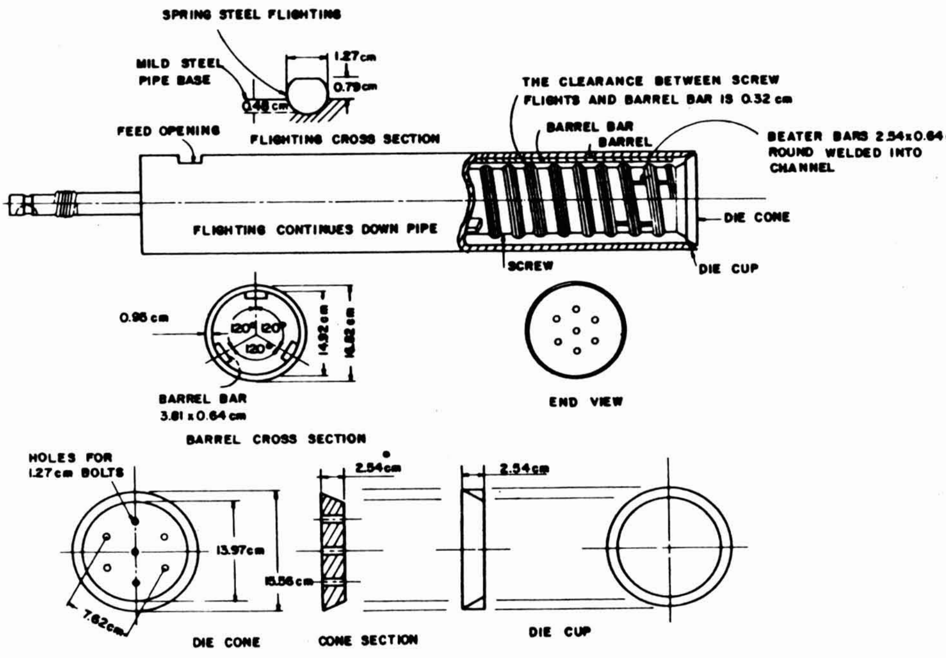

FIG. 1. BRADY EXTRUDER MODEL 206

Characteristics of the extruded product measured were: density, viscosity (consistency), and the increase in reducing sugars.

Energy Balance

The energy input to an autogenous extruder is supplied directly from the power dissipated as viscous shear energy (heat) in the screw channel and in the clearance between the flight lands and the barrel surface. This conversion takes place quickly and efficiently.

The required energy input for an autogenous extruder can be estimated by an energy balance which does not depend upon the extruder design (Darnell 1960). If the plasticized mass is assumed to behave like an incompressible fluid, and if the small inertial effects are neglected, an energy balance around the barrel of an autogenous extruder can be expressed as:

$$E = \int_{T_1}^{T_2} \dot{m}\, C\, dT + \int_{P_1}^{P_2} Q\, dP + \int_{O}^{q} \dot{m}\, dq_{ch} \qquad (1)$$

Continued

$$+ A \int_{T_{w_1}}^{T_{w_2}} (H_c + \sigma \epsilon_w T_w^3) dT_w \qquad (1)$$

Concluded

Conversions are not shown but consistent units must be used. Equation 1 indicates the total power input to the screw (E) equals the sum of the energy to: supply sensible heat (first term), increase the pressure inside the barrel (second term), promote chemical, structural and phase changes (third term), and provide heat lost by convection and radiation from the barrel and die. If input energy to the extruder is varied, a number of changes can occur with the most likely being changes in product temperature or the amount of chemical alteration of the products. If both sides of Eq. (1) are divided by the mass flow rate, $\dot{m}$, the specific energy is obtained.

EXPERIMENTAL

Experimental Extrusion Equipment

The autogenous extruder used in the study was a Brady extruder, Model 206, manufactured by Koehring Farm Division, Appleton, Wisconsin. Three different temperatures of extrusion (149°, 163°, and 171°C) and screw speeds ranging from 500 to 1,000 rpm were tested. Five screw configurations (Fig. 2) having varying number, placement and dimensions of flow restriction dams between flights. The original screw is shown as configuration 1. This screw has two sets of four dams each, placed in the last two channels of the screw. The dimensions of the dams were 2.54 cm long × 0.64 cm high, and were located at $\pi/2$ radians around the circumference of the screw. In configuration 2, one additional set of dams was placed in the third channel from the discharge. Configuration 3 had five sets of dams located in channels 1, 2, 3, 5, and 8, starting from the discharge end of the screw. In configuration 5, three sets of four dams were placed in the first three channels, and two sets of eight bars each were placed in channels 5 and 6. These later dams measured one-half of the length of the ones previously used (1.27 × 0.64 cm) and were distributed in pairs, separated by a circumferential distance of 2.54 cm.

Process Monitoring Equipment

The temperature profile along the barrel was determined by nine type J thermocouples attached to the outer barrel wall. The power output

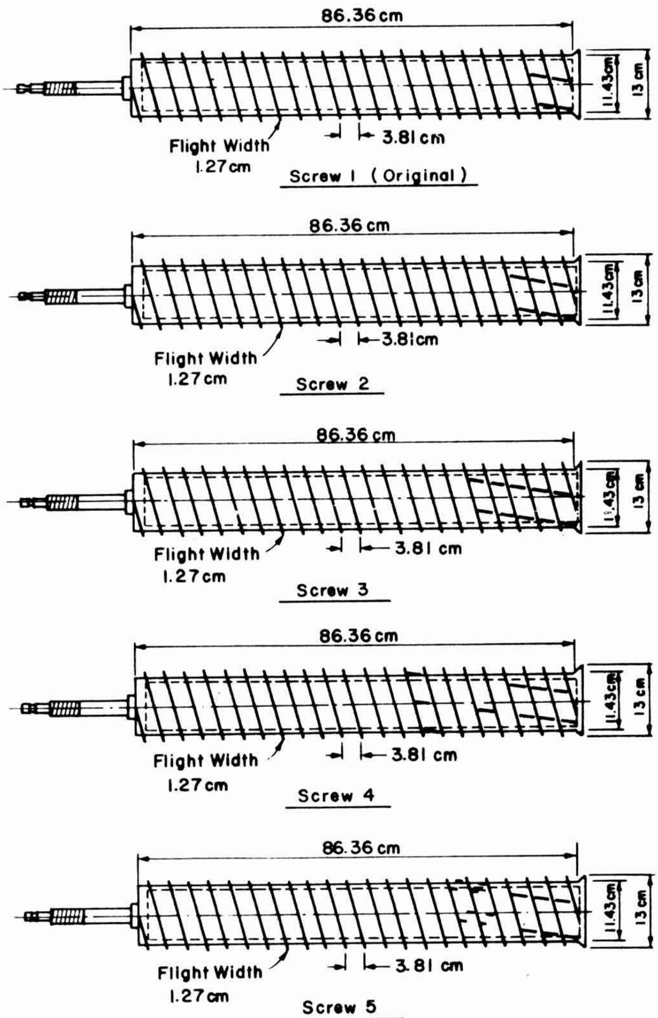

FIG. 2. LOCATION OF RESTRICTIVE DAMS IN CHANNELS BETWEEN FLIGHTS OF SCREWS TESTED

from a diesel tractor used to drive the extruder was determined using a Baldwin-Lima-Hamilton Torque Sensor, Model A12 and a D. C. tach-generator.

Feed Ingredients

Whole No. 2 yellow dent corn and whole soybeans were obtained locally. The raw grains were initially at 12% moisture and blended to 72/28 weight ratio of corn and soy. All feed materials were ground to approximately —40 mesh in a hammer mill before they were fed to the extruder.

Extruder Operation

The operation of the Brady extruder has been described in Harper and Jansen (1976). The machine is started with an open die and feed materials having higher than operating moistures. Once drier feed materials emerge from the annular die, the die is slowly closed until the desired operating temperature is achieved.

The tests were performed in sequence starting with samples extruded at 149°C. The machine was allowed to operate under steady state conditions for at least 10 min, after which all processing data were taken: throughput, temperature distribution along the barrel, torque, rpm, residence time, and samples. After sampling, the cone clearance was adjusted further until temperatures of 163°C and 171°C, respectively, were achieved.

Characteristics of Extruded Product

The concentration of reducing sugars present in the extruded product was studied in order to determine the effect of screw restrictions on starch damage. For this purpose, the dinitrosalicylic acid (DNSA) method for reducing sugars developed by Miller (1959) was used.

Paste consistency tests were performed using the American Corn Miller's Federation method, (Bookwalter *et al.* 1968), which was designed to specify the condition of starches in corn meal used in CSM. The test measures the viscosity of an extruded product-water mixture after a specific hydration time.

Paste viscosities of the extruded samples were measured using a Brookfield Viscometer, Model RVT. The samples were prepared as outlined under methods of analyses for the commodity specifications of CSB, with minor modifications as follows: 1) samples were ground to a flour-like particle size (—80 mesh) in a Fitz Mill, Model D, and 2) 100 mℓ of water at 25°C was added to 37 g of the ground sample and stirred for 3 minutes with a spatula to remove all lumps. Brookfield viscosities were measured using spindle No. 7 at a speed of 20 rpm.

Bulk densities in g/cm^3 were determined by weighing a tared 1 liter container filled with the extruded product. The mass of the contents in grams divided by 1,000 gave the bulk density.

RESULTS AND DISCUSSION

Extruder Operation

Temperature Distribution Along the Barrel. Typical temperature profiles for runs carried out at 600 and 1,000 rpm using the original screw (configuration 1) are shown in Fig. 3 and 4. The data collected from the nine thermocouples followed a similar pattern for each discharge temperature for the two screw speeds. Temperatures in the feed zone were about 50°C for screw speeds of 1,000 rpm and 30°C for 600 rpm. The higher feed zone temperatures occurring at higher operating speeds persisted for the last 60 cm of barrel length, after which temperature differences between different screw speeds were less noticeable.

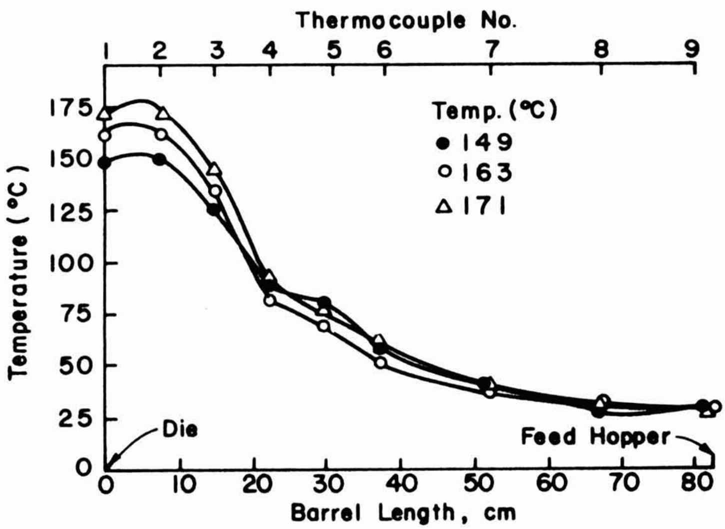

FIG. 3. TEMPERATURE PROFILE ALONG THE BARREL FOR THREE FINAL TEMPERATURE SETTINGS (N = 600 rpm, $\dot{m}$ = 6 kg/min, ORIGINAL SCREW)

The 20 cm at the discharge of the barrel saw the product rapidly increasing in temperature at an almost constant rate of 4°C per cm of barrel length. Consequently, the product was subjected to relatively high temperatures for only a short time. The highest product temperature was reached approximately 7 cm from the extruder discharge with some cooling following this point. The decrease in temperature was probably

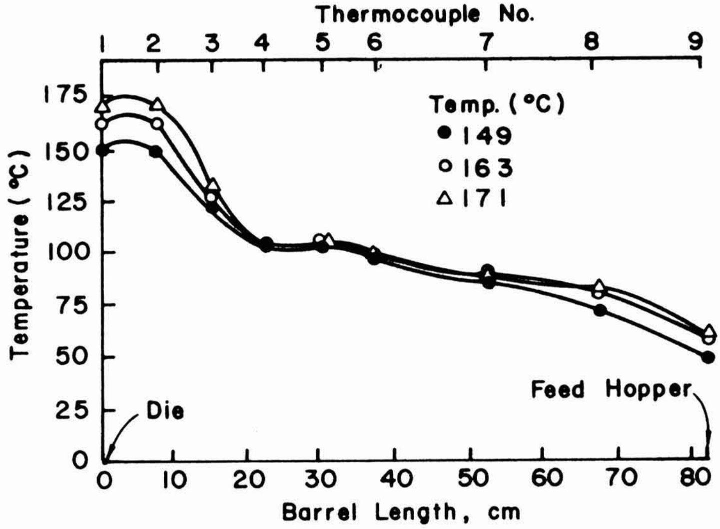

FIG. 4. TEMPERATURE PROFILE ALONG THE BARREL FOR THREE FINAL TEMPERATURE SETTINGS (N = 1,000 rpm, $\dot{m}$ = 7 kg/min, ORIGINAL SCREW)

due to heat losses from the die consisting of a large mass of metal. At the extruder discharge, the dough viscosity was lowest so viscous dissipation of mechanical energy is reduced and unable to compensate for the heat losses causing the drop in temperature.

Figure 5 shows the manner in which the temperature along the barrel was influenced by feed rate with the original screw. Test runs at high throughputs consistently showed lower temperature profiles compared to runs at lower feed rates with constant screw speed and final temperature settings. Temperatures obtained with feed rates of 8.5 kg/min were consistently 5°C lower than those obtained at feed rates of 7 kg/min, and 10°C lower than the ones obtained with feed rates of 5.5 kg/min. The longer residence times associated with lower extrusion rates caused temperatures to rise faster in agreement with these observations.

Figure 6 indicates a noticeable shift in temperature profiles occurring when steaming back developed inside the extruder. Steaming back results when a plug of material is not formed in the screw allowing steam at the discharge to pass over the tops of and down the screw channel to exit violently at the feed hoper. Under these unsteady conditions, feeding is disrupted and extrusion operations are erratic. Temperatures recorded with steaming back are about 45°C higher in the feed section than those recorded under steady flow conditions because of the presence of the steam at the feed port.

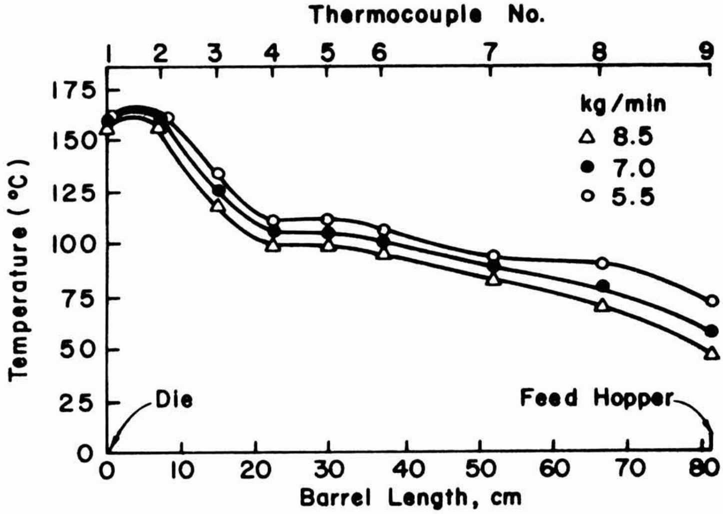

FIG. 5. TEMPERATURE DISTRIBUTION ALONG THE BARREL AS A FUNCTION OF MASS FLOW RATE (N = 1,000 rpm, T = 163°C, ORIGINAL SCREW (1))

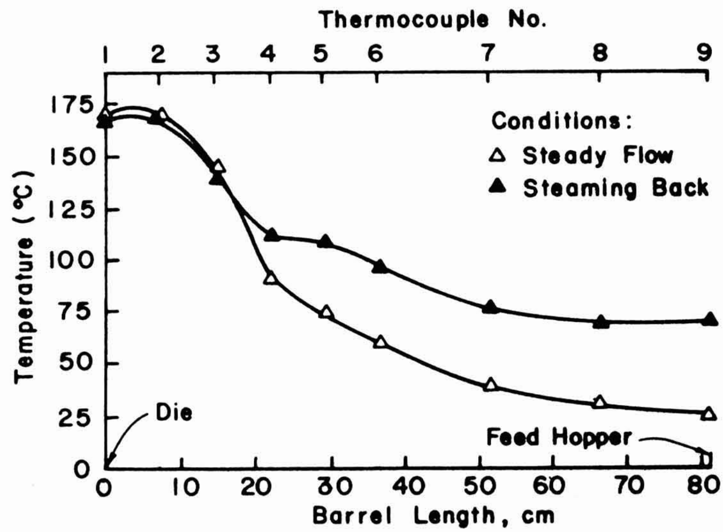

FIG. 6. TEMPERATURE PROFILE ALONG THE BARREL UNDER STEADY FLOW CONDITIONS (△) AND STEAMING BACK CONDITIONS (▲) (N = 600 rpm, $\dot{m}$ = 6 kg/min, ORIGINAL SCREW (1))

Modifications in the number and distribution of restrictive dams in the screw channel proved to have a significant influence on temperature profiles along the barrel. Figure 7 indicates the manner in which the five screw configurations tested affected temperature distributions with a discharge temperature of 149°C. Trends noted at this temperature were similar to those found at higher discharge temperatures. The original screw (configuration 1) and configuration 5 showed similar profiles and exposed the product to lower temperatures in the feed zone. These two screw configurations were found to be most effective in preventing steaming back, thus improving the extruder operating characteristics. Mixing of the product in the screw channel seemed to be improved by screw configurations 2 and 5, as indicated by visual observations on the uniformity and homogeneity of the extruded product. Observations tended to indicate restrictions placed closer to the discharge end of the extruder had the greatest effect on operating conditions and other extrusion parameters.

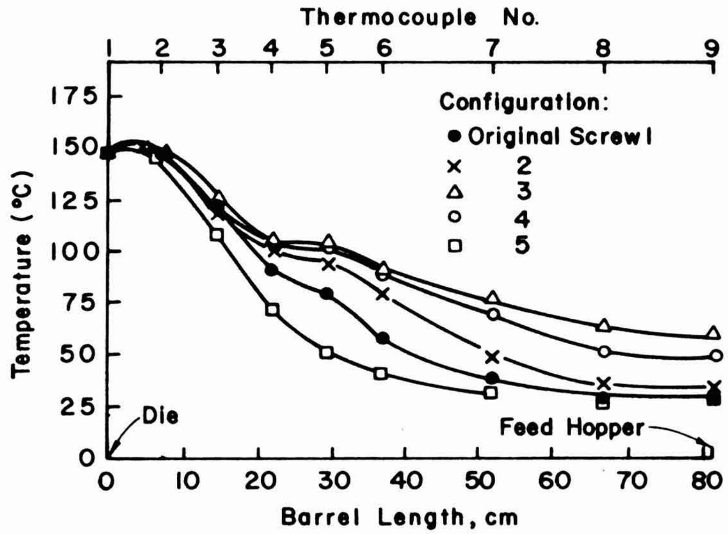

FIG. 7. EFFECT OF SCREW GEOMETRY ON TEMPERATURE DISTRIBUTION PROFILES ALONG THE BARREL ($T = 149°C$, $\dot{m} = 5.5$ kg/min, $N = 600$ rpm)

Energy Input. As predicted by Eq. (1), power requirements were directly related to throughput, with higher feed rates requiring higher energy inputs. Figure 8 shows the linear effect of throughput and final temperature settings on energy requirements.

Specific energy, kW-h/kg, is the amount of energy required to extrude

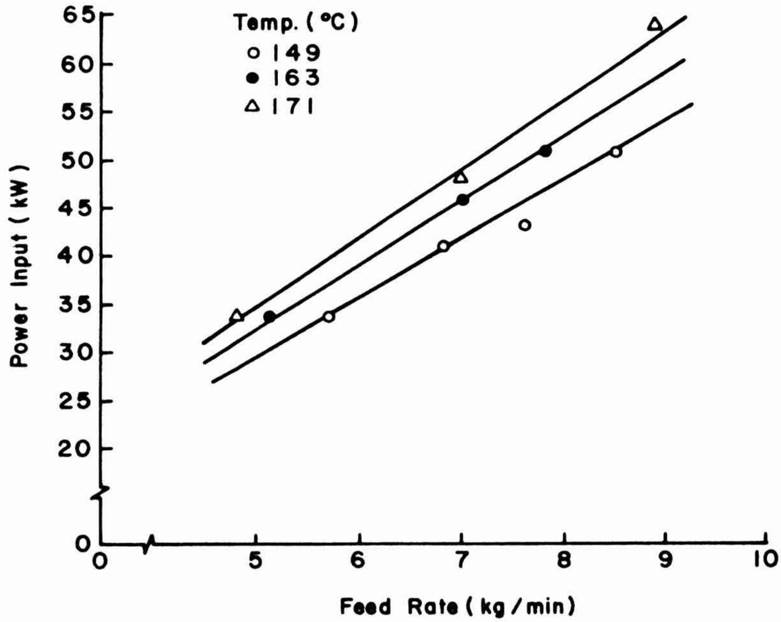

FIG. 8. POWER INPUT TO EXTRUDER AS A FUNCTION OF FEED RATE AND TEMPERATURE OF EXTRUSION (N = 1,000 rpm, ORIGINAL SCREW (1))

one kilogram of raw material at a specific set of conditions. Average specific energy inputs for the original screw configuration at temperatures of 149, 163, and 171°C were calculated to be 0.10, 0.11, and 0.12 kW-h/kg, respectively. Equation 1 predicts an increase in energy with increasing temperature due to the sensible heat term. An energy balance around the extruders showed that about 60% of the total energy input to the extrusion system is required for the sensible heat rise while about 19% of the energy is consumed by chemical changes to the material such as gelatinization and dextrinization of the starch.

The slope of each line (Fig. 8) represents the specific energy for each temperature of extrusion. If the slope of each line is divided by the corresponding temperature rise during extrusion, a specific heat (C) is obtained. The value, 2.9 kJ/kg•K was calculated in this manner, which was 45% higher than the specific heat calculated using literature data for raw corn and soybeans — 2.0 kJ/kg•K. This 45% difference can be attributed to approximately 20% of the input energy causing chemical changes and 20% being lost from the extruder barrel.

High screw speeds (1,000 rpm) resulted in higher specific energy as indicated by Fig. 9. The result is expected since at these conditions the

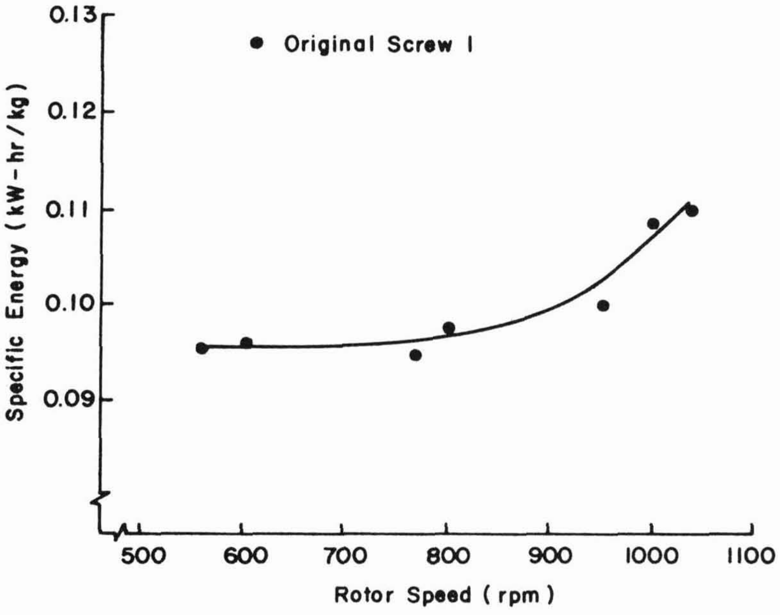

FIG. 9. SPECIFIC ENERGY AS A FUNCTION OF ROTOR SPEED (T = 149°C, ORIGINAL SCREW (1))

material is exposed to higher shear and mechanical forces which promote increased chemical changes such as gelatinization and dextrinization and protein denaturization. The pressure gradient should also increase at higher screw speeds, thus raising the total energy input as predicted by Eq. (1), although this effect is relatively small.

The effects of changing the location and types of restriction in the screw channel on specific energy are summarized in Fig. 10. Each screw configuration affected energy requirements differently. Higher energy requirements with increasing number of dams placed closer to the discharge was a trend.

Minimum specific energy demands were attained when using screw configuration 5, where dams measuring half the length of the conventional dams were located in opposite sides of the screw-channel, promoting early plug development to reduce steaming back. The lower specific energies resulting with configuration 5 are probably due to this configuration having the lowest temperature profile of the configurations tested reducing the heat loss from barrel. No meaningful information related to energy inputs could be derived from configuration 3, which created a number of operating problems when extrusion temperatures above 149°C were attempted.

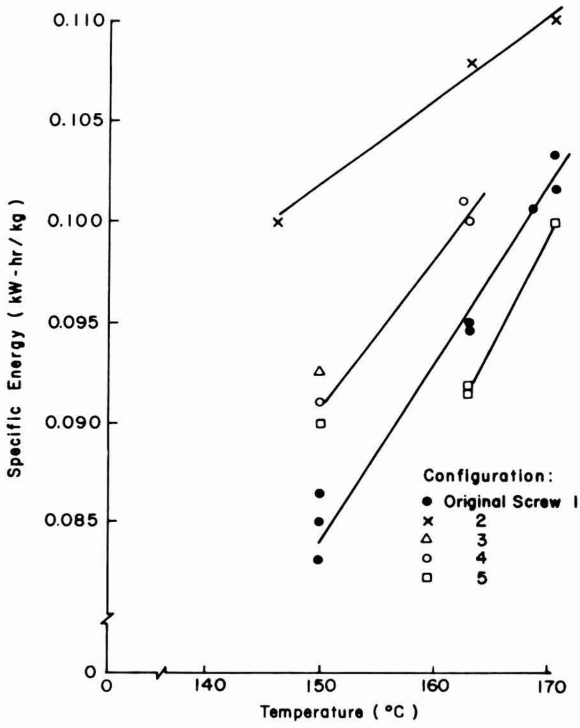

FIG. 10. SPECIFIC ENERGY AS A FUNCTION OF TEMPERATURE OF EXTRUSION AND SCREW GEOMETRY (N = 600 rpm, $\dot{m}$ = 5 kg/min)

Extruded Product Functional Properties

Tests were performed to determine how the functional properties of the extruded product were affected by variations in the extrusion conditions and screw geometries. Screw speed and feed rate did not show an effect on product properties to any extent.

Starch Damage Results. Reducing sugars were measured on products extruded with different screw configurations and temperatures. The results give some insight into the extent to which the starch molecule was damaged during dry extrusion. Table 1 indicates that high extrusion temperatures produced slightly greater cleavage of the starch molecule. Screw geometry, on the other hand, was also found to affect modifications to the starchy components. Increasing the number of dams in the screw channel restricting flow and inducing higher shear resulted in higher levels of reducing groups in the cooked starch.

Table 1. Reducing sugar content of extruded products

Screw Configuration	Extrusion Temperature (°C)	Glucose Concentration mg/g
1	149	4.45
(original)	163	4.50
	171	5.35
2	149	3.70
	163	3.55
	171	3.55
4	149	5.90
	163	6.15
	171	6.65
5	149	5.60
	163	5.70
	171	5.85

Consistency Results. Precooked composite flours made with simple extruders are often used as gruels. The consistency of the hydrated flour measures the viscosity of the hydrated flour. Typical results obtained from the ring consistometer for flours extruded at different final temperatures and five screw configurations are given in Fig. 11. These data indicate that products obtained from lower extrusion temperatures and/or with screws having fewer numbers of dams had higher consistency values or lower viscosities. Similarly, paste viscosities measured by a Brookfield viscometer shown in Fig. 12 indicate that higher paste viscosities were obtained from products extruded at higher temperatures and with screws having increased number of dams. Screw configuration **2** does not follow this general trend, which may be attributed to inconsistencies in the experimental conditions during testing.

The higher gruel viscosities recorded for products extruded at higher temperatures and greater shear are due to the increase in gelatinization as previously reported (Tribelhorn *et al.* 1976). Gelatinization increases the rapid water absorption of the starch molecules and yields a thicker gruel.

Bulk Density. Bulk densities (g/cm^3) were determined for products extruded at three temperatures with three screw configurations are shown in Fig. 13. The data indicate that regardless of the screw configuration used, bulk densities were affected by temperatures of extrusion, with higher temperatures giving lower bulk densities and greater expansion. Screw configurations having increased number of dams also promoted higher expansion and reduced the density of the product.

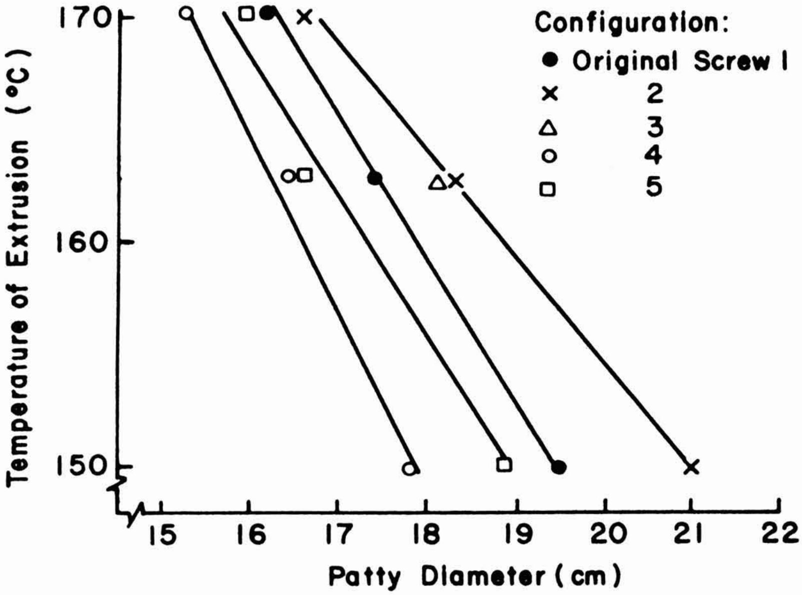

FIG. 11. CONSISTOMETER TEST RESULTS FOR FIVE SCREW CONFIGURATIONS AND THREE TEMPERATURES OF EXTRUSION

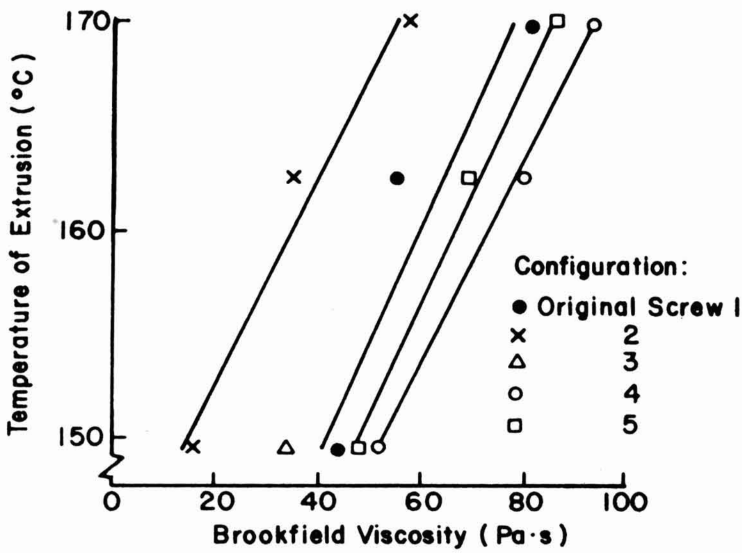

FIG. 12. VISCOSITY TEST RESULTS FOR FIVE SCREW CONFIGURATIONS AND THREE TEMPERATURES OF EXTRUSION AT N = 600 rpm

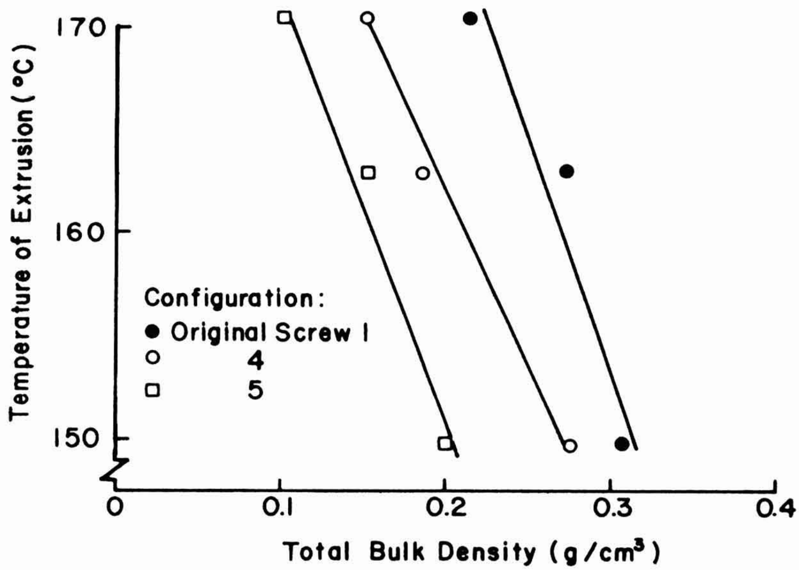

FIG. 13. TOTAL BULK DENSITY OF PRODUCTS EXTRUDED AT THREE TEMPERATURES WITH THREE DIFFERENT SCREW CONFIGURATIONS AT N ≃ 600 rpm

CONCLUSIONS

Flow restrictive dams, placed across the screw channel, were found to alter energy inputs to the product due to greater viscous dissipation of mechanical energy. Dams may also be used as an approximate method of controlling product temperature profiles down the barrel in autogenous extruders.

As expected, total energy input to the screw was highly correlated to extrusion discharge temperature. Extruded product characteristics were more affected by increasing the number of restrictions in the channel near the discharge of the screw. Under these conditions, the products were more expanded, had higher paste viscosities indicating gelatinization, and showed greater amounts of reducing sugar.

The functional properties of the extruded product were greatly affected by temperature of extrusion and screw geometry, but less so by screw speed and feed rate. Increasing the number of restrictions in the channels supplied extra energy to the material and created a high shear environment promoting some starch damage.

In cases where higher than normal amounts of energy are required during extrusion, the addition of flow restrictions in the screw channel showed beneficial results. The number, dimensions and location of these dams are critical in order to ensure uniform operating conditions and desired product properties.

NOMENCLATURE

A = area, m^2

C = specific heat, $\frac{kJ}{kg^\circ K}$

E = power input to extruder, kW

ϵ_w = emissivity of barrel surface

H_c = surface heat transfer coefficient, $\frac{kW}{m^2\,^\circ K}$

$\dot{m}$ = mass flow rate, kg/h

P = pressure, $\frac{Pa}{m^2}$

Q = volumetric flow rate, $\frac{m^3}{h}$

q_{ch} = energy associated with chemical changes, $\frac{kJ}{kg}$

σ = Stephan-Boltzman constant

T_w = wall temperature, $^\circ K$

T = product temperature, $^\circ K$

subscripts

1 = feed end of screw

2 = discharge end of screw

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PERFORMANCE MODELS FOR CONTINUOUS DIELECTRIC PASTEURIZATION OF MILK

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ABSTRACT

The steady-state performance of a continuous parallel-plate heat exchanger was generally predicted for nonfat milk solutions of measured conductivity by a model equation obtained from energy balance on the exchanger. Electrical properties of the milk were determined from the Hasted-Debye models for aqueous ionic solutions. Heating characteristics of an experimental exchanger agreed closely with predicted values for various flow rates and voltage gradients at temperatures of interest in pasteurization of biological fluids. Such models could be employed in the development of electrical pasteurization or sterilization processes for a variety of food products. Electrical heating processes would reduce thermal denaturation of heat-labile food constituents, as compared with conventional heating processes, due to rapid heat penetration, uniform heating and low surface temperatures and would give products of improved nutritional value and organoleptic quality. Theoretical considerations also suggest that higher thermal death rates would be obtained for vegetative microbial contaminants at process temperatures and holding times comparable to those of conventional heating processes.

INTRODUCTION

Electrical pasteurization processes at line frequency have been known for several decades (Getchell 1935) and are based on the principles esgablished by Pasteur in 1864 and later defined by the U.S. Public Health Service in terms of temperature-holding time requirements. Early investigations showing severe damage to milk nutrients and flavor constituents in conventional pasteurization processes, due to fluid contact with high-temperature surfaces, led to the development of such processes, which give rapid and uniform heating as compared with conduction heating processes. It is also reported that electrical pasteurization destroys harmful bacteria commonly found in milk with greater efficiencies than those of conventional heating methods. A recent review (Lund 1977) of thermal process design for maximizing nutrient retention observed that pasteurization is a thermal process which inactivates some, but not all, of the vegetative microorganisms in foods and must be used in conjunction with preservation methods such as refrigeration, anaerobic conditions, high salt concentrations or low pH to provide an environment unsuited to the growth of spoilage or hazardous microorganisms. The review also notes that thermal death rates for vegetative cells of bacteria, yeast and fungi are more temperature-dependent than thermal denaturation rates of nutrients, enzymes and quality factors such as color, flavor and texture. Thus, high temperature/short time (HTST) processes are generally favored for optimization of conventional pasteurization processes (Hartman and Dryden 1965; Thompson 1969). HTST processes were also favored in viscous fluid sterilization by relative thermal destruction rates of thiamin and bacterial spores at higher temperatures (Feliciotti and Esselen 1957). Pasteurization efficiencies in milk are based on thermal death of a Rickettsial species and are determined by the activity of an enzyme which is destroyed under similar temperature-time conditions. Pasteurization of low viscosity fluids, such as milk, is generally by a plate heat exchanger (Earle 1966), with HTST processes up to 260°F — 4 s. Interestingly, thermal denaturation rates of enzymes are generally several orders of magnitude lower than those of vegetative microorganisms, but are of the same order of magnitude as the most heat resistant spores (Lund 1977). This suggests that blanching of enzymes at high temperatures may also sterilize process fluids and vice versa, a condition which would be undesirable if enzyme activity is to be retained in processing.

The objective of the present work is to demonstrate that the heating characteristics of a continuous flow parallel-plate dielectric heat exchanger may be predicted based on theoretical considerations of exchanger geometry, voltage gradient, volumetric flow rate and fluid physical properties. These conditions clearly suggest that the heating characteristics of such an exchanger would be identical over a wide range of frequencies below the microwave region for a given set of operating conditions. A performance model for steady-state operation of an exchanger is then proposed as a basis for the development of dielectric heating processes for pasteurization or sterilization of heat-labile food products in the fluid state. A conceptual diagram for such a process, with feedback control of flow rate to maintain constant outlet temperatures, is shown in Fig. 1.

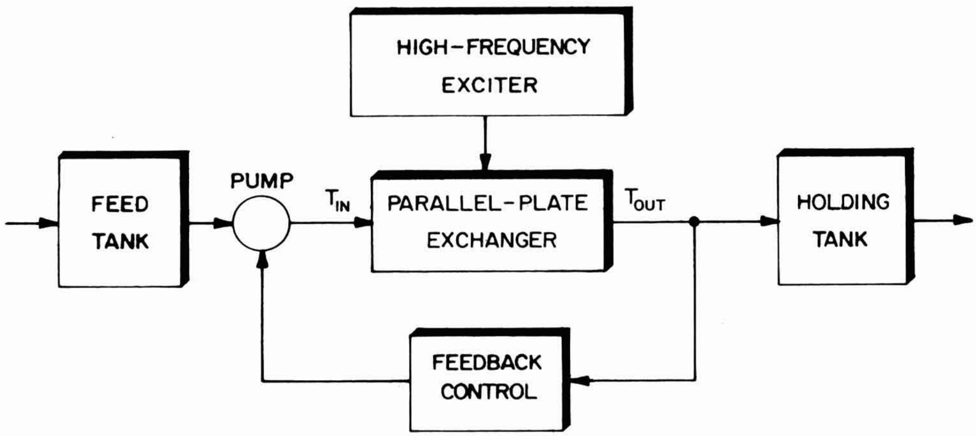

FIG. 1. DIELECTRIC PASTEURIZATION PROCESS DIAGRAM

THEORETICAL CONSIDERATIONS

The dielectric properties of water are given by the Debye equations for pure polar solvents (Collie *et al.* 1948):

$$K'_w = \frac{(K_s - K_o)}{1 + (\lambda_s/\lambda)^2} + K_o \qquad (1)$$

$$K''_w = \frac{(K_s - K_o)(\lambda_s/\lambda)}{1 + (\lambda_s/\lambda)^2} \qquad (2)$$

where K'_w and K''_w are the relative dielectric constant and loss factor of water, respectively, K_s and K_o are the static and optical dielectric constants, λ_s is the critical wavelength and λ is the irradiating wavelength. At submicrowave frequencies, the dielectric constant of water is its static value at a given temperature and the dielectric loss is negligible. These equations have been modified to give the Hasted-Debye equations (Hasted *et al.* 1948) which predict the behavior of aqueous ionic solutions by adding correction terms for dielectric constant depression by ionic water binding and for dielectric loss elevation by ionic conductivity at frequencies of interest in dielectric heating processes:

$$K'_s = K'_w - 2\,\bar{\delta}\,C \tag{3}$$

$$K''_s = K''_w + \frac{\Lambda C}{1000\omega\epsilon_o} \tag{4}$$

where K'_s and K''_s are the relative dielectric constant and loss, respectively, of an aqueous ionic solution, $\bar{\delta}$ is the average hydration number, i.e., the average number of water molecules bound by counterions of a dissolved salt, C is the molar concentration of the dissolved salt, Λ is an equivalent conductivity which can be obtained as a function of concentration and temperature from the International Critical Tables, ω is the angular frequency of irradiation and ϵ_o is the dielectric constant of free space. At submicrowave frequencies, the dielectric constant of an aqueous ionic solution with an effective salts concentration typical of milk is nearly that of water. At such frequencies, dielectric constant depression effects are negligible, and the dielectric loss of the solution is completely determined by the ionic conductivity. Fluids of low colloidal content, i.e., suspended solids, may be modelled by the Hasted-Debye equations to predict dielectric constants and loss factors (Mudgett *et al.* 1974a) which determine penetration depth and power absorption in an irradiated fluid. Fluids of high colloidal content have been modelled by a modification of the Fricke equation for heterogeneous mixtures (Fricke 1955; Mudgett *et al.* 1974b):

$$K^*_m = \frac{K^*_c\,[K^*_s\,(1 + X\,V_s) + K^*_c\,(1 - V_s)X]}{K^*_c\,(X + V_s) + K^*_s\,(1 - V_s)} \tag{5}$$

where K^*, K^*_c and K^*_s are the complex permittivities of a mixture, its continuous phase and its suspended phase, respectively, V_s is the volume fraction of the suspended phase, and X is a form factor depending on the shape of the suspended particles. The permittivity of mixtures obtained by solution of this equation in complex notation can be resolved to give dielectric constant and loss of the mixture. Power absorption by a material in a uniform electrical field is given by an equation which can be expressed in temperature-dependent form (Goldblith 1967):

$$P\,(T) = \frac{\omega\epsilon_o E^2 K''\,(T)}{2} \tag{6}$$

where P (T) is the average power density, ϵ_o is the dielectric constant of free space, ω is the angular frequency of irradiation, E is the voltage gradient of the field and K″ (T) is the dielectric loss of the absorbing material at a given temperature. The rate of heat generation in the material resulting from power absorption at the same temperature may then be expressed as a direct function of power density:

$$\dot{q}\,(T) = K_d\,P\,(T) \tag{7}$$

where $\dot{q}$ (T) is the instantaneous rate of heat generation, K_d is a dimensional constant and P (T) is the average power density in the material at the given temperature.

A performance model for a dielectric heat exchanger at submicrowave frequencies may then be obtained by energy balance on a differential element of length along the exchanger. The exchanger is assumed to consist of two parallel plates of length L and width W separated by distance D and to be excited by an external power modulator; it is also assumed, as a first approximation, that transverse and longitudinal disperson of dissolved salts may be neglected. For plug flow conditions at steady-state:

$$(\dot{m}c_pT)_x - (\dot{m}c_pT)_{x\,+\,dx} + \dot{q}\,(T)\,Adx = 0 \tag{8}$$

where $\dot{m}$ is the mass flow rate of the fluid, c_p its heat capacity, T the temperature at steady-state, $\dot{q}$ (T) the instantaneous rate of heat generation in a differential element of volume, A the flow cross-sectional area of the exchanger and dx a differential element of length. Expanding this equation and integrating from the inlet to the outlet of the exchanger leads to the relationship:

$$Q = \frac{AL}{\rho c_p \displaystyle\int_{T_{in}}^{T_{out}} \frac{dT}{\dot{q}\,(T)}} \tag{9}$$

where Q is the volumetric flow rate and ρ the density of the fluid. This can be expressed in various forms, depending on the nature of its intended application. The equation may be used in conjunction with Eq. (4), (5), (6) and (7) to obtain predictions of exchanger performance for a wide range of design conditions and fluid properties. The design of continuous-flow pasteurization or sterilization processes might, for example, involve solving for flow rates required to give a specified temperature rise in an exchanger at some maximum level of power consumption. This could be done by modelling the dielectric loss factor of the fluid to be processed as a function of temperature in Eq. (4) and (5), substituting in Eq. (6), (7) and (9) and solving for the required flow rate by analytical or numerical integration. This may generally be accomplished by a fourth order Runge-Kutta method. Performance predictions are based on the assumption of uniform conditions in final processing. While it is true that the electrical field in a parallel-plate exchanger is generally uniform at frequencies and temperatures of interest, fluid residence time distribution (RTD) effects are known to depend on flow regimes classified by Reynolds number (Levenspiel 1972; Smith 1970). Hence, the assumption of plug flow is not strictly valid. However, RTD effects are seen to be much less significant, for conditions of practical interest, than the effects of high surface temperatures and nonuniform heating in conventional heat exchangers.

MATERIALS AND METHODS

Experimental Apparatus

An experimental parallel-plate exchanger was employed to simulate the performance characteristics of a process for milk pasteurization at submicrowave frequencies. The exchanger was constructed from two polystyrene plates 1 in. thick × 6 in. wide × 14 in. long. These were milled to provide rectangular slots for mounting stainless steel electrodes 12 in. long with silver-soldered posts at their centers extending through the plates to provide terminals for external power connections. The electrodes were epoxied in place to give a water-tight seal. The plates were then bolted together and sealed by silicone gasket material with the slots aligned to form a 1 cm × 1 cm channel between the electrodes. Channel ends were drilled and tapped for hose adapters at the inlet and outlet of the exchanger. The unit was mounted vertically with the inlet end at the bottom connected to a reservoir through a peristaltic pump and the outlet end connected to a collector, as indicated in Fig. 2. Inlet and outlet fluid temperatures were measured at steady-state. The exchanger was connected to a 110 VAC line power source by means of a power variac initially at zero volts. Voltage and current in the exchanger were continuously monitored. Nonfat milk solutions with an effective salts concentration of 0.06M sodium chloride equivalents were continuously heated in the apparatus at voltage gradients from 25—75 volts/cm and volumetric flow rates from 250—750 cm^3 /min for comparison of

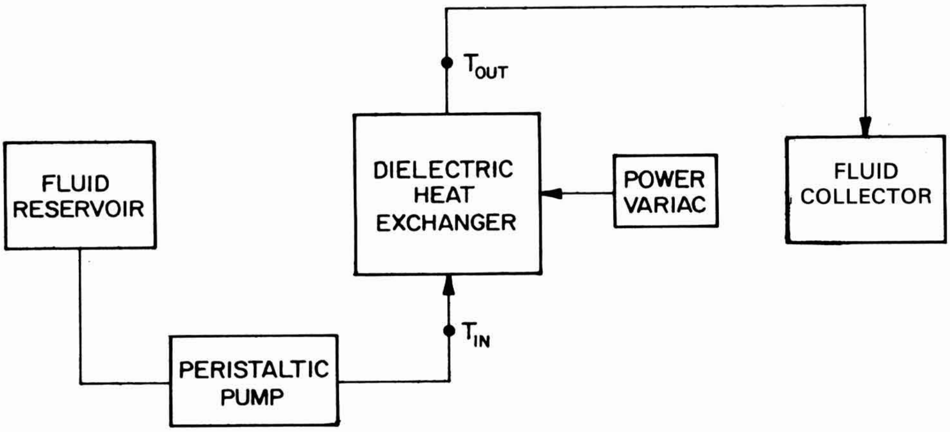

FIG. 2. EXPERIMENTAL APPARATUS

outlet temperatures with model predictions. Replicate measurements were obtained for each set of operating conditions within ± 1°C.

Nonfat Milk Solutions

Ten percent (w/v) aqueous solutions of nonfat dried milk solids (Carnation Company) containing 32.2% protein, 52.9% carbohydrate and 11.9% ash on a dry weight basis, as indicated by the manufacturer's label, were employed as a standard test fluid for each set of operating conditions.

Temperature Measurements

Temperatures were measured at the entrance and exit of the exchanger by thermistor probes (Yellow Springs Instrument Company) for steady-state conditions.

Flow Rates

Constant flow rates were maintained by a tubing pump (Cole-Parmer Company, Model 7555) calibrated by water collection measurements in a graduated cylinder as a function of motor speed.

Conductivity Measurements

Electrical conductivities of nonfat milk solutions were measured by an impedance bridge (General Radio Company, Model 650A) at 1 KHz and nulled by an oscilloscope (Tektronix Company, Model 536). A water-jacketed conductivity cell was employed with platinum electrodes of 1 cm^2 area amounted 1 cm apart and with temperature control by a circulating water bath. The cell constant was determined by calibration with standard solutions of aqueous sodium chloride. Electrodes were platinized by electrodeposition of 2% (w/v) chloroplatinic acid with a trace of lead acetate following electro-cleaning in 20% (v/v) hydrochloric acid with a scavenger electrode.

Model Predictions

Predictions were obtained by a Fortran program employing fourth order Runge-Kutta integration to determine model values of outlet temperature for each set of operating conditions, i.e. voltage gradient and flow rate, based on geometry of the exchanger and fluid properties. Fluid density, heat capacity and electrical conductivity were modelled as functions of temperature based on values obtained from the International Critical Tables.

RESULTS

Results of the simulation of high frequency heating characteristics for nonfat milk solutions employed in the experimental exchanger are shown in Fig. 3—5. Measured outlet temperatures are compared with performance model predictions based on conductive losses of the test fluid, i.e. it can be shown that the dipole loss of water is negligible at submicrowave frequencies for temperatures of interest in dielectric pasteurization. Figure 3 is a comparison for flow rates from 0.25—0.75 liters/min at a gradient of 25 volts/cm. Figure 4 is a comparison for the same flow rates at a gradient of 50 volts/cm. Figure 5 is a comparison for gradients from 25—75 volts/cm at a flow rate of 0.5 liters/min. Predicted and measured outlet temperatures are seen to agree within ± 5% at all flow rates and voltage gradients. At constant voltage gradients, the outlet temperature decreases at increasing flow rates, as predicted by the performance model. At a constant flow rate, the outlet temperature increases exponentially at increasing voltage gradients, again as predicted by the performance model. It is noted in all cases that the transient heating period during startup was less than two minutes.

DISCUSSION

These measurements show that steady-state heating characteristics of a continuous flow parallel-plate dielectric heat exchanger may be predicted at line frequency as a function of exchanger geometry, operating

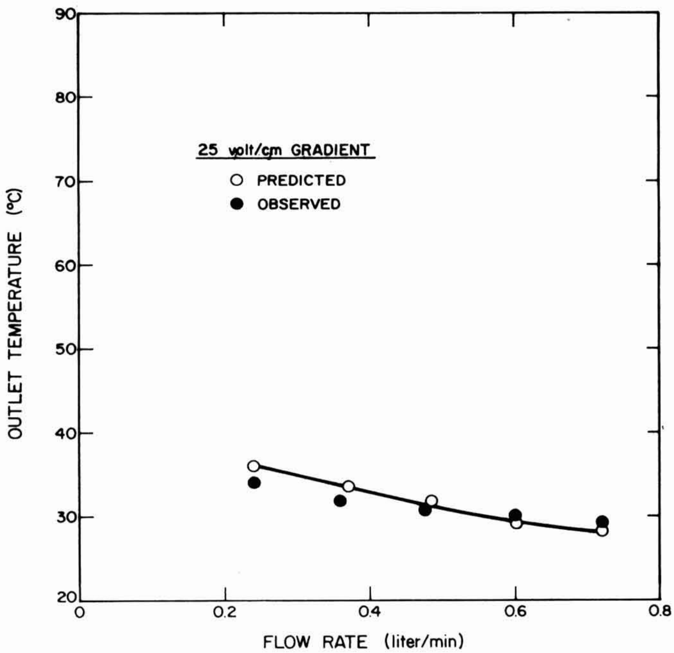

FIG. 3. OUTLET TEMPERATURE VERSUS FLOW RATE AT GRADIENT OF 25 VOLTS/cm

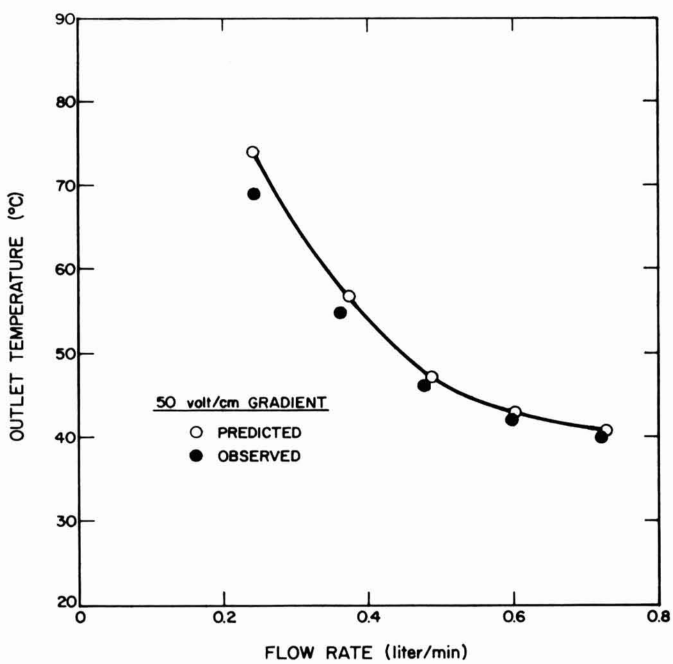

FIG. 4. OUTLET TEMPERATURE VERSUS FLOW RATE AT GRADIENT OF 50 VOLTS/cm

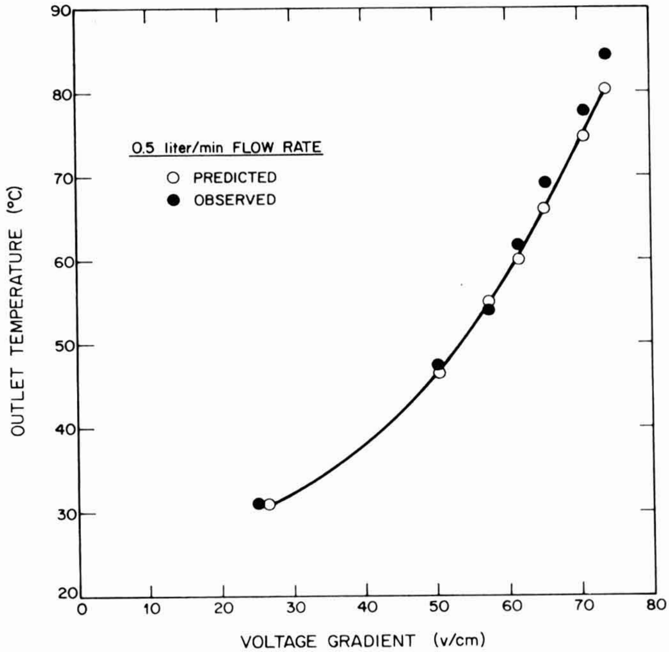

FIG. 5. OUTLET TEMPERATURE VERSUS GRADIENT AT FLOW RATE OF 0.5 LITERS/MIN

conditions and fluid properties. They also imply, based on theoretical considerations, that similar predictions can be made for a variety of food products in the fluid state at pasteurization temperatures for frequencies below the microwave region, i.e. frequencies at which dipole water losses may be neglected. Parenthetically, such models could also be employed at microwave frequencies for continuous cavity heating of fluids, subject to modifications for field penetration depth and voltage coupling effects (Mudgett and Nash 1980). However, excitation at a submicrowave frequency, e.g. 27 MHz, would be considerably more cost-effective, since voltages can be directly coupled to the load and uniform heating is not subject to penetration depth limitations observed at microwave frequencies. On the other hand, heating at very low frequencies, e.g. 60 Hz, is known to involve polarization effects which are associated with oxidation-reduction reactions at the electrodes. These may result in plating of metallic ions, precipitation of solids, gas evolution or the formation of undesirable compounds which could alter product quality. Such effects would be avoided at high frequencies.

There is also reason to believe that biological compartments of high conductivity relative to their surroundings, e.g. the intracellular environment of vegetative microorganisms (Carstensen *et al.* 1971) and plant tissue cells (Mudgett *et al.* 1977) may selectively absorb energy from an electrical field. This is not inconsistent with enhanced electrical pasteurization efficiencies (Getchell 1935) and lethal effects in cultures of *E. coli* (Fleming 1944) which were first believed to be athermal in nature, but later shown to be of thermal origin (Wang and Goldblith 1967). Such considerations encourage the idea that electrical pasteurization processes may be more efficient in killing vegetative cells than conduction heating methods, due to differences in the mechanisms of electrical and thermal conduction in terms of penetration rate and uniformity of heating. But whether or not such effects are significant, there would be considerably less thermal denaturation of labile constituents and quality factors due to lack of fluid contact with high-temperature surfaces. Such contact leads to severe "burn-on" problems, with solids coatings that reduce overall heat transfer coefficients in convective transfer and significantly alter organoleptic and nutritional quality of over-processed fluids (Lund 1979; Harper and Hall 1976).

There is, of course, a relative cost differential between electrical and conventional heating processes based on operating and capital costs. But with rising fossil fuel costs, energy cost differentials are decreasing and capital costs of an electrical heat exchanger and its peripheral control and distribution equipment may be comparable with those of a conventional plate exchanger and its auxiliary boiler and piping equipment. Electrical equipment would require less plant space and would also permit conservation of petroleum and natural gas fuels by utilization of alternative electrical power sources.

ACKNOWLEDGMENTS

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LITERATURE ABSTRACTS

ABSTRACTS FROM TRANSACTIONS OF THE ASAE

THE FLUIDIZATION CHARACTERISTICS AND HYDRAULIC TRANSPORATION OF FRENCH FRIES. H. McLain, G. McKay. Trans. ASAE *22*FE, 671—677.

A laboratory system has been designed to study the transportation properties of French fries in vertical pipelines. The results indicate that a number of factors should be considered when designing a French fry conveying system. Factors which have been found to influence the extent of fluidization, and hence transportation properties of French fries, include pressure drop, French fry dimensions and the mass of French fries to be transported. The experimental results indicate how the minimum fluidization velocity and the transportation velocity can be determined for given systems, and how the pressure drop across a fluidized bed of French fires can be measured, in order to help predict the power requirements of the water circulating pump.

ENERGY SAVINGS AND QUALITY DETERIORATION FROM HOLDING FROZEN FOODS AT TWO DAILY TEMPERATURE LEVELS. B. H. Ashby, A. H. Bennett, W. A. Bailey, W. Moleeratanond, A. Kramer. Trans. ASAE *22*FE, 938—943.

For a 1-yr period, pallet lots of frozen foods were stored in one room where a constant temperature was maintained and in three other rooms where the daily temperature was maintained at a high level for 12 h and at a low level for 12 h. Within certain constraints, a net energy saving was realized by holding frozen foods at two daily temperature levels without serious quality losses.

THE FINITE ELEMENT APPROACH FOR SOLUTION OF TRANSIENT HEAT TRANSFER IN A SPHERE. R. N. Misra, and J. H. Young. Trans. ASAE *22*FE, 944—949.

The finite-element method is used for solution of a time dependent heat transfer problem in a sphere. The element equations for spherical coordinates are derived from the basic fundamentals. These equations are used to solve a sample problem of cooling a freshly harvested apple and the numerical solution is compared with the analytical solution. This technique has great potential for applications in the processing of products (chemical/biological) which have wide material property variations and whose shape may be approximated by a sphere.

DESORPTION ISOTHERMS OF ROUGH RICE FROM 10°C TO 40°C. C. Zuritz, R. P. Singh, S. M. Moini and S. M. Henderson. Trans. ASAE *22*FE, 433—436.

Equilibrium moisture contents (EMC) for smooth-hulled medium grain rice variety (M5) were determined at 10, 20, 25, 30 and 40°C and relative humidities ranging from 11.2 to 92.5%. A static method of equilibrium was used by suspending 16 g of samples in one quart wide-mouth jars with 200 ml of different saturated salt solutions. Triplicated samples were used for all trials. Data obtained at relative humidities of 90% and higher were erroneous due to condensation on the samples and corrosion of sample basket. A new empirical equation was proposed to correlate the EMC data and compared with Day-Nelson and Chung-Pfost equations. Root Mean Square Error (RMSE) and Analysis of Variance (ANOVA) tests were performed to evaluate the goodness of fit of the data by the different equations. The ANOVA test showed that there was no difference among Day-Nelson, Chung-Pfost and the new empirical equation. Either one could be used to predict the EMC data.

PROPERTIES OF SQUID USEFUL IN DESIGNING OF CLEANING AND HANDLING SYSTEMS. L. A. Brooks, R. P. Singh. Trans. ASAE *22*FE, 658—663.

This paper presents physical properties of California Market Squid (*Loligo opalescens*) which are useful in designing of cleaning and handling systems. Information on surface friction characteristics and forces to remove viscera and fins using water sprays is presented.

MINNESOTA DAIRY PROCESSING PLANT WASTEWATER — CURRENT TREATMENT AND ALTERNATIVE COSTS. J. A. Moore and B. M. Buxton. Trans. ASAE *22*FE, 664—670.

To measure the impact of new EPA discharge regulation on the dairy processing industry, four "typical" plants were selected in the state and sampled hourly for 24 h. The resulting wastewater characteristics are included. Three standard treatment/disposal systems were designed and their resulting costs are reported.

MECHANICAL PROPERTIES OF BONE: A REVIEW. J. L. Baker and C. G. Haugh. Trans. ASAE *22*FE, 678—687.

Most researchers now agree that bone is not a simple isotropic material and that it more closely resembles a transversely isotropic material at low strain levels. However, the viscoelastic nature will have to be considered for a full characterization of bone. What is needed at this stage is more pioneering research to evaluate the mechanical properties of bones of animals that are useful to man. Also the work at a continued characterization of bone for analytical purposes of stress and strain need to be continued. However, in future research a greater effort should be made to consult the literature and contact other laboratories with some experience in the selected area to be sure that the previous experimental and theoretical work has been thoroughly reviewed.

In summary, much additional research is needed to quantify and qualify the transversely isotropic material assumption for bone. There also exists a total lack of information for the many bones of the many animals that are useful to man.

TEMPERATURE DEPENDENCE OF THE STRESS RELAXATION BEHAVIOR OF AQUEOUS SUGAR GLASSES. P. B. McNulty and D. G. Flynn. Trans. ASAE *22*FE, 445—448.

We have demonstrated that the theories of linear viscoelasticity may be successfully applied to model aqueous sugar glasses simulating the structure of hard boiled candy. In particular, we have shown how the criteria for the applicability of the time-temperature superposition principle may be systematically investigated. Further studies on the temperature dependence of the mechanical and rheological properties of food and agricultural materials should employ this approach. to ensure that the time-temperature superposition principle applies to their data. In such cases, the results may be usefully applied to design problems in agricultural engineering where knowledge of the response of materials to various loading regimes at variable temperature is required.

MECHANICAL SEPARATION OF FIBROUS ASPARAGUS. R. R. Wolfe and D. P. Krivoshik. Trans. ASAE *22*FE, 437—440.

A separator for asparagus was developed, capable of removing the tough, fibrous material from raw spears while leaving the remainder of the spears intact and undamaged. Performance evaluations were conducted using spears having a wide range of lengths and cross sectional diameters. Results indicate that spear length and diameter variations do not seriously affect performance and the prototype has a capacity of over 500 kg per h. The separator is capable of providing a whole spear product containing about 4% fibrous material with a loss of 3% of the tender material during separation.

IMPROVED SAMPLE HOLDER FOR Q-METER DIELECTRIC MEASUREMENTS. S. O. Nelson. Trans. ASAE *22*FE, 950—954.

A new sample holder is described for use with a Q-Meter to measure the dielectric properties of materials. It includes provision for controlling the temperature of the dielectric sample. It also is equipped with two calibrated, variable air capacitors — one for measurements to determine the dielectric constant, and the other for measurements that determine the loss tangent. The improved design eliminates possible errors in determining the loss tangent, loss factor, and conductivity that can be caused by residual and lead inductance at the higher frequencies. Results of measurements between 10 and 40 MHz on samples of hard red winter wheat of different moisture contents are presented and discussed. Measured values of the dielectric constant of wheat were somewhat dependent upon electrode spacing, because kernel dimensions were appreciable in relation to interelectrode distances.

TEMPERATURE AND STRESS ANALYSIS OF CORN KERNEL — FINITE ELEMENT ANALYSIS. R. J. Gustafson, D. R. Thompson and S. Sokhansanj. Trans. ASAE *22*FE, 955—960.

Finite element analysis is used to study transient heat transfer and thermal stresses in a corn kernel. Stress during both heating and cooling are reported for a step change in environmental temperature. Sensitivity of stress results to variation in material properties is studied.

SUPPLEMENTAL FISH PROTEIN AS MILK REPLACER FOR ANIMALS. P. O. Heggelund and G. M. Pigott. Trans. ASAE *22*FE, 1226—1228.

Biologically extracted supplemental fish protein, due to its high functionality and nutritive value, has a commercial application as a high protein food source, particularly as a milk replacer for animals. This paper reports results of an investigation modifying a peptic enzyme process, giving a product that meets the specifications for milk replacers.

MODELING THEORY FOR PHYSIOLOGICAL SYSTEMS. G. H. Smerage. Trans. ASAE, *22*FE, 1488—1493.

Organism and ecosystem physiologies are physicochemical compositions. An overview is presented of an approach currently under development for physicochemical representation of physiologies. The approach evolves from the theory of discrete physical systems by compatibly treating chemical systems. Elementary components and structural properties of chemical systems are defined. Modeling methodology and applications are discussed using examples from plant physiology.

MATHEMATICAL MODEL OF THE GRIT CONCENTRATION IN THE WATER OF AN EXPERIMENTAL LEAFY-GREENS WASHER USING RECIRCULATION. M. E. Wright, J. K. Brzozowski and R. C. Hoehn. Trans. ASAE *22*FE, 1482–1487.

A prototype leafy vegetable washing system using recirculated wash water was built and tested at a commercial vegetable processing plant. The system consisted of two washers in series, each with an associated settling tank, and water recirculation and screening system. Cleaner product was produced with one fifth the water of a comparable conventional system. A mathematical model to predict the concentration of grit in the water of each of the four units as a function of time and inputs was written. Coefficients of determination for predicted vs. measured values ranged from 0.932 to 0.765 over four trials. These results, using data taken in uncontrolled conditions, indicate that food washing systems can be successfully modeled.

A COMPUTER TECHNIQUE FOR CALCULATING THERMAL INACTIVATION. I. J. Ross, T. C. Bridges and F. A. Payne. Trans. ASAE *22*FE, 194–201.

A computer program was developed to estimate the thermal inactivation of heat treatment processes. A number of process curves were evaluated and error estimates involved with program use were obtained.

AVAILABLE LYSINE LOSSES IN A REAL FOOD SYSTEM. D. R. Thompson and J. C. Wolf. Trans. ASAE *22*FE, 202–206.

Previously reported kinetic equations for predicting losses of available lysine in model food systems are evaluated experimentally with real food systems. The influence of salts used in pH adjustments on available lysine loss is also experimentally evaluated.

A PRAWN POPULATION MANAGEMENT MODEL. R. T. Gibson and J. K. Wang. Trans. ASAE *22*FE, 207–210.

A deterministic population model was developed for prawns in a rectangular earthen pond from pre-existing data. A theoretical mortality function relating mortality to stocking density was first hypothesized, then tested against actual data. Empirical growth and harvesting functions were determined by use of simple linear regression analysis. The mortality, growth and harvesting functions were combined to form a predictive model, using past performance to estimate the model parameters.

ABSTRACTS FROM THE JOURNAL OF FOOD SCIENCE

A COMPARISON OF METHODS FOR PREDICTING THE FREEZING TIMES OF CYLINDRICAL AND SPHERICAL FOODSTUFFS. A. C. Cleland and R. L. Earle. J. Food Sci. *44*, 958–963.

A series of experiments was carried out to determine the freezing time of cylindrical and spherical blocks of a widely used food analogue. material. These results were used to assess the accuracy of calculation methods in the literature, including both numerical (computer) and modified analytical methods. A three-level implicit finite difference scheme was developed which gave good accuracy, but no better than an extension of an analytical method which is therefore advocated on the grounds of ease of use. It covers the range of conditions most likely to be encountered in practical food freezing situations.

PREDICTION OF FREEZING TIMES FOR FOODS IN RECTANGULAR PACKAGES. A. C. Cleland and R. L. Earle. J. Food Sci. *44*, 964—970.

A previous study of methods for predicting the freezing times of slabs, cylinders and spheres was extended to cover rectangular bricks of food materials. Experimental measurements of the freezing time were made over a wide range of conditions using a food analogue material, and these results compared to times calculated from various available prediction methods. The three-dimensional version of a three time-level finite difference scheme was found to be the most accurate numerical solution. Simple formulae are available for predicting the freezing time of rectangular bricks using the geometric factors derived by Plank. These factors are shown to be subject to error, and none of this group of methods gave accurate prediction of freezing time. A previously proposed group of formulae are extended to cover rectangular bricks. These formulae are simple to use and accurate. They are applicable to slabs (±5% with 95% confidence), and to cylinders and spheres (±7% with 95% confidence), as well as to bricks (±10% with 95% confidence). These extend the previously published formulae for slabs, cylinders and spheres without significant loss of accuracy.

LOW OXYGEN RECYCLED VAPOR (LORV) FOR FOOD DRYING. J. P. Morgan, E. L. Durkee and J. R. Wagner. J. Food Sci. *44*, 1556—1557.

An exploratory study has been made where drying was done by reheating the vapors of evaporation which were then recycled with the combustion gasses through a partially closed system containing a low oxygen atmosphere. Fresh carrots dried in this manner were simultaneously dried and blanched and appeared to have more flavor and color and a more natural texture compared to conventionally air-dried carrots when reconstituted. Drying temperatures greater than 143°C throughout drying caused heat damage to the drying product, but higher temperature may be possible in the initial drying stages by replacing the batch system used in this investigation with a two-stage continuous system.

WATER BINDING OF FOOD CONSTITUENTS AS DETERMINED BY NMR, FREEZING, SORPTION AND DEHYDRATION. H. K. Leung and M. P. Steinberg. J. Food Sci. *44*, 1212—1216.

The water binding properties of some common food constituents were determined by water sorption, dehydration, freezing and NMR methods. The sorption isotherms of sodium alginate, pectin, corn starch, casein and cellulose were obtained and the heats of absorption and monolayer values were calculated. The unfreezable water contents of these five materials were determined and the values corresponded to the equilibrium moisture contents at a water activity of about 0.90. The bound water capacities of 14 food materials were determined using wide-line NMR. These values correlated closely with the tertiary moisture contents determined by a drying rate study and the equilibrium moisture contents at 100% relative humidity. The different

NMR properties of free and bound water were discussed in terms of nuclear relaxation times and molecular mobilities.

COMMERCIAL FEASIBILITY OF AN IN-LINE STEAM PROCESS FOR CONDITIONING PECANS TO IMPROVE SHELLING EFFICIENCY AND MAINTAIN NUTMEAT QUALITY. W. R. Forbus Jr., B. L. Tyson and J. L. Ayres. J. Food Sci. *44*, 988—993.

Tests at a commercial plant showed that a new in-line steam process was better than the existing process in conditioning inshell pecans for cracking, as determined on the basis of shelling efficiency, or yield of unbroken nutmeat halves. Steam conditioning was more effective than commercial conditioning in reducing total plate count and yeast and mold count on the product. Peroxide and free fatty acid values of oils, Hunter color values of nutmeat halves, and sensory taste analyses indicated that the quality of the nutmeats conditioned by the two methods was essentially the same immediately after conditioning. Commercial test results agreed with results of previous pilot-scale studies.

A METHOD FOR THE CONCENTRATION OF PROTEINACEOUS SOLUTIONS BY SUBMERGED COMBUSTION. A. H. Luedicke Jr., B. Henderickson and G. M. Pigott. J. Food Sci. *44*, 1469.

Proteinaceous solutions are difficult to concentrate in conventional facilities due to denaturation, followed by "bake-on" of insoluble material on heat exchange surfaces. Vessels used are expensive and difficult to clean and are generally heated by steam from high first-cost boilers at low fuel utilization percentages, due to inefficiencies inherent in such units. A technique of concentrating fish hydrolysate (6—8% solids w/w) prepared by enzyme digestion was developed, using submerged combustion. In this method, combustion products of commonly available gaseous fuels are exhausted beneath the liquid surface. Heat transfer is extremely rapid and since it occurs across bubble film surfaces, there is no bake-on. Use of secondary air cools the burner surfaces and allows regulation of bulk liquid temperature. Spray-dried material prepared from the concentrate is a fully functional protein: PER tests show high indices; fish protein averages 100% of the PER for casein. Fuel utilization is excellent; approximately 86% thermal energy input is used for evaporation. Bulk liquid temperatures were controlled from 158—169°F in concentrating hydrolysate with initial solids contents of 6—8%. Solutions of acidities ranging from pH 2.7—5.9 were concentrated to 30% solids, using commercial propane and compressed air. The cost was approximately $0.02/lb of 30% solids solution. Air-cooled submerged combustion appears to offer a very efficient method of heating and con-concentrating heat-sensitive solutions without incurring the penalties of "bake-on" and difficult clean-up. Low first-cost equipment may be used; the possibility exists of using disposable tank liners.

DESIGN OF A GENERATOR FOR STUDYING ISOTHERMALLY GENERATED WOOD SMOKE. E. Ugstad, S. Olstad, E. Vold, K. I. Hildrum, D. Fretheim and T. Hoyem. J. Food Sci. *44*, 1543—1544 + 1549.

A laboratory size smoke generator, working under controlled conditions, has been constructed. The generator is basically a closed system to allow control over the supply of air, and it can produce smoke at a specific, desired temperature (within

± 10°C) in the region 300—550°C. This makes possible meaningful and systematic studies of important properties of smoke generated at various temperatures, such as its antimicrobial, antioxidative, flavor- and color producing effects, and content of polycyclic aromatic hydrocarbons.

COEFFICIENT OF SLIDING FRICTION FOR NONUNIFORM SURFACE PROPERTIES. J. M. Henderson. J. Food Sci. *44*, 1550—1551.

The determination of the sliding coefficients of friction of the two major parts of squid moving on a metallic surface required using the whole squid. The investigation of the relationship between the coefficients of friction of the individual parts and the average coefficient for the whole lead to the derivation of a general relationship analogous to the relationship for the center of mass of a body. Specific results from the squid investigation are included to illustrate the application of the general friction relationship.

OPTIMAL RETORT TEMPERATURE PROFILE IN OPTIMIZING THIAMIN RETENTION IN CONDUCTION-TYPE HEATING OF CANNED FOODS. I. Saguy and M. Karel. J. Food Sci. *44*, 1485—1490.

The maximum principle theory (Pontryagin *et al.* (1962) "The Mathematical Theory of Optimal Processes," Wiley Interscience, New York) was used to optimize thiamin retention during sterilization of a conduction-heating canned food. The optimal retort temperature profile determined by this procedure improved thiamin retention by more than 2%, as compared with other methods, and showed that a single solution for the temperature profile exists. The optimization method may be applicable to other processes in which retention of nutrients or other characteristics is to be improved.

REVISION OF THE FORMULA METHOD TABLES FOR THERMAL PROCESS EVALUATION. R. J. Steele, P. W. Board, D. J. Best and M. E. Willcox. J. Food Sci. *44*, 954—957.

Inaccuracies in the Formula method for thermal process evaluation — which could lead to overestimates of the lethal value and reduce the margin of safety of processes — were found. Revised tables for C:g and f_h/U:g systems are presented as well as revised coefficients for polynomials fitted to the tables for use in programmable calculators.

BOOK REVIEW

Food Engineering, Principles and Selected Applications. M. Loncin and R.L. Merson, Academic Press Inc., New York. 1979. 494 pp. $47.00.

The authors produced an excellent book. C. Judson King is to be joined in his congratulations expressed in his foreword to the book. Yet there is a peculiarity, the book shares with all its competitors on the subject of Food (Process) Engineering: The most fundamental — and most elaborately treated — component of its content is the common foundation of Food and Chemical (Process) Engineering. As C. Judson King expresses it in his foreword: "The chemical engineer . . . will find that he is working in very familiar territory."

Loncin and Merson's book might be commented as one of the best textbooks known on the general principles of Process Engineering. It has a special value for engineers in the food industry because of its emphasis on applications of process engineering principles in the field of food production. The interesting collection of 79 problems with solutions at the end of the book provide a training in application of principles to realistic food production cases.

IR. W.A. BEVERLOO

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Materials and Methods: Enough information should be provided to allow other investigators to repeat the work. Avoid repeating the details of procedures which have already been published elsewhere.

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HASSON, E. P. and LATIES, G. G. 1976. Separation and characterization of potato lipid acylhydrolases. Plant Physiol. *57*, 142–147.

ZABORSKY, O. 1973. *Immobilized Enzymes*, pp. 28–46, CRC Press, Cleveland, Ohio.

Journal abbreviations should follow those used in *Chemical Abstracts*. Responsibility for the accuracy of citations rests entirely with the author(s). References to papers in press should indicate the name of the journal and should only be used for papers that have been accepted for publication. Submitted papers should be referred to by such terms as "unpublished observations" or "private communication." However, these last should be used only when absolutely necessary.

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