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CONTENTS

Air Drying Behavior of Fresh and Osmotically Dehydrated Pineapple M.S. RAHMAN and J. LAMB	163
Evaporation in a Horizontal Thin Film Scraped Surface Heat Exchanger H. ABICHANDANI and S.C. SARMA	173
Specific Heat of Dehydrated Pulps of Fruits J.D. ALVARADO	189
Convection Heat Transfer Coefficient for a Restructured Pork/Soy Hull Product K. UNKLESBAY, N. UNKLESBAY and K. BIEDRZYCKI	197
Kinetic Study of Quality Losses in Frozen Scallop Meats S.L. CHUNG and J.H. MERRITT	209
Electrical Conductivities of Selected Solid Foods During Ohmic Heating S. PALANIAPPAN and S.K. SASTRY	221

AIR DRYING BEHAVIOR OF FRESH AND OSMOTICALLY DEHYDRATED PINEAPPLE

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ABSTRACT

Fick's Law of diffusion was used in the analysis of the air drying behavior of fresh (non-osmosed) and osmosed pineapple. The drying rates of osmosed pineapples were significantly decreased due to the presence of infused solute. The effective diffusion coefficient decreased with the increasing solid gain during osmosis.

INTRODUCTION

Osmotic dehydration is the process of water removal by immersion of a water containing cellular solid in a concentrated aqueous solution. The driving force for water removal is the concentration gradient between the solution and the intracellular fluid. If the membrane is perfectly semipermeable, solute is unable to diffuse through the membrane into the cells. However, it is difficult to obtain a perfect semipermeable membrane in food systems due to their complex internal structure, and there is always some solid diffusion into the food which means that osmotic dehydration is actually combination of simultaneous water and solute diffusion processes. Osmotic dehydration generally will not give a product of low enough moisture content to be considered shelf-stable. Consequently, osmosed product should be further processed (generally by air, freeze or vacuum drying methods) to obtain shelf-stable product. Many investigators recommended that the quality (color, flavor and texture) of air or freeze dried fruits and vegetables was improved by a prior osmotic dehydration step during air drying (Ponting 1973; Flink 1975; Dixon *et al.* 1976; Flink 1979; Voilley and Simatos 1979). Islam and Flink (1982) and Islam (1982) noted that the moisture removal

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resistance from osmoted potato significantly increased during air drying. The objectives of these studies was to study the effect of solid gain due to prior osmotic dehydration on the moisture diffusion resistance during air drying of pineapple.

Fick's diffusion law is widely used to analyze air drying process (Chirife 1971; Saravacos and Charm 1962; Vaccarezza *et al.* 1974; Vaccarezza and Chirife 1975). Mass balance in diffusion kinetics:

$$\frac{\delta M}{\delta t} = \frac{\delta}{\delta x} \left(D \frac{\delta M}{\delta x} \right) \quad (1)$$

where, M is the moisture content (kg water/kg dry solids), x is the diffusion path (m), t is the time (s) and D is the moisture dependent diffusivity (m^2/s).

For an infinite slab being dried from both major faces and with the assumptions, (1) initially uniform moisture distribution and (2) negligible external resistance to mass transfer, the initial and boundary conditions:

$$M = M_o \text{ at } t = 0 \text{ for all } x \quad (2)$$

$$M = M_s = M_e \text{ at } t > 0, x = x_{\text{surface}} \quad (3)$$

$$M = \text{finite, at } x = 0 \text{ for all } t > 0 \quad (4)$$

The solution of Eq. (1) for constant diffusivity (D):

$$\frac{W - W_e}{W_o - W_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[- \frac{(2n+1)^2 \pi^2 D t}{4 L_o^2} \right] \quad (5)$$

where W is the average moisture content (kg water/kg dry solids) and L_o is the half sample thickness (m).

The other assumptions involved for Fick's diffusion analysis are: (1) no shrinkage of the slab and (2) negligible external and internal heat transfer effect. The Eq. (5) is also shown in Fig. 2. For low values of W_e , it is possible to consider $(W - W_e)/W_o - W_e = W/W_o = M_r$ (moisture ratio) (Islam 1982; Yusheng and Poulsen 1988). The diffusivity (D) varies considerably with moisture and can be estimated by an analysis of the drying data (moisture vs time), applying one of the following methods: (1) the method of slopes (Perry *et al.* 1984; Saravacos and Raouzeos 1984) (2) a computer optimization method (Bakshi and Singh 1982) and (3) the regular regime method (Singh *et al.* 1984; Coumans and Luyben 1988). In general cases of nonlinear drying curves, the method of slopes can be applied to estimate the effective moisture diffusivity at various

moisture contents. The application of this method is illustrated in Fig. 2. The experimental drying curve $\log(M_r)$ vs t is compared to the theoretical diffusion curve ($\log M_r$ vs F_o) for the given shape of the material. The slope of the experimental curve (dM_r/dt) and the theoretical curve (dM_r/dF_o) are estimated at a given moisture ratio (M_r). The effective moisture diffusivity (D_e) at a given moisture ratio (or moisture) can be estimated from the equation:

$$D_e = [(dM_r/dt)_{\text{exp}}/(dM_r/dF_o)_{\text{th}}]L_o^2 \quad (6)$$

where, L_o = slab half thickness,

$F_o = D t/L_o^2$ = Fourier number of diffusion.

MATERIALS AND METHODS

Giant kew (African) varieties of pineapple purchased in Leeds were used for the experiments. Two slices of 6.5 mm thickness prepared from cored pineapple were threaded on a rod and lowered into a static sucrose bath for a constant time of 5 h. At 20°C the sucrose bath concentration was varied from 40–60% (m/v) and a sucrose concentration of 60% (m/v) was used at water bath temperatures from 20–60°C. After the end of osmosis, the slices were quickly rinsed and gently blotted with tissue paper to remove surface water before the start of air drying. The mass reduction of one slice was recorded and used for air drying. The percent moisture content was measured from the other slice. The mass reduction was the net mass loss of the sample on an initial mass basis:

$$\mu = \frac{m_o - m_e}{m_o} \times 100 \quad (7)$$

Water loss (ω) was the net water loss on an initial mass basis:

$$\omega = \frac{W_o - W_e}{m_o} \times 100 \quad (8)$$

The solid gain (σ) was the net solid transported into the sample on an initial mass basis:

$$\sigma = \omega - \mu \quad (9)$$

A pilot tunnel dryer (Fig. 1) was used for the air drying experiments. The air drying conditions were constant for all experiments. The air velocity, percent relative humidity and dry bulb temperature were 4 m/s, 10% and 60°C respec-

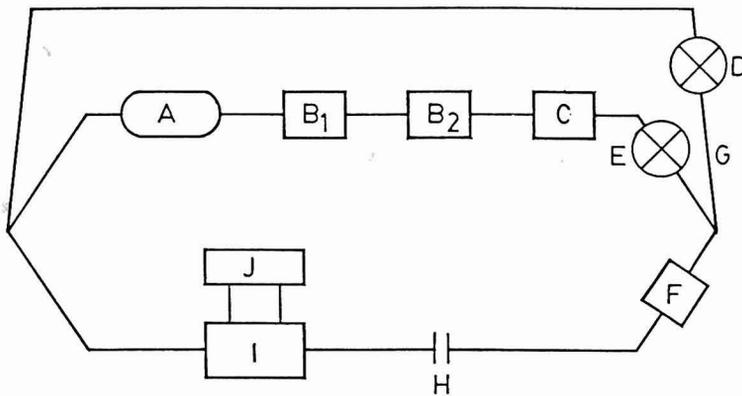


FIG. 1. EXPERIMENTAL ARRANGEMENT FOR TUNNEL DRIER

A. Centrifugal fan; B₁. Electric heater; B₂. Silica gel basket; C. Dry bulb, wet bulb and humidity controller; D. Air bypass valve; E. Air velocity controlling valve; F. Dry- and wet-bulb temperature recorder; G. Air bypass line; H. Orifice meter for measuring air velocity; I. Sample tray; J. Balance.

tively. Slice weight was recorded at intervals during air drying. The mesh bottom tray was used and air flow was parallel to the two faces and drying commencing from both the major faces of the slice. The water content and total solids were measured gravimetrically. Vacuum oven drying (5–6 h) at 70°C and 1.0×10^5 N/m² gave the solid content of the slices.

RESULTS AND DISCUSSION

Non-osmosed 6.5 mm slices were dried at the same air drying conditions to investigate the effect of osmotic treatment on air drying rate. There was no evidence of a constant rate drying period during air drying of fresh and osmotically dried pineapple. Many investigators have stated that the immediate onset of the falling rate was a characteristic of food materials. (Chirife 1971; Vaccarezza *et al.* 1974; Karathanos *et al.* 1990). During the analysis, initial moisture content was considered as the critical moisture content.

The experimental drying curves were drawn by plotting $\log(M_r)$ vs t , as shown in Fig. 2, 3 and 4. Non-osmosed samples gave the highest drying rate (Fig. 2) and osmosed sample at 60% sugar solution and 60°C gave the lowest drying rate (Fig. 4). Moisture is bound within the solid matrix in a variety of ways (e.g., capillaries, physico-chemical bonding to the solid constituents). Hence, the observed differences in drying rates may be related to the compositional changes which occur following osmosis. The observation of air drying rate is slower in osmosed samples is in agreement with the literature (Flink 1979; Islam 1982;

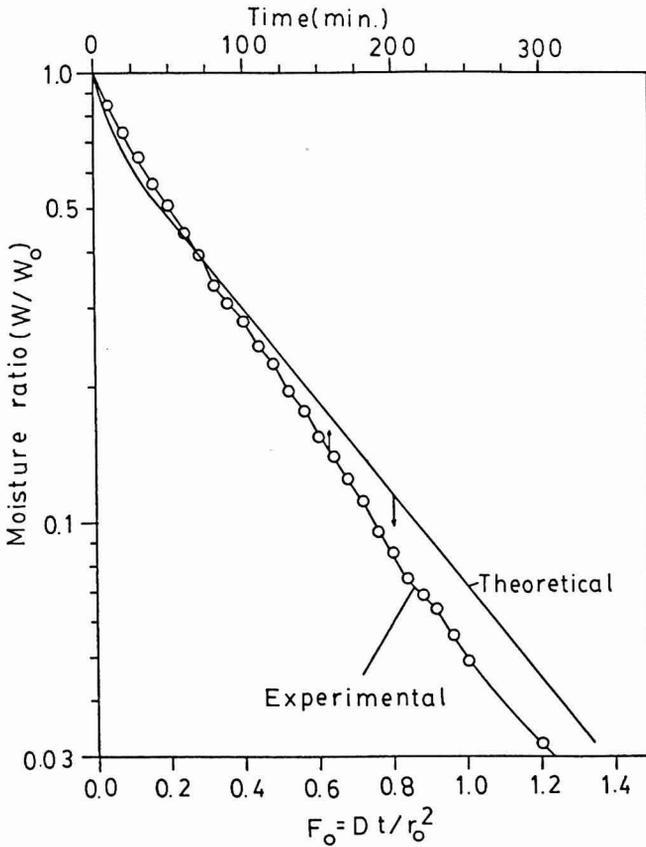


FIG. 2. DRYING CURVE OF 6.5 MM FRESH PINEAPPLE SLICE

Islam and Flink 1982). According to the above authors, lower drying rate was due to the solute uptake, which resulted in higher internal mass transfer resistance.

The effective moisture diffusivity (D_e) estimated from drying data represents an overall mass transport property of water in the material, which may include liquid diffusion, vapor diffusion, hydrodynamic flow and other possible mass transfer mechanisms. The experimental D_e values of the osmosed and non-osmosed samples, obtained by the method of slopes of the drying curve, varied with moisture content and the physical structure of pineapple (1.62×10^{-10} to 12.54×10^{-10} m²/s). The effective diffusivities of osmosed and non-osmosed samples are given in Fig. 5 and Fig. 6 as a function of moisture content. The effective diffusivities decreased (i.e., water removal resistance increased) with the increase of solid (i.e., sucrose) gain (σ) in the pineapple slices during the prior osmosis at the same drying conditions (Fig. 5 and Fig. 6). Sucrose infused

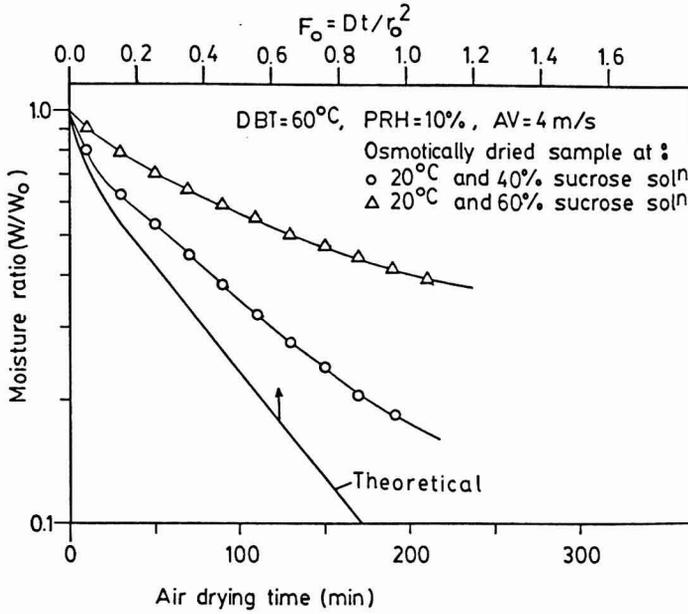


FIG. 3. DRYING CURVES FOR OSMOSED PINEAPPLE OF 6.5 MM SLICES

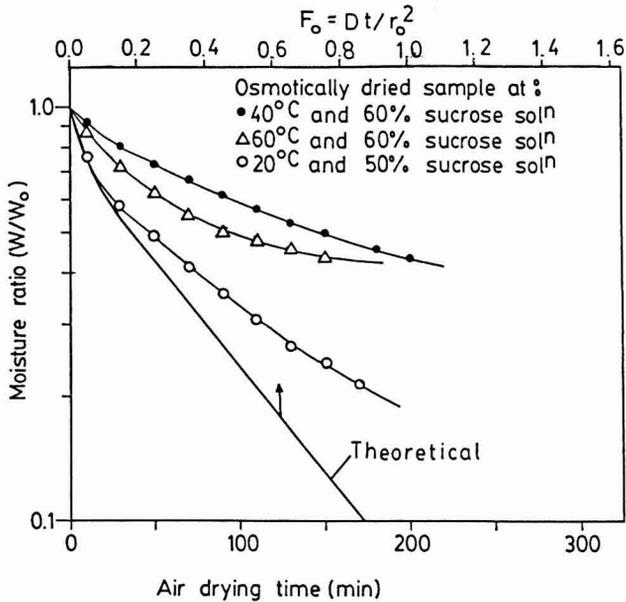


FIG. 4. DRYING CURVES FOR OSMOSED PINEAPPLE OF 6.5 MM SLICES

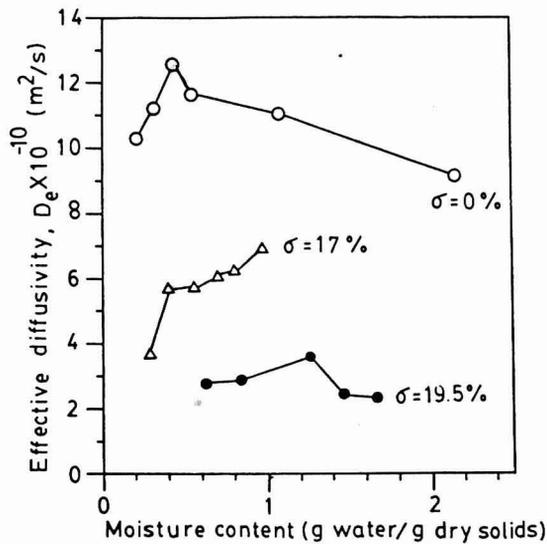


FIG. 5. EFFECTIVE DIFFUSIVITY AS A FUNCTION OF MOISTURE CONTENT
 ○ Non-osmosed, osmotically dried at: Δ 20°C and 50% sucrose solⁿ; ● 20°C and 60% sucrose solⁿ.

in pineapple as the water binding agent (i.e., hygroscopic) gave increased internal resistance to moisture movement. The extent and the nature of the surface on which adsorption can take place appears to be the prime factor in molecular adsorption. The hygroscopic material, for example starch in corn kernel, contains more polar sites for attraction of water molecules than does the cellulose. This should allow a large amount of moisture to be adsorbed by starchy material than cellulosic material (Mohsenin 1980). Hence, osmosed pineapple containing more sucrose, which is hygroscopic in nature, gave slower drying rates. Again, Karathanos *et al.* (1990) studied the air drying characteristics of hydrated starch and 75% starch/25% sucrose and found that the effective diffusivity decreased about 8 times with the changed shape of the diffusivity curves (D_e vs W) when 25% sucrose was added in gel. For pure starch, D_e increased to a maximum value with the decrease in moisture content and then again decreased; but for samples containing (75% starch/25% sucrose), effective diffusivity decreased with the decrease of moisture content. In the case of pineapple, different sucrose contents also gave different shapes of the diffusivity curves (Fig. 5 and 6).

CONCLUSION

Pineapple that had been osmosed was found to have lower drying rates than fresh pineapple due to higher initial solid content and/or the action of solute on

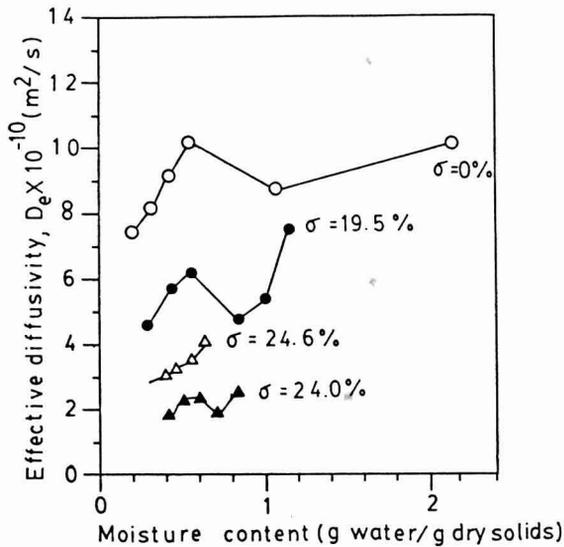


FIG. 6. EFFECTIVE DIFFUSIVITY AS A FUNCTION OF MOISTURE CONTENT

○ Non-osmosed, osmotically dried at ● 20°C and 40% sucrose solⁿ;
 △ 60°C and 60% sucrose solⁿ; ▲ 40°C and 60% sucrose solⁿ.

the water sorption behavior. Effective diffusivity of moisture transport during air drying decreased with the increase of solid gain during prior osmotic dehydration.

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EVAPORATION IN A HORIZONTAL THIN FILM SCRAPED SURFACE HEAT EXCHANGER

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ABSTRACT

Literature surveys have revealed inadequate information on heat transfer characteristics during evaporation in straight-sided horizontal thin film scraped surface heat exchangers (SSHE). The evaporation of water, concentration of milk and dehydration of cream (30–40% total solids) at different rotor speeds, number of blades, flow rates and temperature differentials were studied in 108 tests with objectives to develop a predictive equation for overall heat transfer coefficient and to study its variation with regard to above parameters in the light of proposed mechanism governing fluid flow, film formation and heat transfer. Data were processed in HCL System-4 computer to fit in quadratic form by method of least squares. Experiments were conducted at higher temperatures compared to those encountered in milk evaporators. The information would be useful in designing SSHE for processing several Indian dairy products.

INTRODUCTION

Process engineers in the food industry often have to transfer heat to heat-sensitive fluids and to fluids with scaling and foaming tendencies. One way to handle such difficult fluids is to continuously scrape the surface over which the liquid is heated. Freeze and Glover (1979) have described the performance characteristics of mechanically agitated thin film evaporators. Fischer (1965), Hauschild (1969), Holdt (1978), Arlidge (1983) and Angell and Baird (1983) have detailed process applications of agitated thin film evaporators (vertical and horizontal) in the food and chemical industries. Gudheim and Donovan (1957) studied heat transfer in thin film centrifugal processing units, where rotating blades turning inside a cylinder or truncated cone develop centrifugal force in process liquid, causing a violently agitated thin film to form on the circular wall.

Thermal performance of a horizontal tapered (1° taper) unit was compared with that of a vertical straight sided unit. Water was used as the test fluid and steam as the heating medium. Very high heat fluxes per unit transfer surface (up to 42,000 Btu/h/sq ft) were obtained in the reverse tapered machine at feed rates of 20–100 lb/h/sq ft. In a broad band of feed rates, the tapered unit efficiencies were at maximum fixed by thermal saturation of the wall metal. In the vertical straight sided unit, the heat transfer rate was found to be a linear function of the feed rate until thermal saturation of the heat sink was reached. Temperature differential and vacuum had no influence on the overall heat transfer coefficient in the horizontal tapered unit. However, variation in these factors had a significant effect on heat transfer in the vertical unit. In brief, it was concluded that within the confines of tests, thermal performance of the horizontal reverse-tapered unit was superior to that of the vertical straight sided unit. However, exact reasons for this were not established.

Though the technique of scraping heat exchanger surface is well known, little data on the factors which affect the heat transfer rates during evaporation have been published. The only information available on heat transfer correlations in case of vertical thin film SSHEs have been provided by Bressler (1958), Bott and Sheikh (1966) and Skoczylas (1970). However, these results were obtained in small electrically heated thin film SSHEs. Practically no appropriate design correlations as regards evaporation in straight-sided horizontal thin film SSHE have so far been published. There are several Indian dairy products which require processing at high temperature, essentially evaporation at atmospheric pressure. This demands the heating medium to be in the range of 110–130°C. Severe scaling of the surface would result at such high temperatures. Therefore, use of scraped surface heat exchanger is essential for manufacture of these products. For designing such heat exchangers, information on an overall heat transfer coefficient under actual conditions is required. Therefore, a study was carried out on evaporation of water, buffalo milk and cream at atmospheric pressure in a straight-sided horizontal thin film scraped surface heat exchanger with objectives to evolve a predictive equation for an overall heat transfer coefficient and to examine its variation with respect to rotor speed, number of blades, flow rates and temperature differential.

MATERIALS AND METHODS

Process Variables

The process fluids selected were (1) Water, (2) Whole milk (Buffalo) and (3) Cream (30–40% TS). The latter two fluids have scaling and foaming tendencies. Flow rates were varied from 0.025–0.075 kg/s, while scraper speeds were kept in the range 1.67–4.46 rps. The experiments were conducted at 3

different condensing temperatures of steam viz. 110, 120 and 130°C. Number of blades employed in the study were 2, 4, 6 and 8.

Experimental

The schematic hookup of the experimental setup is shown in Fig. 1. Water was filled in feed tank (1) and steam at atmospheric pressure was admitted into jacket of the tank. The agitator motor was switched on. The water was heated to 96–97°C. The hot water was then pumped by a lobe-type positive displacement pump (2) into the scraped surface heat exchanger (5) (304 type stainless steel with 0.354 m.O.D., 0.007 m wall thickness and 0.55 m, heated length). The steam condensing temperature in the heat exchanger jacket was adjusted to desired value. The variable speed drive (8) was energized and the scraper's (6) speed was adjusted by means of a manual speed controller. The scraper was provided with flat hinged blades which pressed against the wall due to centrifugal force. Flow rate was regulated by means of valves (3) and indicated by rotameter (4). Due to formation of a thin film by the mechanical action of the blades, evaporation was rapid. The vapors flowed through vapor outlet (7) to condenser (9). Tap water was used as cooling medium. Condensate was collected at the outlet of the condenser and measured to determine the rate of evaporation. The outlet temperature of the water at the exit of the SSHE was found to vary from 99.7 to 99.9°C.

The procedure was repeated with remaining fluids in the range of process variables mentioned earlier. In all, 108 experiments were conducted.

Calculation of Heat Transfer Coefficients

Overall Heat Transfer Coefficient, U_o . The fluid was pumped into the heat exchanger at near to saturation temperature. The entire heat transferred by the condensing steam was assumed to cause the evaporation as the heat exchanger jacket was adequately insulated to prevent convective heat losses. The steam condensate temperature was same as that of steam inlet temperature. Thus

$$Q = U_o A_o \Delta T \quad (1)$$

But
$$Q = \dot{M}_v L_v \quad (2)$$

$$U_o = \frac{\dot{M}_v L_v}{A_o \Delta T} \quad (3)$$

Steam Side Film Coefficient, h_o . Steam side heat transfer coefficients for condensing steam on horizontal pipe were calculated, assuming film type condensation (McAdams 1963).

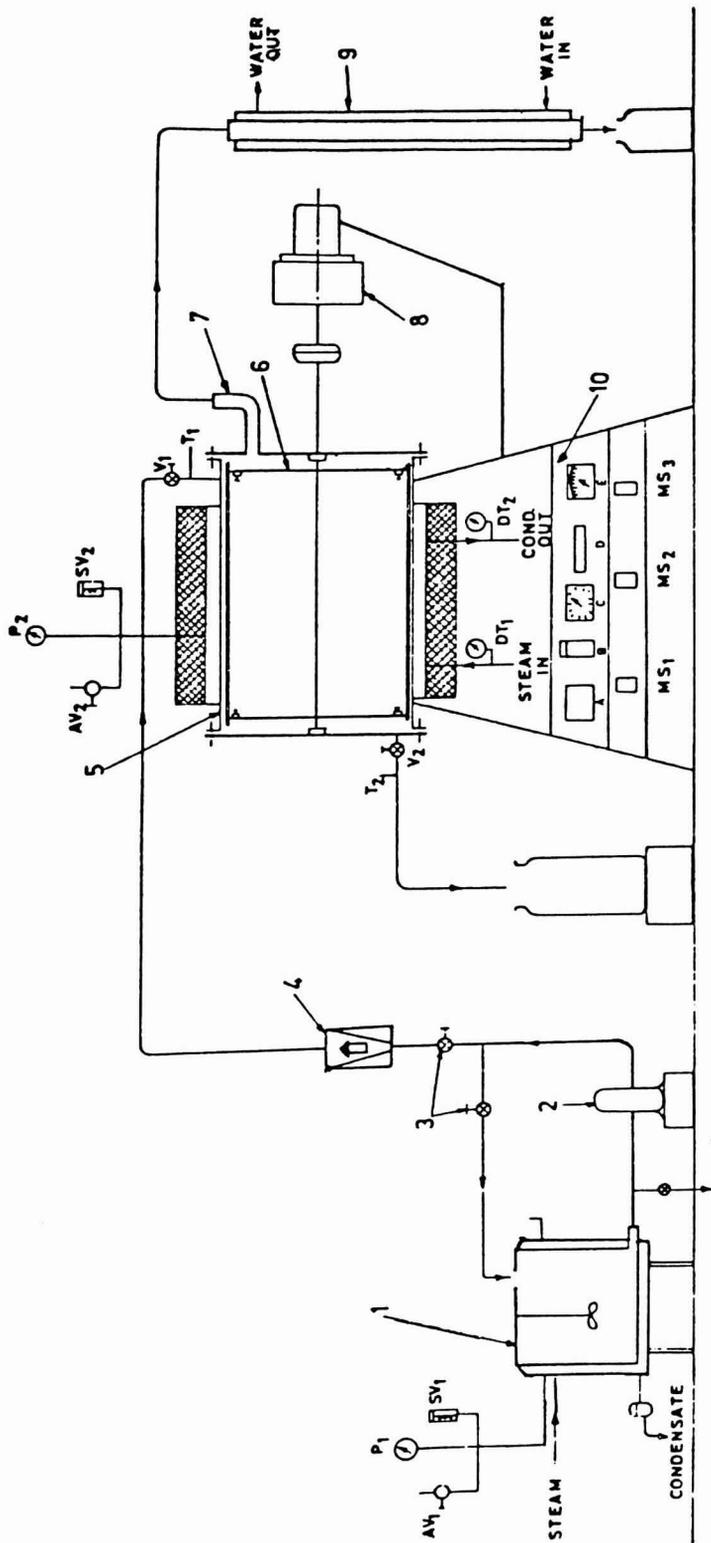


FIG. 1. SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP

1. Feed tank; 2. Feed pump; 3. Flow regulating valves; 4. Rotamer; 5. Heat exchanger; 6. Scraper; 7. Vapor outlet; 8. Variable speed drive; 9. Condenser; 10. Instrument panel; A. Electronic regulator; B. Manual speed controller; C. Selector switch; D. Millivolt meter; E. Watt meter; V_1 and V_2 . Inlet and outlet valves; T_1 and T_2 . Inlet and outlet thermo-wells; MS_1 , MS_2 and MS_3 . Motor starters; AV_1 and AV_2 . Air vents; P_1 and P_2 . Pressure gauges; DT_1 and DT_2 . Dial thermometers; SV_1 and SV_2 . Safety valves.

$$h_o = 1.51 \phi \left\{ \frac{4\gamma}{\mu_f} \right\}^{-1/3} \quad (4)$$

The average value of $\left\{ \frac{4\gamma}{\mu_f} \right\}$ was 130 which is far lower than the critical value of 4200 ($2 \times$ Reynolds number) recommended for film type condensation on horizontal pipe.

The properties of the condensate were evaluated at its saturation temperature.

Scraped Film Heat Transfer Coefficient, h_s . The individual scraped film heat transfer coefficients were calculated from:

$$\frac{D_o}{D_i} \frac{1}{h_s} = \frac{1}{U_o} - \frac{1}{h_o} - \frac{D_o}{2K_m} \ln \frac{D_o}{D_i} \quad (5)$$

RESULTS AND DISCUSSION

Overall Heat Transfer Coefficient, U_o

Most physical situations can usually be approximated by a quadratic function over a reasonable range of variables (Hoerl 1959; Perry *et al.* 1963. Therefore, it was proposed to develop such correlation for an overall heat transfer coefficient involving all the process variables, i.e., $U_o = f(E, S, V_c, B, \Delta T)$.

The experiments on evaporation of water, buffalo milk and 35–40% cream were carried out, and data collected for different operating conditions were processed in HCL System-4 Computer to fit a Box-Wilson model in the form:

$$\begin{aligned} U_o = & 620.083 - 2.181 (E) - 32.313 (S) + 585.562 (V_c) + 133.336 (B) \\ & - 11.673 (\Delta T) \\ & - 0.234 (E)^2 + 0.483 (S)^2 - 73.616 (V_c)^2 - 6.293 (B)^2 - 0.168 (\Delta T)^2 \\ & - 0.246 (E)(S) + 0.641 (E)(V_c) - 0.029 (E)(B) + 0.706 (E)(\Delta T) \\ & + 2.243 (S)(V_c) + 0.758 (S)(B) - 0.21 (S)(\Delta T) \\ & - 11.987 (V_c)(B) - 0.464 (V_c)(\Delta T) - 0.302 (B)(\Delta T) \\ & (3\% < E < 62\%; 0 < S < 49\%; 1.78 < V_c < 4.46 \text{ and} \\ & 10 < \Delta T < 30) \end{aligned} \quad (6)$$

Correlation coefficient was 93.14%. Error analysis of 409 data sets was done on HCL System-4 Computer. The standard error was found to be 108.27. Figure 2 shows the plot of (U_o) experimental versus (U_o) prediction for selected data sets. The 45° line corresponds to (U_o) experimental = (U_o) prediction. It can be observed that most of the data points lie near to this line for all the three

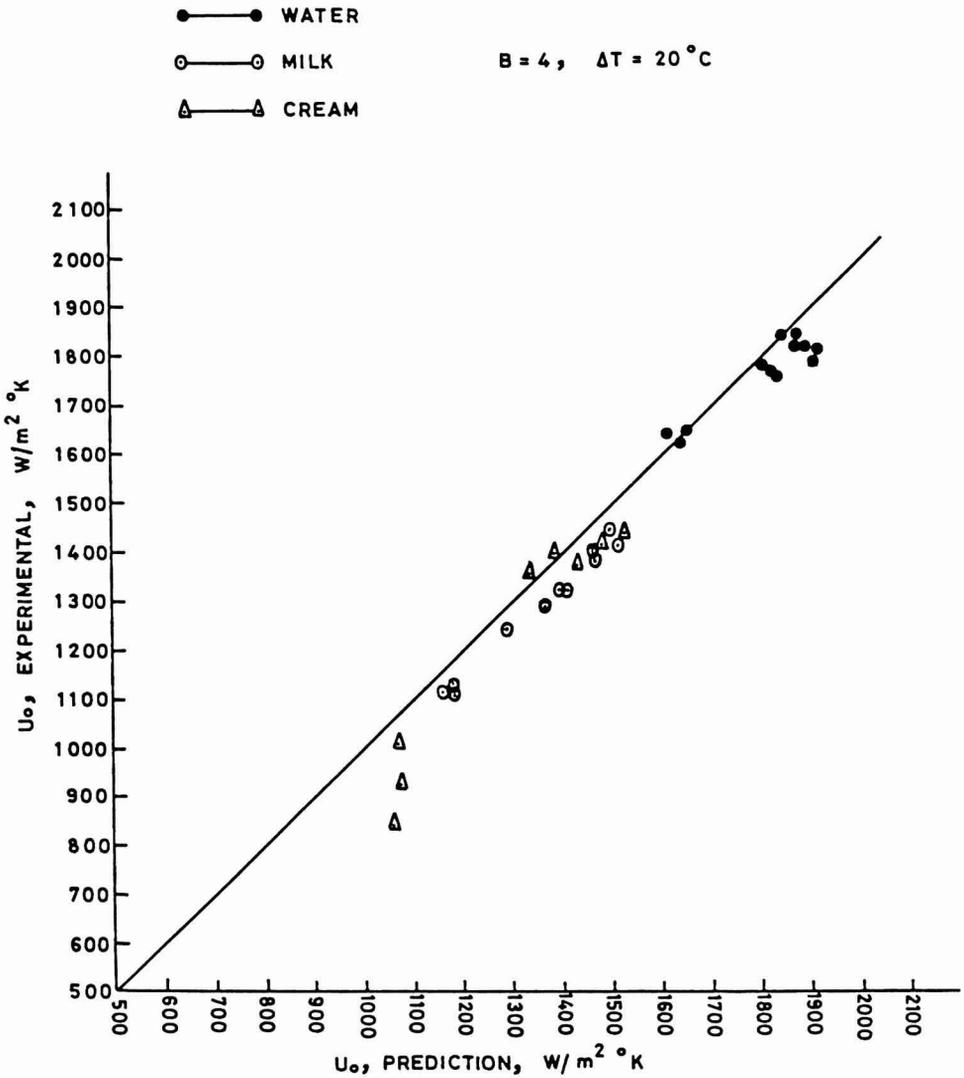


FIG. 2. COMPARISON OF U_o , EXPERIMENTAL AND U_o , PREDICTION

experimental fluids. Thus Eq. (6) can be used to predict overall heat transfer coefficient during evaporation in horizontal thin film SSHE. It also helps in optimizing the process variables. For instance, the optimum value of rotor speed, V_c is obtained by setting $\partial U_o / \partial V_c = 0$ and determining the value of V_c for which $\partial^2 U_o / \partial V_c^2 < 0$.

For cream, if $B = 4$, $E = 39\%$, $S = 48\%$ and $\Delta T = 30^\circ C$; then, by setting $\partial U_o / \partial V_c = 0$, we obtain $V_c = 4.46$ m/s. For this value $\partial^2 U_o / \partial V_c^2 < 0$.

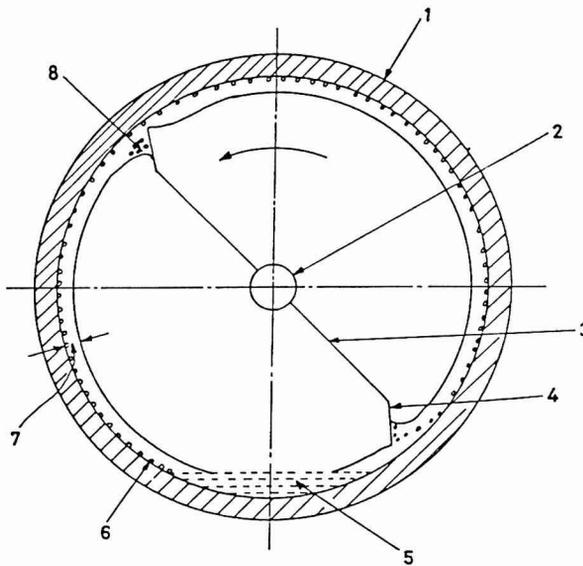


FIG. 3. EVAPORATION FROM FILM FORMED IN SSHE

1. Heat exchanger wall; 2. Rotor Shaft; 3. Rotor arm; 4. Blades; 5. Liquid pool; 6. Bubbles; 7. Liquid film; 8. Liquid fillet.

Proposed Heat Transfer Mechanism

In order to explain the effect of operational parameters on the overall heat transfer coefficient U_o , a possible mechanism governing the fluid flow, film formation and heat transfer is proposed. Refer to Fig. 3.

The fluid after entering the heat exchanger initially tends to remain at its bottom portion and would have found its way to the outlet but for the action of rotating blades. Each blade scoops a certain amount of fluid from the pool and accelerates it along the heat exchanger surface. At any given instant, the fluid picked up by the blade is partly in form of film behind the blade and partly in form of fillet carried in front of the blade. The blade action which is similar to that of a plough causes part of the fluid in the film to mix with that in the fillet, simultaneously restoring film thickness by allowing an equal amount of fluid to squeeze past the tip of the blade. The heat transfer first occurs through the fluid film by conduction. This film later mixes with the fillet due to the ploughing action of the blades. As the blades advance the fillet temperature continuously increases. When the fluid at the interface of the film and heating surface attains saturation temperature, bubbles are formed. If allowed, the bubbles gradually could cover the entire surface and cause additional resistance to heat transfer. As earlier proposed, the action of the blade, causes the fluid and bubbles in the film to mix with that in the fillet. When the temperature of the liquid in the fillet

is saturated, the bubbles leave the fillet. Simultaneously, the fluid squeezing past the tip of the blade renews the film. The reformation of bubbles continues till they are dislodged by the blade following from behind. It is possible for a part of the fluid in the film to attain super heat by blade action. In the case of vertical thin film SSHEs, the possibilities of bubble formation and the fluid in the film having superheat were also suggested by Kramers *et al.* (1955), Zolkowski and Skoczylas (1965), and Bott and Sheikh (1966).

The effects of various operating parameters, viz. M , N , B and ΔT on U_o , were examined and are discussed in light of the proposed mechanism governing the evaporation.

Mass Flow Rate, M

Figure 4 illustrates the effect of M on U_o at various rotor speeds for water, milk and cream. It was observed that increase in M caused U_o to increase for milk and cream only at low rotor speeds, viz. 1.67 rps. At higher rotor speeds, the effect of M on U_o was insignificant. For water, the effect of M on U_o at all rotor speeds was less pronounced.

It is envisaged that increase in mass flow rate would cause the fillet volume to increase only after the film had attained steady thickness corresponding to rotor speed (Fiend 1960; Ujhidy and Babos 1967; Dieter and Hubner 1970; Frank and Lutcha 1980). Also it was pointed out the possibility of a part of the fluid in the film attaining superheat by blade action. As the mass flow rate was increased from 0.025–0.045 kg/s, increasing amount of super heated fluids from the film joined the fillet at saturation temperature. This maintained the increasing trend of evaporation rates. However, when the flow rate was further increased, the amount of superheated fluid joining the fillet might have remained unchanged owing to the film attaining steady thickness.

Rotor Speed, N

Figure 5 shows the effect of the rotor speed, N on the overall heat transfer coefficient. In general, U_o increased with increasing rotor speed and in particular, its change was rapid when the speed was increased from 1.67–2.50 rps. For instance, the U_o for milk increased from 720–1470 W/m²K for a mass flow rate of 0.025 kg/s in this speed range. Further, compared to water, the changes in milk and cream were more significant.

The increasing rotor speeds caused higher turbulence and radial mixing of the superheated liquid from the film at much higher frequency. In addition, the dislodging of bubbles was also rapid. These factors enhanced the rates of evaporation.

It can be seen from Fig. 5 that, under similar operating conditions, the U_o values for milk and cream were less than those of water. This can be easily

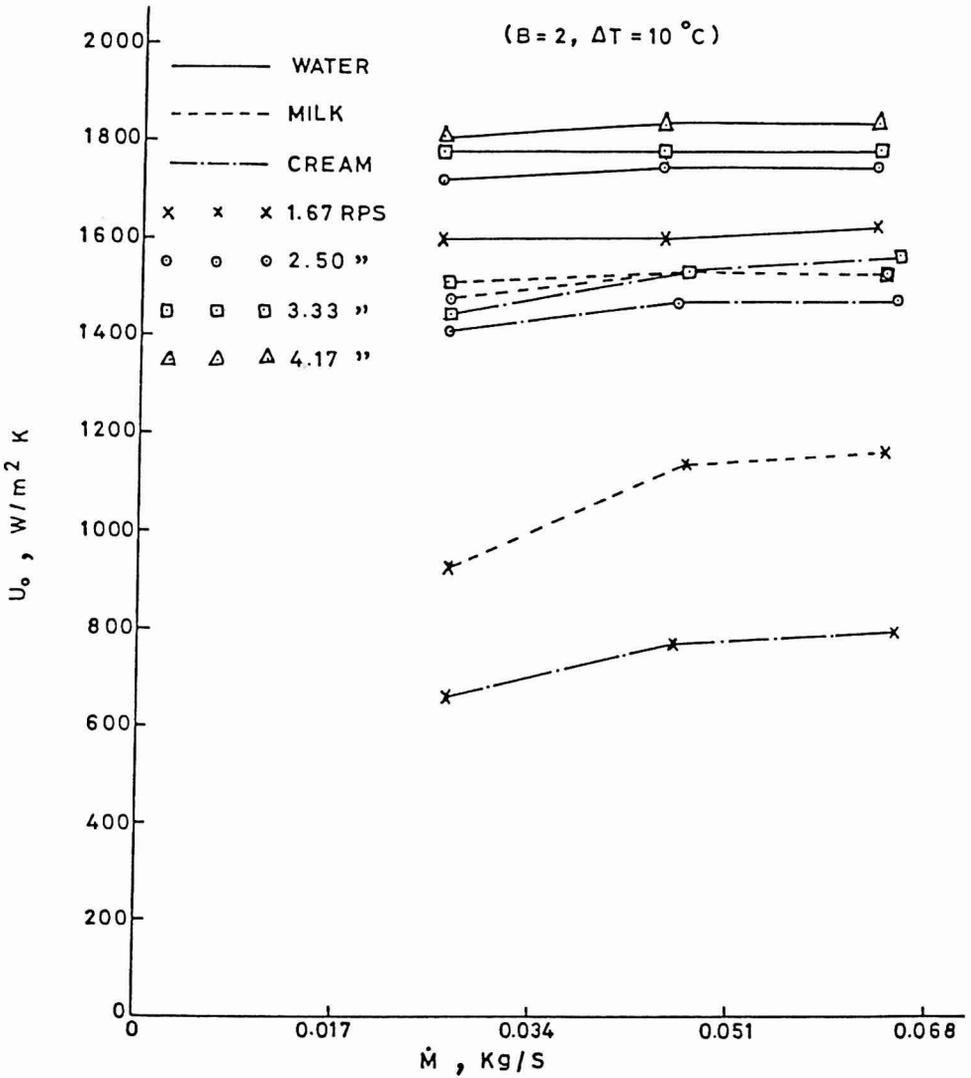


FIG. 4. EFFECT OF \dot{M} ON U_o .

attributed to the fouling tendencies of these fluids. Higher turbulence in the film and frequency of its mixing resulting from increased speeds reduced the fouling effects. For this reason, the U_o for milk and cream rapidly increased with the increasing rotor speeds. It was observed that beyond a rotor speed of 2.50 rps, the further change in U_o was not significant.

Bressler (1958) made an observation for vertical thin film SSHE that there was an optimum rotor speed beyond which an increase in speed had little effect on heat transfer. The above conclusion is in agreement with this observation,

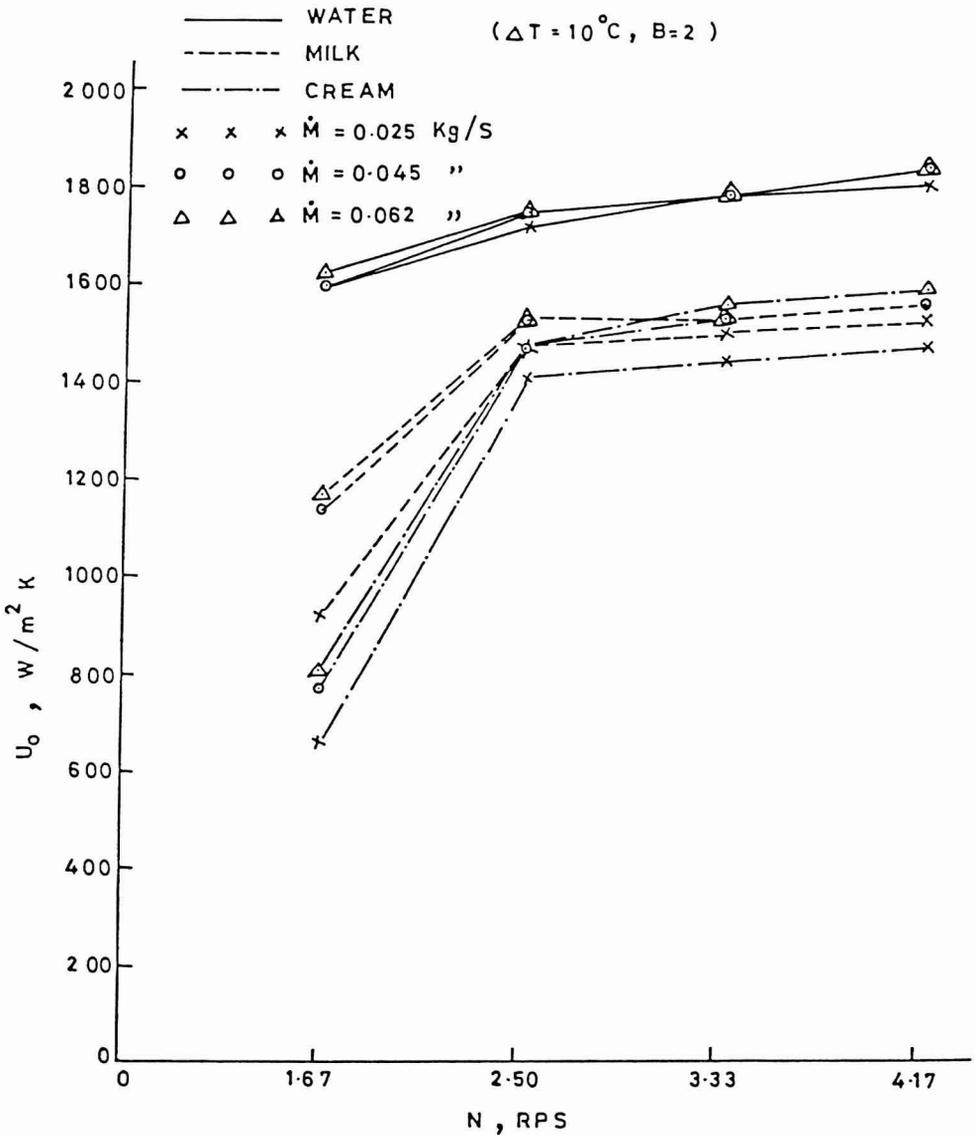


FIG. 5. EFFECT ON N ON U_o .

as increasing the rotor speed beyond 2.50 rps did not result in appreciable increase in U_o , even for fluids with fouling tendencies.

Number of Blades, B

Figure 6 illustrates the effect of the number of blades, B on the overall heat transfer coefficient (U_o) for water, milk and cream at various speeds. It can be easily seen that the effect of increasing the number of blades is similar to that

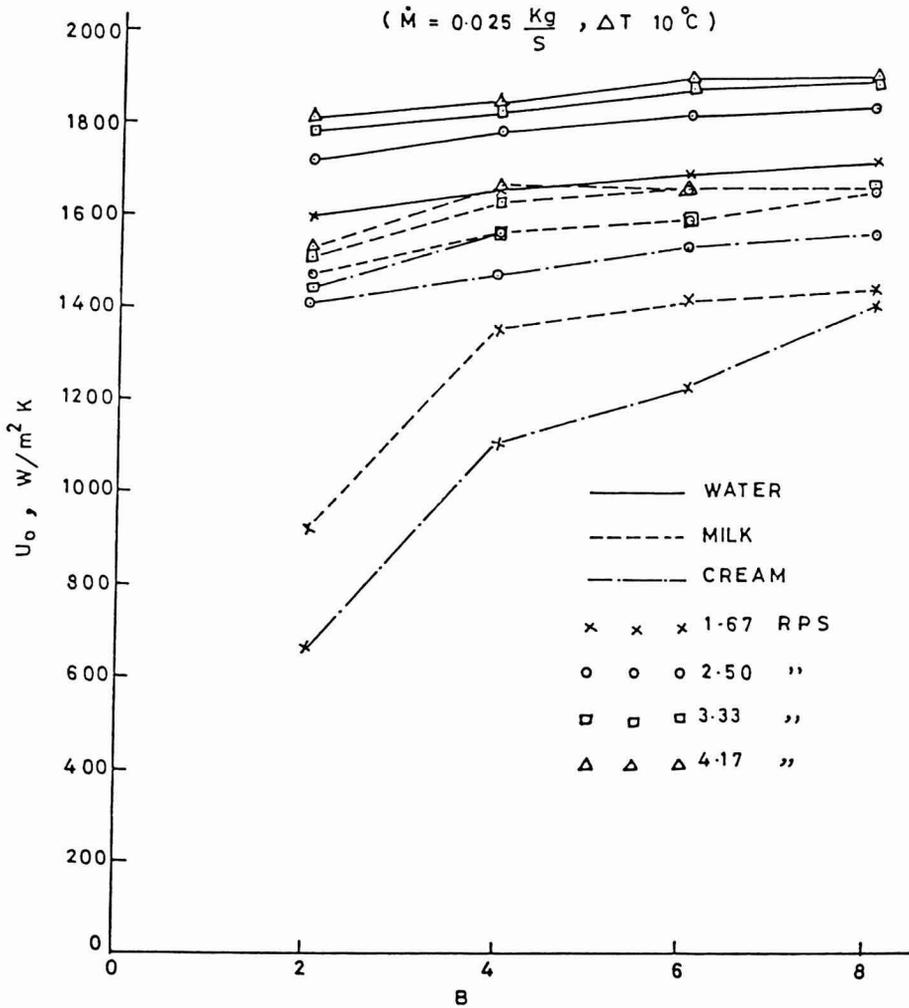
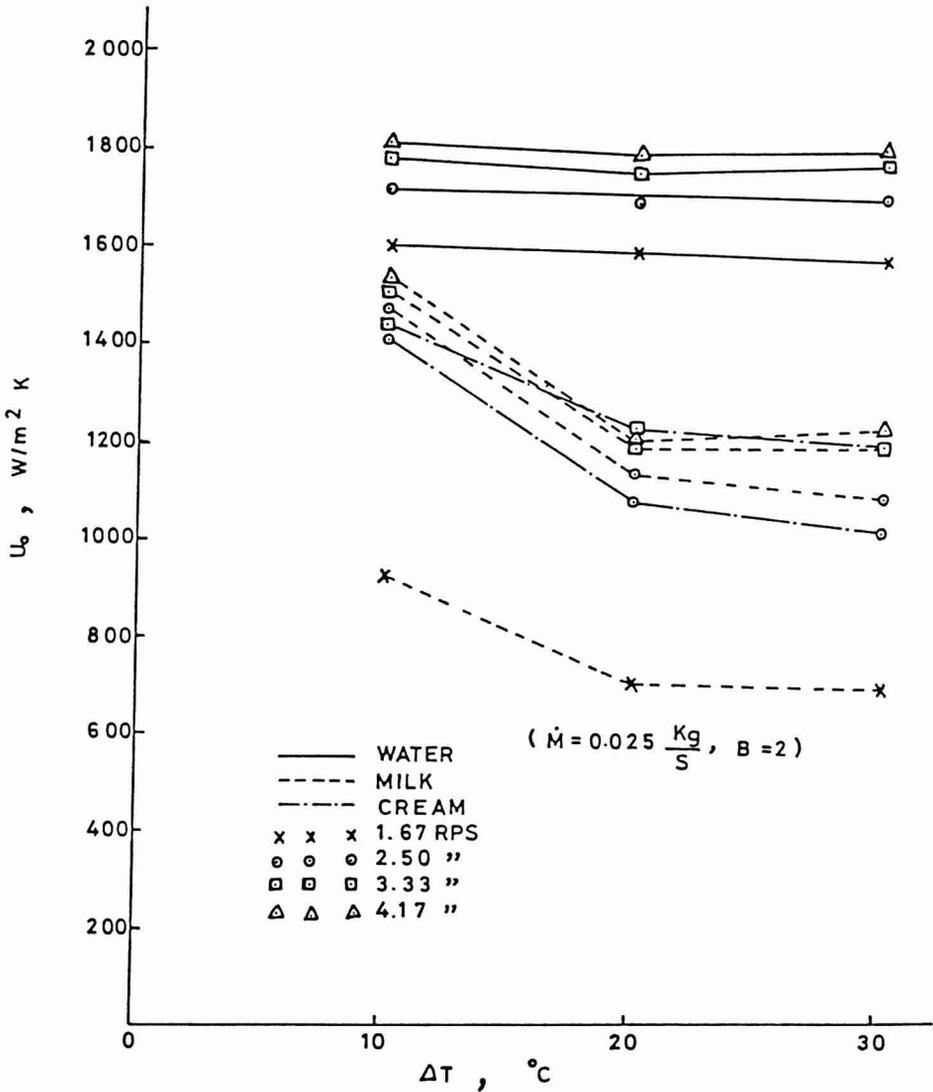


FIG. 6. EFFECT ON B ON U_o .

produced by increase in rotor speed. It is evident from the figure that at a given speed U_o increases with the number of blades. However, at higher speeds, viz., 3.33 rps and above, B had little effect on U_o . There does not seem to be any advantage in increasing the number of blades beyond 4 at rotor speeds of 2.50 rps and above. Rotor power consumption increases significantly with increasing number of blades and speed (Abichandani and Sarma 1988).

Temperature Differential, ΔT

Figure 7 shows the effect of ΔT on U_o . It is seen from the figure that for milk and cream, U_o decreased with increasing ΔT at all rotor speeds and this trend

FIG. 7. EFFECT OF ΔT ON U_o .

greatly slowed down when ΔT increased beyond 20°C . This was mainly due to the formation of tenacious layer of denaturated proteins and other milk constituents on the surface of SSHE. This layer of deposits contributed as an additional resistance to heat transfer. This resistance is implied in U_o . The estimated thermal resistance for selected data sets are reported in Table 1. It is interesting to observe that the U_o for milk and cream had not appreciably changed at higher values of ΔT at which the tendency to scale the surface was far more intense. The products

TABLE 1.
TYPICAL THERMAL RESISTANCES COMPUTED UNDER THE CONDITIONS
($M = 0.025$ to 0.0255 kg/s, $N = 3.333$ rps and $B = 4$)

Liquid	Steam Temp. °C	Thermal resistance $\times 10^6$ m ² °K/W			Overall 1/U _o
		Condensing steam film 1/h _o	Heat exchanger wall	Scraped film 1/h _s	
Water	110				
	120	107.2	438.9	5.69	552.1
	130				
Milk	110			66.5	615.4
	120	"	"	171.6	724.8
	130			233.35	789.1
Cream	110			89.67	639.5
	120	"	"	171.60	724.8
	130			199.57	753.9

processed under these conditions were subjected to chemical and organoleptic tests and their quality was found acceptable. Thus, the SSHE appears to have an excellent potential for application in processing of some indigenous milk products due to its ability to maintain the U_o even at higher surface temperatures.

For water, it is easy to see the reason why U_o remained practically unchanged at all values of ΔT . It can be seen from Table 1 that the principal resistance to heat transfer during evaporation of water primarily is due to the heat exchanger wall. The water employed in this study, being soft, did not contribute to scale resistance unlike cream and milk. Thus, for water the resistance to heat transfer remained constant at all values of ΔT .

CONCLUSIONS

Equation (6) helps in predicting the overall heat transfer coefficient during evaporation at higher temperatures compared to those encountered in conventional milk evaporators. The U_o values computed from this equation implicits for surface fouling.

The effects of operating parameters on U_o show that there is no specific advantage in increasing the number of blades beyond 4 at rotor speed of 2.5 rps.

Most of the Indian dairy products are processed in kettles where possibilities to control and optimize heat treatment process generally are very limited. The horizontal thin film SSHE offers efficient continuous processing of such milk products.

NOMENCLATURE

- A_o Heat transfer area ($\pi D_o L$), m^2
 B Number of blades
 D_i Inside diameter of heat exchanger shell, m
 D_o Outside diameter of heat exchanger shell, m
 E Percentage of feed evaporated ($\dot{M}_v/\dot{M} \times 100$)
 h_o Film heat transfer coefficient for condensing steam, $W/m^2 \text{ } ^\circ K$
 h_s Scraped film heat transfer coefficient, $W/m^2 \text{ } ^\circ K$
 K_f Thermal conductivity of steam condensate, $W/m \text{ } ^\circ K$
 K_m Thermal conductivity of wall material of heat exchanger, $W/m \text{ } ^\circ K$
 L Heated length, m
 L_v Latent heat of vaporization of water at atmospheric pressure, J/kg
 \dot{M} Mass flow rate kg/s
 \dot{M}_v Evaporation rate kg/s
 Q Rate of heat transfer, W
 S_i Percent total solids in feed
 S_o Percent total solids in product at outlet
 S Percent average total solids $(S_i + S_o)/2$
 T_s Saturation temperature of steam, $^\circ C$
 T_i Saturation temperature of fluid corresponding to atmospheric pressure, $^\circ C$
 ΔT $T_s - T_i$, $^\circ C$
 U_o Overall heat transfer coefficient, $W/m^2 \text{ } ^\circ K$.
 V_c Circumferential velocity of rotor blades, m/s

Greek Letters

- γ Mass flow rate of steam condensate from the lowest point divided by heated length, $kg/s - m$
 μ_f Absolute viscosity of condensate film, $Pa - S$
 ρ_f Density of condensate film, kg/m^3

$$\phi = \left\{ \frac{k_f^3 \rho_f^2 g}{\mu_f^2} \right\}^{1/3}$$

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SPECIFIC HEAT OF DEHYDRATED PULPS OF FRUITS

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ABSTRACT

Specific heat of dehydrated pulps, which were obtained from 31 different fruits at several moisture contents, was determined by the indirect mixing method. Data are reported for each fruit. They confirm the application of linear functions, especially at moisture contents above 50%. An exponential regression equation for calculation of specific heat in the whole range of moisture content was established using all the values.

INTRODUCTION

During the manufacture of some commercial products, juice or pulp fruits are concentrated. It is necessary to know the specific heat changes due to different factors, as a function of moisture content, since, for the purpose of many engineering calculations, the variations due to temperature are small and an average value of specific heat is used for limited temperature ranges (Lewis 1987).

Heldman and Singh (1981), pointed out that one of the most important limitations in process design for food products is the lack of information on their thermal properties. One way to solve the large amount of required data for all products, conditions and compositions is the prediction based on the properties of their components.

Sweat (1986) and Miles *et al.* (1983) compiled several equations to calculate the specific heat of foods. Above freezing, the simple models are linear functions and lead to converge at 100% water, there is a greater variation as the water content approaches 0%. Choi and Okos (1986), developed a general additive model to predict the specific heat of food products based on the weight fractions and properties of the major pure components as a function of temperature. For

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fruit juices which have moisture contents greater than 50% the equations of Dickerson (1969) and Earle (1968) are widely used. Polley *et al.* (1980), Hall *et al.* (1978), Farrall (1976) and Rha (1975) present compilations about thermal properties of foods; however, values of specific heat for some tropical fruits were not included, especially for pulps at low moisture contents.

The objective of the present work was to measure specific heat of some tropical and subtropical pulp fruits and, especially, to relate the specific heat to moisture content at low values.

MATERIALS AND METHODS

Thirty-one different fruits were analyzed; each sample was obtained from lots of at least 57 units bought in markets of Ambato city. The fruits were ready for human consumption or industrial use. The determinations were replicated with another lot of fruits.

For pulp preparation, ripe fruits were washed with water and then placed on an inspection table to eliminate damaged fruit. In some cases they were peeled, cored and cut. The product was then passed through a pulper equipped with 0.0635–0.0838 cm screen and blanched to inactivate the enzymes in the tissues and to shrink the material, by indirect heating in boiling water at 92°C for 10 min. In addition to the original sample, 3 samples were separated for concentration by heat in open containers during 1.0, 2.5 and 4.0 h. Five commercial types of dry product for juice reconstitution were placed in 2 ovens, at 77°C for 14 h and 60°C for 26 h to obtain samples with 12% moisture content or less.

Specific heat was determined in duplicate by using the indirect mixing calorimetric method developed by Hwang and Hayakawa (1979), in which the food and heat exchange medium are not in direct contact, thus eliminating the need for evaluation of the heat of solution. Previously the heat capacity of each calorimeter was determined; the average value was 309.5 J/°C (calorimeter). Tests with distilled water were done for calibration, differences of 1% or less were registered in comparison with reported values for water.

The moisture content was determined in duplicate in a Brabender oven equipment at 110°C for at least 1 h, until constant weight was achieved.

RESULTS AND DISCUSSION

Figure 1 shows the time-temperature curves of water in a calorimeter for determining heat loss factor for banana pulp (*Musa cavendishii*) at 4 levels of moisture content; the initial moisture content of 75.6% corresponds to natural product. The application of the method to pulps is reliable and reproducible with few problems. The initial sample temperature in this test was 84.7°C, and the

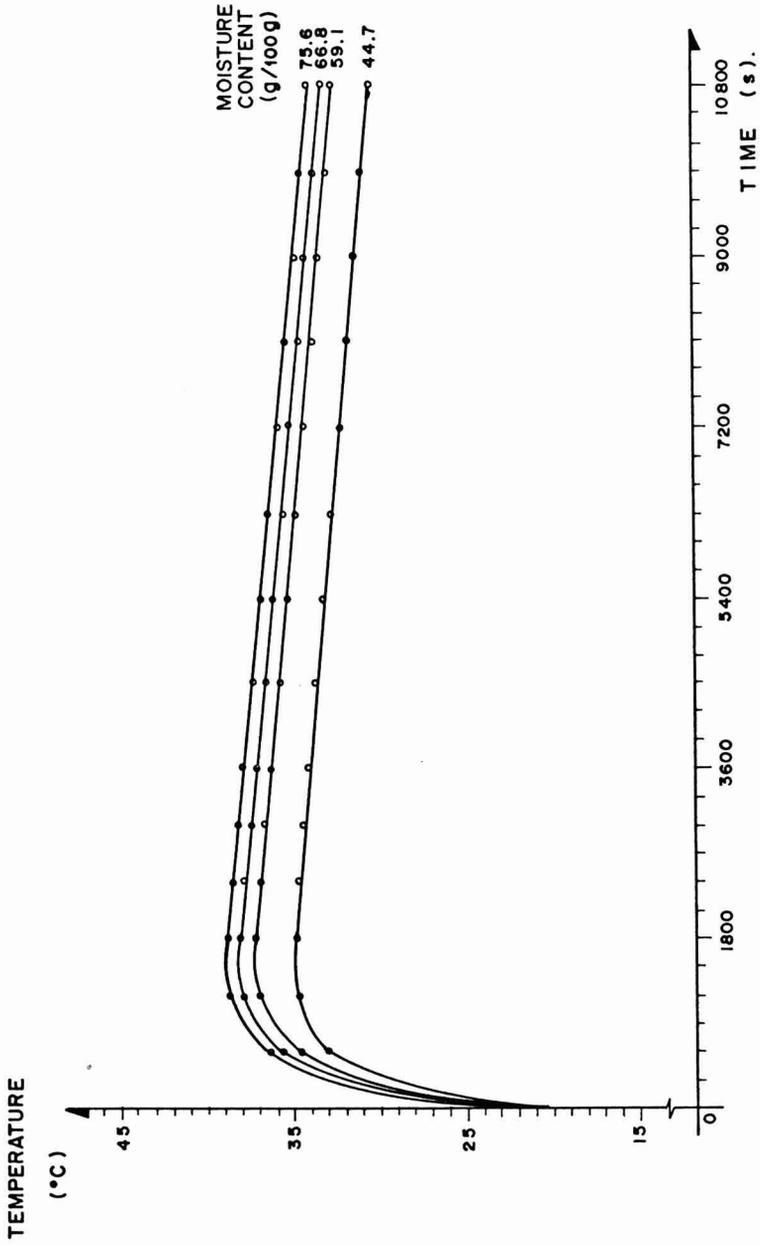


FIG. 1. TIME-TEMPERATURE CURVES OF WATER IN CALORIMETERS FOR DETERMINING SPECIFIC HEAT OF BANANA PULP AT 4 MOISTURE CONTENTS

constant heat loss rate was obtained after 1800 s and continued until 10800 s or more.

Table 1 lists the specific heat values determined experimentally in 31 fruits at different moisture contents. For several fruits it is difficult to find values in the literature, especially for pulps, however it is possible to establish comparisons with published data in a few cases.

Polley *et al.* (1980) reported values of 3350–3770 J/kg °K for fresh fruits in a range from 75–92% of moisture content and between 0 and 100°C. Considering the first values for each fruit to correspond to the fresh product, for avocado, bananas, black cherry, with moisture content of 75%, values between 3330 and 3410 J/kg °K, were estimated similar to those reported. In a similar manner, babaco or starfruit, strawberry, muskmelon, naranjilla and watermelon with moisture contents of 92% had values between 3690 and 4010 J/kg °K. It is noted

TABLE 1.
MAGNITUDES OF SPECIFIC HEAT OF FRUIT PULPS AND CORRELATION EQUATIONS

FRUIT (Botanical name)	SPECIFIC HEAT (Moisture content)				$C_p = A + \frac{R}{B}$	
	kJ/kg.°K (g/100 g)				A	B
Apple (<i>Malus communis</i>)	3.64(87.6)	3.31(82.4)	3.27(75.9)	2.68(49.7)	1.51	0.0232
Avocado (<i>Persea drymifolia</i>)	3.39(74.0)	3.06(65.4)	2.97(61.1)	2.39(44.2)	0.92	0.0332
Babaco (<i>Carica pentagona</i>)	3.89(92.5)	3.56(88.0)	3.06(83.5)	2.89(71.5)	-0.53	0.0463
Banana (<i>Musa cavendishii</i>)	3.39(75.6)	3.01(66.8)	2.85(59.1)	2.55(44.7)	1.34	0.0262
Banana var. (<i>Musa auriens</i>)	2.97(68.1)	2.85(62.1)	2.64(55.2)	2.26(39.8)	1.24	0.0255
Banana var. (<i>Musa paradisiaca</i>)	3.35(73.8)	2.97(63.6)	2.76(59.4)	2.47(49.2)	0.66	0.0362
Banana var. (<i>Musa rosacea</i>)	2.93(70.0)	2.85(65.0)	2.72(59.4)	2.43(45.7)	1.48	0.0209
Candletree (<i>Parmentiera aculeata</i>)	3.39(83.1)	3.06(77.8)	2.93(72.5)	2.39(54.6)	0.55	0.0332
Cherry, black (<i>Prunus capuli</i>)	3.31(77.5)	2.89(58.2)	2.47(47.4)	2.51(40.6)	1.47	0.0237
Grape (<i>Vitis vinifera</i>)	3.52(81.2)	3.14(70.6)	2.93(67.1)	2.35(47.5)	0.68	0.0346
Grapefruit (<i>Citrus paradisi</i>)	3.68(88.7)	3.31(83.5)	3.10(78.6)	2.64(63.1)		
	1.71(11.4)	1.55(9.2)	1.62(1.9)	1.37(1.4)	1.41	0.0229
Guava (<i>Psidium guajaba</i>)	3.56(86.6)	3.22(76.7)	2.85(66.7)	2.51(50.7)	0.97	0.0294
Lemon (<i>Citrus limon</i>)	1.70(11.4)	1.69(9.4)	1.63(1.9)	1.45(1.2)	1.51	0.0179
Lime (<i>Citrus aurantifolia</i>)	3.64(89.9)	3.35(78.3)	2.76(64.7)	2.26(47.3)	0.66	0.0334
Mulberry (<i>Rubus glaucus</i>)	3.60(86.5)	3.10(77.0)	2.89(66.1)	2.64(59.4)	0.55	0.0353
Muskmelon (<i>Cucumis melo</i>)	3.77(93.9)	3.48(90.5)	3.18(85.1)	2.97(76.6)	-0.52	0.0447
Naranjilla (<i>Solanum quitense</i>)	3.68(92.4)	3.31(82.8)	3.10(72.8)	2.76(63.1)	0.85	0.0303
Nectarine (<i>Prunus spp.</i>)	3.60(86.6)	3.39(79.7)	3.10(67.2)	2.60(44.2)	1.56	0.0232
Orange (<i>Citrus sinensis</i>)	3.52(83.1)	3.27(76.8)	3.01(72.4)	2.68(62.9)		
	1.85(10.5)	1.68(10.1)	1.78(1.9)	1.36(1.3)	1.52	0.0219
Papaw (<i>Carica papaya</i>)	3.35(89.7)	3.31(77.3)	2.97(70.7)	2.55(55.7)	1.23	0.0248
Pear (<i>Pyrus communis</i>)	3.52(81.2)	3.22(63.1)	3.10(60.3)	2.43(33.1)	1.70	0.0230
Peach (<i>Prunus persica</i>)	3.43(87.5)	3.22(80.0)	3.10(71.6)	2.72(56.6)		
	1.78(12.6)	1.71(10.4)	1.69(2.0)	1.43(1.3)	1.51	0.0218
Pineapple (<i>Ananas comosus</i>)	3.48(84.7)	2.97(71.0)	2.60(62.1)	2.39(46.0)	0.98	0.0286
Plum (<i>Prunus salicina</i>)	3.68(88.9)	3.10(75.0)	2.97(70.4)	2.81(67.7)	0.11	0.0401
Pricklypear (<i>Opuntia tuna</i>)	3.64(84.6)	3.22(73.6)	3.10(68.2)	2.85(53.7)	1.45	0.0250
Strawberry (<i>Fragaria vesca</i>)	3.81(92.0)	3.39(86.1)	3.22(78.1)	2.93(67.1)	0.68	0.0329
Strawberry var. (<i>Fragaria chiloensis</i>)	3.68(90.4)	2.93(79.7)	2.76(74.2)	2.64(65.2)	-0.21	0.0415
Tangerine (<i>Citrus reticulata</i>)	3.69(87.0)	3.18(76.8)	2.85(64.2)	2.30(48.3)		
	1.83(12.8)	1.78(10.6)	1.77(2.0)	1.47(1.5)	1.52	0.0221
Tomato (<i>Lycopersicon esculentum</i>)	3.94(94.5)	3.48(81.6)	3.18(74.8)	2.83(64.1)	0.71	0.0339
Treetomato (<i>Cyphomandra betacea</i>)	3.56(87.4)	3.18(82.7)	2.97(73.6)	2.64(62.7)	0.45	0.0344
Watermelon (<i>Citrullus vulgaris</i>)	3.98(92.0)	3.68(89.0)	3.18(76.3)	2.97(66.8)	0.33	0.0385

Mean values of two determinations for duplicate.

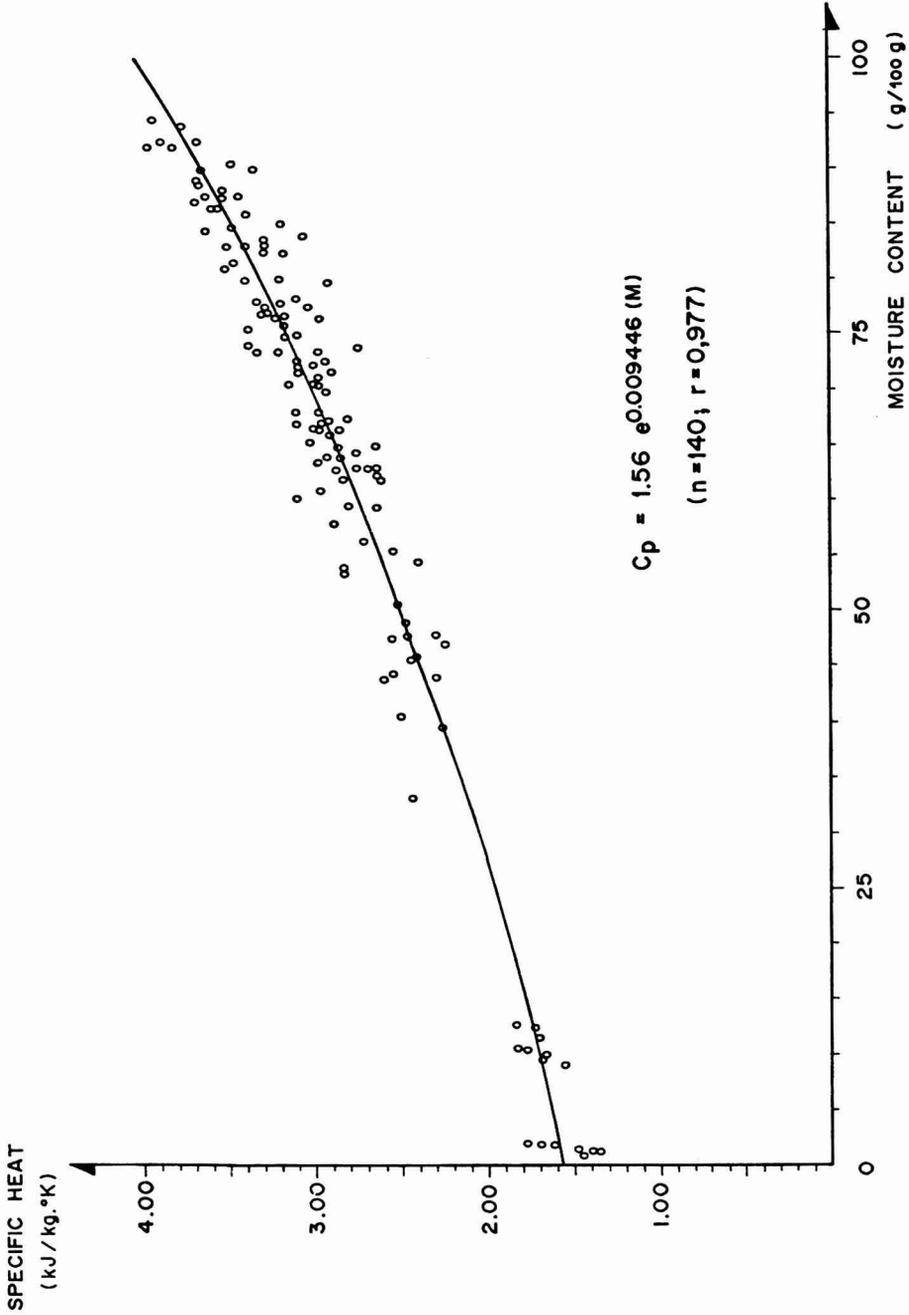


FIG. 2. RELATION BETWEEN SPECIFIC HEAT AND MOISTURE CONTENT FOR PULP FRUITS

that the value 3980 of watermelon with 92.0% of moisture content is close to that reported for watermelon with 92.1% of moisture content 4060 J/kg °K.

Comparison of the present data with values in J/kg °K reported by Rha (1975) indicate differences lower than 5%: strawberry with 92.0% water, 3820 against 3852 reported; tomato with 94.0% water, 3930 against 3978; grape with 81.0% water, 3510 against 3600. The small differences may be due to differences in the composition due to fruit varieties and characteristics of pulps.

Linear regression equations for each fruit were determined, and they confirmed the application of Earle or Dickerson equations in fruits with 50% or more moisture content. Considering all data, especially at low moisture contents, an exponential regression equation provided the best adjustment to experimental values. Figure 2 shows the plot of moisture content against specific heat, with 140 observations and a correlation coefficient $r = 0.977$:

$$C_p = 1.56 e^{0.009446(M)}$$

where C_p is the specific heat in kJ/kg °K, M is the moisture content in g water/100 g product, e is the base of Napierian logarithms.

Specific heat values predicted by the above equation are closer than those calculated by using models presented for fruit juices by Charm (1981), Heldman and Singh (1981), Choi and Okos (1986). Differences were smaller, especially at moistures higher than 90% because the solids content in the pulps were greater than in the juices. Further, it is known that the solid constituents of foods cause a decrease in specific heat. It is interesting to note that at 0% water content the calculated value 1.56 is similar to 1.424 reported for carbohydrates by Heldman and Singh (1981) and to 1.610 kJ/kg °K calculated with the equation proposed by Choi and Okos (1986) for carbohydrates at 35°C. We note that the solids in fruit pulps are mainly sugars and fiber. At 100% water the value is 4.00 lower by 4% with respect to 4.175 kJ/kg °K for water at 35°C.

The linear or additive models do not consider the interactions among components. In those foods in which moisture content is above 50%, the water is free water; below that figure, the bound water increases. This phenomenon could explain the exponential model presented.

In conclusion, the equation presented here permits calculation of specific heats of fresh and concentrated fruit pulps within a range of 1–96% moisture content and temperatures above the freezing point and below the boiling point. If greater accuracy is necessary, the individual values or equations for each fruit must be considered.

ACKNOWLEDGMENTS

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CONVECTION HEAT TRANSFER COEFFICIENT FOR A RESTRUCTURED PORK/SOY HULL PRODUCT¹

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ABSTRACT

Heat transfer coefficients, h , ($J/cm^2 \text{ } ^\circ C \text{ min}$) were determined for a pork/soy hull mixture during heating in a convection oven ($142^\circ C$) with and without control of the dew point. Data were acquired by heat processing 5 stacked layers of product ($10 \times 10 \times 1 \text{ cm}$) so that heat was only conducted into the top surface. One experiment was designed to determine h when the second layer from the top reached one of 6 temperatures: 20, 32, 44, 56, 68 and $77^\circ C$, with no control of the dew point. The second experiment determined h for 60 min of heating for 5 dew point levels: 6, 21, 31, 40 and $50^\circ C$. Without the control of humidity, values for h ranged from $0.0170\text{--}0.0366 \text{ J/cm}^2 \text{ } ^\circ C \text{ min}$. The heat transfer coefficient increased with temperature and heat processing time. Product yield and surface area ratios decreased as h increased. When relative humidity was controlled, values for h ranged from $0.0167\text{--}0.0270 \text{ J/cm}^2 \text{ } ^\circ C \text{ min}$, decreasing for dew points above $31^\circ C$.

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INTRODUCTION

When designing innovative food products, new production processes must be developed in parallel to ensure that the product can be economically mass produced. For products produced using convective heat transfer, the convective heat transfer coefficient is an important quantity being essentially an aerodynamic property of the heat transfer system. While the convective heat transfer coefficient is not a material property it is affected by properties of the food such as size, shape, and surface roughness. In addition, food characteristics such as moisture content and crust formation affect convective heat transfer due to their affect on vapor migration across the food surface.

Convection heat transfer with foods involves complex interactions between the food and the surrounding fluid, and therefore cannot be computed theoretically as easily as can conduction or radiation. Its determination is commonly based on experimental rather than theoretical results. Considering the huge number of food products of varying shapes and forms, and the variety of heat transfer methods, the amount of surface heat transfer data is very inadequate (Arce and Sweat 1979).

Several recent studies have been performed on heat transfer in forced convection ovens. Sato *et al.* (1987) investigated heat transfer in a forced convection oven when producing sponge cakes. The convection heat transfer coefficient was determined experimentally using an aluminum cylinder to model the cakes. Holtz and Skjoldebrand (1986) reported a mathematical model of the heat and mass transfer during the cooking of meat loaf. Burfoot and James (1988) examined the variations in the heat transfer coefficient over the surface of meat products which were characterized as finite cylinders.

The purpose of this investigation was to determine the convection heat transfer coefficient for restructured pork/soy hull mixtures when exposed to convective heating in a commercial convection oven operating with various levels of humidity. Previous research with pork/soy hull mixtures has reported the benefits hydrated soy hulls provide. They add fiber, iron, zinc and moisture (Klopfenstein and Owen 1987), provide serum cholesterol-lowering abilities for humans (Cho *et al.* 1985; Ibrahim *et al.* 1990) and reduce the food energy, lipid and cholesterol contents of pork tissue (Muzilla *et al.* 1990). Several thermal properties of hydrated soy hulls (Muzilla *et al.* 1991) and pork/soy hull mixtures (Muzilla *et al.* 1990) have been reported. Data is needed about the heat transfer coefficient of this new product.

MATERIALS AND METHODS

Theoretical Development

The fundamental definition of the convection heat transfer coefficient is given by:

$$q = hA(T_a - T_s) \quad (1)$$

The convection heat transfer coefficient can be determined explicitly if all of the other quantities in the equation are known. The problem with this approach is that it is difficult to determine q experimentally. Two approaches are commonly used. If heat can be removed at a known rate from the material being heated so that the material is in a steady state with respect to temperature, then the known amount of heat being removed is equal to q . These experimental conditions are difficult to establish when tests are being run in standard food preparation equipment. Therefore, a second method is more often used.

In this method, the heat flowing into the material is computed from knowledge of the thermal properties of and temperature distribution in the material. Due to the complexity of heat transfer in foods, foods are often modeled with other materials for which heat transfer can be more easily computed. The most often used model materials are metals with high conductivities: copper or aluminum. These metals have well-known thermal properties, and, since they have high values of conductivity, it can be assumed that the temperature is uniform throughout. This requires that only the surface temperature be measured. The disadvantage of this method is that the metal object is not always a valid model of the food. For food items of nonregular shape with nonsmooth surfaces which change shape during the process and which have a significant amount of moisture expire from their surfaces, the metal model is inadequate.

When a model with high conductivity is not used, information sufficient to compute the heat flux must be known. For this research, a one-dimensional heat flow process was established so that only temperatures at points along the direction of heat flow needed to be measured. The samples to be heat processed were insulated on all sides except the top so that heat entered the food only from above. Each sample was built up of five layers and the temperature in the geometric center of each layer was measured. The heat entering the food was absorbed in three ways. The mathematical description of this process is:

$$q = \sum_{i=1}^5 (c_i m_i \frac{dT_i}{dt}) - r \frac{dM}{dt} - (T_s - 100) c_v \frac{dM}{dt} \quad (2)$$

The first term gives the heat absorbed by the pork/soy hull mixture which resulted in a raising of the mixture temperature. The heat absorbed by the water near the surface as it changed from the liquid to vapor phase is given by the second term. The last term accounts for the heat absorbed by the vapor near the surface which resulted in superheated vapor being released from the surface. The last term is only used when the surface temperature is greater than 100°C. By combining equations 1 and 2, h can be determined.

Heat Processing

Two types of experiments were performed in order to determine the convection heat transfer coefficient. These experiments differed in that during the first type no control of the oven humidity was maintained. The second type was performed with the dew point controlled at five different levels.

For the nonhumidity controlled experiments, pork shoulder from the same lot of hogs fed a regular diet was obtained. The meat tissue and visible fat were separated and ground (Hobart Model K 5-A) with screen size of 6.0 mm. Ground tissue and fat were mixed so that the total mixture would contain approximately 12% fat. The fat content was determined using the Rapid Babcock Method. The mixture was portioned (500 g), wrapped with freezer paper and stored at -12°C for not more than 3 weeks. Each portion was tempered at 5°C for 24 h before formulation. Crushed soy hulls were obtained from the Archer-Daniel Midland Soybean Processing Plant, Mexico, MO. The size of the crushed soy hulls was determined with a Rotap Shaking Sieve Tester (Taylor Model No. 11404). The results are given in Table 1.

The pork/soy hull mixture was prepared in two steps. First, crushed soy hulls (50 g), mild BBQ rub seasoning and sauce mix (24 g) (Milwaukee Seasoning Laboratories, Inc., Germantown, WI), salt (5 g) and 2% milk (200 g) were mixed and allowed to set 15 min to allow the soy hulls to absorb all of the liquid. The ground meat (500 g) was added and mixed in a Hobart mixer (Model K5-A, Troy, Ohio) until thoroughly blended.

A galvanized steel sheet metal box ($10 \times 10 \times 6$ cm) was constructed to enable the placement of a wire mesh screen (mesh size: $6 \text{ mm} \times 6 \text{ mm}$), 1 cm from the bottom and 5 layers of the mixture, each 1 cm thick. Portions of the mixture were rolled into a slab 1 cm thick; squares 10 cm on each side were cut from this slab. The first square was placed in the box above the wire mesh. A

TABLE 1.
SIEVE SIZES FOR CRUSHED SOY HULLS

U.S. Sieve (Size)	Soyhulls Remaining (%)
20	24.5
25	11.9
35	24.1
> 35	39.5

thermocouple (Type K, 28 gauge) attached to a Data Logger (Omega Model OM-500), was placed through a hole in one side of the box, so that it was located in the geometric center of the square layer. The top of the layer was covered with nylon mesh (mesh size: 1.6 mm \times 1.6 mm) so that the layers could be separated after each experiment was performed. Each of the remaining four layers was placed in the box one at a time in the same manner. The surface of the top layer was flattened and smoothed. Surface roughness affects the flow regime, thus affecting the surface heat transfer coefficient (Arce and Sweat 1979). The top surface of the box was covered with aluminum foil and stored at 5°C overnight.

The box was then placed in a larger box (26 \times 26 \times 14 cm) filled from the bottom to a level of 8 cm with vermiculite (Grace Zonolite Construction Product, Cambridge, Mass.). More vermiculite was added so that the small box was insulated by 8 cm of vermiculite from all sides except the top. A cover was placed on top of the large box. An opening (10 \times 10 cm) in the center of the cover enabled the surface of the layers of mixture in the small box to remain uncovered. The edges of the opening were marked with lines perpendicular to each edge spaced 1 mm apart so that changes in surface area could be observed. With this procedure, heat could only be transferred to the top surface of the stacked layers.

An infrared pyrometer (Cole Parmer Model No. 8158-5) was located in front of the door of the oven. A hole (12 cm \times 13.5 cm) in the door was covered with an aluminum door, which could be opened briefly to take surface temperature readings. The optical pyrometer was used so that the surface temperature could be acquired without altering its value. The pyrometer was located so that its field of view was limited to the surface of the mixture. Because this device measures the average temperature over its field of view, it is not necessary to take multiple measurements in order to determine the average surface temperature.

The large box was placed in an electric non-preheated forced air convection oven (Lang Co-20). In order that the mass of the product could be measured throughout heat processing, the box was placed on a support which consisted of three vertical rods extending through the floor of the oven. The lower end of these rods rested on the top of an electronic balance (Fisher Scientific Model No. XT-7K). The surface of the meat layers was located in the center of the oven cavity.

The air velocity was measured in the horizontal plane one cm above the surface of the mixture at 10 degree increments around the center of the mixture surface. The measurements were made using a flowmeter (Omega Model HH-615MHT).

The exposed meat surface was covered with an insulated cover and the oven, set at 142°C, was turned on. The air temperature was measured using a thermocouple (Type K) located 2 cm above the center of the product surface. When the air temperature reached the set point, the insulated cover was removed and

data were recorded at 2 min intervals. The data recorded were the air temperature, lengths of edges of product surface, surface temperature, center temperatures of five layers, and total mass of boxes and product.

This heating process was continued until the second layer from the top reached one of 6 temperatures: 20, 32, 44, 56, 68 or 77°C. It was necessary to terminate the tests at various intermediate temperatures so that the layers could be individually analyzed to determine their thermal properties and mass. At the end of each test, the layers were separated, weighed, vacuum-packaged (Multivac AC 800, Wolfertschwenden, W.G.), and stored at -45°C in covered aluminum foil pans.

For the experiments during which humidity was controlled, the procedure described above was used with the following variations. The dew point of the air in the oven was measured using a digital humidity analyzer (EG&G Environmental Equipment Co. Model 911). Air was drawn from the oven through a duct into the humidity analyzer. The duct was heated so that no condensation occurred prior to the humidity sensor. Water was injected into the inlet of the oven fan to increase the dew point in the oven. The flow rate of the injected water was controlled by a manually operated valve. Heat transfer coefficient experiments were performed with the oven operating at five levels of dew point listed in Table 2. A dew point of 50°C was the maximum level attainable because the oven was not sealed sufficiently to hold additional moisture. In each case, the oven was preheated and the desired dew point was attained before the non-covered box was positioned in the oven. Heat processing was performed for 60 min with measurements being made at 2 minute intervals.

Analysis

For the nonhumidity controlled experiments, five replications were performed for each of the six ending temperatures. For the humidity controlled experiments, five replications were performed at each dew point value. Cores, 5 cm in di-

TABLE 2.
OVEN CONDITIONS WHEN DEW POINT WAS CONTROLLED¹

Dew Point (°C)	Kg H ₂ O/m ³ dry air	Relative Humidity (%)
6	.0051	<.1
21	.0136	<.1
31	.0255	<.1
40	.0430	.3
50	.0770	1.7

¹Oven Temperature: 142°C

iameter, were taken from the center of each layer. The cores were divided into two equal parts and randomly assigned to moisture or fat analysis. Moisture content was determined by the vacuum oven method 7.003 (AOAC 1984). Fat content was determined by the chloroform: methanol (2:1), extractable fat procedure (Folch *et al.* 1957) as recommended by Rhee *et al.* (1988) for meats. The specific heat of each composite sample was computed using the following equation (Holtz and Skjoldebrand 1986):

$$C = 1600 + 2600w + 15TF \quad (3)$$

Quadratic curve fit equations were determined which express the internal product temperature for each layer as a function of time. Cubic curve fit equations were also found which express the total mass as a function of time. Curve fits were computed using the GLM procedure (SAS 1985). The first derivatives of layer temperature and total mass required in Eq. (2) were computed by taking the derivative of the curve fit equations. Once the heat transfer coefficients were calculated, the results of each experiment were analyzed using general linear model procedures and analysis of variance with least square means (Snedecor and Cochran 1980).

RESULTS AND DISCUSSION

Air Velocity

Factors affecting the heat transfer coefficient are related to the boundary layer that forms outside the food product (Arce and Sweat 1979). This layer is greatly affected by the dynamics of the surrounding fluid and the conditions at the surface of the food. The convection oven used had a blower located in the rear of the cavity so that the inlet was located in the center of the back wall. Air entered this inlet in a generally front-to-back direction. The outlet of the blower was around the periphery of the back wall so that air moved primarily along the oven walls from back to front. This produced two vortices as the air moving forward along the walls returned through the center of the oven to the rear. Since the samples were located in the center of the oven, the air flow over them was primarily from the front of the oven to the rear, although some side-to-side flow did occur. The velocity of the air flowing from front to rear was 6.1 m/s on the average and the region of this flow extended 50 degrees to either side of the front-rear axis of the oven. The velocity in the side-to-side direction had an average value of 1.6 m/s. These values represent those actually used within commercial convection ovens and are compatible with studies of heat transfer coefficients determined in experimental ovens with air velocity ranging from 5–9 m/s. (Skjoldebrand 1980).

Surface Temperature

Figure 1 shows the surface temperature versus heat processing time for various values of dew point. The surface temperature consistently achieved higher values when the air in the oven was dryer. For the higher humidity values there was little difference in the surface temperature. This was because the crust formed under low humidity conditions was dryer and was not cooled by the presence of moisture. The moist crusts did not heat up as rapidly because the heat absorbed during the vaporization of the moisture in the crust did not produce a temperature increase. Cleland and Earle (1976) found that the surface temperature of the food was the temperature which was most affected by a change in the surface heat transfer coefficient. Therefore, they recommended using materials with thermal properties similar to foodstuffs when values of h were obtained. Using the procedures in this study, values of h could be obtained for the actual food product.

Heat Transfer Coefficients

The results shown in Table 3 show that as the pork/soy hull mixture was exposed to the convected hot air for longer periods of time, the internal temperature increased. As a result, more and more moisture was driven off through the surface. This caused the yield, calculated as (final mass/initial mass), and surface area to decrease. The surface contracted as it formed into a crust as it dried. Balaban and Pigott (1988) emphasized the importance of using shrinkage data in mathematical models. When Holtz and Skjoldebrand (1986) simulated the temperature of meat loaf during heat processing, they neglected to measure

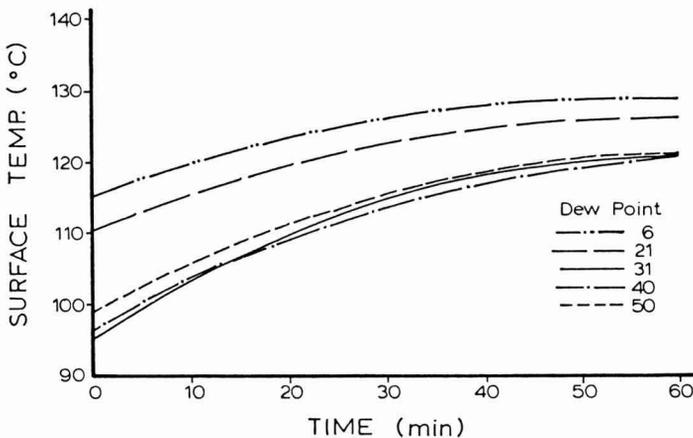


FIG. 1. SURFACE TEMPERATURE OF PORK/SOY HULL MIXTURE FOR DIFFERENT DEW POINTS

TABLE 3.
HEAT PROCESSING CONDITIONS AND HEAT TRANSFER COEFFICIENT
WITHOUT HUMIDITY CONTROL¹

Mean Time (min)	Mean Temp ² (°C)	Yield (%)		Final Surface Area (cm ²)		Heat Transfer Coefficient (J/cm ² °C min)	
		mean	S.E.	mean	S.E.	mean	S.E.
19.0	20.3	97.4 ^a	0.24	99.0 ^a	0.44	0.0170 ^b	0.0039
31.4	32.2	96.6 ^a	0.40	91.2 ^{ab}	1.00	0.0199 ^b	0.0021
43.6	44.2	94.6 ^b	0.40	88.4 ^c	0.51	0.0329 ^a	0.0065
56.2	56.1	94.2 ^b	0.49	84.1 ^d	1.07	0.0366 ^a	0.0032
71.2	68.1	92.8 ^c	0.58	82.5 ^{dc}	1.52	0.0343 ^a	0.0036
89.6	77.0	90.6 ^d	0.51	78.3 ^f	1.00	0.0293 ^a	0.0038

¹ $N = 5$

² Refers to the final interval temperature of the second layer from the top.

³ Where superscripts differ within a column, mean values are significantly ($p < 0.05$) different.

shrinkage. They later attributed this fact to most of their reported differences between simulated and measured product temperatures. In this study, the minced pork was mixed with soy hulls, which can absorb up to 10 times their weight in water (Muzilla *et al.* 1989), under various processing conditions. In this study, product yield was greater than with pork tissue alone, probably because on a microscale, the water migrated from the denatured proteins to the soy hulls and was absorbed by them.

The heat transfer coefficient (Table 3) increased during the initial period of exposure, but then stabilized. This is due to the fact that the heat transfer mode was different with and without the presence of steam escaping from the surface of the mixture. The presence of steam in the fluid layer directly above the surface enhanced heat transfer to the surface therefore causing a higher heat transfer coefficient. These findings are in agreement with those of Holtz and Skjoldebrand (1986) when they reported heat transfer coefficient values for a meat loaf formula. They emphasized that the magnitude of the heat transfer coefficient depended on mass transfer rates as a major part of the energy was used to evaporate the water, compared to that to heat the product. Table 4 contains the results when the dew point of the convected air was varied. All results are reported after a 60 min exposure to the hot air. The shrinkage of the surface diminished as the

TABLE 4.
HEAT PROCESSING CONDITIONS AND HEAT TRANSFER COEFFICIENT
ACCORDING TO DEW POINT¹

Dew Point (°C)		Yield (%)		Final Surface Area (cm ²)		Heat Transfer Coefficient (J/cm ² °C min)	
mean	S.E.	mean	S.E.	mean	S.E.	mean	S.E.
6.14 ^a	0.59	93.6	0.51	84.45 ^a	0.98	0.0270 ^b	0.0038
20.98 ^b	0.09	93.8	0.49	88.36 ^b	0.94	0.0231 ^b	0.0020
30.92 ^c	0.11	94.8	0.37	89.50 ^b	0.81	0.0186 ^a	0.0017
40.38 ^d	0.16	93.2	0.37	88.18 ^b	1.67	0.0179 ^a	0.0009
49.92 ^e	0.16	94.4	0.40	88.74 ^b	0.82	0.0167 ^a	0.0017

¹ $N = 5$

² Where superscripts differ within a column, mean values are significantly ($p < 0.05$) different.

dew point was initially raised but then stabilized for further increases. The yield was unaffected by humidity changes. This was caused by the fact that less moisture was driven off the surface as the partial vapor pressure of the humid air increased. Even though the surface shrunk initially, the yield did not because the exchange of surface moisture was very small in comparison to the total quantity of moisture in the mixture. The heat transfer coefficient essentially did not change as the moisture content of the convected air increased. This is in agreement with Skjoldebrand and Oste (1980) who determined that the effect of humidity upon product quality, within a convection oven, was negligible when the amount of water was less than 0.6–0.7 kg/m³. Furthermore, they concluded that for some meat products, water vapor was effective for oven temperatures below 175°C.

For the heat transfer coefficients determined in both experiments, no significant ($p < 0.05$) differences were found for heat processing times above 44 min (Table 3) or for dew points above 31°C (Table 4). When Burfoot and James (1988) determined the heat transfer coefficient for meat processing, they concluded that using a constant mean heat transfer coefficient of the magnitude likely to occur during heat processing, rather than a temperature-dependent coefficient, would produce only a small error in computer predicted times and temperatures. Data in Tables 3 and 4 tend to verify their findings.

In these experiments, the heat transfer coefficients increased initially when exposed to 142°C and then tended to stabilize at these higher values. The phe-

nomenon is the thermal response to steam escaping from the surface. When the dew point in the oven cavity was increased from 6 to 50°C, the heat transfer coefficients did not substantially change. Thus, at these humidity levels, the reported benefits to quality from increasing relative humidity, can be attained without altering the heat transfer coefficient.

NOMENCLATURE

A	Surface area (cm ²)
c	Specific heat of product (J/g °C)
c_v	Specific heat of vapor (J/g °C)
F	Fat content of product (g/g)
h	Heat transfer coefficient (J/cm ² °C min)
m	Mass of layer (g)
M	Mass of five layers (g)
q	Heat transfer rate (J/min)
T	Center temperature of layer (°C)
T_a	Temperature of air (°C)
T_s	Temperature of surface (°C)
t	Time (min)
r	Latent heat of vaporization (J/g)
w	Moisture content of product (g/g)

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KINETIC STUDY OF QUALITY LOSSES IN FROZEN SCALLOP MEATS

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ABSTRACT

The rates of changes of texture, cook drip and free fatty acid during frozen storage of scallop meats at -30 , -18 , -12 , -8 and -5°C were studied. Both the physical and chemical changes were found to follow first order kinetics. The activation energies for toughness, cook drip and free fatty acid were 43.6, 69.3 and 37.9 kJ/mol, respectively.

INTRODUCTION

Freezing has been considered as one of the best methods for the preservation of seafoods. The two most important factors associated with freezing are the storage temperature and time. Cold storage temperature of -30°C has been highly recommended for seafood products to assure high product quality. Prolonged cold storage and temperature fluctuation during storage and transportation will cause quality degradation which will eventually result in visible loss of product quality.

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According to Connell (1962), loss of tenderness, water holding capacity and flavor are associated with the effect of frozen storage of fish products. This is because protein denaturation will cause significant deterioration of texture and loss of drip on thawing and cooking of the products. This will consequently affect the acceptability of the final products.

Quantitative analysis of quality losses in seafood products as a function of cold storage time and temperature has been limited. Dingle and Lall (1979), Kim and Heldman (1985) and LeBlanc *et al.* (1988) have reported the physical and chemical changes of minced cusk and cod fillets during frozen storage in terms of a kinetic model. However, there is no report on the rate of quality deterioration of scallop meats during frozen storage. The prediction of quality changes as influenced by storage temperature and time is very important for highly prized seafood like the scallop. The knowledge of kinetics of food deterioration could be used to minimize undesired changes and optimize the quality retention.

The main objective of the present study was to develop quantitative kinetic models to describe the textural changes and drip loss in frozen scallop meats. Attempts also were made to measure and model the chemical change in frozen scallop meats and to correlate them with the physical changes. The kinetic results will be useful for the prediction of the quality changes during storage or transportation.

EXPERIMENTAL

Materials

Scallops were caught at Georges Bank, Canada, in early March, 1988, by a scallop dragger with a chilled sea-water installation. They were shucked on board and placed in cotton bags before stowage in ice and then transported to the pilot plant of Canadian Institute of Fisheries Technology, Halifax, Nova Scotia, Canada. While in the pilot plant, the adductor muscles (meats) were buried in ice until the sixth day, by which time they had passed the rigor state. The meats were frozen individually in the horizontal plate freezer at -40°C for 2 h. After freezing, the meats were packed in polyethylene bags and wrapped in aluminum foil and stored at -30 , -18 , -12 , -8 and -5°C , respectively. Samples at each temperature were removed after 1 day, 7 days and thereafter at 14-day intervals for the next 84 days for chemical and physical analyses.

Free Fatty Acid Determination

Ten frozen meats were first diced and mixed thoroughly. Twenty-five grams of the diced samples were used for the determination of free fatty acid and lipid contents. The method of Woyewoda and Shaw (1984) was used. The chloroform

layer was titrated for free fatty acid with 0.5 M sodium hydroxide, using meta-cresol purple as an indicator. The results were expressed as micromoles of acid per gram of muscle tissue. Total lipid content of the muscle was determined by drying 20 mL of the extracted chloroform in an oven at 103°C for 1 h, and weighing the dried samples. Lipid extractions were done in triplicate.

Cook Drip

The frozen samples were first weighed, and 4 meats (about 50 g) were placed in a polyethylene bag, and 2 bags at a time were plunged into boiling water (100°C) to be cooked for 7.5 min. After cooking, the drip was poured away and the meats were cooled for 1 h on a wire gauze supported on a plastic cup. The whole system was covered with a polyethylene bag. The cooled meats were dried carefully on the surface and weighed. The cook drip was calculated as the weight difference before and after cooking as the percentage of the original frozen weight. Cook drip was determined in quadruplicate, i.e., a total of 16 meats were used.

Texture Measurement

Instron compressive force at 50% deformation was used to measure the toughness of cooked meats at various storage temperatures. Details of texture measurement have been given elsewhere (Chung 1989).

Statistical Analyses

The loss of scallop meat quality as a function of frozen storage time was described by first order kinetic model:

$$\ln C = \ln C_0 + k t \quad (1)$$

where C = quality factor measured

C_0 = initial value of the quality factor

t = time, day

k = rate constant, day^{-1}

The temperature dependency of food quality deterioration rate during frozen storage was described by Arrhenius equation:

$$k = k_0 \exp(-E_a/RT) \quad (2)$$

where k_0 = preexponential factor, day^{-1}

E_a = activation energy, kJ/mol

R = gas constant, 8.315 J/mol K

T = absolute temperature, K

By combining Eq. (1) and (2),

$$\ln C = \ln C_o + k_o \exp(-E_a/RT) t \quad (3)$$

Rate Constant

The rate constant at each temperature from Eq. (1) was determined by performing a multiple linear regression proposed by Arabshahi and Lund (1985) on a model shown below:

$$\ln C = \ln C_o + k_{-30}t_{-30} + k_{-18}t_{-18} + k_{-12}t_{-12} + k_{-8}t_{-8} + k_{-5}t_{-5} \quad (4)$$

where k_{-30} , k_{-18} , k_{-12} , k_{-8} and k_{-5} are the rate constants at -30 , -18 , -12 , -8 and -5°C respectively, and

$$t_{-30} = 1, 7, \dots, 91 \text{ days at } -30^\circ\text{C}, \text{ otherwise } t_{-30} = 0,$$

$$t_{-18} = 1, 7, \dots, 91 \text{ days at } -18^\circ\text{C}, \text{ otherwise } t_{-18} = 0,$$

$$t_{-12} = 1, 7, \dots, 91 \text{ days at } -12^\circ\text{C}, \text{ otherwise } t_{-12} = 0,$$

$$t_{-8} = 1, 7, \dots, 91 \text{ days at } -8^\circ\text{C}, \text{ otherwise } t_{-8} = 0,$$

$$t_{-5} = 1, 7, \dots, 91 \text{ days at } -5^\circ\text{C}, \text{ otherwise } t_{-5} = 0.$$

This method is preferred over the conventional individual linear regression which based on Eq. (1) at each temperature because it gives a single value of $\ln C_o$, which is estimated using all the nonisothermal data.

Arrhenius Parameters

Arrhenius parameters, E_a and k_o can be estimated using two methods: linear least squares method and nonlinear least squares method.

Linear Least Square Method. According to Eq. (2), the regression of $\ln k$ against $1/T$ will yield the slope, E_a/R and the intercept $\ln k_o$. This has been referred to as a two-step procedure because it involves two subsequent linear regressions, the first for $\ln C$ against t , Eq. (4), and the second, $\ln k$ against $1/T$, Eq. (2).

Nonlinear Least Squares Method. This method is based on Eq. (3) and parameter estimation is done by regression of $\ln C$ against the two independent variables, t and T . Because the derivatives of the parameters to be estimated are functions of the parameters themselves, the problem becomes nonlinear (Draper and Smith 1981) and the nonlinear least squares method has to be used for parameter estimation. In short, the nonlinear method performed the regression on all original data to produce estimates of $\ln C_o$, k_o and E_a in one step. To avoid convergence problems, the Arrhenius expression was reparameterized as suggested by Arabshahi and Lund (1985). This is done by a rearrangement of Eq. (3):

$$\begin{aligned} \ln C &= \ln C_0 + k_0 t \exp(-E_a/RT_0) \exp[-E_a/R(1/T - 1/T_0)] \quad (5) \\ &= \ln C_0 + k' t \exp[-E_a/R(1/T - 1/T_0)] \end{aligned}$$

where $k' = k_0 \exp(-E_a/RT_0)$, and T_0 is a suitable reference temperature. In the present study, it was taken as -10°C . The computation was performed using NLIN procedure of SAS (1985).

RESULTS AND DISCUSSION

Figures 1, 2 and 3 show the plots of logarithm of compressive force for the cooked meats, cook drip and free fatty acid versus storage time at -12°C . These plots show straight line relationships, indicating first-order kinetics. The changes of these quality variables with time at -30 , -18 , -8 and -5°C also show first-order kinetics.

Multiple linear regression was carried out to determine the rate constants at the five temperature levels and results are given in Tables 1, 2 and 3. Arrhenius parameters are given in Table 4.

The Arrhenius parameters can be determined in two ways: linear and nonlinear regression methods. Although the former is simpler to use, it is statistically unsound. This is because the method involves two steps of linear regression and

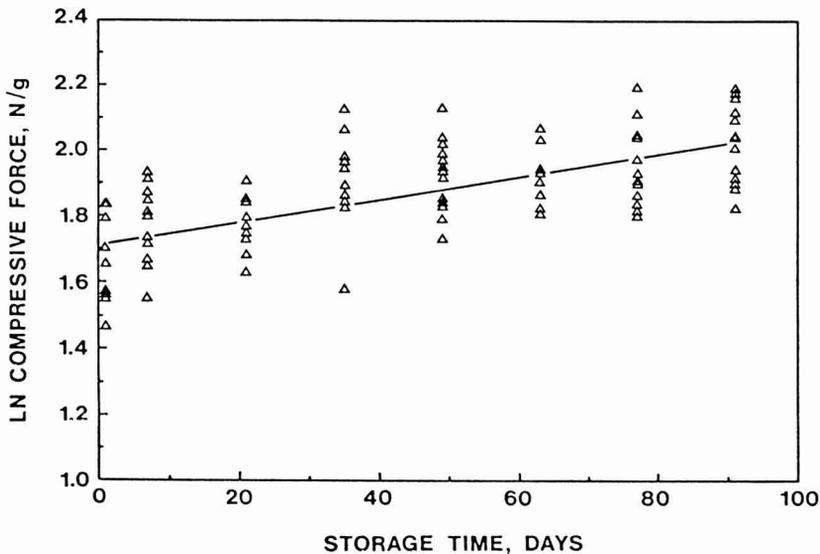


FIG. 1. A FIRST-ORDER PLOT OF COMPRESSIVE FORCE FOR SAMPLES STORED AT -12°C

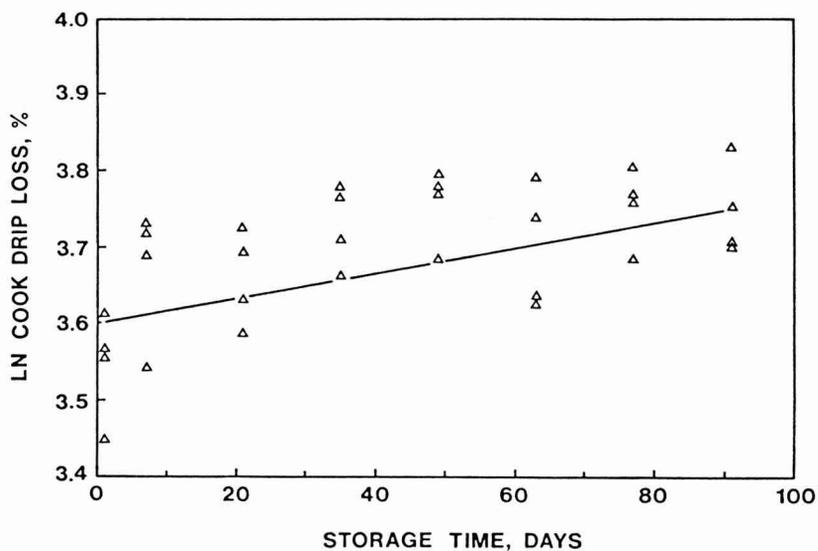
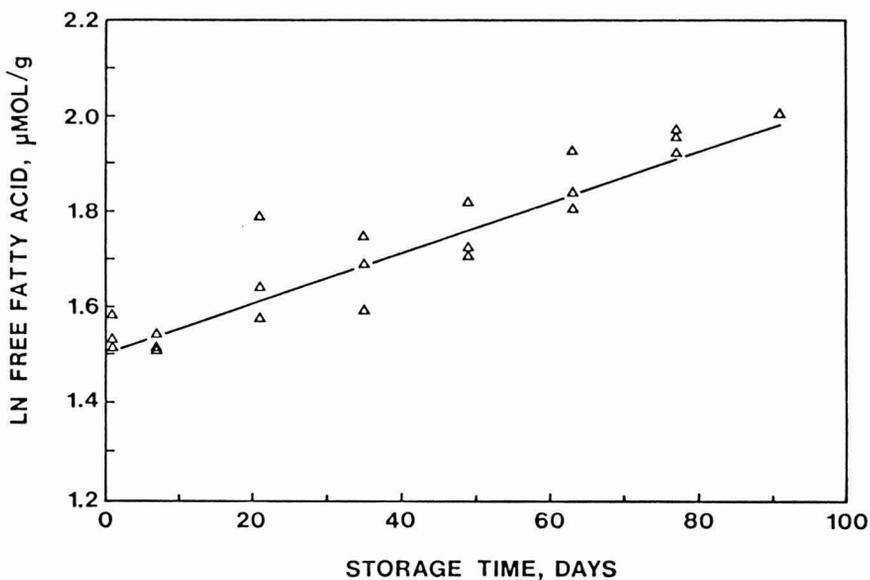
FIG. 2. A FIRST-ORDER PLOT OF COOK DRIP FOR SAMPLES STORED AT -12°C FIG. 3. A FIRST-ORDER PLOT OF FREE FATTY ACID FOR SAMPLES STORED AT -12°C

TABLE 1.
FIRST-ORDER RATE CONSTANTS FOR COMPRESSIVE FORCE DETERMINED AT
VARIOUS FROZEN STORAGE TEMPERATURES

$\ln C_o = 1.71$ Standard Deviation = 0.009501		
Temperature (°C)	Rate Constant k (day ⁻¹)	Standard Deviation
-30	0.00124	0.000276
-18	0.00167	0.000303
-12	0.00359	0.000270
-8	0.00502	0.000291
-5	0.00584	0.000270

does not consider the data as a whole set and neglects the variability of each k value, thus resulting in less reliable results. On the other hand, the nonlinear regression provides a complete utilization of the data, and the variability of the measured response variable with respect to time and temperature is being accounted for in one step. Generally the two step method results in a larger confidence interval in E_a because it involves smaller number of degrees of freedom. Therefore nonlinear method is a more appropriate parameter estimation method and has been highly recommended (e.g., Arabshahi and Lund 1985; Cohen and Saguy 1985). Conclusions drawn in the present study are based on the results from this method.

Nevertheless, it is often useful to carry out the two-step method first to check if the rate constants at all the temperature levels follow the same kinetic model. Therefore both the two-step linear and one step nonlinear methods were used for comparison purposes.

The rate of development of toughness of meats was slowest at -30°C (Table 1). Activation energy for compressive force was 35.6 kJ/mol using the two-step linear regression and 43.6 kJ/mol using the nonlinear regression (Table 4).

Large amount of drip loss on cooking will affect the acceptability of the final product since cook drip loss causes shrinkage of meats and affects appearance, texture and flavor of the products. The rate constants from multiple regression are given in Table 2. The estimate of k at -30°C was negative. This is probably due to very slow rate of deterioration at this temperature and taking the variabilities of the samples and measurement into account, k at -30°C should be close to 0.

TABLE 2.
FIRST-ORDER RATE CONSTANTS FOR COOK DRIP LOSS DETERMINED AT VARIOUS
FROZEN STORAGE TEMPERATURES

$\ln C_0 = 3.61$		Standard Deviation = 0.0145	
Temperature (°C)	Rate Constant k (day ⁻¹)	Standard Deviation	
-30	-0.000411	0.000302	
-18	0.000189	0.000302	
-12	0.00190	0.000302	
-8	0.00271	0.000302	
-5	0.00347	0.000302	

Because the rate constant at -30°C using multiple linear regression was a negative value, the Arrhenius parameters could not be estimated using the 2-step linear regression. Nonlinear regression based on the 5 temperature levels was performed and the activation energy was found to be 69.3 kJ/mol (Table 4). Activation energy for cook drip loss was larger than the texture of the cook

TABLE 3.
FIRST-ORDER RATE CONSTANTS FOR FREE FATTY ACID DETERMINED AT VARIOUS
FROZEN STORAGE TEMPERATURES

$\ln C_0 = 1.51$		Standard Deviation = 0.0103	
Temperature (°C)	Rate Constant k (day ⁻¹)	Standard Deviation	
-30	0.00092	0.000233	
-18	0.00315	0.000233	
-12	0.00555	0.000233	
-8	0.00756	0.000233	
-5	0.00762	0.000225	

TABLE 4.
ARRHENIUS PARAMETERS FOR COMPRESSIVE FORCE, COOK DRIP AND
FREE FATTY ACID

	$\ln C_0$	$\ln k_0$ (day ⁻¹)	E_a (kJ/mol)	Standard Deviation
<u>Compressive force</u>				
Linear method	1.71	10.7	35.6	6.62
Nonlinear method	1.71	14.4	43.6	4.42
<u>Cook drip</u>				
Linear method	3.61	-	-	-
Nonlinear method	3.59	25.5	69.3	11.8
<u>Free fatty acid</u>				
Linear method	1.51	16.8	48.1	3.45
Nonlinear method	1.50	12.2	37.9	2.49

meats (Table 4) indicating that textural changes were more easily activated than cook drip loss.

Kim and Heldman (1985) have reported that the activation energies for toughness and cohesiveness (defined as the measurement of water holding capacity) of cod muscle during frozen storage were 25.4 kJ/mol and 10 kJ/mol, respectively. However, the standard deviation associated with the activation energy for cohesiveness was over 50% and if a 95% confidence interval is considered, the possible value for the activation energy of cohesiveness could be from about 0 to 20 kJ/mol. LeBlanc *et al.* (1988) reported that the activation energies for toughness of cooked cod fillets were 25.2 kJ/mol (by Instron peak slope) and 47.4 kJ/mol (by Instron peak force) and total water loss on cooking was 51.6 kJ/mol. However, the standard deviations associated with the activation energies were not reported.

Review of the literature has revealed that the hydrolysis of lipids with the release of free fatty acids occurs concurrently with protein deteriorations during frozen storage of fishery products (Anderson and Ravesi 1970; Sikorski *et al.* 1976). However there is little information on free fatty acid production with frozen storage time (Punjamapirom 1962) and no report on the rate of its production at different frozen storage temperatures for scallop meats.

In the present study, analysis revealed that scallop meats contain about 1% lipid. The rate constants for free fatty acid production, determined by multiple regression, are shown in Table 3. They show that the rate of free fatty acid production is much slower at -30°C than at the higher temperatures. Free fatty acid production occurred parallel to the increase in toughness and cook drip loss of the scallop meats, but the rate of free fatty acid formation was generally faster than those of toughness and cook drip loss (Tables 1, 2 and 3). The activation energy for free fatty acid production is 37.9 kJ/mol as given in Table 4. This value was lower than those of toughness and cook drip loss. This indicates that chemical reaction was more easily activated than the physical changes.

From the observations on physical and chemical changes at various storage temperatures, frozen scallop meats during transportation or in cold store should not be kept above -30°C , if high quality products were to be maintained. Temperature fluctuation during distribution of frozen scallop meats or in cold store should be avoided. Although at -30°C , quality loss is still taking place, the rate of loss is, however, comparatively slow. Dyer *et al.* (1957) and LeBlanc *et al.* (1988) investigated the influence of fluctuation of temperature over a span of 8°C above storage temperature of -18°C , and $8-18^{\circ}\text{C}$ above the storage temperature of -30°C , respectively, on quality loss in frozen cod fillets. Both groups of authors reported a considerable deterioration in quality as compared to the control at constant temperatures of -18 and -30°C , respectively.

Although the mechanism of textural deterioration and cook drip loss is complex, the quantitative kinetic model provides a satisfactory means of predicting quality loss. The adequacy of the first order reaction kinetics of textural deterioration, cook drip loss and free fatty acid production was checked by examination of the distribution of residuals (Draper and Smith 1981). The residual plots against predicted response variable, storage time and storage temperature show no evidence of systematic behavior among the residuals, indicating an acceptable fitted model.

CONCLUSIONS

Rates of textural deterioration and cook drip loss in scallop meats at -30 , -18 , -12 , -8 and -5°C were studied. The results show that loss of quality increases with increase in temperature. At -30°C , the rate of development of toughness and cook drip loss were relatively slow compared with those at other temperature levels. The free fatty acid formation appears to be related to the deterioration of physical quality on frozen storage.

The changes in toughness, cook drip loss and free fatty acid development were found to follow the first order kinetics. The activation energies for toughness, cook drip loss and free fatty acid formation were 43.6, 69.3 and 37.9 kJ/

mol, respectively. This indicates that chemical change was more easily activated than the physical changes; also, textural changes were more easily activated than the cook drip loss.

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SYMBOLS

- C Value of quality factor
- C_0 Initial value of quality factor
- E_a Activation energy, kJ/mol
- k Rate constant, day⁻¹
- k_0 Preexponential factor, day⁻¹
- k' Reparameterized constant defined in Eq. (5)
- R Gas constant, 8.315 J/mol K
- t Time, day
- T Absolute temperature, K
- T_0 Reference temperature defined in Eq. (5)

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ELECTRICAL CONDUCTIVITIES OF SELECTED SOLID FOODS DURING OHMIC HEATING¹

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ABSTRACT

Electrical conductivities of three vegetable and two meat samples were determined by subjecting them to a constant voltage power supply in a static ohmic heating device. Conductivities of vegetable samples were increased by soaking them in salt solutions, while soaking in water resulted in reduced conductivity due to leaching of electrolytes. Conductivities under ohmic heating conditions increased linearly with temperature. When field strengths were decreased, the conductivity-temperature curve gradually became nonlinear, and under conventional heating conditions, a sharp transition was observed.

INTRODUCTION

Recent interest in rapid methods of heating foods has resulted in revived attention towards electrical resistance heating. This process, which was called the "Electro-pure Process" in the late 1910's (Anderson and Finklestein 1919), is now being called electroconductive or ohmic heating. In this process, foods are heated by passing alternating current through them. Mizrahi *et al.* (1975) reported rapid heating of corn on the cob, using this method. Biss *et al.* (1987) reported rapid and uniform heating of both liquid and particulates during ohmic heating of particulate foods. Among the advantages claimed for this technology are uniformity of heating, product safety, and improvements in quality with minimal structural, nutritional or organoleptic changes (Skudder 1988). The initial promise of this technology has resulted in its serious consideration for aseptic processing of liquid-particle mixtures.

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Currently, liquid foods are being aseptically processed using heat exchangers. Food industries are interested in extending this technology to foods containing particulate materials. Product safety cannot be easily assured since the particles suspended in fluids experience thermal lags within heat exchangers. Conservative design of thermal process will ensure product safety at the expense of quality. Ohmic heating, in which foods reportedly have uniform temperature distribution, appears to show promise for aseptic processing of particulate foods.

The electrical conductivity (σ) of food materials is a critical parameter when processing foods by ohmic heating. Dedek (1946) reported an increase in electrical conductivity of beet tissue during heating. Brüniche-Olsen (1962) confirmed the increase in electrical conductivity of beet tissue during heating by subjecting the tissue to an alternating current. Since there was no change in σ when circulating cold water while passing 40 V current through the sample, he concluded that the increase in σ was only due to the heat given off by the current, and there is no special effect due to electric current.

It is known that cell rupture, tissue shrinkage, changes in membrane permeability, phase changes, dehydration, starch gelatinization, etc., occur in foods during heating. These changes may have effects on electrical conductivity with temperature. During heating, dissolution of protopectin and other cell wall components occurs, resulting in the loss of cell rigidity and intercellular adhesion (Linehan and Huges 1969). These changes may cause an increase in the electrical conductivity. Halden *et al.* (1990) have suggested that the breakdown of cell wall components, which may lead to cell lysis, will make possible the movement of cytoplasm components and surrounding fluid across the cell wall. Depending on the conductivities of the internal and external fluids, these processes may either increase or decrease the electrical conductivity of foods. However, the conductivity of foods has generally been observed to increase rather than decrease with temperature.

Mitchell and de Alwis (1989) developed an electrical conductivity cell to measure the conductivity of firm foods at a frequency of 50 Hz. They measured the σ values of some foods at 25°C, and reported marked differences when the material has skin or distinct growth anisotropy. However, the cell had to be immersed in a water bath to determine the variation in conductivity with temperature. Halden *et al.* (1990) reported that melting of fats, starch transition and cell structural changes affect the electrical conductivity during ohmic heating. They suggested enhanced diffusion of cell fluids and electro-osmotic dehydration as possible reasons for the changes in electrical conductivity of foods in the presence of an electric field.

Recently, de Alwis *et al.* (1989 and 1990) demonstrated, through experiments and simulation, the importance of electrical conductivities of liquid and solids for the heating rates of food particles during ohmic heating. Knowledge of electrical conductivities of foods under ohmic heating conditions is essential for

process design. Accordingly, the objectives of the present study were (1) measurement of electrical conductivities of selected solid foods during conventional and ohmic heating, (2) modelling electrical conductivity as a function of temperature history, and (3) determination of the effect of salt solutions on the electrical conductivities of vegetable tissue.

MATERIALS AND METHODS

Experimental Device

The experimental device (Fig. 1) consisted of a cylindrical sample chamber, made of steel tube with a teflon sleeve inside it, a thermocouple opening at the center and rhodium plated stainless steel electrodes at both ends. The tube was fitted with a metallic jacket with a thermocouple opening, and an inlet and outlet for circulating heat exchange fluids. A T-type copper-constantan, teflon coated thermocouple with a compression fitting was used to measure the temperature at the geometric center of the sample. Voltage and current transducers were used to measure voltage across and current through the samples. A computer control system (Rosemount) was used to maintain constant voltage during heating.

Methodology

Cylindrical samples of 1.0 cm length and 2.35 cm diameter were placed in the sample chamber before inserting electrodes on either side. A thermocouple was then inserted at the geometric center of the sample, and the port was closed by the compression fitting. The sample was heated up to 120°C using alternating current of 60 V and 60 Hz. The voltage, current, time and temperature data were continuously measured and logged every second by a data logger linked to a microcomputer. The study was carried out for triplicate samples of potato, carrot, yam, lean beef and chicken. In addition, studies were conducted with the vegetable tissue saturated with distilled water ($\sigma = 0$), 0.2, 0.4 and 0.8% NaCl solutions.

Another set of experiments was conducted to determine the effect of input voltage on the electrical conductivity changes during ohmic heating. The vegetable samples were heated up to 100°C using 4 different power supply voltages (< 60 V). The conductivity of the vegetable samples were also measured during conventional heating by circulating 95°C hot water in the jacket. Conductivity measurements during this study were accomplished by subjecting the sample to low voltage pulses (4–6 V) at constant time intervals. Dehydration and structural breakdown of the tissue were studied by heating the samples ohmically without the compression fitting or thermocouple.

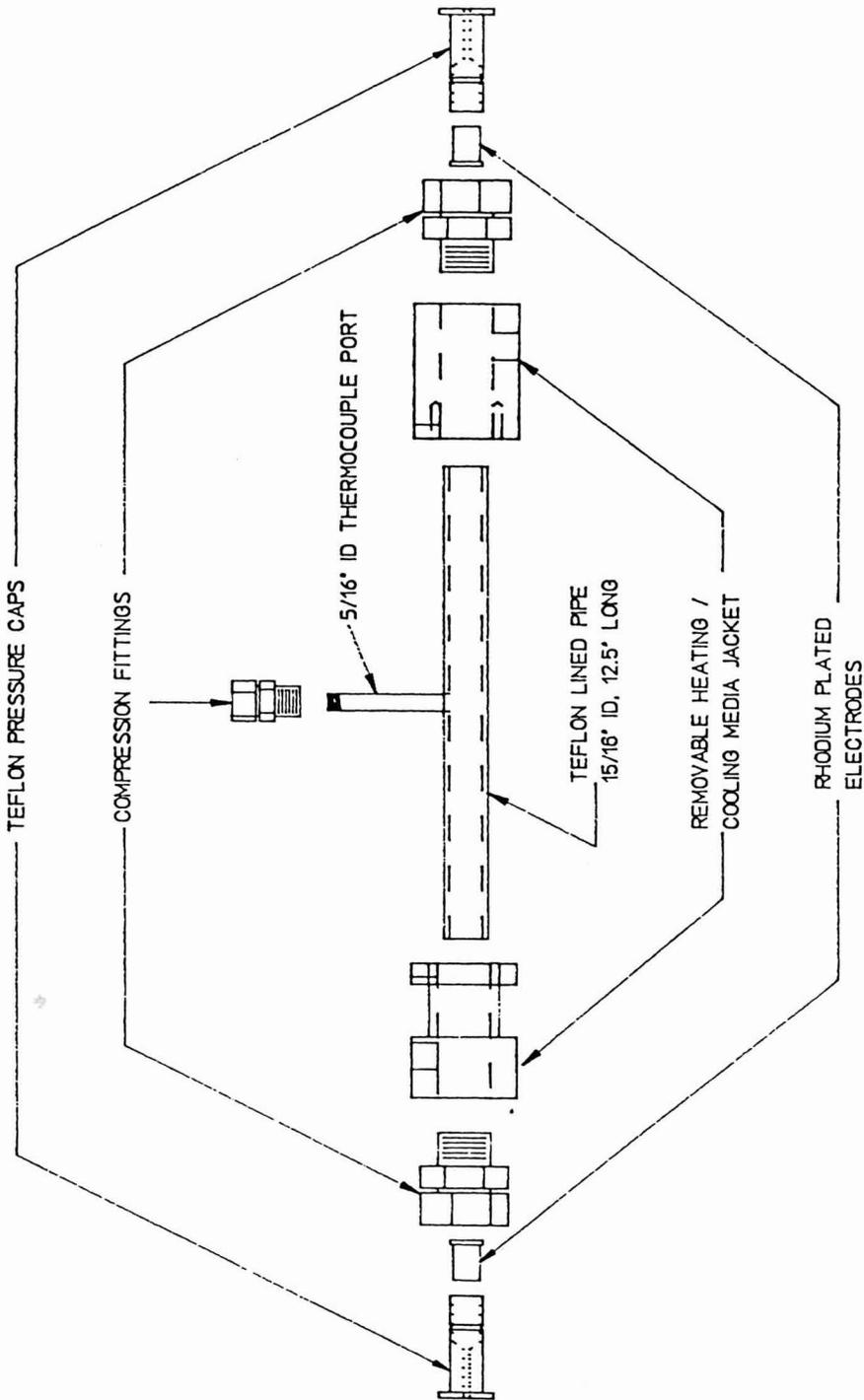


FIG. 1. EXPLODED VIEW OF THE OHMIC HEATING DEVICE

Analysis

The time-temperature data were plotted to obtain the heating curves for the test samples during ohmic heating. A uniform electric field was assumed for electrical conductivity calculations, since the electrodes were in excellent contact with the food solid. The electrical conductivities of samples were calculated from voltage and current data, using the equation:

$$\sigma = (L/AR) \quad (1)$$

where,

σ = specific electrical conductivity (S/m)

A = area of cross-section of the sample (m²)

L = length of the sample (m)

R = resistance of the sample (ohm)

The accuracy of the device was tested by determining the electrical conductivities of two salt solutions, and comparing them with literature or commercial conductivity meter values. Table 1 shows the reference and measured values of conductivities of these solutions. Most of the measured values were within 5% of the reference values, and the maximum difference was 6.3%. The center temperature of the sample was used for the purpose of electrical conductivity modeling, since uniforming heating was assumed. This assumption was made after measuring the temperatures at different locations of the samples and finding the difference to be within 1.4°C.

RESULTS AND DISCUSSION

Heating curves for potato, carrot and yam samples are shown in Figs. 2, 4, and 6, respectively, and the corresponding electrical conductivity versus tem-

TABLE I.
COMPARISON OF CONDUCTIVITIES AT 25°C BETWEEN REFERENCE
AND MEASURED VALUES

Solution	Concentration, M	σ_{ref} , S/m	σ_m , S/m	Difference, %
Sodium Chloride*	0.02	0.20	0.19	5.0
	0.05	0.57	0.55	3.5
	0.17	1.76	1.79	1.7
Sodium Phosphate**	0.03	0.19	0.19	0.0
	0.05	0.34	0.36	5.5
	0.10	0.63	0.67	6.3

* Reference values are literature values.

** Reference values are conductivity meter values.

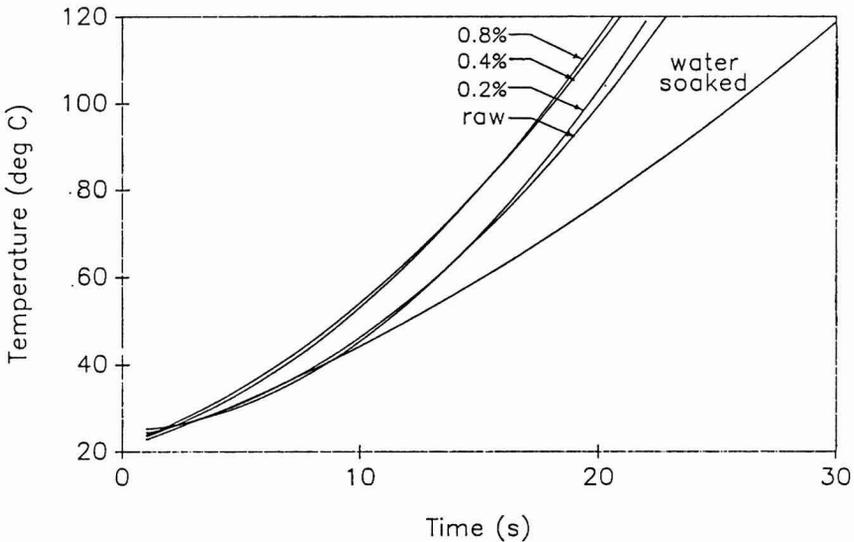


FIG. 2. HEATING CURVES FOR POTATO SAMPLES (RAW, AND SATURATED WITH WATER, 0.2, 0.4 AND 0.8% NaCl SOLUTIONS) DURING OHMIC HEATING

perature curves are shown in Figs. 3, 5, and 7, respectively. These figures do not show individual data points because their numbers were too large (one data point per second per replication) to accommodate meaningfully on the curve. In general, samples with high conductivities showed higher heating rates, exceptions being likely due to variations in specific heat. Heating rates were found to increase with temperature as a direct result of increasing electrical conductivity. In all these tests, the electrical conductivity showed a linear relationship with temperature.

In all cases, vegetable samples that were saturated with distilled water had lower electrical conductivities than untreated controls. This effect is likely due to leaching of electrolytes from the tissue during soaking. Infusion of salt solutions increased the conductivity, with the extent of increase depending on the salt concentration (Figs. 3, 5 and 7). At low temperatures, sample electrical conductivities were not necessarily directly related to the salt concentration. However, as heating proceeded, the conductivity of samples showed an increasing trend with salt concentration. The likely reason for this behavior is the existence of concentration gradients within the samples at the time of testing (end of soaking). As heating progresses and the tissue breaks down, allowing equilibration of salt solution, the results fall more in line with expectation.

Similar heating and electrical conductivity versus temperature curves for meat (lean beef and chicken samples) are presented in Figs. 8 and 9, respectively.

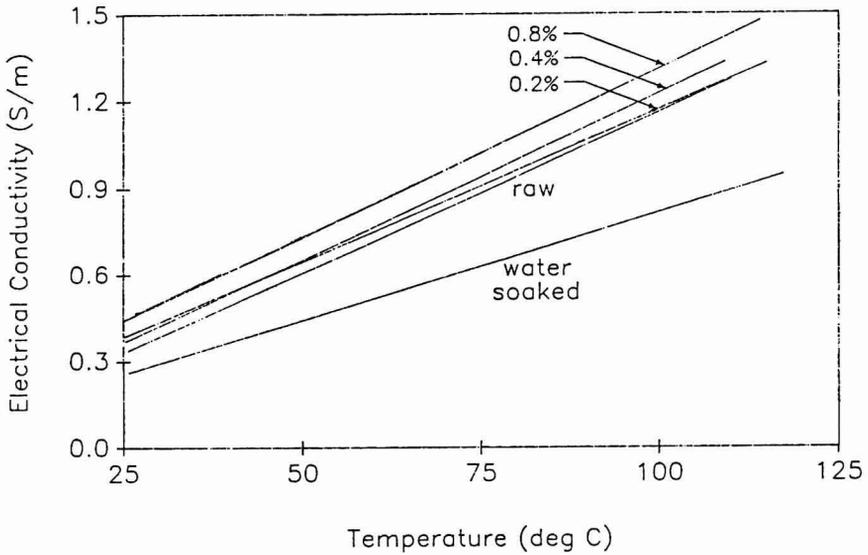


FIG. 3. ELECTRICAL CONDUCTIVITY CURVES FOR POTATO SAMPLES (RAW, AND SATURATED WITH WATER, 0.2, 0.4 AND 0.8% NaCl SOLUTIONS) DURING OHMIC HEATING

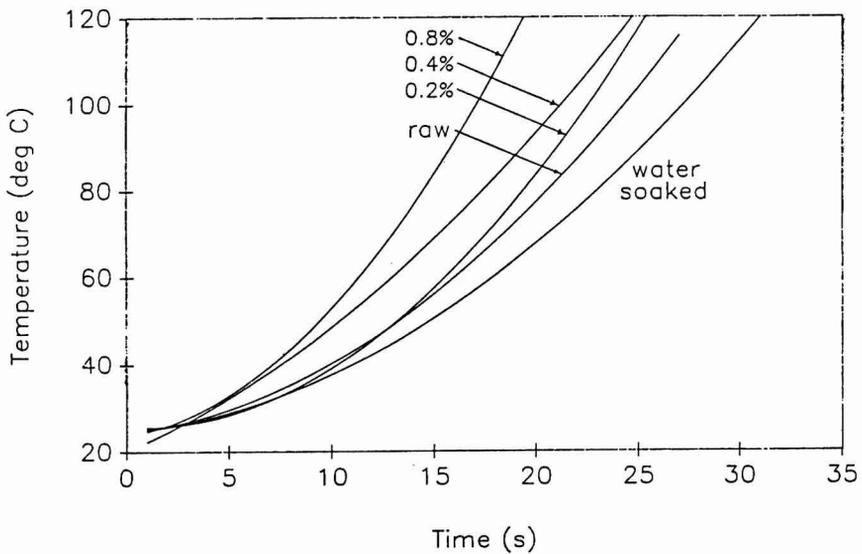


FIG. 4. HEATING CURVES FOR CARROT SAMPLES (RAW, AND SATURATED WITH WATER, 0.2, 0.4 AND 0.8% NaCl SOLUTIONS, PARALLEL TO STEM AXIS) DURING OHMIC HEATING

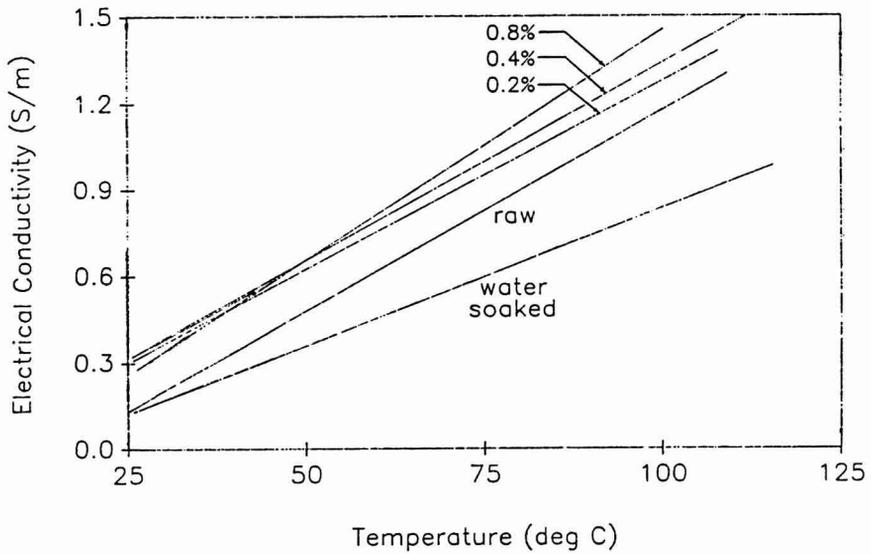


FIG. 5. ELECTRICAL CONDUCTIVITY CURVES FOR CARROT SAMPLES (RAW, AND SATURATED WITH WATER, 0.2, 0.4 AND 0.8% NaCl SOLUTIONS, PARALLEL TO STEM AXIS) DURING OHMIC HEATING

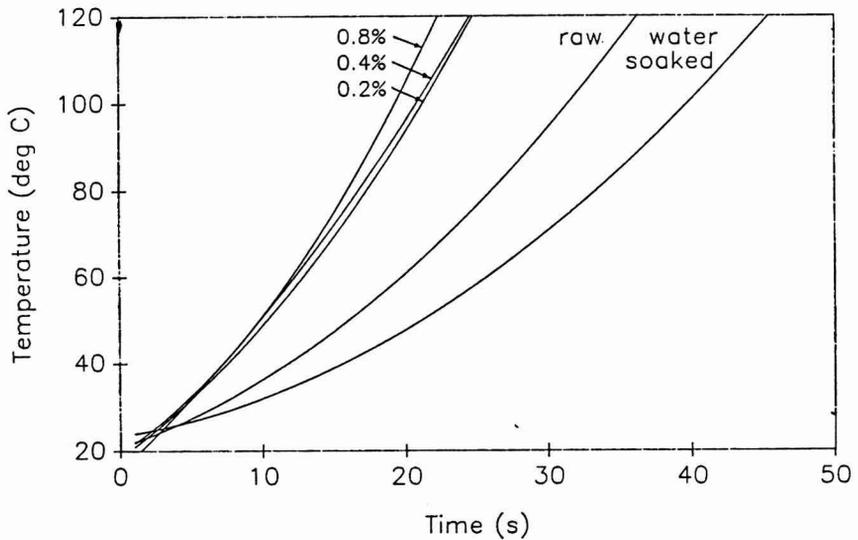


FIG. 6. HEATING CURVES FOR YAM SAMPLES (RAW, AND SATURATED WITH WATER, 0.2, 0.4 AND 0.8% NaCl SOLUTIONS) DURING OHMIC HEATING

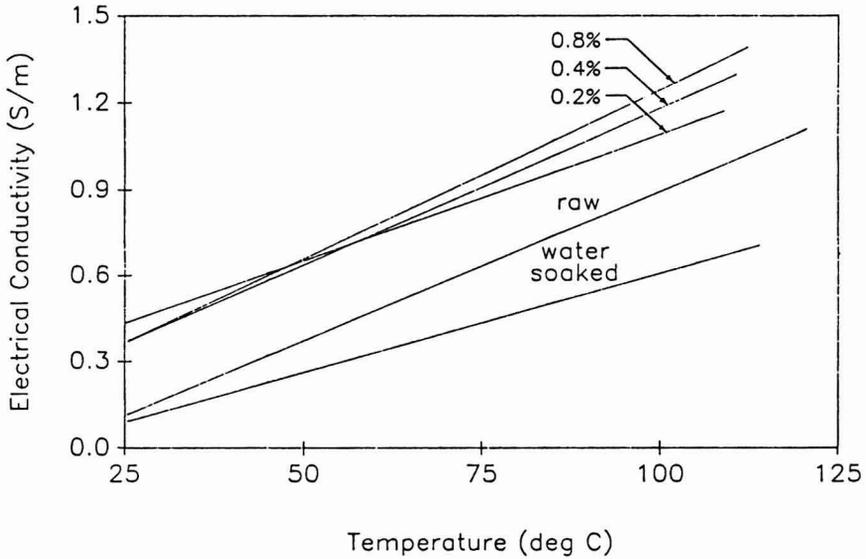


FIG. 7. ELECTRICAL CONDUCTIVITY CURVES FOR YAM SAMPLES (RAW, AND SATURATED WITH WATER, 0.2, 0.4 AND 0.8% NaCl SOLUTIONS) DURING OHMIC HEATING

Once again, the electrical conductivity of samples showed a linearly increasing trend with temperature, and caused increased heating rates at higher temperatures. Lean beef was found to have a higher conductivity than chicken.

The electrical conductivity of the test samples at 60 V was modelled as a function of temperature. The electrical conductivity at 25°C was considered as a reference conductivity for modelling. The general form of the equation fitted was:

$$\sigma_T = \sigma_{p25} [1 + K(T - 25)] \quad (2)$$

where,

- σ_T = electrical conductivity at any temperature T (S/m)
- σ_{p25} = electrical conductivity of particulate at 25°C (S/m)
- K = temperature compensation constant
- T = temperature (°C)

Results of regression of electrical conductivity versus temperature data for all samples are shown in Table 2. High coefficients of determination (in most cases $r^2 > 0.94$) obtained indicate the suitability of a linear model for conductivity variation with temperature.

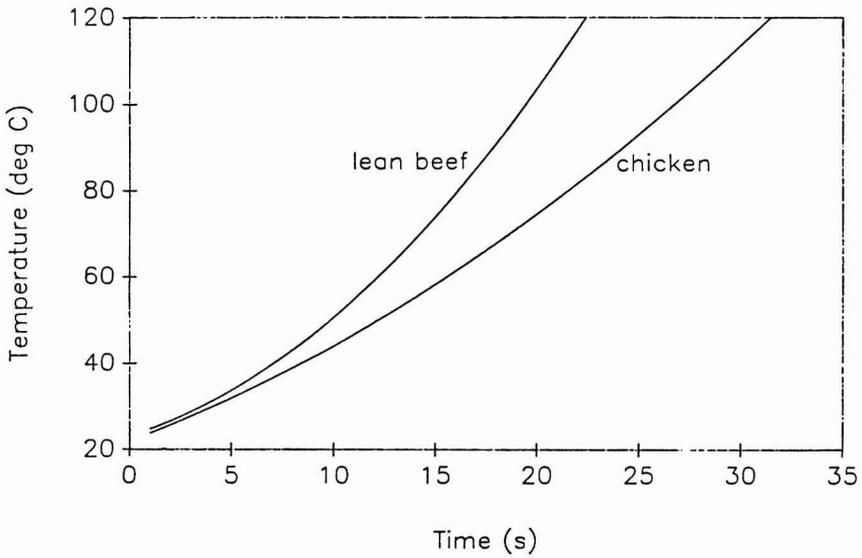


FIG. 8. HEATING CURVES FOR MEAT SAMPLES DURING OHMIC HEATING

Comparison of these data with those from the literature indicates consistent trends. Increasing electrical conductivity with temperature *per se* is as expected from the literature (e.g., Biss *et al.* 1987). As biological tissue is heated, struc-

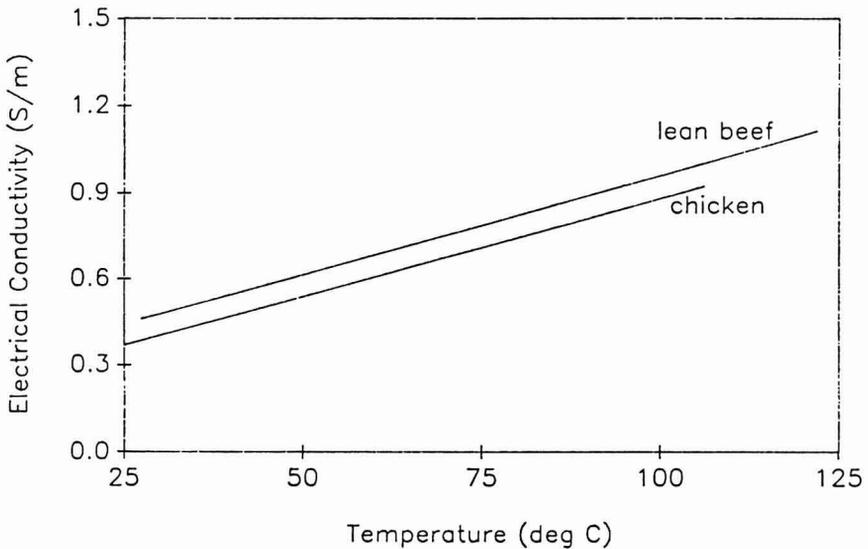


FIG. 9. ELECTRICAL CONDUCTIVITY CURVES FOR MEAT SAMPLES

TABLE 2.
PARAMETERS OF THE ELECTRICAL CONDUCTIVITY MODELS

Material	Treatment	σ_{p25} (S/m)	K (°C) ⁻¹	r ²
Potato	raw	0.32	0.035	0.94
	water	0.25	0.030	0.96
	0.2% NaCl	0.37	0.028	0.98
	0.4% NaCl	0.36	0.033	0.88
	0.8% NaCl	0.43	0.027	0.94
Carrot	raw	0.13	0.107	0.96
	water	0.12	0.078	0.98
	0.2% NaCl	0.29	0.044	0.92
	0.4% NaCl	0.31	0.044	0.96
	0.8% NaCl	0.25	0.062	0.98
Yam	raw	0.11	0.094	0.98
	water	0.09	0.079	0.98
	0.2% NaCl	0.42	0.021	0.85
	0.4% NaCl	0.35	0.032	0.94
	0.8% NaCl	0.35	0.034	0.96
Chicken	raw	0.37	0.019	0.90
Beef	raw	0.44	0.016	0.96

tural changes occur (e.g., cell wall protopectin breakdown, expulsion of non-conductive gas bubbles, softening and tissue damage) that increase ionic mobility (Brüniche-Olsen 1962; Bean *et al.* 1960; Sasson and Monselise 1977).

Quantitative comparison with data of Halden *et al.* (1990) shows some differences which require further examination. The only direct comparison possible involves the data for potato tissue under ohmic heating, for which Halden *et al.* indicate a nonlinear increase in conductivity with temperature (slow initial rise followed by a steep increase around 80°C). Another notable difference is in the magnitude of the values obtained (our values are considerably higher than theirs). Although the frequencies studied were different (50 versus 60 Hz), the differences seem too striking to be attributed to frequency alone. The accuracy of our results were checked as being satisfactory by comparison with standard salt solutions (Table 1). Checks of applied voltage versus current revealed the absence of electrode polarization phenomena.

Meaningful comparison of data can be made only if details of both experimental setups and methodology were available. Halden *et al.* (1990) cited the use of an experimental setup described by Mitchell and de Alwis (1989). The latter paper describes an electrical conductivity cell in which the sample temperature

is controlled by immersion in a water bath. Neither Mitchell and de Alwis (1989) nor Halden *et al.* (1990) explain how the device could be used to determine electrical conductivity versus temperature data under ohmic heating conditions. Another detail that is not available in either paper is whether or not their sample cell was sealed from the environment to restrict moisture loss and permit heating above 100°C.

For their ohmic heating studies, Halden *et al.* (1990) describe a static ohmic heater in which particle samples were heated in brine, although they do not indicate that it was used for particle electrical conductivity determination. Our study appears to have been different in that it involved simultaneous measurement of electrical conductivity and ohmic heating of particles without brine. Another major difference between our ohmic heating setup and the static ohmic heater of Halden *et al.* (1990) involved the voltage gradient (60 V/cm in ours, compared to 10.87 V/cm in theirs). Accordingly, the influence of voltage gradient on electrical conductivity was considered worthy of investigation.

Figure 10 shows data on electrical conductivity versus temperature for carrot tissue parallel to the axis, obtained using successively lower voltage gradients, including 0 V/cm (conventional heating using hot water in the jacket). Interestingly, the electrical conductivity appears to decrease with decreasing voltage gradient. As the voltage gradient decreases, the curve takes on an increasingly nonlinear aspect, ending in a curve exhibiting a sharp transition at about 60°C

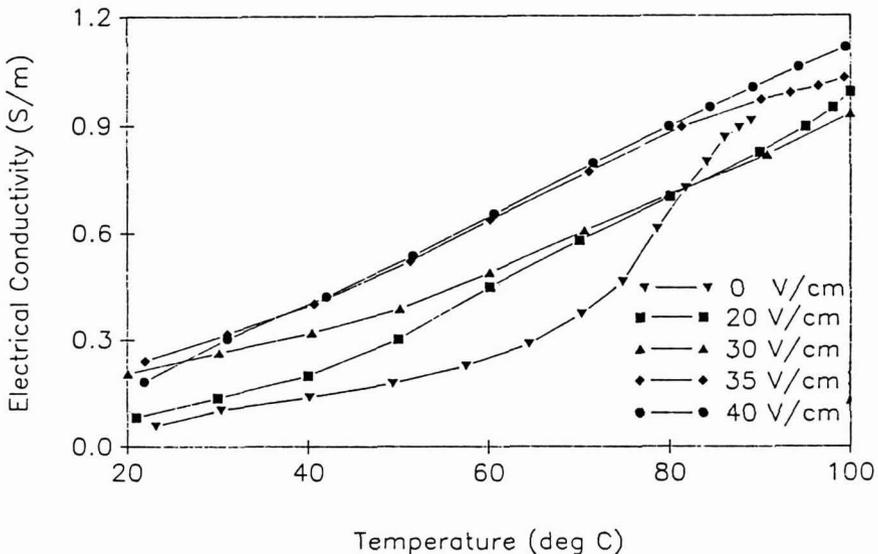


FIG. 10. ELECTRICAL CONDUCTIVITY CURVES FOR CARROT (PARALLEL TO STEM AXIS) SUBJECTED TO VARIOUS VOLTAGE GRADIENTS

under conventional heating conditions (0 V/cm). Similar curves have been observed for conventionally heated beet tissue (Brüniche-Olsen 1962; Halden *et al.* 1990). The electrical conductivities at room temperatures also appear to be more in the range of values reported by Mitchell and de Alwis (1989) for carrot tissue parallel to the axis. It should be noted that ohmic heating studies at very low field strengths resulted in slow sample heating, and, over long periods of time, conductivity decreased due to scorching of tissue in the vicinity of the electrodes.

The reason for increasing electrical conductivity with increasing applied voltage (Fig. 10) appears to be primarily due to electro-osmotic effects, which have been discussed in detail by Halden *et al.* (1990). Since biological tissue consists of a large aggregation of porous membranes, the application of voltage results in fluid motion through the capillaries. The osmotic pressure exerted across a straight capillary has been shown, in a simplified analysis, to be directly proportional to the voltage gradient (Crow 1988).

The reasons for the changing shape of the curve with increasing applied voltage are less obvious. Under conventional heating conditions, fluid motion across membranes is not significant, and the transition in conductivity is mainly due to microstructural changes discussed earlier. As the applied voltage increases, the increased alternating osmotic motion of fluids may contribute to membrane rupture at temperatures well below that associated with conventional heating. This may well account for the more gradual transition that was observed under these conditions.

Tests involving conventional heating of potato and yam tissue also yielded sharp transitions in electrical conductivity (Fig. 11), as observed by Halden *et al.* (1990) for ohmic heating. The electrical conductivity value for potato at 25°C also agrees well with the value of Mitchell and de Alwis (1989), although at higher temperatures, our values are considerably higher than those of Halden *et al.* (1990). Our results for conventional heating of potato tissue, therefore agree qualitatively with those of Halden *et al.* (1990) for ohmic heating.

Halden *et al.* (1990) indicate that electro-osmotic dehydration of their samples (resulting in increased ionic concentrations) may have been the reason for their results, and cited weight losses of 5–10% in their experimental setup. Typical weight losses for our samples were in the range of 4–6%, being due to evaporation into the pressurized headspace of the experimental setup. A situation involving significant dehydration was studied by conducting experiments on carrot tissue without compression fittings at the thermocouple port. Under these conditions, reproducible conductivity-temperature data were difficult to obtain, because as the samples approached 60°C, violent evaporation of moisture occurred, with substantial evaporative cooling effects (time-temperature data are shown in Fig. 12). It is interesting to note that the flash point temperature of 60°C coincides with the temperature at which a sharp transition in electrical conductivity begins

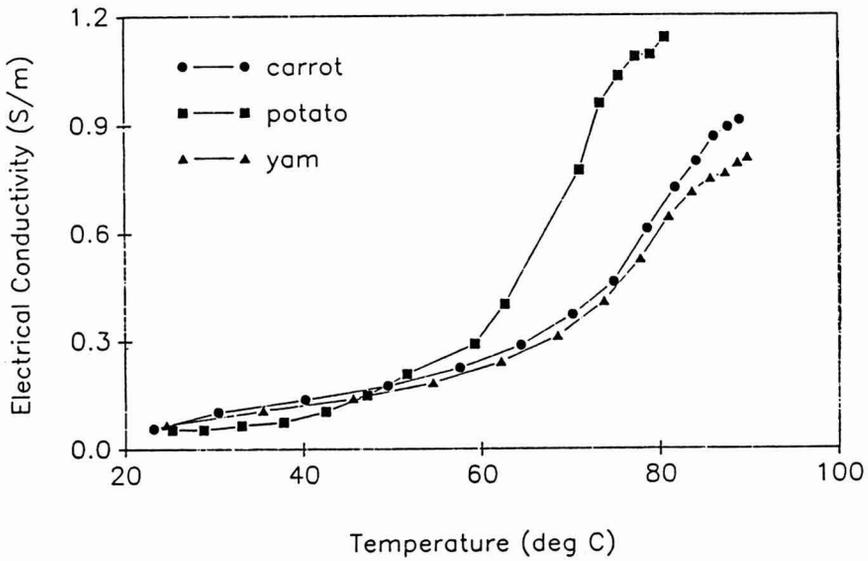


FIG. 11. ELECTRICAL CONDUCTIVITY CURVES FOR VEGETABLE TISSUE DURING CONVENTIONAL HEATING

during conventional heating. This indicates the relationship between electrical conductivity and tissue softening. Weight losses under these conditions were also greater (6–10%) than those involving the pressurized setup.

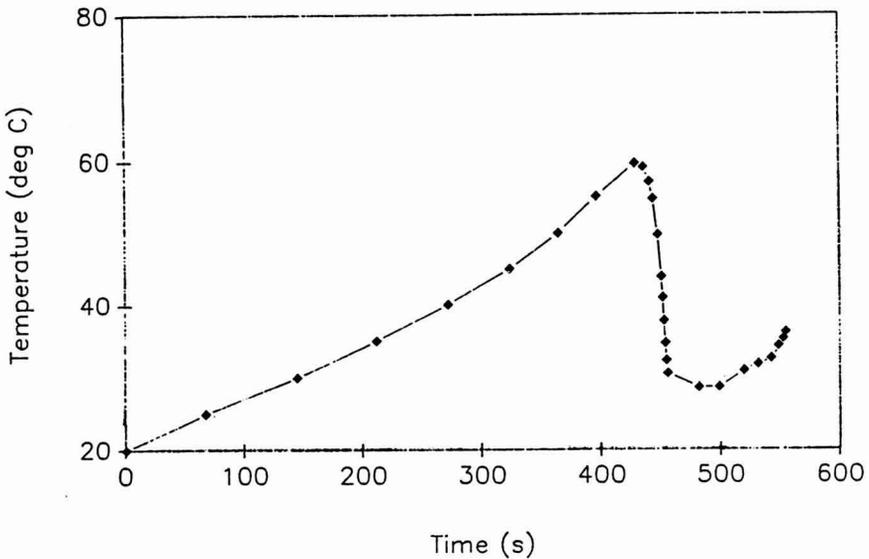


FIG. 12. HEATING CURVE OF A CARROT SAMPLE DURING OHMIC HEATING (30 V/cm) WITHOUT COMPRESSION FITTING

While dehydration is a phenomenon worthy of investigation, its relevance to heating of liquid-particle mixtures is questionable, since evaporative dehydration effects cannot occur under these conditions. The likely scenario in this situation is an exchange of fluid between particles and liquid carrier.

A final point of comparison between our data and those of Halden *et al.* (1990) relates to the data on meat samples under ohmic heating. Our data (Fig. 9) indicate linearly increasing electrical conductivity with temperature during ohmic heating. Halden *et al.* (1990) show a slightly decreasing trend with temperature for pork meat and state that other meats such as chicken gave similar results. Comparison of results is not possible, since Halden *et al.* (1990) do not indicate whether these data were obtained under conventional or ohmic heating conditions. The differences may be due to one of the many different conditions of experiment, as discussed above.

CONCLUSIONS

Electrical conductivity of the solid foods studied increase linearly with temperature during ohmic heating at a voltage gradient of 60 V/cm. Soaking of vegetable samples in water decreases electrical conductivity by leaching of solutes, whereas infusion of salt solutions increases electrical conductivity. The electrical conductivity curves for vegetable tissue exhibited nonlinear trends when decreasing the voltage gradient, and under zero voltage gradient (conventional heating), a sharp transition at about 70°C was observed, coinciding with significant softening of the tissue. Electrical conductivity increase with voltage gradient can be explained by electro-osmotic effects.

It was also shown that the heating rates of solid foods depend on the electrical conductivity which could be adjusted using water or salt solutions. Rapid heating of foods due to high electrical conductivity will be useful in reducing the product residence time during processing. Adjustment of electrical conductivity could be considered if the composition and other properties of foods are not greatly affected. Obviously, a balance between processability and organoleptic/nutritional considerations will be important.

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CONTENTS

Air Drying Behavior of Fresh and Osmotically Dehydrated Pineapple M.S. RAHMAN and J. LAMB	163
Evaporation in a Horizontal Thin Film Scraped Surface Heat Exchanger H. ABICHANDANI and S.C. SARMA	173
Specific Heat of Dehydrated Pulps of Fruits J.D. ALVARADO	189
Convection Heat Transfer Coefficient for a Restructured Pork/Soy Hull Product K. UNKLESBAY, N. UNKLESBAY and K. BIEDRZYCKI	197
Kinetic Study of Quality Losses in Frozen Scallop Meats S.L. CHUNG and J.H. MERRITT	209
Electrical Conductivities of Selected Solid Foods During Ohmic Heating S. PALANIAPPAN and S.K. SASTRY	221