



**Journal of  
FOOD PROCESS  
ENGINEERING**

**Edited by  
D. R. HELDMAN**

**FOOD & NUTRITION PRESS, INC.  
WESTPORT, CONNECTICUT 06880  
USA**

**VOLUME 5, NUMBER 1**

**QUARTERLY**

# JOURNAL OF FOOD PROCESSING ENGINEERING

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All subscriptions and inquiries regarding subscriptions should be sent to Food & Nutrition Press, Inc., 1 Trinity Square, Westport, CT 06880 USA.

One volume of four issues will be published annually. The price for Volume 5 is \$55.00 which includes postage to U.S., Canada, and Mexico. Personal subscriptions to other countries are \$67.00 per year via surface mail, and \$75.00 per year via airmail.

Subscriptions for individuals for their own personal use are \$35.00 for Volume 5 which includes postage to U.S., Canada, and Mexico. Personal subscriptions to other countries are \$47.00 per year via surface mail, and \$55.00 per year via airmail. Subscriptions for individuals should be sent direct to the publisher and marked for personal use.

The *Journal of Food Process Engineering* (ISSN-0145-8876) is published (March, June, September and December) by Food & Nutrition Press, Inc. — Office of publication is 1 Trinity Square, Westport, Connecticut 06880 USA, (current issue is March 1982).

Second class postage paid at Westport, CT 06880.

POSTMASTER: Send address changes to Food & Nutrition Press, Inc., 1 Trinity Square, Westport, CT 06880.

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28. ต.ค. 2525

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Westport, Connecticut USA

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ISSN 0145-8876

Printed in the United States of America

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## MEETINGS

### NOVEMBER 1982

**November 14-19: The Importance of Reliable Physical Properties in Heat Transfer.** 1982 ASME Winter Annual Meeting, Phoenix, AZ. Contact: E. P. Dewitt, School of Mechanical Engineering, Purdue University of West Lafayette, IN 47907.

**November 14-19: Role of Thermal Physical Properties and Engery Technology.** 1982 ASME Winter Meeting, Phoenix, AZ. Contact: B. Latto, Dept. of Mechanical Engineering, McMaster University, West Hamilton, Ontario, Canada L8S 417.

### DECEMBER 1982

**December 14-17: Winter Meeting of the American Society of Agricultural Engineers.** Palmer House, Chicago, IL. Contact: Mark A. Purschwitz, American Society of Agricultural Engineers, Box 410, St. Joseph, MI 49085.

### JANUARY 1983

**January 23-27: Annual Meeting, American Society of Heating, Refrigeration and Air Conditioning Engineers.** Atlantic City, NJ. Contact: J. L. McClung, Manager of Technical Activities, ASHAE, 1991 Tullie Circle, NE, Atlanta, GA 30329.

# HEAT TRANSFER IN A VERTICAL, LIQUID-FULL SCRAPED-SURFACE HEAT EXCHANGER. APPLICATION OF THE PENETRATION THEORY AND WILSON PLOTS MODELS

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Received for Publication February 4, 1981  
Accepted for Publication June 22, 1981

## ABSTRACT

*Heat transfer characteristics of a scraped-surface heat exchanger (Contherm Model 6 × 2) were evaluated at ultra high temperatures using water and soybean water extracts as model systems. The resistance equation was used to calculate internal (scraped-side) heat transfer coefficients ( $h_i$ ) from the overall heat transfer coefficient, the wall coefficient and the external (steam-side) coefficient (calculated from the Nusselt Theory using an iteration procedure). The Penetration Theory of Harriot (1958) predicted  $h_i$  values quite well at low axial mass flow rates, where laminar flow conditions prevail. However, turbulent axial flow resulted in experimental  $h_i$  greater than predicted by the theory. A correction factor based on Prandtl number suggested by Trommelen et al. (1971) did not improve the prediction. The Wilson Plots method was useful for explicitly accounting for axial and rotational velocity effects, both of which significantly affected heat transfer, especially at high values of either variable.*

## INTRODUCTION

In most heat transfer situations, even a very thin layer of almost any material on the heat transfer surface seriously retards the rate of heat transfer. These layers can be removed very effectively by the use of blades or scrapers (Huggins 1931) and this is the principle on which scraped-surface heat exchangers (SSHE) are based. SSHE are finding increased use in thermal processing applications, especially for those liquid foods that have suspended solids, high viscosity or display non-Newtonian rheology (Anton 1977; Bolanowski 1967). However,

there are very few studies on the heat transfer characteristics of SSHE used for continuous ultra high temperature sterilization applications, where temperatures are in the region of 120-150° C and, since holding times are of the order of seconds, where high mass flow rates tend to prevail (i.e., high axial Reynolds numbers). Under such operating conditions, the basic heat transfer theories may fail to predict the performance of these units. This paper is a study of the heat transfer phenomena in SSHE operated under ultra high temperature conditions, with the ultimate goal of developing semiempirical models correlating performance factors to operating parameters and physical properties. This should enable us to gain an insight into the mechanism of heat transfer in SSHE, an important consideration in the optimum design of thermal processes.

## MATERIALS AND METHODS

### Overall UHT System

The scraped-surface heat exchangers used in this study were the Contherm model 6 × 2 units (The DeLaval Separator Co., Newburyport, MA) mounted vertically on a portable column frame, each fitted with two scraping blades of the "floating" type. Specifications of the heat exchangers are given in Table 1. The two units were identical except the heater had a rotor (shaft) diameter ( $D_s$ ) of 4.375 in. and product ports of 2 in. diameter, while the cooler had a rotor diameter of 2.00 in. and product ports of 1.5 in. diameter. No modifications were made to the units themselves for this study. The rotation of the shaft and blades was controlled using a hydraulic orbit motor and a Rivett hydraulic system (Applied Power Industries Inc., Needham Heights, MA). Rotational speed of the blades was determined with a phototachometer (Model 12, Pioneer Electric and Research Corp., Forest Park, IL), accurate to 2% of full scale reading. High pressure steam, with an in-line adjustable reducing valve, and chilled water were used as the heat transfer media.

Feed (either water or the model low acid liquid food) was fed from jacketed, stirred storage tanks via a low pressure centrifugal "booster" pump to a Manton-Gaulin high pressure, reciprocating pump fitted with a variable speed drive. The feed was pumped through a mass flow meter (Model L50A, Micro Motion Inc., Boulder, CO) which was basically a deflected U-tube (Coriolis type) mass flow sensor with electronic converter and digital readout. The mass flow sensor had an accuracy of  $\pm 0.4\%$  full scale, with a repeatability of  $\pm 0.2\%$  and a least

Table 1. Specifications of Contherm Model 6 × 2 Scraped Surface Heat Exchanger (Source: The DeLaval Separator Co., 1970)

---

Heat Transfer Tube	
Inside Diameter ( $D_i$ )	6.065 in.
Outside Diameter ( $D_o$ )	6.625 in.
Wall Thickness ( $x_w$ )	0.280 in.
Length (L)	18.188 in.
Material of Construction	200-Nickel
Shaft/Rotor	
Diameter in Heater	4.375 in.
Diameter in Cooler	2.000 in.
Material of Construction	316 SS
Blades	
Number Each (B)	2
Length	17.188 in.
Leading Edge	1/64 in.
Thickness	1/8 in.

---

significant figure of 0.1 lb/min. Heater and cooler outlet temperatures were measured with platinum resistance temperature devices mounted into pressure fittings placed immediately after the product ports, and Omega digital readouts (Model 175, Omega Engineering Inc., Stamford, CT). Their overall error was  $\pm 0.25\%$  of the reading between 212-1500° F, with 1° F resolution. Chilled water inlet and outlet temperatures were measured with bimetal helix-type industrial thermometers (Model 4313, Weston Instruments, Newark, NJ) accurate within 1% of the range. When operating above the boiling point of the feed, a back-pressure of 50-80 psig was maintained with a Tri-Clover back pressure valve after the cooler.

### Physical Properties of Model Liquid Foods

Water and water extracts of soybeans were used as the model liquid foods. Water extracts of soybeans were prepared as described earlier (Omosaiye *et al.* 1978) by a series of unit operations involving soaking of whole soybeans, blanching briefly, grinding and filtering out the coarse insoluble matter. Solids content (S, % w/w) were varied by adjusting the amount of water in the whole process. Total solids was measured by a gravimetric method (AOAC 1970). Density ( $\rho$ ) of the liquids were measured at different concentrations and temperature using precalibrated pycnometers. The data was fitted to a correlation of the form:

$$\rho = A - BT \quad (1)$$

where  $\rho$  = density in gm/mL,  $T$  = temperature in °K, and  $A$  and  $B$  are functions of  $S$ , the solids content, and take the form:

$$A = 1.1501 + 5.21 \times 10^{-3}S + 3.678 \times 10^{-4}S^2 \quad (2)$$

$$B = 5.037 \times 10^{-4} + 5.59 \times 10^{-6}S - 7.083 \times 10^{-7}S^2 \quad (3)$$

Viscosity ( $\mu$ ) of the working fluid was measured with a Brookfield Viscometer with UL adapter (model LVF, Brookfield Engineering Laboratories, Stoughton, MA) operating at 60 rpm. The viscometer had been precalibrated using Brookfield viscosity standards. No significant deviations from Newtonian rheology was observed for any of the liquids studied here. The data were best correlated with a model as shown below:

$$\mu = 2.438 \times 10^{-2} \cdot e^{-0.0464 S} \cdot e^{(1108.7 + 189.4S)/T} \quad (4)$$

where  $\mu$  = viscosity in centipoise,  $T$  = temperature in °K

Specific heat ( $C_p$ ) was estimated using Dickerson's (1968) model:

$$C_p = 0.4 + 0.006(100 - S) \quad (5)$$

For liquid foods of low solids content,  $C_p$  is almost independent of temperature.

Methods for estimating thermal conductivity ( $k$ ) of liquid foods were recently reviewed (Cuevas and Cheryan 1978) and the model that describes available data the best was found to be:

$$k = (0.486 + 0.00155T - 5 \times 10^{-6}T^2)(1 - 0.0054 S) \quad (6)$$

where  $k$  is in Kcal/h.m.°C,  $T$  is in °C and  $S$  is the solids content (% w/w).

### Heat Transfer Calculations

Overall heat transfer coefficients ( $U$ ) were calculated based on the outside heat transfer area ( $A$ ) and the log mean temperature difference ( $\Delta T_{ln}$ ) as follows:

$$Q = UA\Delta T_m \quad (7)$$

The heat transferred ( $Q$ ) was determined from the heat uptake equation:

$$Q = WC_p(T_o - T_i) \quad (8)$$

where  $T_o$  = heater outlet temperature,  $W$  = mass flow rate and  $T_i$  = heater inlet temperature. Definitions and levels of the variable studied are given in Table 2. Temperature profiles as a function of these variables are available elsewhere (Cuevas *et al.* 1982; Cuevas-Garcia 1981).

Table 2. Definition and Levels of Operating Parameters

Operating Parameter	Symbol	Units	Range of Operating Conditions
Mass flow rate	$W$	lb/min	10 – 35
Blades rotational speed	$N$	RPM	0 – 575
Steam pressure	$P_s$	psig	60, 110
Feed inlet temperature	$T_i$	°F	120, 160
Solids content of feed	$S$	% w/w	0 – 6.14

Individual heat transfer coefficients were calculated on the basis of the resistance concept, taking into account the system geometry. The resistance equation is:

$$\frac{1}{U} = \frac{D_o}{D_i h_i} + \frac{D_o}{D_L h_w} + \frac{1}{h_o} \quad (9)$$

where  $D_o$  and  $D_i$  are outside and inside wall diameters and  $D_L$  is the log mean diameter.  $h_i$  is the internal or scraped-side heat transfer coefficient,  $h_o$  is the outside or steam-side heat transfer coefficient and  $h_w$  is the wall heat transfer coefficient.

**Steam-side Heat Transfer Coefficient ( $h_o$ ).** This was calculated assuming film type condensation of steam, which is the basis for the Nusselt theory (McAdams 1954; Bird *et al.* 1960):

$$h_o(\text{BTU}/\text{h ft}^2\text{ }^\circ\text{F}) = 1.13 \frac{k_f^3 \rho_f^3 g \Delta H_v}{\mu_f L (T_s - T_w)^{0.25}} \quad (10)$$

- where  $k_f$  = thermal conductivity of condensate at mean film temperature  
 $\rho_f$  = density of condensate at mean film temperature  
 $\mu_f$  = viscosity of condensate at mean film temperature  
 $\Delta H_v$  = latent heat of condensation  
 $L$  = heated length of the tube  
 $T_s$  = steam condensation temperature (i.e., dew point at prevailing pressure)  
 $T_w$  = temperature of outside surface of tube wall

The physical properties required for calculating  $h_o$  were obtained from thermodynamic or semiempirical equations. A number of models for estimating the physical properties of steam were evaluated statistically using techniques similar to those used for evaluating models for thermal conductivity of liquid foods (Cuevas and Cheryan 1978). The models chosen on the basis of this analysis are (Cuevas-Garcia 1981):

Antoine model for obtaining steam temperature ( $T_s$ ) from steam pressure (Perry and Chilton 1973; Reid *et al.* 1977).

Watson model for obtaining latent heat ( $\Delta H_v$ ) from steam temperature (Reid *et al.* 1977).

Mathias model, for density of steam condensate ( $\rho_f$ ) (Perry and Chilton 1973).

Andrade model, for viscosity of steam condensate ( $\mu_f$ ) (Perry and Chilton 1973).

Touloukian *et al.* model for thermal conductivity of steam condensate ( $k_f$ ) (Cuevas and Cheryan 1978).

These properties were determined at the mean film temperature, ( $T_f$ , shown below as Eq. 11), which means that the wall temperature ( $T_w$ ) must be known. In this particular case, there was no way of actually

measuring the wall temperature due to the construction of the SSHE unit. Hence, an alternative method was found for this purpose.

**Method of Estimating Wall Temperature.** The basis of using this procedure was a heat transfer analysis of the SSHE, together with a trial and error procedure adapted for use with a computer. Essentially, the method consists of first assuming a wall temperature (steam-side), then calculating the film condensate temperature by the relationship (McCabe and Smith 1956):

$$T_f = T_s - \frac{3}{4}(T_s - T_w) \quad (11)$$

The condensate physical properties at this temperature are then determined using the appropriate models discussed earlier. These in turn are then used to determine  $h_o$  from the Nusselt theory, Eq. 10. The heat flux equivalence concept is then used to calculate a "new" wall temperature. The overall temperature drop is proportional to  $1/U$ , and the temperature drop through a given resistance is proportional to that resistance:

$$\frac{\Delta T}{1/U} = \frac{\Delta T_o}{1/h_o} = \frac{T_s - T_w}{1/h_o} \quad (12)$$

Therefore, the wall temperature on the steam-side ( $T_w$ ) is:

$$T_w = T_s - \Delta T \cdot U/h_o \quad (13)$$

This new wall temperature is now used to repeat the above set of calculations, and this procedure is repeated until the two values (i.e., the assumed wall temperature and the "new" calculated wall temperature) converge. The final  $h_o$  value is then used in the resistance equation.

**Wall Heat Transfer Coefficient ( $h_w$ ).** This value was obtained from the thermal conductivity and thickness of the wall, taking into account the geometry of unit. By definition:

$$h_w = \frac{k_w}{x_w} \quad (14)$$

where  $k_w$  = wall thermal conductivity  
 $x_w$  = wall thickness



For the Contherm, the heat transfer wall is 0.28 in. thick, made of pure nickel (the effect of hard chroming the surface is considered negligible). For nickel 200,  $k_w = 35 \text{ BTU/h ft}^2 (\text{°F/ft})$  (Perry and Chilton 1973; Table 23-25). Therefore,  $h_w$  is  $1500 \text{ BTU/h ft}^2 \text{°F}$  ( $8517 \text{ W/m}^2 \text{K}$ ) which is in fair agreement with the value of  $1679.5 \text{ BTU/h ft}^2 \text{°F}$  given by Anton (1977). The scraped side coefficient ( $h_i$ ) can then be calculated from Eq. (9).

## RESULTS AND DISCUSSION

### Steam-Side Heat Transfer Coefficient

Since the resistance to heat transfer will probably be greater on the working liquid-side than on the condensing steam-side (McAdams 1954), the wall temperature will be closer to the steam temperature than to the working liquid temperature; and hence the initial choice of the iteration variable (wall temperature) was  $T_w = T_b + 50$ , where  $T_b = (T_o + T_i)/2$ . This proved to be appropriate, since no more than three iterations were needed in any case to meet the convergence criterion established (less than 1% difference between subsequent values of  $T_w$ ).

Average steam-side heat transfer coefficients ( $h_o$ ) obtained ranged from 1404-1513  $\text{BTU/h ft}^2 \text{°F}$  with standard deviations of  $\pm 86$ -107. The significance of  $h_o$  data is two fold: since these values are within normal ranges for vertical condensation (1000-3000  $\text{BTU/h ft}^2 \text{°F}$ , McAdams 1954), and only three iterations were needed for the iterative method to converge, the method is a valid procedure for determining this parameter. In addition, in each loop during the iteration, a corrected  $\Delta T_w = T_s - T_w$  was computed using a calculated overall heat transfer coefficient. This implies that the assumptions necessary for the calculation of  $h_o$  from the Nusselt theory, as well as the assumptions for calculating U values (i.e., that the logarithmic mean temperature difference applies) are valid criteria in all our calculations. This further implies that axial dispersion or backmixing effects can be considered to be negligible under our operating conditions, at least to a first approximation. Further discussion on backmixing effects have been presented by Cuevas *et al.* (1982). It should be remembered that, unlike many previous SSHE studies, mass flow rates in our studies correspond to the region of "high" laminar axial Reynolds numbers, where axial dispersion effects are expected to be negligible.

### Scraped-Side Heat Transfer Coefficients, $h_i$

**Penetration Theory.** An important theory for predicting the heat transfer coefficients and explaining the heat transfer mechanism in

scraped-surface heat exchangers is the Penetration Theory. This theory states that the heat transfer between the wall and the liquid takes place by a mechanism resembling unsteady state conduction between successive blade passes. When the blade passes a point on the surface, complete mixing is obtained so that at that instant the temperature from the wall to the vessel is equalized (Kool 1958; Harriot 1959). Hence, the temperature difference between the scraped plane and the bulk fluid occurs almost completely across a thin layer of material near that plane. This film is scraped from the wall and mixed with the bulk of material, and, according to Kool (1958), "clean heat transfer surface is exposed to fresh material," resulting in increased rates of heat transfer.

For unsteady state heat conduction, and assuming constant and isotropic thermal diffusivity, the basic energy equation (Bird *et al.* 1960) can be used to derive the final form of the Penetration Theory:

$$h_i = \frac{2}{\sqrt{\pi}} \left( \frac{k C_p \rho}{t} \right)^{0.5} \quad (15)$$

This equation gives the scraped-side heat transfer coefficient  $h_i$  for a contact time  $t$ . In the SSHE, contact time is:

$$t = 1/60 N B \quad (16)$$

where  $N$  = revolutions per minute of the scraping blades

$B$  = number of scraping blades = 2 for the Contherm.

Therefore:

$$h_i = 12.36 (k C_p \rho N)^{0.5} \quad (17)$$

This is the Penetration Theory (Harriot) model for predicting  $h_i$  in a SSHE. Kool (1958) derived a similar equation for  $h_i$ , based on a slightly different approach, obtaining:

$$h_i = 14.59 h_o^{-0.03} (k C_p \rho N)^{0.515} \quad (18)$$

The Penetration Theory as stated above assumes that heat transfer is independent of viscosity, which is known to be incorrect, especially in the turbulent regime. In addition, in SSHE units such as Votator, the hydrodynamic lift force may keep the blades off the wall, thus always leaving a thin residual film on the wall which affects heat transfer (Penney and Bell 1967, 1969). Modifications of the Penetration

Theory have been proposed to include the effects of the physical properties, the most important one being that of Trommelen *et al.* (1971), who expressed it in terms of dimensionless numbers:

$$\text{Nu} = 8.74 (\text{Re}_R \cdot \text{Pr} \cdot B)^{0.5} (2 \text{Pr}^{-0.25}) \quad (19)$$

where Nu is the Nusselt number,  $\text{Re}_R$  is the rotational Reynold's number and Pr the Prandtl number.

### Evaluation of the Models

The two models of the Penetration Theory, Harriot's Eq. 17 and Trommelen *et al.* Eq. 19, were evaluated in this work. The physical properties were all evaluated at the bulk average temperature ( $T_b$ )

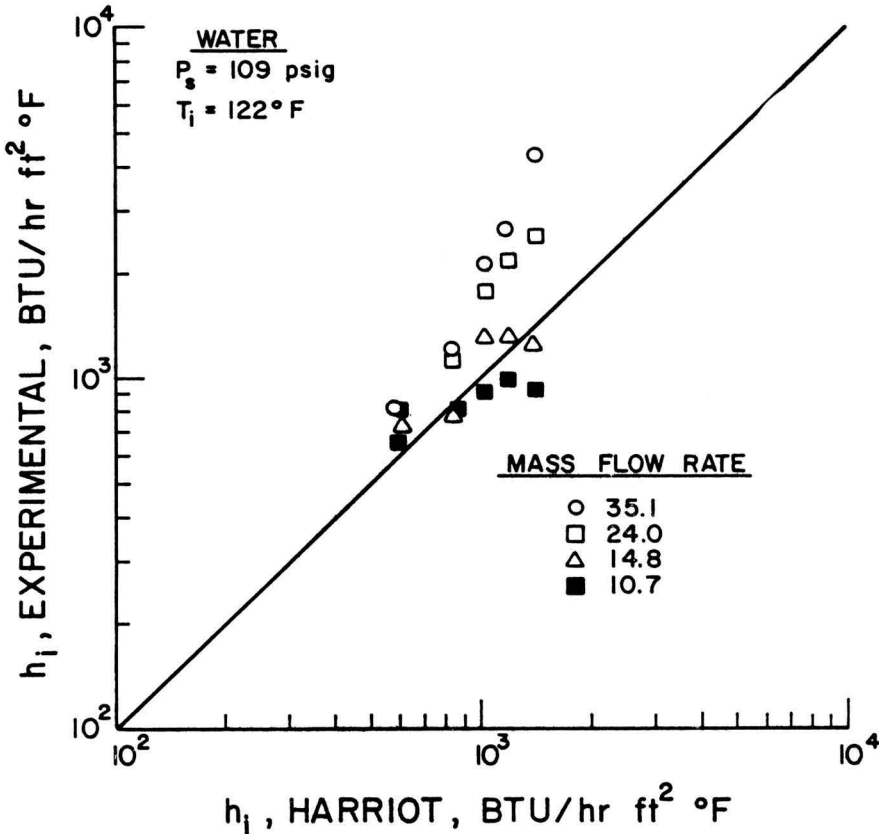


FIG. 1. COMPARISON OF EXPERIMENTAL AND THEORETICAL (PENETRATION THEORY, HARRIOT MODEL) HEAT TRANSFER COEFFICIENTS FOR WATER

SSHE heater (1 BTU/h  $\text{ft}^2 \text{ }^\circ\text{F} = 5.678 \text{ W/m}^2 \text{ K}$ ).

where  $T_b = (T_o + T_i) / 2$ . Figures 1 and 2 show plots of  $(h_i)_{\text{experimental}}$  versus  $(h_i)_{\text{Harriot}}$ , for selected data sets. The 45° line corresponds to  $(h_i)_{\text{exp}} = (h_i)_{\text{Harriot}}$ . Those graphs indicate that at higher blade speeds and higher mass flow rates, the experimental value tends to be greater than the theoretical value. Data corresponding to axial laminar flow ( $W = 10.7$  lb/min and some points at  $W = 14.8$  lb/min for water and all data for soybean extracts) match the Penetration Theory predictions. Figure 1 suggests that data at different mass flow rates show different behavioral patterns: at values of  $h_i$  below approximately 1000 BTU/h ft<sup>2</sup> °F, the coefficient data fall on lines with fairly constant slope. For  $h_i > 1000$ , at high flow rates, there is a shift to regions where  $(h_i)_{\text{exp}} > (h_i)_{\text{Harriot}}$ , whereas at low flow rates, the shift is to regions where  $(h_i)_{\text{exp}} < (h_i)_{\text{Harriot}}$ . This behavior could mean that at high blade speeds the effect of mass flow rate on heat transfer results in (1) lower theoretical values at levels where turbulence (i.e., high flow

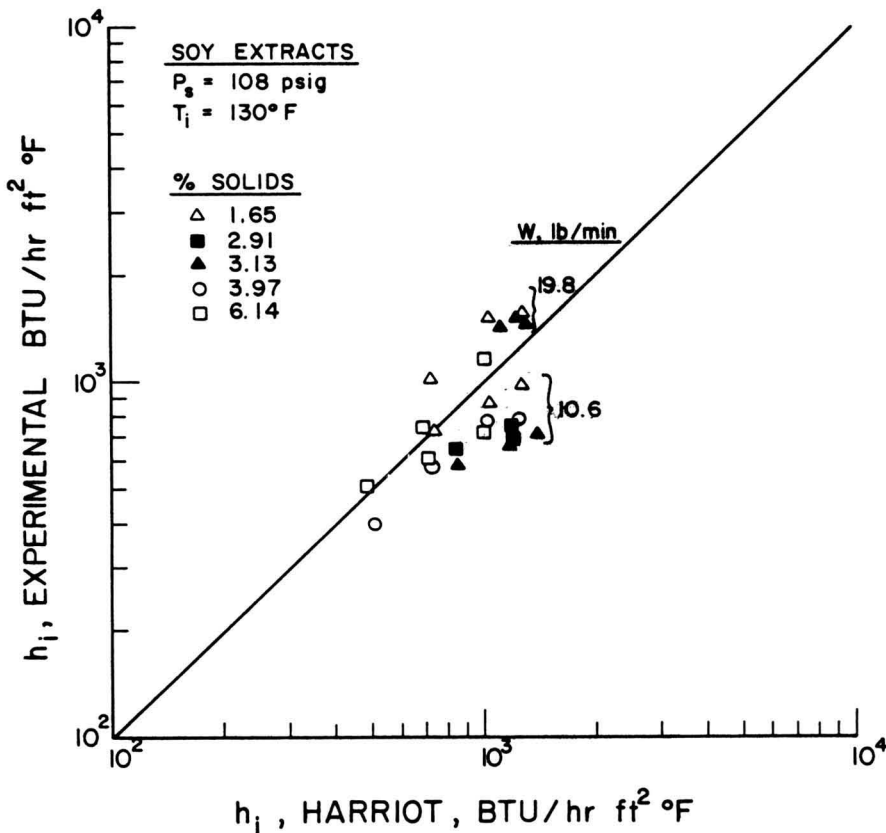


FIG. 2. COMPARISON OF EXPERIMENTAL AND THEORETICAL HEAT TRANSFER COEFFICIENTS FOR SOYBEAN EXTRACTS

rates) plays an important role in the form of convective mechanisms; and (2) an apparent trend of the experimental values to show diminishing or even zero increase with increases in blade speed. In other words, while the Penetration Theory predicts that  $h_i$  will increase for as long as  $N$  is increased, our results suggest that (1) turbulent axial flow becomes more important than scraping after a certain value of  $N$  has been reached, and (2) when the conditions are laminar,  $(h_i)_{exp}$  will not increase after a certain value of  $N$  has been reached. This further indicates the existence of interactions between the axial and rotational forces which affect the heat transfer phenomenon, as was suggested earlier when evaluating the raw data (Cuevas *et al.* 1982).

The data reported in the literature regarding scraped-side coefficients are generally for much lower mass flow rates than was considered here. Since the Penetration model is based on a conduction mechanism, a better agreement between theoretical and experimental values might be expected as the flow becomes more laminar. The possible mass flow rate effects were also noticed by Harriot (1959), who described them as resulting in a "slight increase in the coefficient with flow rate." Therefore, the deviation from theory would depend on the degree of mixing in the system and thus might be correlated with some type of Reynolds number (Harriot 1959). On the other hand, turbulence (caused either by high speed of blade rotation or by high axial flow

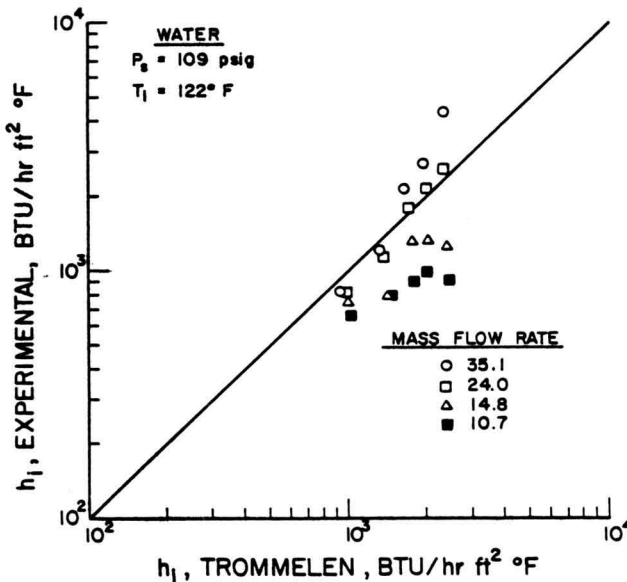


FIG. 3. COMPARISON OF EXPERIMENTAL AND CORRECTED THEORETICAL HEAT TRANSFER COEFFICIENTS FOR WATER

SSHE heater

rate) would promote a better heat transfer and therefore the experimental values should be higher than theoretical predictions, as our results show. In addition, the possibility exists, especially in units with relatively small diameter and at high blade speeds, that some of the material scraped from the walls may be thrown back against the wall again, resulting in lower coefficients of heat transfer (Kool 1958). This phenomenon is noticeable in our data also at the low mass flow rates (Fig. 1).

No significant improvement in the prediction was obtained when the physical properties were evaluated on the basis of the average radial temperature instead of the bulk average temperature. Similarly, Kool's modification of the theory (Eq. 19) did not significantly change the trends in the data (not shown here: see Cuevas-Garcia 1981).

The attempt by Trommelen *et al.* (1971) to improve the Penetration Theory model by introducing a correction factor (based on the Prandtl number) is shown in Figs. 3 and 4 applied to the Contherm SSHE. The inclusion of the correction factor shifts the points to below the 45° line (i.e., to the region where  $(h_i)_{exp} < (h_i)_{theory}$ ). However, the scatter of the points, as well as the behavior which results from blade speed-mass flow rate interactions (discussed earlier), remain essentially the same as was found for the "uncorrected" penetration equation. The failure of a factor based on the Prandtl number to correct the theoretical predic-

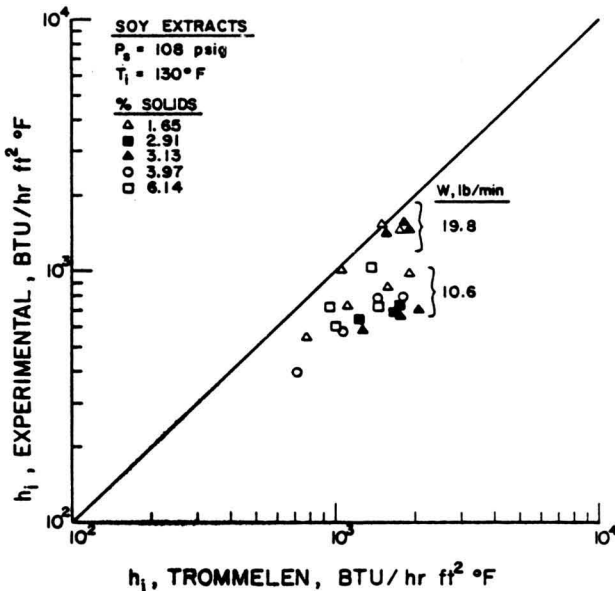


FIG. 4. COMPARISON OF EXPERIMENTAL AND CORRECTED THEORETICAL HEAT TRANSFER COEFFICIENTS FOR SOYBEAN EXTRACTS

SSHE heater

tions for the heat transfer coefficients might indicate that the phenomenon responsible for the discrepancy is not dependent on the physical properties per se.

It may be concluded then that any theoretical approach for describing the heat transfer phenomenon in scraped-surface heat exchangers should explicitly include both  $V_z$  and  $V_\theta$ , the axial and the rotational components of the velocity field. Similar conclusions were arrived at by Ramdas *et al.* (1977) for liquid-full SSHE and by Miyashita and Hoffman (1978) for film-type SSHE units. In both cases, the axial velocity effects, accounted for in the axial Reynold's number, were found to be important.

### Wilson Plots Model

This is a graphical method for analyzing heat transfer data and isolating the contributions of the axial and rotational velocity components to heat transfer (McAdams 1954; Wilson 1915) and is based on the resistance concept described earlier Eq. (9). The working liquid-side resistance ( $1/h_i$ ) is an inverse function of the liquid velocity ( $V$ ), and if the effects of changes in temperature due to changes in velocity are neglected, the product side resistance could be taken as  $f(V)$  alone. Accordingly, a plot of  $1/U$  versus  $1/f(V)$  should give a straight line in cartesian coordinates. Since in the case of scraped-surface heat exchangers there are two nonzero components of the velocity field, the axial ( $V_z$ ) and rotational ( $V_\theta$ ) components,  $h_i$  in the resistance equation can be expressed as:

$$h_i = K V_z^a V_\theta^b D_o/D_i \quad (20)$$

where  $K$ ,  $a$ , and  $b$  are empirical parameters. When working liquids other than water are used a term accounting for composition ( $S^c$ ) can be added to equation 20. The resistance concept (Eq. 9) and the definition of  $h_i$  (Eq. 20) imply that a plot of  $1/U$  versus  $1/V_z^a V_\theta^b S^c$  will be a straight line with  $1/K$  as the slope and  $(1/h_o + 1/h_w)$  as the intercept (where the term  $1/h_w$  is equivalent here to  $x_w D_o/k_w D_L$ ).

To use this concept, the values of  $K$ ,  $a$ ,  $b$  and  $c$  have to be known, or alternatively, determined. Nonlinear regression techniques were used taking Eq. 9 and 20 as the basis. The computer program used was fed data of  $U$  (obtained from the heat transfer Eq. 7 and 8),  $h_o$ ,  $h_w$ ,  $V_z$ ,  $V_\theta$ , and  $S$ , where

$$V_z = \frac{W}{\rho A_f 60} (\text{ft/sec}) \quad (21)$$

and

$$V_{\theta} = \frac{\pi D_t N}{60} \text{ (ft/sec)} \quad (22)$$

where  $\rho$  = working liquid density at  $T_b$ , lb/ft<sup>3</sup>

$A_f$  = annular area for flow, ft<sup>2</sup>

$D_t$  = tube diameter, ft

$N$  = blade speed, RPM

Table 3 shows the values of the empirical parameters,  $K$ ,  $a$ ,  $b$  and  $c$ . Each data set represents a particular combination of  $P_s$ ,  $T_i$ , and working liquid. Within each data set, the data were analyzed separately according to whether conditions were laminar (axial Reynolds number  $Re_a < 1800$ ) or turbulent ( $Re_a > 1800$ ), or the data for both conditions were analyzed together.

The  $K$  values for the combined data or the laminar data (with  $K$  representing  $h_i$  when  $V_z = 1$  ft/s and  $V_{\theta} = 1$  ft/s) are much higher for water (1556-8465) compared to soy extracts (905). This is no doubt due to the effect of solids on the physical properties. When considering individual flow regimes, the  $K$  value is generally smaller for turbulent than for laminar flow. (This does not necessarily mean that  $h_i$  is actually greater for laminar flow than for turbulent flow since other factors also determine the actual magnitude of  $h_i$ .)

For individual data groups ( $P_s$ ,  $T_i$  combinations) the "a" value for laminar data tends to be greater than for turbulent data, while the "b" value is greater for the turbulent than for the laminar set. This implies that the effects of  $V_{\theta}$  on  $h_i$  are greater when the axial flow is turbulent than when it is laminar. Within an individual data group, the sum of squares decreases when the data are subdivided into the laminar and turbulent sets, indicating that there could be different phenomena being exhibited in the heater depending on the state of axial flow.

The suitability of the Wilson plots models is shown in Figs. 5 and 6 using the combined laminar + turbulent flow empirical parameters. Our data indicates substantial deviation from values reported in the literature for various systems, even considering the differences in flow geometries. For pipe flow, the exponent on the axial velocity term ( $a$ ) should be 0.8 for turbulent flow and 0.33 for laminar flow (McAdams 1954). Our values for the combined data were 0.42-0.43 for water, and 0.22 for soy extracts. For the data separated according to flow conditions, the exponents were 0.22-0.8 in the laminar region and 0.25 and 0.33 in the turbulent region. The exponent on the



Table 3. Parameters and Statistics for Wilson Plots Models Obtained by Nonlinear Regression Analysis

Working Liquid	P, (psig)	T, (°F)	Flow Conditions	K	a	b	c	Sum of Squares
Water	109	122	Laminar + Turbulent	1760	0.417	0.443	0	$2.32 \times 10^{-6}$
			Laminar	1556.7	0.360	0.353	0	$4.99 \times 10^{-7}$
			Turbulent	1019.9	0.329	0.625	0	$7.52 \times 10^{-7}$
Water	65	123	Laminar + Turbulent	1658.9	0.431	0.421	0	$2.69 \times 10^{-6}$
			Laminar	8465.2	0.804	0.229	0	$7.01 \times 10^{-7}$
Soy Extracts	108	130	Turbulent	765.4	0.254	0.594	0	$6.14 \times 10^{-7}$
			Laminar	905.5	0.221	0.355	-0.16	$3.88 \times 10^{-6}$

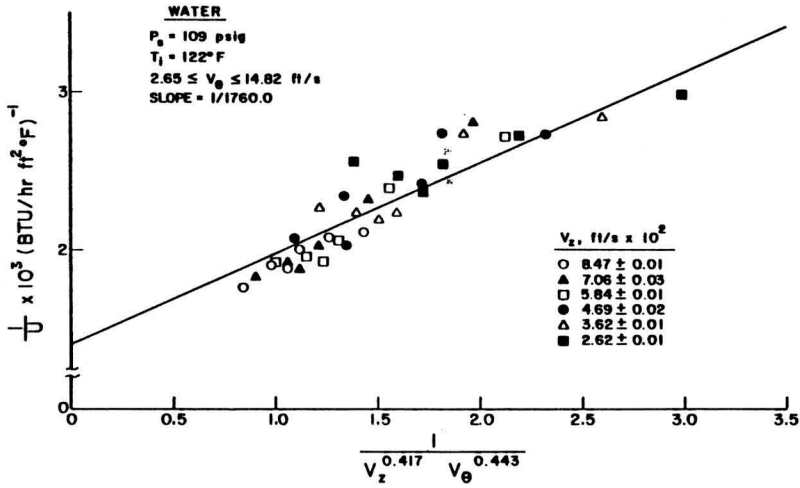


FIG. 5. WILSON PLOT FOR SSHE HEATER FOR WATER

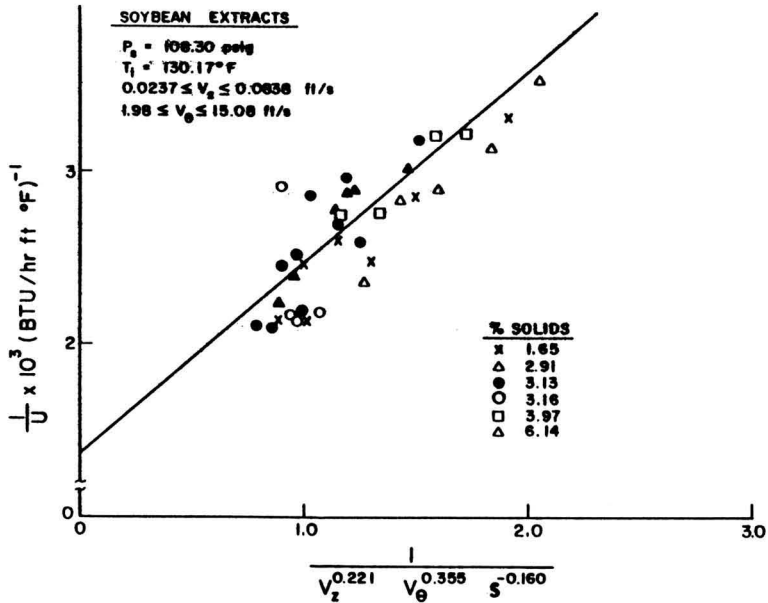


FIG. 6. WILSON PLOT FOR SSHE HEATER FOR SOYBEAN EXTRACTS

rotational velocity term (b) is commonly taken as 0.67 for agitated (batch) vessels (Moo Young and Cross 1969). Our values for the combined data ranged from 0.33-0.44. The deviations may be due to the fact that the physical properties of the liquids (and the effects of operating conditions on those properties) were not considered in the Wilson plots method.

Note that the intercept on both plots for water (Fig. 5) and soybean extracts (Fig. 6) is approximately equal. This is not unexpected since the intercept represents the sum of the wall resistance ( $1/h_w$ ) and steam-side resistance ( $1/h_o$ ) which will be relatively unaffected by the nature of the product on the scraped side.

The correlations obtained from this type of analysis can be used to calculate  $h_i$ . For example, for water at  $P_s = 109$  psig and  $T_i = 122^\circ\text{F}$ ,

$$(h_i)_{Wilson\ Plots} = 1760 V_z^{0.417} V_\theta^{0.443} D_o/D_i \quad (23)$$

A comparison of  $(h_i)_{Wilson}$  versus  $(h_i)_{experimental}$  is shown in Fig. 7. Values toward the lower part of the graph correspond to lower blade speeds. Since both  $(h_i)_{exp}$  and  $(h_i)_{Wilson}$  include, in an explicit manner, the effect of mass flow rate, the data would normally be expected to fall randomly distributed in a region close to the  $45^\circ$  line. However,

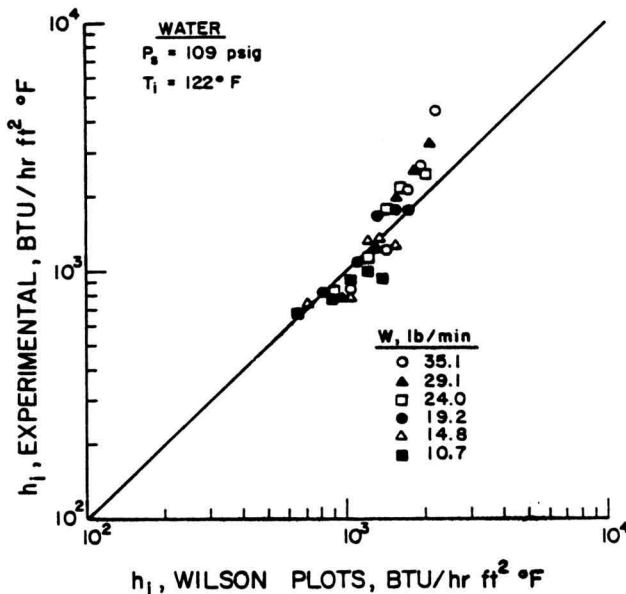


FIG. 7. COMPARISON OF EXPERIMENTAL VERSUS PREDICTED HEAT TRANSFER COEFFICIENTS USING WILSON PLOTS FOR WATER

it can be observed that deviations from the line (which result in  $(h_i)_{exp} > (h_i)_{Wilson}$ ) resulted at higher blade speeds. One possible explanation is that the coefficient obtained from the Wilson plots include both  $V_z$  and  $V_\theta$  in an explicit way, whereas the experimental  $h_i$  includes only  $V_z$  explicitly, with  $V_\theta$  implicit in  $T_o$ , the outlet temperature of the heater, which in turn affects  $\Delta T_{ln}$  in Eq. (7). Another possibility is that in the Wilson plots method the effect of changes in temperature due to changes in the rotational velocity are neglected, i.e., changes in physical properties due to changes in temperature profiles. Therefore, the product-side resistance of heat transfer might not be a function of the velocity field alone.

On the other hand, a plot of  $h_i$  from the Wilson method versus  $h_i$  from the Penetration model shows a different behavior, as Fig. 8 indicates. The exponent "b" used for  $V_\theta$  was 0.44, which is close to the exponent for  $N$  used in the Penetration Theory and, therefore, it

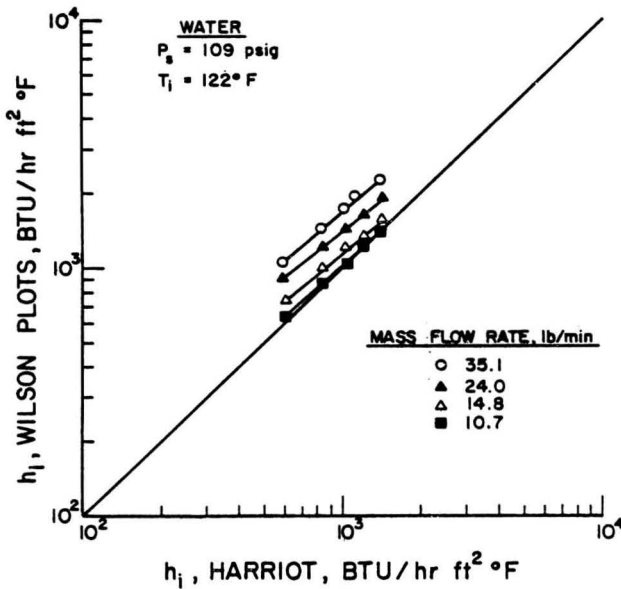


FIG. 8. COMPARISON OF HEAT TRANSFER COEFFICIENTS PREDICTED USING WILSON PLOTS VERSUS PENETRATION THEORY (HARRIOT MODEL) FOR WATER

was expected that the data would fall on lines close to the  $45^\circ$  line. However, Fig. 8 shows this to be true only at low (axial laminar) flow conditions. This is significant since it indicates that, as axial flow gets more laminar in nature, convective forces are less important than conduction mechanisms, and hence better agreement with

the Penetration Theory might be expected. Houlton's (1944) water data also showed a similar phenomenon, in that the experimental  $h_i$  values fell on a line parallel to, and above, the 45° theoretical line.

### CONCLUSIONS

The Penetration Theory has been frequently used to explain the heat transfer phenomena in scraped-surface heat exchangers. However, this study shows that only at laminar (axial) flow conditions, where conduction mechanisms become more important than convection, do the penetration model predictions come close to the experimental data. Axial velocity ( $V_z$ ) and its interactions with rotational velocity ( $V_\theta$ ) were important, especially at high values of either variable. Solids content (S) of the model liquid food also had an effect. All these factors could be accounted for explicitly by using the Wilson Plots technique. The model derived from this analysis was of the form

$$h_i = K V_z^a V_\theta^b S^c D_o/D_i \quad (24)$$

where  $K = 1709$ ,  $a = 0.42$ ,  $b = 0.43$ ,  $c = 0$  for water and  $K = 905.5$ ,  $a = 0.22$ ,  $b = 0.33$ ,  $c = -0.16$  for soy extracts for the range of heater temperatures of 120–300° F.

### ACKNOWLEDGMENTS

This research forms part of a doctoral dissertation submitted by RC to the Graduate College, University of Illinois, Urbana, and was supported in part by the Agricultural Experiment Station, University of Illinois, and by Research Corporation, New York.

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# OPTIMIZATION OF PARAMETERS FOR PACKAGING OF FRESH PEACHES IN POLYMERTIC FILMS<sup>1</sup>

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Received for Publication February 13, 1981  
Accepted for Publication July 9, 1981

## ABSTRACT

*Fresh produce packaged in polymeric films represents a dynamic respiration-permeation model. Control of equilibrium concentrations of respiratory gases is an important variable in extending the shelf life if critical vectors of quality deterioration and transport properties of packaging materials are known.*

*Fresh peaches were stored at  $5 \pm 1^\circ \text{C}$  under various modified atmospheres for a period of up to thirty days. Samples were removed at ten day intervals for chemical and physical analyses of vulnerable quality factors. Parameters evaluated include soluble solids, titratable acidity, and texture and profile parameters such as hardness, elasticity, and cohesiveness.*

*An internal atmosphere of 10 to 15%  $\text{O}_2$  and 15 to 25%  $\text{CO}_2$  inside the package provided better retention of quality attributes such as hardness and cohesiveness than any other treatments. Springiness did not provide any significant index of quality. Soluble solids decreased over time as did the amount of acid present in the fruit. Anaerobic fermentation did not occur under any storage conditions.*

*Subsequent to establishing the optimal gaseous concentrations, respiration rates were determined as a function of time and gas composition. Permeability of polymeric films were determined using ASTM method. Analytical equations were employed to optimize packaging parameters or to estimate transient and equilibrium gas concentrations in polymeric packages. Equations were set up to estimate transient and steady state time values for oxygen and carbon dioxide concentrations inside a package. This approach is applicable in extending the storage quality of other fresh produce.*

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<sup>1</sup>Technical contribution No. 1906 of the South Carolina Agricultural Experiment Station, Clemson University, Clemson, SC 29631.



## INTRODUCTION

It has been demonstrated that surrounding gas composition can affect respiration rate and quality of harvested produce. This concept has been successfully exploited in extending the quality of fresh produce during storage and is the subject of numerous research articles and reviews (Kidd and West 1930; McGill *et al.* 1966; Lebermann 1868; Wang *et al.* 1971; Singh *et al.* 1972 and Brecht 1980). Gas composition around the produce is modified/controlled through regeneration of the ambient air with specific concentrations of O<sub>2</sub> and/or CO<sub>2</sub>. Each commodity has optimum levels of various gas concentrations for maximum storage life. However, most of the work reported on modified/controlled atmosphere storage of produce has been on bulk storage practices. The equipment and facilities for such a system might be a limiting factor for small packers. Also, the growing practice of overwrapping produce requires considerations related to quality attributes, moisture loss, and appearance as a function of packaging parameters.

Developments in packaging materials and technology over the past decade have suggested that polymeric films may be tailored, within limits, which will allow the produce to establish its own optimal modified atmosphere. The equilibrium gaseous concentrations developed within the package can be utilized to prolong the acceptable shelf life of produce.

In an attempt to predict concentrations of respiratory gases in polymeric film packages of produce, Jurin and Karel (1963) developed graphical solutions. This approach when applied to packaged bananas gave good correlation with experimentally determined gas concentrations (Karel and Go 1964). Henig (1972) developed numerical solutions of two simultaneous first-order ordinary differential equations representing changes in concentrations of O<sub>2</sub> and CO<sub>2</sub> within polymeric packaging systems of produce. The computer aided finite difference technique was employed for the determination of equilibrium and steady state gas concentrations. However, since packaging parameters are not explicitly included in the solution, their optimization is achieved through a trial and error technique. Assuming that the rate of O<sub>2</sub> consumption or the rate of CO<sub>2</sub> production is influenced by O<sub>2</sub> and CO<sub>2</sub> concentration in surrounding atmosphere, Hayakawa *et al.* (1975) derived analytical formulae from ordinary differential equations for estimating transient and steady state gas concentrations in a fresh produce package. Their solutions produced fair agreement between mathematical and experimental time values for O<sub>2</sub> exchange while great differences were found in the case of CO<sub>2</sub> values.

The objective of this paper is to report an approach for optimization of parameters for packaging of produce in permeable materials during constant respiration-rate period. Attempts have been made to integrate produce variables such as respiration rate, weight, and optimum gaseous composition requirements with packaging parameters like permeability, surface area and free volume into a set of analytical equations. These simple equations can be solved to provide prediction of transient and equilibrium time values for O<sub>2</sub> and CO<sub>2</sub> concentrations within a produce package or, conversely, can be used to design a package which will help set up a known gaseous composition.

### THEORETICAL CONSIDERATIONS

A produce packaged in a permeable film is a dynamic system and involves two simultaneous processes, respiration and permeation. Oxygen is continually consumed and carbon dioxide is evolved. As a result, a gradient is set up between the outside and inside of a package and O<sub>2</sub> starts permeating into the package, while the flux of CO<sub>2</sub> simultaneously occurs in the opposite direction. The rate of gas permeation depends on structure of the polymeric film, thickness, area, temperature, and concentration gradient between external and internal atmospheres. The produce parameters affecting the rate of permeation include weight, respiration rate, and free volume created within the package.

The respiration rate is an important characteristic when analytical determinations are being made on fresh produce packages. It has been shown that respiration rate curves for tomatoes and bananas contain a linear rate portion and an exponential rate portion when change in O<sub>2</sub> concentration was plotted over time. These results were obtained when CO<sub>2</sub> was absorbed. When CO<sub>2</sub> was allowed to accumulate, its respiration curve showed two linear segments when plotted over time (Hayakawa *et al.* 1975; Henig 1972). Similar respiration patterns were observed in this investigation for peach fruits.

The permeation of gas across a polymeric film can be represented by mass balance of the gas components. In a fresh produce system the mass balance can be depicted mathematically by the following two ordinary differential equations:

$$\frac{dy}{dt} = \frac{SK_y}{V} (y_a - y) - \frac{W}{V} R_y \quad (1)$$

$$\frac{dz}{dt} = \frac{SK_z}{V} (z_a - z) + \frac{W}{V} R_z \quad (2)$$

Analytical solutions of the above equations by the Laplace transformation technique provide a method for estimation of transient and steady state gaseous composition for cases where the rates of O<sub>2</sub> consumption and CO<sub>2</sub> production are influenced by O<sub>2</sub> and CO<sub>2</sub> concentrations around the produce. However, great differences have been reported between mathematical and experimentally determined time values. This has been ascribed to certain assumptions made (Hayakawa *et al.* 1975).

### Derivation of Formulae

Rewriting Eq. (1) for constant respiration rate of oxygen:

$$\frac{Vdy}{dt} = SK_y (y_a - y) - WR_y$$

For equilibrium conditions:

$$\frac{dy}{dt} = 0, y = \hat{y}$$

$$\text{Then, } SK_y (y_a - \hat{y}) = WR_y$$

$$\hat{y} = y_a - \frac{W}{SK_y} R_y \quad (3)$$

Also, the solution of ordinary differential Eq. (1) with initial conditions:

$$y(0) = y_a \text{ at } t = 0 \text{ gives:}$$

$$y[t] = y_a - \frac{W}{SK_y} (1 - e^{-SK_y t/V})$$

$$\text{and, } \lim_{t \rightarrow \infty} y(t) = y_a - \frac{WR_y}{SK_y}$$

Hence:

$$[y(t) - \hat{y}] = (y_a - \hat{y}) e^{-SK_y t/V}$$

$$\text{or, } y(t) = \hat{y} + (y_a - \hat{y}) e^{-SK_y t/V} \quad (4)$$

Similarly for carbon dioxide:

$$\hat{z} = z_a + \frac{W}{SK_z} R_z \quad (5)$$

$$\text{and } z(t) - \hat{z} = (z_a - \hat{z}) e^{-SK_z t/V}$$

$$\text{or, } z(t) = \hat{z} + (z_a - \hat{z}) e^{-SK_z t/V} \quad (6)$$

Equations (3) through (6) can be used to predict equilibrium and transient state concentrations of  $O_2$  and  $CO_2$  at a constant temperature.

Inspection of Eq. (3) and (5) indicate that equilibrium concentration is independent of time. It is understandable, since the time of equilibrium will be dependent upon the free volume inside the package. Time required for equilibrium to be reached can be obtained from Eq. (4) and (6). These equations can be graphically represented for a given temperature as shown in Fig. 1.

Similar solutions can be obtained for exponential rate portion of the respiration curve. However, the optimal composition for quality retention in peaches was found to be in the linear rate region of the respiration curve and solutions were obtained for this region only.

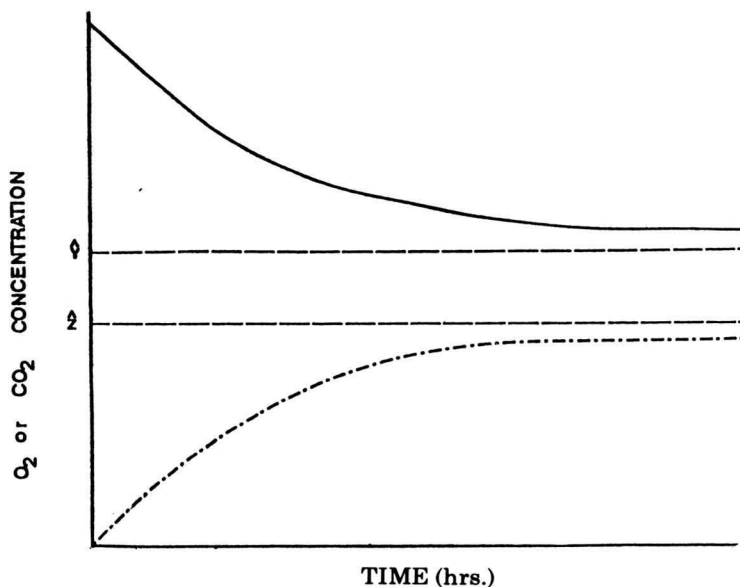


FIG. 1. A GRAPHICAL REPRESENTATION OF ANALYTICAL EQUATIONS FOR CALCULATION OF TRANSIENT AND EQUILIBRIUM  $O_2$  AND  $CO_2$  CONCENTRATIONS

## EXPERIMENTAL

Freshly picked Crest Haven peaches were obtained from the Clemson University Horticulture Department. The peaches were defuzzed, chilled, and held at  $5 \pm 1^\circ\text{C}$  prior to the start of the experiment.

### Modified Atmosphere Studies

The modified atmospheres were produced by evacuating storage chambers (18 cm dia  $\times$  13 cm long, plexiglass) and then regenerated to the desired gas concentrations manometrically. The modified atmosphere initial gas concentrations studied are included in Table 1.

Table 1. The effect of modified atmospheres on the hardness<sup>a</sup> of Crest Haven peaches

Treatment Time (Days)	Control	Hardness (KgF)				
		%O <sub>2</sub> : %CO <sub>2</sub> :	1 5-10	2 10-15	3 10-15 15-25	4 5-10 25-30
0	22.45		22.45	22.45	22.45	22.45
10	24.85		20.05	16.05	24.85	17.84
20	11.45		11.65	22.43	31.81	16.65
30	7.84		14.25	9.85	22.43 <sup>b</sup>	15.35
Treatment mean	14.71		15.31	16.11	26.36 <sup>c</sup>	16.61

<sup>a</sup>Values except means are averages of triplicate determinations

<sup>b</sup>Significantly different at  $\alpha = .05$  by Duncans multiple range test

<sup>c</sup>Not significantly different from determination at harvest by least square means at  $\alpha = 0.05$

The internal atmosphere was analyzed in a gas partitioner (Fisher Hamilton Model 29 with a Linear Instrument Corp. automatic digital integrator model CRS-204) for monitoring the concentrations of oxygen and carbon dioxide.

### Quality Analysis

Peaches were analyzed initially and at ten day intervals for physical and chemical properties. Titratable acidity was measured with 10 g of peach fruit blended with 50 ml of distilled water and titrated with 0.1 N NaOH using phenolphthalein as the indicator. Soluble solids were measured by use of a Bausch & Lomb refractometer (model ABBL-3L).

Texture profile parameters were measured on an Instron machine. A plug (28 mm  $\times$  10 mm) from each peach was used to produce a Gen-

eral food Texture Profile. The plug was compressed to 2.5 mm in the "first bite" with a crosshead speed of 50 mm/min. The chart speed of 200 mm/min was maintained to give a 4-fold magnification to force-distance curves. After the crosshead returned to the starting position, the plug was again compressed to 2.5 mm for the "second bite." Parameters of hardness, springiness, and cohesiveness were obtained from the textural profile thus generated. The peak force at the end of the "first bite" is hardness. The distance that the peach tissue recovers after the "second bite" is springiness. The ratio:  $A_2/A_1$ , is cohesiveness (Bourne 1968, 1974).

### Respiration Studies

Respiration chambers used were GasPack jars with modified lids fitted with sampling ports. Approximately 500 grams of peach fruit were placed in each chamber. The glass chambers were 12.5 dia  $\times$  21 cm with an average volume of 2500 ml.

Respiration rates were modified with two series of experiments. In the first set,  $CO_2$  was allowed to accumulate within the chamber. In the second set,  $CO_2$  was continually being absorbed by 40 ml of 15% KOH placed in the chamber. The two sets of experiments were carried out to determine the effect, if any, of  $CO_2$  concentration on the respiration rate of peach fruit.

### Model Package

Peaches were packaged in several polymeric film bags and also in foam trays overwrapped with permeable films. Rubber septums were glued to the bottom of the trays to allow sampling of the internal atmosphere. Initial gas concentration, weight, and free volume inside the package were recorded. The free volumes of the model packages were determined by two methods. The first method utilized injection of a known volume of 99% pure  $CO_2$  into the model package and from the change in  $CO_2$  concentration free volume was calculated. The second method consisted of filling the package with a known volume of water. Gas transmission rates of polymeric film were obtained by ASTM method D-1434-75 (ASTM 1979).

The model packages were stored at  $5 \pm 1^\circ C$  in an environmental chamber with a relative humidity of 85 to 90%. Changes in internal gas concentrations of each package with time were monitored at pre-determined intervals.

### Statistical Analysis

Duncans Multiple Range test was used to determine differences between treatment means. Least Square means were used to determine differences by day and treatment determinations. Predicted gas concentrations were obtained by using General Linear Model technique (SAS 1979).

## RESULTS AND DISCUSSION

The effect of various modified atmospheres on the hardness of peach fruit is shown in Table 1. Hardness, cohesiveness, and springiness were evaluated because they are an index of textural quality and they decrease during ripening. Hardness decreased in peaches over time in all treatments except for peaches stored under gaseous conditions containing 10 to 15% O<sub>2</sub> and 15 to 25% CO<sub>2</sub> (Table 1). Under these conditions peaches developed no significant loss in hardness after 30 days. This might be due to a reduced rate of enzyme activity causing a slowing of metabolic solubilization of pectin (Brecht 1980; Kader 1980). Cohesiveness decreased over time in a similar manner as hardness. This is expected since hardness is measured by the peak height and cohesiveness is obtained by the ratio of areas under the peaks. However, springiness did not show any significant change due to treatment and results are not shown here. Figure 2 shows representative texture profiles of peach fruit at 0 and 30 days for treatments 3 and 4.

Table 2. The effect of modified atmospheres on titratable acidity<sup>a</sup> of Crest Haven peaches

Treatment Time (Days)	Titratable Acidity Meq NaOH/10 gm					
	Control	%O <sub>2</sub> :	1	2	3	4
		%CO <sub>2</sub> :	15-18	10-15	10-15	5-10
		5-10	10-15	15-25	25-30	
0	1.275	1.275	1.275	1.275	1.275	1.275
10	1.193	1.263	1.125	1.055	1.173	1.173
20	1.193	1.133	1.270	1.126	1.043	1.043
30	1.053	<u>1.047</u>	<u>0.987</u>	<u>1.133</u> <sup>b</sup>	<u>1.005</u>	<u>1.005</u>
Treatment mean	1.1.47	1.146	1.127	1.105	1.073	1.073

<sup>a</sup>Values except means are averages of triplicate determinations

<sup>b</sup>Significantly different from other determinations at given time interval by least square means at  $\alpha = 0.05$

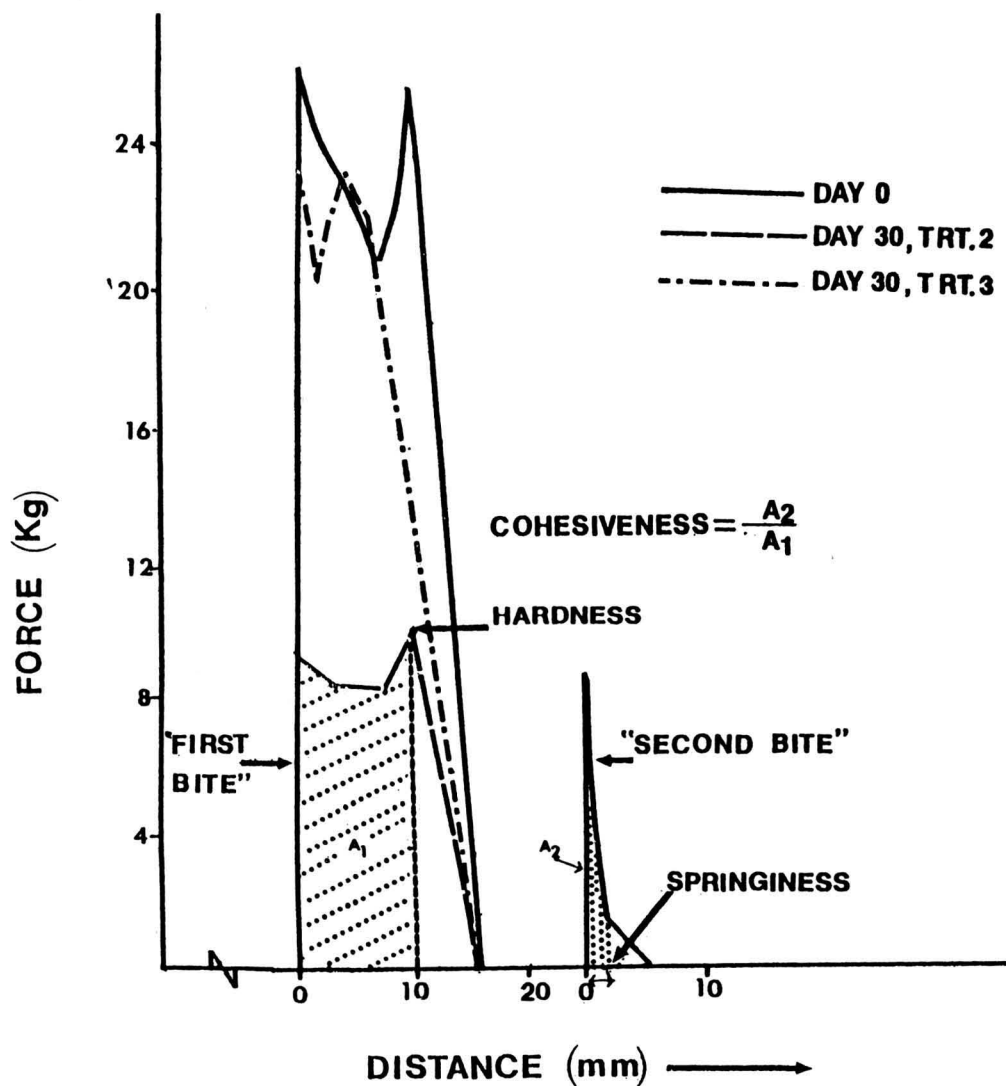


FIG. 2. TYPICAL FORCE-DISTANCE CURVES FOR GENERAL FOOD TEXTURE PROFILE ON CREST HAVEN PEACHES AT DAY 0 AND DAY 30 FOR TREATMENTS 2 AND 3.

Soluble solids are used as an index of total sugars in fruits and usually decrease during ripening. It has been shown that modified atmospheres do not affect total sugar content in peach and apricot fruit (Wankier *et al.* 1970). Similar results were obtained in this investigation. The soluble solid levels were not significantly affected by



storage treatments and all treatments showed a decrease over time. It appears that the enzyme systems responsible for the breakdown of sugars are not affected by various gas concentrations (Wankier *et al.* 1970).

Typically, titratable acidity in fruits decreases as ripening progresses and a similar trend was observed in the present study (Table 2). However, after 30 days, treatment 3 had the highest retention of titratable acidity. This would indicate that alterations in metabolism were induced by treatment 3 which provided a better retention of acids after 30 days (Do and Salunkhe 1975). However, biochemical changes occurring under storage conditions were not investigated in these experiments.

Visual quality analysis was also performed on peach fruit after storage treatments. Initial and after-storage quality changes were photographed and compared for internal and external quality. These results, along with organoleptic evaluation showed that treatment 3 gave the best retention of quality attributes after 30 days of storage.

From physical and chemical considerations treatment 3 (10 to 15% O<sub>2</sub>, 15 to 25% CO<sub>2</sub>) provided the best retention of textural and organoleptic quality attributes. The gaseous composition of treatment 3 appeared to be optimal in reducing metabolic processes of ripening in Crest Haven peaches, thereby extending the quality attributes.

Preliminary studies indicated negligible influence of surrounding carbon dioxide concentrations on the rate of oxygen consumption by peach fruits. Respiration characteristics were thus evaluated in presence of accumulating CO<sub>2</sub>.

A representative respiration plot, the percentage of O<sub>2</sub> and CO<sub>2</sub> concentration with time, is shown in Fig. 3. Inspection of this figure reveals that the respiration process can be divided into a linear rate and an exponential rate region before it asymptotically approaches a constant value. Similar results have been reported for other produce systems (Henig 1972; Hayakawa *et al.* 1975). The point of inflection in peaches occurs at around 5% for O<sub>2</sub> and at 20% for CO<sub>2</sub>. Since the optimal quality retention in peach fruit was found to occur in the range of 10 to 15% O<sub>2</sub> and 15 to 25% CO<sub>2</sub>, respiration rates were analyzed in the linear region only. Exponential region was fitted, by nonlinear regression analysis of experimental data, to the equation of the form  $\% O_2 = \alpha + \beta e^{-\alpha t}$  with good agreement (results not shown). Regression analysis of data on O<sub>2</sub> and CO<sub>2</sub> concentrations in the linear region using General Linear Model (SAS 1979) showed excellent fit and regression curves thus obtained are also shown in Fig. 3. The percent respiration rates were multiplied by the free volume and divided by the weight to obtain respiration rates in cc/h/kg. Values obtained for

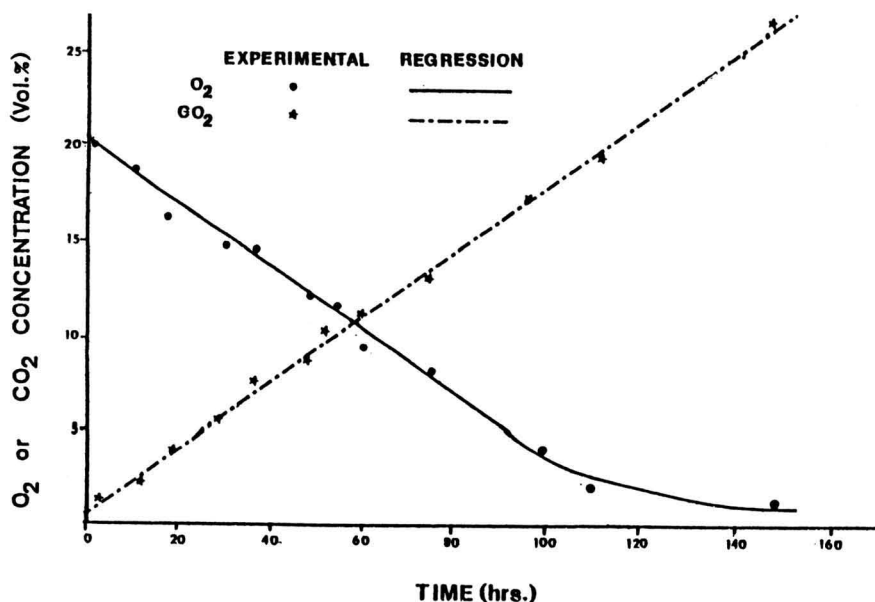


FIG. 3. RESPIRATION OF FRESH PEACH FRUIT SHOWING TRANSIENT OXYGEN AND CARBON DIOXIDE CONCENTRATIONS OVER TIME

Table 3. Respiration rates of peach fruit for O<sub>2</sub> consumption and CO<sub>2</sub> production

Observations	Weight (kg)	Volume (cc)	O <sub>2</sub> Rate (%O <sub>2</sub> /h)	O <sub>2</sub> Rate/Weight (cc/h/kg)	CO <sub>2</sub> Rate (%CO <sub>2</sub> /h)	CO <sub>2</sub> Rate/Weight (cc/h/kg)
1	0.5246	1964	0.2094	7.84	0.2018	7.55
2	0.5117	1987	0.1923	7.47	0.1835	7.124
3	0.4170	2075	0.1628	8.10	0.1597	7.95
Average	0.48443	2088.6	0.1882	7.80	0.1817	7.54

three different runs are shown in Table 3. The values indicate that consumption of O<sub>2</sub> and evolution of CO<sub>2</sub> is nearly equimolar and that the respiration quotient is close to unity (i.e. moles of CO<sub>2</sub> evolved equals moles of O<sub>2</sub> consumed). These rates were used for solutions of analytical equations in estimating the equilibrium and time concentration values of O<sub>2</sub> and CO<sub>2</sub> inside a polymeric film package of peach fruits.

A point to remember is that the time for respiration curves to transform from linear to exponential region is regulated by the weight of produce and free volume inside the package.

The optimal gaseous concentrations for maximum quality retention and respiration rates data were utilized to test the reliability of formulae derived in the present investigation and to optimize the packaging parameters.

In order to develop retail size packages of suitable volume and surface areas which would maintain optimal gaseous composition (10 to 15% O<sub>2</sub>, 15 to 25% CO<sub>2</sub>), it becomes apparent that the polymeric film to be used should have a lower transmission rate for CO<sub>2</sub> than for O<sub>2</sub>. Gas transmission rates for a range of polymeric films (Modern Packaging Encyclopedia 1976) with required gas transmission rates for achieving optimal gaseous compositions are listed in Table 4. It is obvious that CO<sub>2</sub> transmission rates are anywhere from 2 to 10 times as high as those for O<sub>2</sub>. The higher values for CO<sub>2</sub> are attributed to its decreased viscosity molecular diameter and higher solubility in polymeric materials (Stannett 1968). This indicates that slow respiring systems whose optimal requirements for concentrations of CO<sub>2</sub> is higher than O<sub>2</sub>, cannot use only the inherent properties of polymeric films to set up both of the concentrations. However, the optimal gas concentration for one of the components is possible. If the optimal level of CO<sub>2</sub> is below that of O<sub>2</sub> then polymeric films alone can be used to establish the desired conditions.

To test the applicability of the derived formulae for predicting the gaseous composition after certain time intervals, test packages were developed and their parameters are listed in Table 5. Time values for O<sub>2</sub> and CO<sub>2</sub> were calculated using Eq. (4) and (6). Calculated values are shown in Table 5. Good agreement, within experimental error, was found between the calculated and experimental values as shown in Fig. 5. The low permeable films did not obtain equilibrium concentrations over time. These results were also obtained by solution of analytical equations. Sample calculations follows:

Package Type: Super-L-Bag

$$S = 0.1179 \quad W = 0.2059 \quad V = 2,340$$

$$R_y = 7.84 \quad R_z = 7.55$$

Equilibrium O<sub>2</sub> concentration from Eq. (3):

$$\hat{y} = 0.207 - \frac{(0.2059)(7.84)}{(0.1179)(166.6)} = 0.1248 = 12.48\%$$

Table 4. Gas transmission rates to obtain required gaseous composition and average values for various polymeric films

Package Parameters		GAS TRANSMISSION RATES													
		Required For				Average Values (cc/hr-m <sup>2</sup> -atm at 73°F) <sup>1</sup>									
		(10-15%O <sub>2</sub> )				(15-25%CO <sub>2</sub> )		1		2		3		4	
W	S	R <sub>y</sub>	R <sub>z</sub>	K <sub>y</sub>	K <sub>z</sub>	K <sub>y</sub>	K <sub>z</sub>	K <sub>y</sub>	K <sub>z</sub>	K <sub>y</sub>	K <sub>z</sub>	K <sub>y</sub>	K <sub>z</sub>	K <sub>y</sub>	K <sub>z</sub>
0.2	0.12	7.8	7.6	158	63	2	3	3	3	3	30	10	35	229	573

- 1 = Cellophane, lacquered
- 2 = Nylon
- 3 = Ethylene vinyl acetate
- 4 = Ionomer

<sup>1</sup>Modern Packaging Encyclopedia (1976)

Table 5. Parameters and results of analytical and experimental determination on model packages of peach fruits

Parameters	PACKAGE TYPES				
	Bags		Film Overwraps on Foam Trays		
	Super-L-Bags*		Super-L-Film*	Barrier Bag*	Polyolefin Film*
W	0.2059	0.2123	0.3205	0.2319	0.3062
R <sub>y</sub>	7.84	7.84	7.84	7.84	7.84
R <sub>z</sub>	7.55	7.55	7.55	7.55	7.55
S	0.1179	0.1137	0.0373	0.0335	0.0293
V	2.340	2.320	553.9	439.6	614.4
K <sub>y</sub>	166.67	166.67	166.67	0.104	0.0570
K <sub>z</sub>	200.0	200.0	200.0	5.54	0.2850
y (%)	12.48	11.92	—	—	—
z (%)	6.62	7.05	—	—	—
t	96.0	108.0	20.0	10.0	10.0
Analt.: O <sub>2</sub> (%)	15.99	15.55	—	—	—
CO <sub>2</sub> (%)	4.12	4.61	—	—	—

\*Cryovac Division, W. R. Grace & Co., Duncan, S.C.

O<sub>2</sub> concentration after 96 h, from Eq. (4):

$$y(96) = 0.1248 + (0.207 - 0.1285) e^{\frac{-(0.1179)(166.6)(96)}{2,340}} = 15.99\%$$

Similarly, equilibrium CO<sub>2</sub> concentration from Eq. (5):

$$z = 0.0003 + \frac{(0.2059)(7.55)}{(0.1179)(200)} = 0.0662 = 6.62\%$$

And CO<sub>2</sub> concentration after 96 h from Eq. (6):

$$\begin{aligned} z(96) &= 0.0662 + (0.0003 - 0.0662) e^{\frac{-(0.1179)(200)(96)}{2,340}} \\ &= 0.0412 = 4.12\% \end{aligned}$$

Using a constant respiration rate for O<sub>2</sub> and CO<sub>2</sub> a computer program was developed (Fig. 4) to predict the time values for gaseous

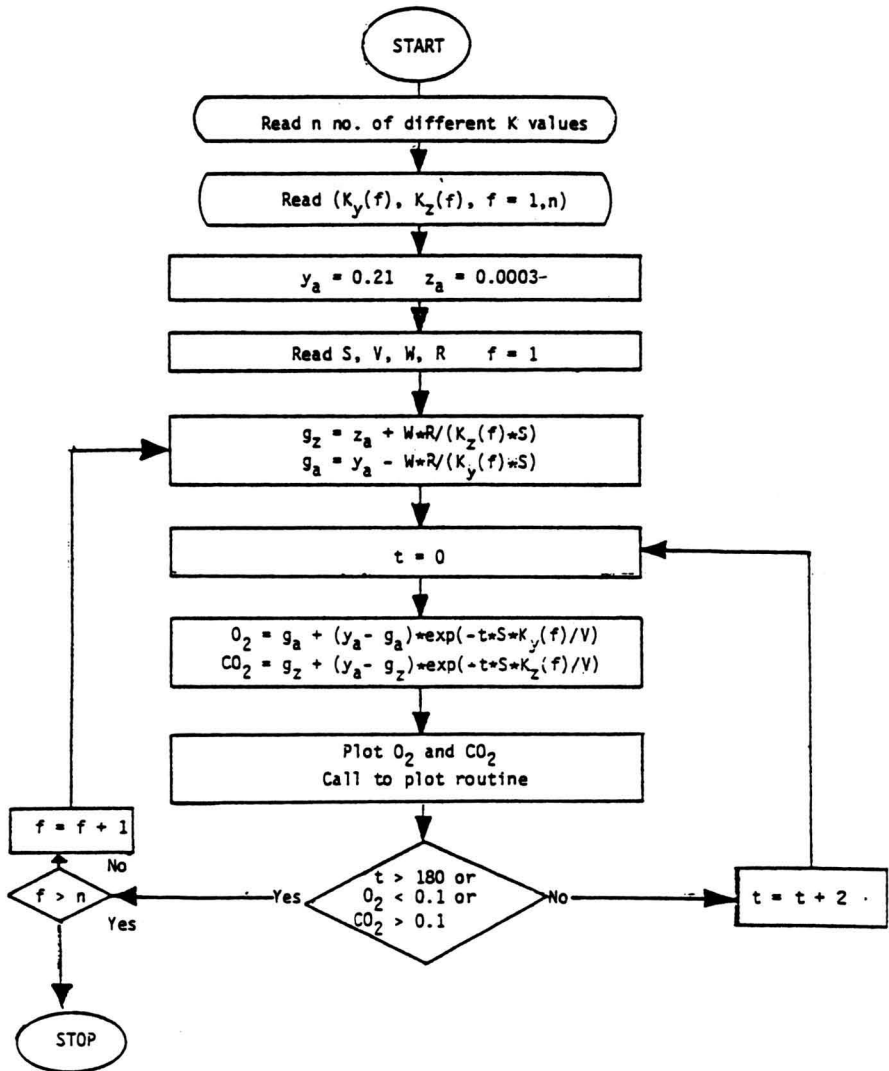


FIG. 4. COMPUTER FLOW CHART FOR CALCULATION OF TRANSIENT AND STEADY STATE GAS CONCENTRATIONS

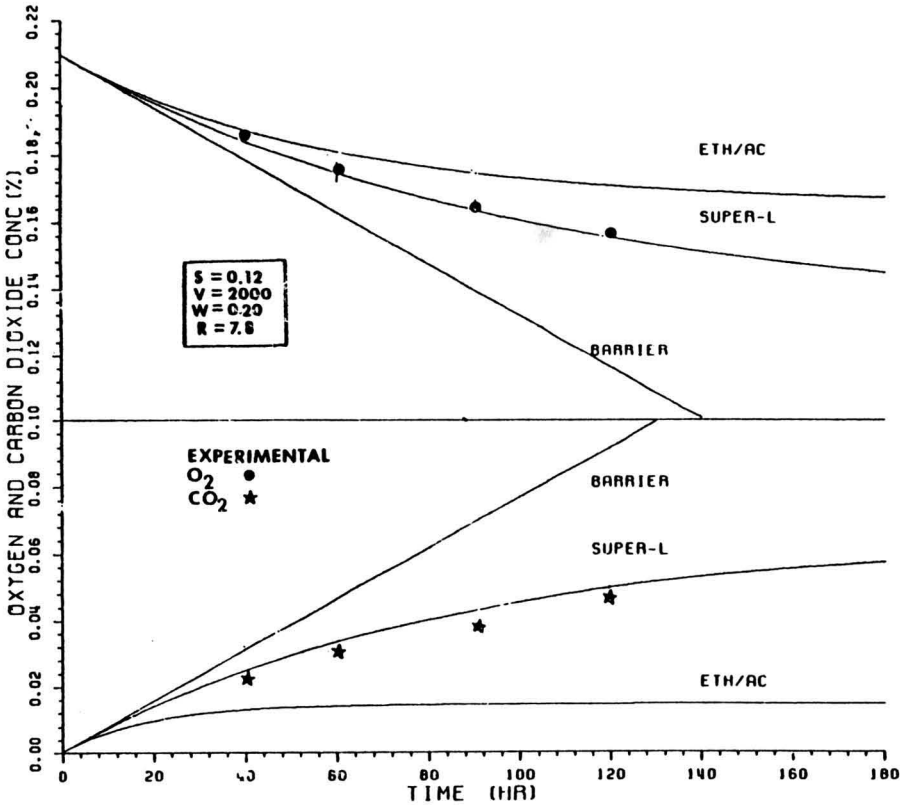


FIG. 5. COMPUTER-PREDICTED OXYGEN AND CARBON DIOXIDE CONCENTRATION CURVES FOR FILMS WITH VARYING TRANSMISSION RATES

composition. Actual and predicted values for different films and for given package parameters were calculated and are plotted in Fig. 5.

The derived equations worked extremely well in predicting the internal composition. This is a valuable technique and can be extended to other produce systems for setting up and predicting time values for various permeating gases.

### CONCLUSION

Simple analytical formulae have been developed in the present investigation for simulating transient and equilibrium state gas concentrations of produce packaged in polymeric films. These equations

can also be solved for optimization of packaging parameters since they are explicitly included in the formulae.

The modified atmosphere concentrations of gas (10 to 15% O<sub>2</sub> and 15 to 25% CO<sub>2</sub>) provided better retention of vulnerable quality factors in peach fruit than other treatments studied. This information, along with respiration rate data, was utilized to design retail size packages, wherein respiration-permeation dynamics would equilibrate to the optimal gaseous composition. Oxygen and carbon dioxide transmission rate requirements through films were calculated using analytical formulae. In the absence of any commercially available polymeric film meeting the calculated O<sub>2</sub> and CO<sub>2</sub> transmission rates, optimum packages could not be created. However, the validity of derived equations was checked by developing retail packages of various polymeric films having different O<sub>2</sub> and CO<sub>2</sub> transmission rates. There is a good agreement between experimentally determined time values for concentrations of oxygen and carbon dioxide and those calculated using analytical formulae. A computer program was also developed for calculation of transient and steady state composition of gases for packages of given dimensions and permeability and filled with produce of known weight and respiration rate.

The approach used in this paper is equally applicable to other produce systems. The results clearly indicate that in cases where optimal requirements include lower concentration of CO<sub>2</sub> than O<sub>2</sub>, packaging parameters can be tailored to let produce establish its own desired internal gas composition through respiration-permeation equilibrium. The analytical formulae will be of great help in optimization of packaging parameters.

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## NOMENCLATURE

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- $K_y$  Oxygen transmission rate of a polymeric film (cc of O<sub>2</sub>/m<sup>2</sup>-h-atm).  
 $K_z$  Carbon dioxide transmission rate of a polymeric film (cc of CO<sub>2</sub>/m<sup>2</sup>-h-atm).  
 $R_y$  Rate of consumption of oxygen (cc of O<sub>2</sub>/kg-h).  
 $R_z$  Rate of evolution of carbon dioxide (cc of CO<sub>2</sub>/kg-h).  
 $S$  Surface area of produce package through which O<sub>2</sub> and CO<sub>2</sub> gases can permeate (m<sup>2</sup>).  
 $t$  Time after packaging (h).  
 $V$  Inside free volume of a package (cc).  
 $W$  Weight of fresh produce per one package (kg).  
 $y$  Volumetric concentration of O<sub>2</sub> gas inside the fresh produce package. O<sub>2</sub> concentration is expressed in atmospheres.
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**NOMENCLATURE (continued)**


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- z Volumetric concentrations of CO<sub>2</sub> gas inside the fresh produce package. CO<sub>2</sub> is expressed in atmospheres.
- ŷ Oxygen concentration at hypothetical equilibrium state (atm).
- ẑ Carbon dioxide level at hypothetical equilibrium state (atm).
- y<sub>a</sub> Oxygen concentration outside the package (atm).
- z<sub>a</sub> Carbon dioxide concentration outside the package (atm).
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# EFFECT OF EXTRUDER RETENTION TIME ON CAPILLARY FLOW OF SOY DOUGH<sup>1</sup>

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Received for Publication January 15, 1981

Accepted for Publication June 22, 1981

## ABSTRACT

*Soy dough (defatted soy flakes), at 120° C and 30% moisture, was extruded through a series of dies of differing length (L) and radius (R). Plots of pressure (P) were linear with the length to radius ratios (L/R) of the dies at constant output rate (Q) and R. The intercepts of the P versus (L/R) plots on the P = 0 axis give the end corrections (e) for capillary flow at each output rate. For soy dough, these end corrections were surprisingly large at low output rates and generally decreased rapidly with increasing output rate. This is contrary to the normal behavior of viscoelastic fluids, such as thermoplastics, where the end correction increases with increasing output rate. Both the end correction, which is a measure of the elastic properties of the soy dough, and the viscosity of the soy dough depended on the output rate as expected and also on the retention time of the material in the system.*

## INTRODUCTION

There is a growing awareness that methods developed in the field of plastic extrusion can be applied to problems arising in food extrusion (Harmann and Harper 1974; Fricke *et al.* 1976; Rossen and Miller 1973; Harper 1973; Harmann and Harper 1973; Jasberg *et al.* 1979). In characterizing the rheological properties of thermoplastic melts, a convenient approach is to force the polymer from a reservoir through capillaries of varying radius (R) to length (L) ratio (L/R)

<sup>1</sup>Presented at the Society of Rheology Golden Jubilee Meeting, Boston, MA, October 28-November 2, 1979.

<sup>2</sup>The mention of firm names or trade products does not imply that they are endorsed or recommended by the U.S. Department of Agriculture over other firms or similar products not mentioned.

(Bagley 1957). It has been shown that for Newtonian fluid the observed pressure (P) for a given output rate (Q) or apparent shear rate at the wall ( $\dot{\gamma}_w$ ) is linearly related to (L/R) by:

$$P = (2\tau_w)(L/R) + 2e\tau_w \quad (1)$$

where  $\tau_w$  is the true shear stress at the capillary wall. The slopes of the linear P versus (L/R) plots give  $2\tau_w$ , and the intercept at P = 0 gives the entrance correction (e) in radii. The apparent viscosity at constant Q ( $\xi_{app}$ ) is independent of L/R and is given by  $\tau_w/\dot{\gamma}_{N,w}$ . Assuming Newtonian flow, the shear rate at the wall for a volumetric flow rate (Q) is:

$$\dot{\gamma}_{N,w} = 4Q/(\pi R^3) \quad (2)$$

The true shear rate at the wall ( $\dot{\gamma}_{t,w}$ ) can be determined by using the Rabinowitch correction to account for non-Newtonian behavior (Jao and Chen 1978).

$$\dot{\gamma}_{t,w} = \frac{\dot{\gamma}_{N,w}}{4} \left[ 3 + \frac{d(\ln \dot{\gamma})}{d(\ln \tau_w)} \right] \quad (3)$$

The end correction (e) is a measure of the elastic energy stored in the viscoelastic fluid entering the capillary (Bagley 1961). For some thermoplastic systems "e" varies with shear stress ( $\tau$ ) according to:

$$e = n + (\tau/2G) \quad (4)$$

where "G" is a shear modulus and "n" is a measure of the viscous losses prior to entry into the capillary. "n" is a constant with a value of about unity.

Plots of "e" versus " $\tau$ " for thermoplastics are often linear, allowing the shear modulus to be determined from the slopes of the curve. Such linearity implies that the material is obeying Hooke's Law in shear with a constant modulus.

Jao and Chen (1978) and Remsen and Clark (1978) evaluated the flow of soy doughs through capillaries of different (L/R) ratios. Jao's primary concern was with the relationship of viscosity to temperature, moisture, and shear rate. There was no attempt to separate effects of retention time on viscosity from effects of shear rate. Thus soy doughs evaluated at different shear rates had much different retention times, especially when different diameter capillaries were

used. The effect of retention time on viscosity was not determined, making comparisons to data derived on other equipment difficult to make. Remsen did include the effect of time-temperature history in his model of soy dough viscosity. This was accomplished by combining extent of reaction data from an Amylograph with results from a capillary flow experiment. Information on the end corrections for soy dough (and hence elasticity) was present in both papers, but it was not evaluated.

Figure 1, taken from Remsen and Clark (1978), shows results for the capillary extrusion of 32% moisture soy dough at 50°C. The plots of pressure (plunger force, lb) versus  $L/D$  are linear for each output rate (crosshead speed, in./min). The entrance corrections decrease as output rate (and shear rate) increases (from 30 D, diameters, at 0.02 in./min to 10 D at 1.0 in./min). This behavior is different than that

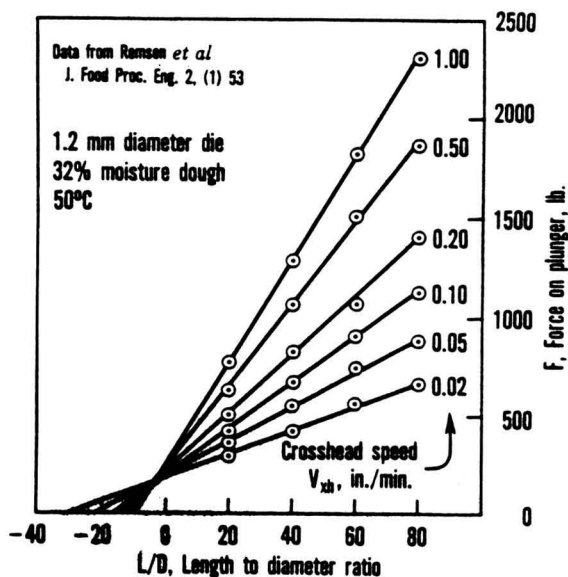


FIG. 1. FORCE ON PLUNGER VERSUS  $L/D$  FOR SOY

shown in Fig. 2 for a typical thermoplastic, polyethylene. The end corrections for polyethylene increase with increasing shear rate from about 4 R to 8 R (in radii) in the range studied.

Figure 3 shows data from Jao and Chen (1978) for the capillary extrusion of 28.5% moisture soy dough at 160°C. The plots of pressure versus  $L/D$  are again linear. In fact, at the lower shear rates (up to 1000  $s^{-1}$ ) the entrance correction increases with increasing shear rate,

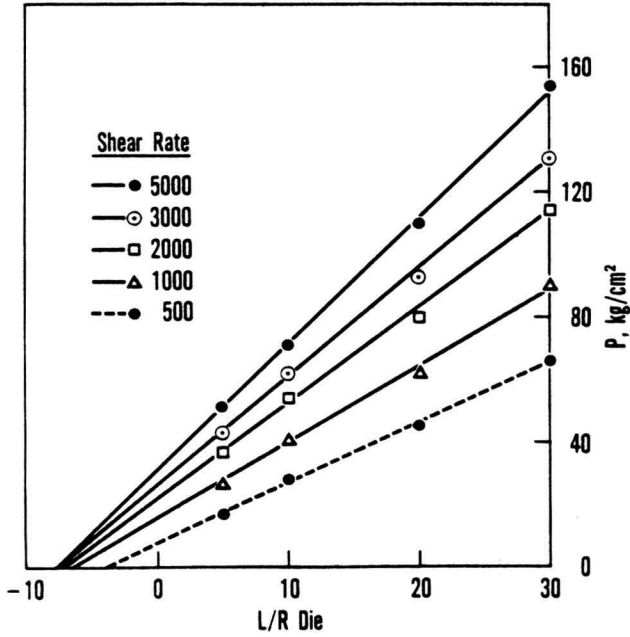


FIG. 2. OBSERVED PRESSURE DROP VERSUS L/R FOR POLYETHYLENE, 1 MM DIES

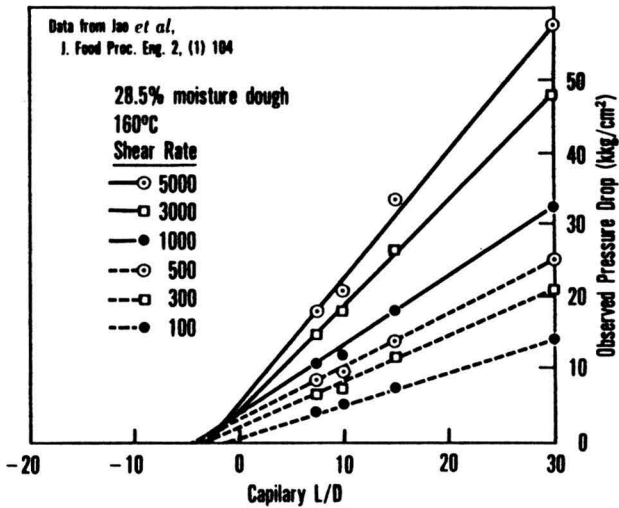


FIG. 3. OBSERVED PRESSURE DROP VERSUS L/D FOR SOY

as it does for polyethylene. However, at the higher shear rates (3000  $\text{s}^{-1}$ , 5000  $\text{s}^{-1}$ ) the entrance correction begins to decrease.

A major difference between thermoplastics and soy doughs is that the dough is undergoing cooking at extrusion temperatures (Harper *et al.* 1971; Thompson *et al.* 1976; Morgan *et al.* 1978; Beetner *et al.* 1974; Cervone and Harper 1978; Chung, 1976; Bruin *et al.* 1978; and Kinsella 1976). Many changes occurring are irreversible, and material properties would be expected to vary with retention time in the extruder (Clark 1978). This work was undertaken to evaluate the end corrections in capillary flow of soy dough (defatted soy flakes) and to determine the effect of retention time on material properties (viscosity and elasticity). The elastic properties of doughs must be considered, especially in puffing or texturization processes. Knowledge of how the viscoelastic properties of soy dough vary with temperature, moisture, shear rate, and retention time is necessary before meaningful modeling of extrusion processes can be achieved.

## MATERIALS AND METHODS

A model PLV 300 Brabender plasticorder 3/4 in. diameter extruder was used. The screw ( $L/D = 20/1$ ) had a standard lead and a 2/1 compression ratio. A combination thermocouple and pressure transducer was used to measure die inlet conditions. Plasticorder accessories included a tachometer (0-200 RPM) to determine screw speed and a balance type torque indicator (0-10,000 meter-grams). Two sets of capillary dies were used, with diameters of 1 and 2 mm (entrance angle of  $180^\circ$ ). The L/R ratios for both sets were 5, 10, 20, and 30.

High NSI (nitrogen solubility index, an indicator of protein solubility), soy flakes were used as the feed. Polyethylene (P.E.) with a melt index of 3.0 and a density of 0.915 was used for comparison purposes and to provide a check on the dies and procedures used. A long die holder and a short die holder were used to vary total residence time in the extruder while keeping the shear rate constant. The dimensions were the same, except for length (10.2 cm and 3.3 cm). Thus the total retention time in the system when using the short die holder was about 60% of the retention time when using the long die holder (at the same shear rate). A range of retention times from 15 s to 15 min was studied.

The soy flakes were moistened with water and mixed in a Hobart Dough Mixer for 5 min. The mixture was chopped into a granular feed using a Comitrol 3600 Food Chopper. Feed moisture was 30% (Cenco moisture balance), and extrusion temperature was  $120^\circ\text{C}$  (temperature



was held constant to eliminate temperature effects on viscosity and at a low enough temperature to prevent texturization). Effects of temperature, moisture, and shear rate on viscosity have been investigated by Jao and Chen (1978). All of the dies (8) were used at screw speeds from 10 to 150 RPM. Temperature, pressure, torque, and mass flow rate (g/min calculated by the method of Jao and Chen 1978) were recorded for each die-screw speed combination. The following calculations were then performed. First, observed pressure versus shear rate (calculated) was plotted for each die. Observed pressure at various shear rates versus die (L/R) ratio was then plotted. Entrance pressure drop at various shear rates was found, along with "e" (equivalent die length causing entrance pressure loss). Entrance pressure loss was subtracted from observed pressure loss to give the capillary pressure loss. The Rabinowitch correction for shear rate was applied. The capillary pressure drop and corrected shear rate were then used to calculate viscosity (at each shear rate). Viscosity vs shear rate plots were drawn. The entrance correction "e" was plotted vs  $\tau_{i,w}$  to determine "n."

Work was done first with a die holder with a long entrance zone for soy and polyethylene (at 190°C). Then a die holder with a shorter entrance zone was used (with soy only) to determine the effect of shorter retention time. NSIs of some extrudates were determined to measure protein solubility changes during processing (AOCS method Ba 11-65, Official and Tentative Methods; AOCS, 1971). The extruder was disassembled and cleaned after each run. P. E. was removed by running a mixture of P. E. and stearic acid through the extruder for several minutes before disassembly.

## RESULTS AND DISCUSSION

Our polyethylene data (Fig. 2) were in the range expected (Bagley 1957; Bagley 1961; Chung 1976). The entrance corrections first increased as the shear rate increased from 500 s<sup>-1</sup> to 2000 s<sup>-1</sup>, and then became relatively constant above 2000 s<sup>-1</sup>. For the 2 millimeter dies the entrance correction increased as the shear rate increased from 100 s<sup>-1</sup> to 1000 s<sup>-1</sup> (Fig. 4). The entrance corrections ranged from 3 to 7 (all results given in radii). There was some unexpected small variation of measured end correction with die radius. This effect will be investigated in more detail in a subsequent study.

With soy dough (30% moisture, 120°C, Fig. 5) using the 1 mm dies (and the long die holder), the entrance correction decreased from 47 to 27 as the shear rate increased from 500 s<sup>-1</sup> to 2000 s<sup>-1</sup>. At higher shear

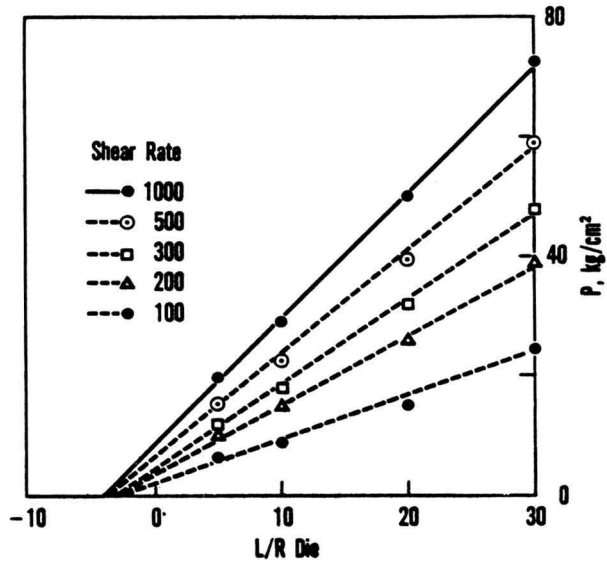


FIG. 4. OBSERVED PRESSURE VERSUS L/R FOR POLYETHYLENE, 2 MM DIES

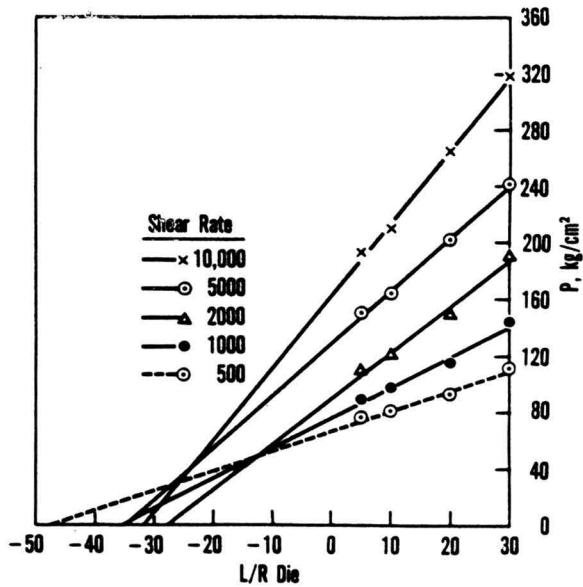


FIG. 5. OBSERVED PRESSURE VERSUS L/R FOR SOY, 1 MM DIES

rates, however, the end correction increased (about 33 at  $5000 \text{ s}^{-1}$  and  $10,000 \text{ s}^{-1}$ ). A similar effect can be seen in Fig. 3, work done by Jao and Chen (1978) at higher temperature. This phenomenon only occurred with the 1 mm dies.

For soy dough using the 2 mm dies (and the long die holder), the entrance correction decreased steadily from over 100 down to 18 as the shear rate increased from  $100 \text{ s}^{-1}$  to  $3000 \text{ s}^{-1}$  (Fig. 6). There was no reversal of direction as seen for the 1 mm dies. The magnitude of the end correction also decreased (for the 1 mm dies, 35 at  $1000 \text{ s}^{-1}$ , 47 at  $500 \text{ s}^{-1}$ , and for the 2 mm dies, 23 at  $1000 \text{ s}^{-1}$ , 33 at  $500 \text{ s}^{-1}$ ).

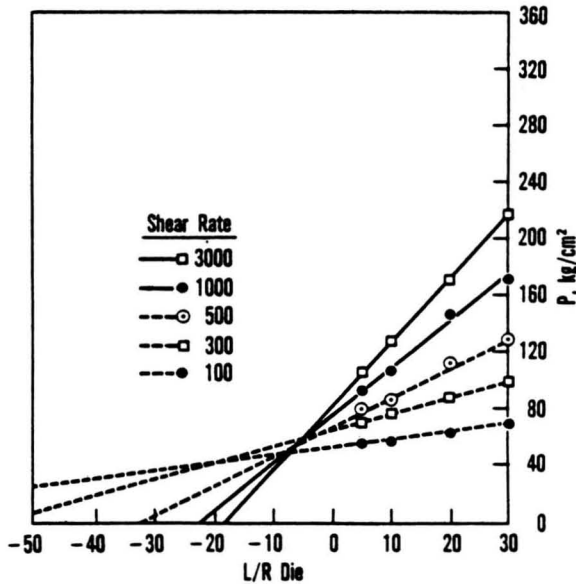


FIG. 6. OBSERVED PRESSURE VERSUS L/R FOR SOY, 2 MM DIES

To determine whether retention time (RT) had any effect on entrance corrections, a shorter die holder was used with the 2 mm dies. RT in the short die holder system was 60% of the RT in the long die holder system at the same shear rate. The trend of decreasing end correction with increasing shear rate (Fig. 7) was similar to that in Fig. 6, but the end corrections were about half as large [10 at  $3000 \text{ s}^{-1}$  (fig. 7) compared to 18 at  $3000 \text{ s}^{-1}$  (Fig. 6)]. Reducing the retention time in the system (by shortening the die holder) while keeping the shear rate constant caused the entrance corrections to decrease.

The effect of retention time on entrance pressure loss ( $P_e$ ) can be seen in Fig. 8. At  $100 \text{ s}^{-1}$ , the entrance pressure loss was about  $55 \text{ kg/cm}^2$  for

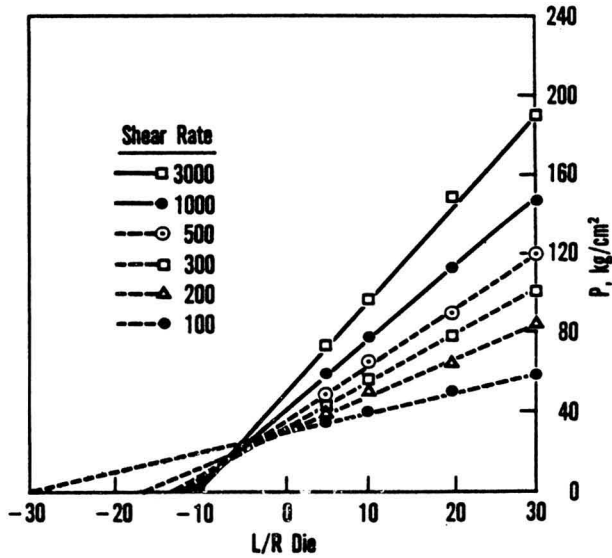


FIG. 7. OBSERVED PRESSURE VERSUS L/R FOR SOY, 2 MM DIES WITH SHORT RETENTION TIME HOLDER

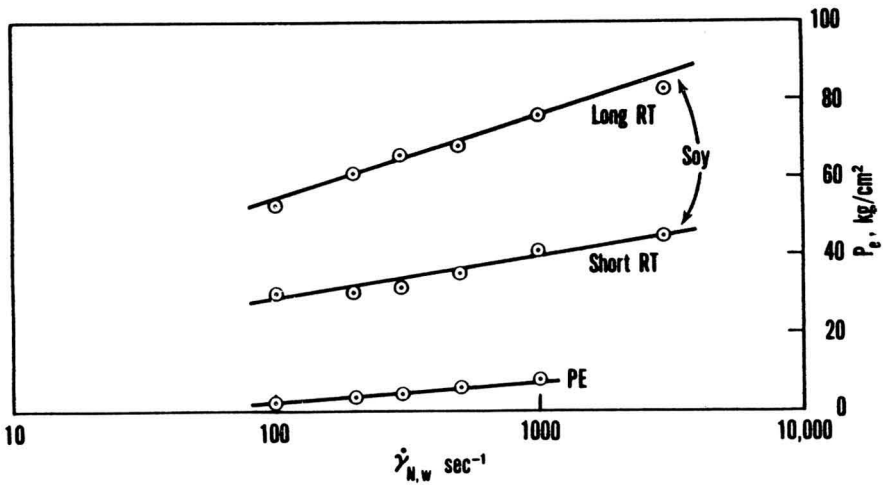


FIG. 8. ENTRANCE PRESSURE DROP VERSUS SHEAR RATE FOR SOY AND POLYETHYLENE

the longer (RT) holder and about 30 Kg/cm<sup>2</sup> for the shorter (RT) holder. The entrance pressure loss for the shorter (RT) holder was about half that of the longer (RT) holder over the shear rate range investigated.

The entrance pressure losses for polyethylene (P.E.) were much smaller ( $3 \text{ kg/cm}^2$  at  $100 \text{ s}^{-1}$ ).

Figure 9 shows entrance correction ( $e$ ) versus shear rate for soy dough and P.E. Values of entrance correction for P.E. were small (2-10) and appeared to increase linearly with  $\log \dot{\gamma}$ . The value of " $e$ " for soy decreased with  $\log \dot{\gamma}$ , opposite to the behavior for polyethylene, with values of " $e$ " for the longer (RT) holder being about twice as large as those for the shorter (RT) holder.

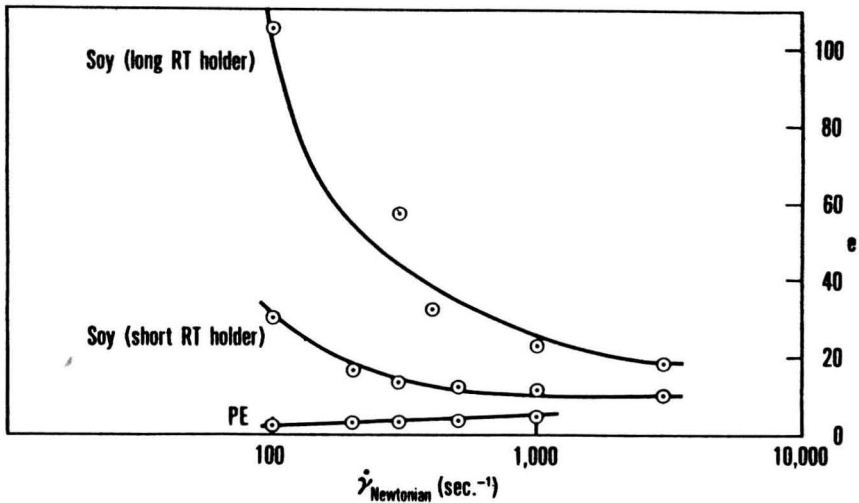


FIG. 9. ENTRANCE CORRECTION VERSUS SHEAR RATE FOR SOY AND POLYETHYLENE

Figure 10 shows viscosity versus shear rate for soy dough and P.E. The P.E. and soy dough had similar viscosities over the range investigated. At shorter retention times (and higher  $\dot{\gamma}$ ) the soy viscosity depended mainly on shear rate, exhibiting shear thinning (power law fluid-solid line). At lower shear rates and longer retention times, each of the three soy curves (for 2 mm dies-long holder, 2 mm dies-short holder, and 1 mm dies-long holder) deviated from the primary curve. This effect was evident for all three die combinations, and it does not appear to be simply the beginning of a Newtonian region.

The viscosity versus shear rate curves for the soy dough were redrawn as a family of curves with varying retention times (Fig. 11). When this was done, viscosity appeared to depend both on shear rate and retention time. The shear thinning nature of soy dough was also reported by Chung (1976) and Jao and Chen (1978). Normally, dependence of calculated viscosity on die radius would be interpreted as a slip phenomenon (Worth and Parnaby 1977). The results reported here for

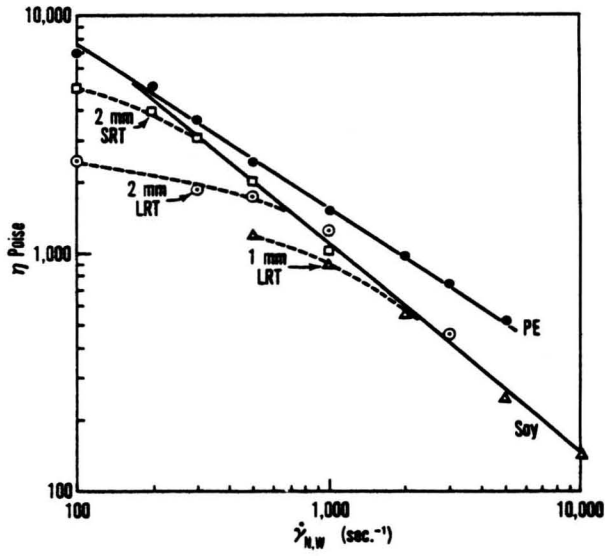


FIG. 10. VISCOSITY VERSUS SHEAR RATE FOR SOY AND POLYETHYLENE

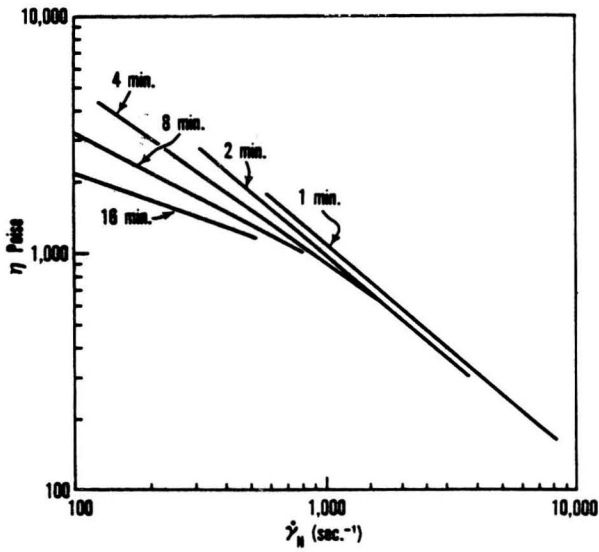


FIG. 11. VISCOSITY VERSUS SHEAR RATE WITH VARYING RETENTION TIME

soy doughs, however, demonstrate a strong dependence of material properties on retention time. Since a change in die radius markedly affects retention time, it cannot be concluded from dependency of viscosity on die radius that slip is occurring in these dough systems.

Direct consideration of the variation of  $e$  with  $\tau$  has been shown, in the case of polymer melts, to yield information of the elastic properties of the material. Thus for polyethylene, as shown in Fig. 12,  $e$  versus  $\tau$  is linear, the slope being dependent on the shear modulus of the melt. Such plots for polymers are not dependent on residence time.

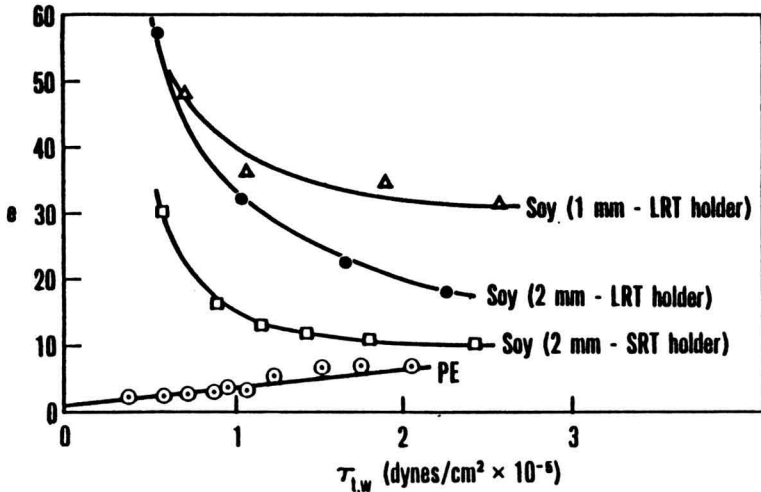


FIG. 12. ENTRANCE CORRECTION VERSUS SHEAR STRESS

For soy doughs, the situation, as shown in Fig. 12, is much more complex. Not only are the  $e$  versus  $\tau$  plots nonlinear but they clearly depend on RT as affected by the die size and holders used in the experiment. The properties of the dough change with time-temperature history of the sample during processing. These experiments suggest that the  $e$  versus  $\tau$  plots should be made at constant RT in a future study.

The NSI range of extrudates was small (8-12). Measuring the possible relationship between NSI, RT, and viscoelastic properties would necessitate using much shorter RT, or lower temperatures. More work in this area is needed, especially in determining how network structures due to inter and intra molecular bond formation can be affected by temperature, residence time, shear rate, and other factors. Research using different extruders will not be comparable if RT effects on food doughs are ignored. Knowledge of RT effects should allow rheological data from a small, laboratory extruder to be used in modeling flow in any extruder.

## CONCLUSIONS

For both soy dough and polyethylene, the end correction plots of pressure versus  $L/R$  were linear. For P.E., the end correction ( $e$ ) increased with increasing shear rate. However, for soy dough  $e$  decreased with increasing shear rate. Reducing the retention time in the extruder (by reducing the length of the die holder) caused both  $e$  and  $P_e$  to decrease.

Viscosity versus shear rate curves for soy dough appeared to be affected by extruder retention time. Viscosity of the soy dough decreased with increasing shear rate (indicating shear thinning).

Because the entrance correction versus shear stress plot was not linear for soy dough, the shear modulus of the soy dough could not be determined.

The methods normally used to determine the properties of plastic melts did not always work for soy dough. Also, the effects of retention time on soy dough had to be separated from the effects of shear rate. More research is needed to determine how the viscoelastic properties of soy dough vary with retention time, temperature, moisture, and shear rate.

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## NOMENCLATURE

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C	= Celsius	R	= die radius
D	= diameter of screw	RPM	= revolutions per minute
e	= entrance correction (in radii)	RT	= retention time
L	= die length	SRT	= short retention time
LRT	= long retention time	$\dot{\gamma}_{N,w}$	= Newtonian shear rate at wall
n	= Couette loss	$\dot{\gamma}_{t,w}$	= true shear rate at wall
NSI	= Nitrogen solubility index	$\eta$	= Viscosity
$P_{cap}$	= capillary pressure loss	$\Pi$	= 3.14
$P_e$	= entrance pressure loss	$\tau_w$	= shear stress at wall
$P_o$	= observed pressure loss	$\tau_{t,w}$	= true shear stress at wall
P.E.	= polyethylene	G	= shear modulus
Q	= volumetric flow rate		

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## BOOK REVIEW

***A Guide to Packaging Machinery.* By Stanley Sacharow. Books for Industry, 747 Third Avenue, New York, NY 10017. 191 pp.**

Like a well-lubricated packaging machine disgorging filled containers in a never-ending parade, Stanley Sacharow has done it again. Another year, another packaging book by Sacharow. Ho hum. But wait, this one is neither a revision nor a rehash. Nor is it a primer or a brain-dulling fleshing out of a reference table.

“A Guide to Packaging Machinery” is precisely what the title states and implies: an orderly systematic recitation of the principles of the principal packaging machinery in the U.S. and Western Europe today. Each chapter is a self-contained description of a specific packaging machinery topic, beginning, as do all Sacharow packaging books, with history, but this time relevant. A comprehension of packaging machinery, even in the 1980's, demands knowledge of the evolution, even if only because some equipment still in use today was from the first design series. Regardless, much equipment in packaging plants today is of first generation vintage, unhampered by microprocessors, servomotors, hydraulic controls and other appurtenances of the space age.

The packages to be formed, filled, weighed, conveyed, closed or otherwise operated on by the equipment, are described. Reasons why a particular package or range of packages are in commercial use are set forth. And then, the chapter climaxes with word descriptions of the equipment and its functions. Each major piece in common use in the U.S. receives a share of attention.

Each of the ten chapters devoted to specific packaging machines contains clear and easily assimilated tabulations of key points such as sequences for thermoforming, comparisons of various types of equipment of the basis of characteristics, and major manufacturers of the basic machinery being described in the chapter.

The information is presented clearly, concisely and in an orderly fashion. Earlier chapters deal with introductory principles that are the key to understanding the specifics. And the final chapter projects, very conservatively, into the future.

To help lighten the reader's burden, each chapter begins with a profound quotation and closes with an entertaining cartoon.

The whole world of packaging machinery is in 191 pages. Obviously, no slim volume could begin to provide the detail required by a packag-

ing engineer or a mechanical packaging developer or student. But the structure, principles and order are present with remarkable clarity and appreciation for the essential building blocks.

The book is uncluttered with engineering detail or driving mechanisms, sizes or model variations. It barely brushes on many of the basic differences between machines, such as intermittent versus continuous motion; high speed versus low speed; big versus small. And, as incredible as it might be in this era of orientation towards minutiae, the book has no index. Perhaps it is in keeping with the tenor of the book—keep it simple—that the first English language book ever published on packaging machinery is devoid of the most basic of all text book components, an index.

As was stated at the outset, this book is not a reference; it is intended to be read for comprehension.

ARRON L. BRODY

## LITERATURE ABSTRACTS

### ABSTRACTS FROM JOURNAL OF FOOD SCIENCE

**PREDICTING CONCENTRATIONS OF INDIVIDUAL SUGARS IN DRY MIXTURES BY NEAR-INFRARED REFLECTANCE SPECTROSCOPY.** R. Giangiacomo, J. B. Magee, G. S. Birth and G. G. Dull. *J. Food Sci.* 46, 531-534.

To support research in nondestructive quality evaluation of fruits and vegetables, near infrared reflectance spectroscopy was used to measure concentrations of fructose, glucose, and sucrose in model systems intended to represent the major constituents of dried apple tissue. Spectra (950-1850 nm) of a series of known samples were recorded, and multiple linear regression techniques were used relate the concentrations of each sugar to reflectance measurements at selected wavelengths. Reflectance measurements at 3 computer-selected wavelengths for each sugar were used to predict the concentrations in an independent set of samples. Correlation coefficients for actual vs predicted values were 0.995 for fructose, 0.994 for glucose, and 0.986 for sucrose, while the respective standard errors computed as variations from the regression lines were 1.48%, 1.39%, and 1.44%.

**A KINETIC STUDY OF THE LOSS OF VITAMIN C, COLOR, AND FIRMNESS DURING THERMAL PROCESSING OF CANNED PEAS.** M. A. Rao, C. Y. Lee, J. Katz and H. J. Cooley. *J. Food Sci.* 46, 636-637.

The kinetic parameters,  $D$  and  $z$ , for the loss of color firmness, and vitamin C were determined during the thermal processing of peas canned in  $303 \times 406$  cans. The  $D_{250}$  values for loss of color, firmness, and vitamin C were 13.2 min, 9.2 min, and 246 min, respectively. The corresponding  $z$  values were:  $69^\circ\text{F}$ ,  $66^\circ\text{F}$ , and  $91^\circ\text{F}$ , respectively. These results are in good agreement with those reported in the literature. With proper precautions and corrections for lags, kinetic parameters for the loss of quality parameters can be determined during thermal processing of foods in relatively large cans.

**ASCORBIC ACID RETENTION IN RETORT POUCHED GREEN BEANS.** T. S. Chen and W. L. George. *J. Food Sci.* 46, 642-643.

The L-ascorbic acid (AA) retention and sensory quality of green beans processed under home-canning conditions in retort pouches and metal cans were compared. Green beans processed in cans retained slightly more AA than that processed in the pouches, possibly due to overprocessing of the pouched product. Metal cans offered better AA retention in the green beans than the retort pouches during 11 wk of storage at  $21^\circ\text{C}$ , due mainly to a higher rate of AA degradation occurring in the pouched product during the first week of storage. Sensory evaluation showed that the retort pouched, beans were significantly better ( $p < 0.05$ ) than the canned green beans in flavor, texture, and overall acceptance, but not in color.

**KINETICS OF VITAMIN A DEGRADATION IN BEEF LIVER ON PUREE ON HEAT PROCESSING.** S. A. Wilkinson, M. D. Earle and A. C. Cleland. *J. Food Sci.* 46, 32-33.

The effects of heating on Vitamin A (measured as trans-retinol) in beef liver puree were investigated. The liver puree was heated in capillary tubes at five temperatures in the range 103-127°C, the typical canning temperature range for meat products. It was found that in this system and over the temperature range studied, the observed rate of degradation followed first order kinetics. The activation energy for the temperature dependence of the rate constant was  $112 \pm 9$  kJ/mole.

**EVALUATION OF THE EFFECTS OF LIQUID BRIDGES ON THE BULK PROPERTIES OF MODEL POWDERS.** E. Scoville and M. Peleg. *J. Food Sci.* 46, 174-177.

Measured amounts of water were admixed with uniform size glass beads (107-475 micron) to form model powders with controlled interparticle liquid films. The viscosity of the films was modified by dissolving carrageenan and its surface tension by a detergent. These model powders were tested for loose bulk density, compressibility, irrecoverable work in compaction, cohesion and residual modulus after relaxation. The effect of the films on these bulk characteristics was considerable in the fine model powders but diminished with the increase of particle size. In comparison to particle size, the film viscosity (1-200 cp) and surface tension (72 and 35 dyne  $\text{cm}^{-1}$ ) had little or insignificant effect on the bulk properties. The results are explained in terms of the internal structure of the bed and their possible implications in real powders are evaluated.

**DEVELOPMENT, EVALUATION AND INDUSTRIAL PRODUCTION OF A POWDERED SOY-OATS INFANT FORMULA USING A LOW COST EXTRUDER.** F. R. Del Valle, H. Villanueva, J. Reyes-Govea, M. Escobedo, H. Bourges, J. Ponce and M. J. Munoz. *J. Food Sci.* 46, 192-197.

A low cost powdered infant formula made from soybeans, oats and sucrose, fortified with methionine, vitamins and minerals, has been developed. A dry process for making the formula, which employs a low-cost Brady extruder, has also been developed. The resulting product is of good microbiological quality and dispenses readily in water to give a milk-like suspension of satisfactory ability to settling. The essential amino acid pattern of the formula, its PER and NPU values, nitrogen balance data with infants, proximal chemical analysis, calorie distribution and low level of trypsin inhibitor indicate it to be adequate for feeding infants 3 months or older. Clinical trials with infants also showed that the formula was well accepted and tolerated, and produced adequate weight gain. Retail prices of the product, packed in cans and polyethylene bags, are appreciably lower than those of comparable cow's milk and other soya-based infant formulas available in the market. The product is currently being manufactured and sold in several parts of Mexico.

**DETERMINATION OF THERMAL PROCESS SCHEDULE FOR ACIDIFIED PAPAYA.** N. Nath and S. Ranganna. *J. Food Sci.* 46, 201-206 + 211.

The pH of papaya varies from 4.2-5.65 and is required to be lowered to enable processing at atmospheric pressure. A thermal process has been evolved on the basis of inactivation of pectinesterase (PE), the heat resistant enzyme naturally present. The values for thermal inactivation of PE in pulp were  $F_{212}^{26.8} = 1.04$  and  $D_{212}^{27} = 0.39$  at pH 4.0. In the syrup homogenate of 20% TSS, the values were  $F_{207.3}^{27.6} = 1.00$  and  $D_{207.3}^{29} = 0.53$  at pH 3.8, and  $F_{212}^{27.2} = 1.23$  and  $D_{212}^{27.5} = 0.8$  at pH 4.0. These F values in syrup homogenate were equivalent to 1.88D at pH 3.8 and 1.53D at pH 4.0. In commercial canning, a 2.5D process at pH 3.8 and 2.0D process at pH 4.0 which are equivalent to the F values of 1.33 and 1.31, respectively, are recommended. Using these F values, process times for different processing conditions were calculated by graphical method and compared with values found by three different procedures of the formula method. The thermal process, thus evolved on the basis of enzyme inactivation, resulted in safe and acceptable product.

**SOME RHEOLOGICAL CHARACTERISTICS OF SOY EXTRUDATES IN TENSION.** J. W. Finkowski and M. Peleg. *J. Food Sci.* 46, 207-211.

Experimental soy flour extrudates, prepared under different processing conditions were tested in tension by an Instron Universal Testing Machine. All the extrudates exhibited a nonlinear stress-strain relationship that is indicative of progressive development of structural failure. Complementary relaxation curves at three prefailure deformation levels were linearized and used for calculation of asymptotic relaxed moduli (also called equilibrium moduli). The relationship between the moduli and the strain or the initial stress indicated that both the break elongation and the ultimate strength could independently be estimated from the relaxation data. A mathematical and computer procedure for such predictions is described and its applicability demonstrated with experimental results.

**YIELD AND QUALITY OF SOYMILK PROCESSED BY STEAM-INFUSION COOKING.** L. A. Johnson, C. W. Deyoe and W. J. Hoover. *J. Food Sci.* 46, 239-243 + 248.

Traditional soymilk is boiled for approximately 60 min at 99° C, pH 6.7, which reduces trypsin inhibitor (TI) activity by more than 90% to improve nutritional value. We evaluated continuous, direct steam-infusion cooking that facilitated higher temperatures (99-154° C) than that traditionally used for cooking soymilk. At temperatures above 120° C in steam-infusion cooking we observed consistent temperature-dependent patterns in yields of soymilk, solids, and protein, characterized by an initial decrease. At 154° C, pH 6.7, maximum recovery occurred at the same point as did adequate inactivation of TI. As much as 90% of the slurry, 86% of the soybean solids, and 90% of the protein were recovered as soymilk after centrifuging at 1050 × G for 5 min. Under optimum conditions for steam-infusion cooking the soymilk also retained less

than 8% residual TI activity, and less chemical browning. Using traditional cooking methods, about 72% of the slurry, 61% of soybean solids, and 73% of the protein are recovered.

**EFFECTS OF HEAT PROCESSING IN CANS AND RETORT POUCHES ON SENSORY PROPERTIES OF FOWL MEAT.** B. G. Lyon and A. A. Klose. *J. Food Sci.* 46, 227-230, 233.

Fowl meat processed in cans and flexible retortable pouches was evaluated for heat effects on sensory properties. A trained panel evaluated texture and off-flavor of canned boned chicken, uncooked fowl meat retorted in flexible pouches, cooked meat retorted in flexible pouches, and simmered fowl meat (control). Results indicated that the retort pouch process may offer a method for improving the texture of processed fowl meat from spent hens by adequately cooking to tenderize the meat but not overcooking it to the extent that meat chunks are reduced to fibrous, shredded, or stringy components. Off-flavor development was related to precooking before retorting.

**RHEOLOGY OF ENZYME MODIFIED CHEESE.** Y. C. Jao, A. H. Chen, R. V. Chaudhari and W. E. Goldstein. *J. Food Sci.* 46, 254-258, 262.

The rheological properties of commercial enzyme modified cheese products (Dariteen<sup>®</sup>, Miles Laboratories, Inc.) are investigated with a micro-rheology type of viscometer with cone-and-plate geometry. These products exhibit thixotropic shear-thinning behavior, where viscosity changes with the duration and the rate of the applied shear. A viscosity model invoking gradually increasing and decreasing shear rate is investigated. The model involves expression of viscosity as a function of shear rate in the range 1.92-384 sec<sup>-1</sup> for the case of increasing shear rate and 384-1.92 sec<sup>-1</sup> for the case of decreasing shear rate. In these investigations, temperature and moisture content range from 24-72° C and 42.3-59.3%, respectively. Hysteresis curves representative of the phenomena are also illustrated.

**PREDICTING WATER ACTIVITY FROM 0.30 TO 0.95 OF A MULTI-COMPONENT FOOD FORMULATION.** K. W. Lang and M. P. Steinberg. *J. Food Sci.* 46, 670-672, 680.

The objective was to develop an equation to calculate the  $a_w$  of a mixture of known composition at a given moisture content. A simple equation was derived by combining the Smith isotherm with the Lang-Steinberg mass balance:  $\log(1 - a_w) = [MW - \sum(a_j w_j)] / \sum(b_i w_i)$  where M is moisture content of the mixture, W is total dry weight of the mixture,  $a_j$  and  $w_j$  is the dry weight of the ingredient. For comparison of experimental and calculated  $a_w$  values, an experimental value was used to calculate M from the mixture isotherm and this M was used to calculate  $a_w$  from the model. Four binary and one ternary mixtures of two macromolecules, two solutes and one complex ingredient were included. Twenty-one comparisons between calculated and experimental  $a_w$  over  $a_w$  over  $a_w$  0.30-0.95 resulted in a maximum error of only

1.86% and a mean error of  $-0.25\%$ , showing excellent agreement. Only one constraint was found; when the mixture contains a solute (sugar or salt) and the  $a_w$  is below the  $a_w$  of saturation for that solute, that solute is deleted from the summations in the Model.

**PREDICTING PROTEIN QUALITY OF CORN-SOY-MILK BLENDS AFTER NONENZYMATIC BROWNING.** G. N. Bookwalter and W. F. Kwolek. *J. Food Sci.* 46, 711-715.

CMS, a corn-soy-milk high-protein supplement for children, was exposed to high temperatures. Various degrees of nonenzymatic browning occurred, and product color ranged from yellow to dark brown. Progressively greater deterioration of protein quality as measured by protein efficiency ratio (PER) occurred with increasing color change as measured by Hunter color values. Protein quality was also estimated by the *Tegrahymena pyriformis* W bioassay and essential amino acid analysis. Linear relationships between PER, available lysine, and Hunter "L" values provided rapid methods for predicting protein quality. Correlation with PER was 0.95 using Hunter "L" and 0.88 using available lysine values. A color standard plate was developed to provide rapid field screening.

**THERMOPHYSICAL PROPERTIES OF APPLES IN RELATION TO FREEZING.** H. S. Ramaswamy and M. A. Tung. *J. Food Sci.* 46, 724-728.

The temperature dependence of different thermo-physical properties of Golden Delicious and Granny Smith apples were studied. Regression relationships for apparent specific heat, thermal conductivity and thermal diffusivity, density changes in the unfrozen and frozen states for the two varieties of apples and the surface heat transfer coefficients associated with freezing under different conditions were discussed. The mean values of the different properties for Golden Delicious apples were (values in the parentheses are for granny Smith apples): thermal conductivity 0.427 and 1.45  $W/m^2C^\circ$  (0.398 and 1.22  $W/m^2C^\circ$ ); apparent specific heat, 3.69 and 1.95  $kJ/kgC^\circ$  (3.58 and 1.68  $kJ/kgC^\circ$ ); and density, 845 and 788  $kg/m^3$  (829 and 786  $kg/m^3$ ), respectively, in the unfrozen and frozen states. The surface heat transfer coefficients, as determined by using Plank's equation, ranged from 1.27  $W/m^2C^\circ$  for freezing in air to 68.4  $W/m^2C^\circ$  for freezing in liquid nitrogen.

**CHEMICAL AND PHYSICAL TREATMENT EFFECTS ON SOLID-LIQUID EXTRACTION OF APPLE TISSUE.** C. R. Binkley and R. C. Wiley. *J. Food Sci.* 46, 729-732.

Various experimental treatments have been selectively applied to apple tissue in an effort to determine whether a solid-liquid extraction process could be utilized for manufacturing single strength beverage juice. Vacuum impregnation of enzymatic and chemical solutions showed a positive effect on accelerating the rate of diffusion in the tissues studied. The greatest overall effect on increasing the rate of diffusion was caused by a pretreatment with radio-



frequency energy. Observed diffusion coefficients were  $4.11 \times 10^{-6}$  cm<sup>2</sup>/sec with this treatment, as compared to  $1.20 \times 10^{-6}$  cm<sup>2</sup>/sec for the control group of samples. Pretreatment techniques are suggested to enhance the rate of diffusion in apple tissue that may be of commercial value.

**STORAGE STABILITY OF  $\alpha$ -TOCOPHEROL IN A DEHYDRATED MODEL FOOD SYSTEM CONTAINING METHYL LINOLEATE.** W. A. Widicus and J. R. Kirk. *J. Food Sci.* 46, 813-816.

The storage stability of  $\alpha$ -tocopherol in a dehydrated model food system containing methyl linoleate was evaluated. The degradation rate of  $\alpha$ -tocopherol was best described by zero order kinetics with rates significantly greater than 0 ( $p \leq 0.002$ ), correlation coefficients ( $|R| \geq 0.88$ ) and standard deviations from 4-13% of the reported rate constants. The zero order rate constants were dependent on the initial  $\alpha$ -tocopherol concentrations, indicating that the concentration of  $\alpha$ -tocopherol and unknown reactant(s) does affect the storage stability of  $\alpha$ -tocopherol. The storage parameters of water activity, storage container oxygen content, and storage temperature affected the rate of  $\alpha$ -tocopherol loss indicating that these parameters must be controlled to maximize  $\alpha$ -tocopherol storage stability.

**EFFECT OF DI-THERMAL STORAGE REGIME ON QUALITY AND NUTRITIONAL CHANGES AND ENERGY CONSUMPTION OF FROZEN BOXED BEEF.** W. Moleeratanond, B. H. Ashby, A. Kramer, B. W. Berry and W. Lee. *J. Food Sci.* 46, 829-833, 837.

Seven types of beef products were commercially packaged, frozen, and stored at top corner pallet positions in three rooms for a year. The storage temperatures were: (1)  $-21^\circ\text{C}$ ; (3)  $-21^\circ\text{C}$  and  $-18^\circ\text{C}$ . Compared to the  $-23^\circ\text{C}$ , constant room (as reference), a net energy saving of 6 and 14% was obtained for the two di-thermal storage rooms by maintaining the temperatures at the lower levels for one 12-hr period. The weight loss for most products was negligible, except for bulk-packed hamburger patties which lost over 1%. The results on sensory, nutritional, and other quality attributes of frozen boxed beef products showed no serious quality damage from both constant and di-thermal storage after 1 yr, except for MPB and beef patties whose practical shelf-life was limited to 6 months.

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

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