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REVERSE OSMOSIS CONCENTRATION OF GREEN TEA JUICE

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ABSTRACT

The reverse osmosis concentration of green tea juice was attempted by using membranes prepared from different polymeric materials. The pore sizes of the membranes were also changed in order to investigate the effect of the pore size on the membrane performance. Special attention was focused on the removal of caffeine from the tea juice while retaining other components such as polyphenols and amino acids. Since severe membrane fouling was observed while tea juice was treated at high concentrations, an attempt was made to describe the membrane fouling by a modified gel model that includes the effect of the interaction between the membrane and the tea juice components.

INTRODUCTION

Membrane processes have been recognized as some of the most versatile separation processes. Reverse osmosis in particular is a pressure driven process in which solvent, in most cases water, is removed as membrane permeate and solutes can be concentrated in the retentate. Since no heat is applied during the separation process, thermal damage to flavor, aroma, and color components in the solution is minimized. Furthermore, the energy requirement is low compared with evaporation, freezing and other thermal separation processes, resulting in a low cost involved in the separation unit operation. It is for this

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reason that the membrane separation process has attracted much attention in liquid food processing. The most typical examples are cheeze whey treatment (Hiddink *et al.* 1980), concentration of fruit and vegetable juices (Merson and Morgan 1968; Matsuura *et al.* 1973; Chua *et al.* 1987) and the treatment of alcoholic beverages (Wucherpfennig and Zuern 1980). All of the above processes are currently of wide industrial practice.

As for the concentration of tea components, there are several reports in the literature. Schreier and Mick (1984) studied the concentration of two black teas, i.e., Indian Broken and Darjeeling Orange Pekoe, by reverse osmosis. Concentration factors up to 6.5 for the extract, phenol and caffeine contents were achieved, although the retention was not as high for some volatile tea flavor compounds. Tamaki *et al.* (1986) used ultrafiltration membranes of 40,000–50,000 molecular weight cutoff to remove "tea cream" at 5–15 °C. Buhler and Olofsson (1981) described a hybrid RO-UF-distillation process to dehydrate tea extract. In the process, volatile tea aroma components were first collected from the tea extract by steam distillation (step A). Then, the tea extract was subjected to ultrafiltration by membranes of molecular weight cutoff ranging from 500 to 5,000 (step B). The permeate from the step B was further subjected to reverse osmosis treatment using a membrane with > 99% sodium chloride rejection (step C). Both retentates from steps B and C were combined to obtain a tea extract of desired concentration. Finally, the tea aroma components collected in the step A were combined with the concentrated tea extract. Nogy (1985) invented a process to filter tea extract by polyvinyl alochol, polyester and other synthetic polymeric membranes having pores of 2–4 nm in diameter to remove microbes and yeasts. The filtrate was further heated to sterilize, packed in a closed can, and held at a low temperature. Bonneau (1981) attempted to produce instant tea by using membrane technology. The tea extract was treated continuously by membranes of three different pore sizes, i.e., molecular weight cutoffs of 30,000, 10,000 and 250. The retentates from each step were combined and further concentrated by freeze drying, evaporation or by vacuum distillation. This process was particularly effective to remove disliked components such as alkaloids, terpenes, and benzpyrene from the tea extract.

Caffeine, polyphenols and amino acids are mainly responsible for tea quality. Preserving these components at a maximum level during tea processing is a great factor governing the quality of instant tea. Caffeine is an alkaloid of the purine group and a colorless compound with a slightly bitter taste. Several attempts were made to reduce the concentration of caffeine in tea because of its physiological function. The term polyphenol is a comprehensive one and includes a wide range of compounds. The substances within this group comprise flavanols, hydroxy flavanols, flavones and phenolic acids. Flavanols are water soluble and colorless, and give an astringent taste. They oxidize readily in an alkaline environment. Tea beverage quality is positively correlated with freshleaf flavanol concentration. Theanine (5-N-ethylglutamine) is an amino acid unique to tea. Other amino acids found in tea are common to most plants. Green tea beverage is pale yellow-green, and slightly more astringent than black tea, having a brothy characteristic imparted by theanine and other amino acids. The reverse osmosis concentration of fresh green tea juice was attempted by Zhang (1987). The number of membranes tested for this purpose was limited, however.

The objective of this work is: (1) To prepare membranes of different pore sizes from different polymeric materials, (2) to test the membranes so prepared for tea juice concentration under different operating conditions, thereby placing emphasis on finding membranes and operating conditions appropriate for the removal of caffeine into the permeate while concentrating other tea juice components in the retentate, and (3) to study the fouling phenomena during tea juice concentration thoroughly. Experimental methods are described and the results reported.

THEORETICAL

Modified Gel-model Theory for Fouling Phenomena

The most widely used model to predict the flux is the so-called "gel" model (Blatt *et al.* 1970).

$$u_{inf} = k \ln(c_g/c_1) \tag{1}$$

where u_{inf} is the limiting value of the permeation velocity u when pressure is increased, k, c_g and c_1 are mass transfer coefficient, gel concentration and feed concentration, respectively. There are, however, several limitations to this model, among them: (1) experimental fluxes are frequently much higher than predicted (Porter 1972; Cheryan 1986; Vassilis and Olund 1988); (2) the value of c_g has to be obtained experimentally, and it has been found to vary with operating conditions (Wijmans *et al.* 1984); (3) it does not account for specific membrane-solute interactions, the major case of fouling. We have modified the gel model by including the term for the interaction force between the membrane surface and the solute.

At a steady state, balance is established among forces working on the solute. As those forces, the diffusive force, F_{diff}, the interaction force, F_{int}, and the friction force, F_{fric}, are considered. The diffusion force is given as,

$$F_{diff} = -RT\, d \ln a/dz \tag{2}$$

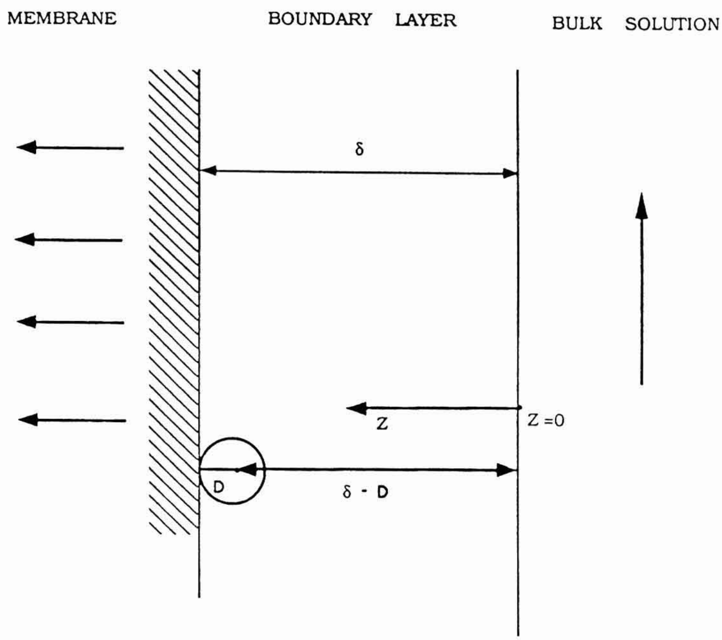

FIG. 1. SCHEMATIC DIAGRAM OF BOUNDARY LAYER

where *R, T, a* and *z* are gas constant, absolute temperature, activity and the distance from the edge of the boundary layer, respectively (see Fig. 1). Assuming that the activity coefficient remains constant,

$$F_{diff} = -(RT/c)dc/dz \tag{3}$$

where *c* is the solute concentration in the boundary layer. Assuming further that the magnitude of the interaction force is reciprocally proportional to the distance between the solute and the membrane surface,

$$F_{int} = \alpha'/(\delta - z) \tag{4}$$

where δ and α' are the boundary layer thickness and the proportionality constant, respectively. Finally, the friction force between the solute and the solvent is assumed to be proportional to their relative velocity, and therefore,

$$F_{fric} = -\chi(u_{solute} - u_{solvent}) \tag{5}$$

where *x* is the proportionality constant. The solute flux, J_{solute}, is written as,

$$J_{solute} = u_{solute}c \tag{6}$$

in the boundary layer and also

$$J_{solute} = u_{solvent} c_3 \tag{7}$$

in the permeate solution, where c_3 is the solute concentration in the permeate. Approximating $u = u_{solvent}$, Eq. 5 becomes,

$$F_{fric} = -\chi u(c_3/c - 1) \tag{8}$$

At the steady state,

$$F_{diff} + F_{int} + F_{fric} = 0 \tag{9}$$

Combining Eq. 3, 4, 8 and 9 and rearranging,

$$-Ddc/dz + \alpha c/(\delta - z) + u(c - c_3) = 0 \tag{10}$$

where $D = RT/x$ and $\alpha = \alpha'/x$. When the solute separation is 100%, $c_3 = 0$, therefore,

$$-Ddc/dz + \alpha c/(\delta - z) + uc = 0 \tag{11}$$

Solving Eq. 11 with the boundary condition,

$$c = c_1 \; at \; z = 0 \tag{12}$$

$$u = (D/z)\ln(c/c_1) - (\alpha/z)\ln(\delta/(\delta - z)) \tag{13}$$

Introducing further,

$$c = c_2 \; at \; z = \delta - \mathbf{D} \tag{14}$$

where c_2 is the solute concentration at the closest vicinity of the membrane surface, and **D** is the distance of the solute that is in the position closest to the membrane surface. For example, when the position of the solute is given by that of the center of a spherical solute, **D** is the radius of the sphere. Usually, δ is much larger than **D** and therefore $\delta - \mathbf{D} \simeq \delta$. Then, Eq. 13 becomes

$$u = k\ln(c_2/c_1) - (\alpha/\delta)\ln(\delta/\mathbf{D}) \tag{15}$$

where $k = D/\delta$. In analogy to the gel model c_2 increases rapidly as u increases, approaching the gel concentration c_g. The limiting velocity u_{inf} is then,

$$u_{inf} = k\ln(c_g/c_1) - (\alpha/\delta)\ln(\delta/\mathbf{D}) \tag{16}$$

When $u_{inf} = 0$,

$$k\ln(c_g/c_1) = (\alpha/\delta)\ln(\delta/\mathbf{D}) \tag{17}$$

Rearranging,

$$c_1 = c_g(\mathbf{D}/\delta)^{\alpha/D} \tag{18}$$

Note that $\mathbf{D}/\delta$ is less than unity and therefore c_1 is smaller than c_g. c_1 becomes even smaller as α increases. In other words, the feed concentration where the permeation velocity u_{inf} becomes zero decreases as the membrane-solute interaction increases. Such c_1 value decreases also, according to Eq. 18, as δ increases. The boundary layer thickness, δ, depends on the hydrodynamic condition of the feed solution and increases when the feed solution is less turbulent.

EXPERIMENTAL

Materials

Cellulose acetate E-398-3 powder supplied from Eastman Chemical Co. was used. Polyether sulfone (PES) Victrex 200P polymer was supplied from I.C.I. PLC in powder form. The polymer was dried at 150 °C for 4 hours before use. Polyvinyl alcohol polymer (molecular weight 100,000) was supplied from Fluka A.G. Polyamide polymer (poly-m-phenylene-iso(70)-co-tere(30)-phthalamide, molecular weight 31,100) was laboratory produced by the method described by Gan *et al.* (1975). Polyethersulfone polymers were used without further treatment. Nonfabric cloth, Tyvek 1079 D^R supplied by Dupont de Nemours Co., was used as a backing material. All chemicals used for the experiment were of reagent grade. Green tea powder was supplied from Zhejiang Province, P.R. China.

Membrane Preparation

Cellulose acetate membranes were prepared according to the method outlined in the literature (Sourirajan and Matsuura 1985). The details of the membrane preparation conditions are given in Table 1. The casting solution kept at 5 °C was cast on a smooth glass plate. The temperature of the casting atmosphere and the relative humidity of the casting atmosphere were 25 °C and 55%, respectively.

TABLE 1.
CONDITIONS OF MEMBRANE PREPARATION

Film number	Casting solution composition			Gelation bath composition		Gelation bath temperature
	Polymer wt-%	Solvent wt-%	Nonsolvent wt-%	Water vol-%	Ethanol vol-%	°C
	CA	Acetone	$Mg(ClO_4)_2$, water			
CA_{35}	17.0	69.2	1.45, 12.35	65	35	3
CA_{40}	17.0	69.2	1.45, 12.35	60	40	3
CA_{us}	17.0	69.2	1.45, 12.35	100	0	3
CA_{60}	17.0	69.2	1.45, 12.35	100	0	3
CA_{80}	17.0	69.2	1.45, 12.35	100	0	3
CA_{85}	17.0	69.2	1.45, 12.35	100	0	3
	PA	DMA	$LiNO_3$			
PA_{11}	16.9	76.2	6.9	100	0	3
PA_{13}	16.9	76.2	6.9	100	0	3
PA_{19}	16.9	76.2	6.9	100	0	3
	PVA	DMSO	water			
PVA_1	14.0	21.5	64.5	[a]		25
PVA_2	10.1	0.0	89.9	[a]		25
	PES	DMSO	PVP			
PES_1	23.0	72.4	4.6	100	0	3
PES_2	23.0	76.2	0.8	100	0	3

Shrinkage temperature, CA_{60} = 60 °C, CA_{80} = 80 °C, CA_{85} = 85°C, no shrinkage for other membranes

Solvent evaporation time, PA_{11} = 11 min, PA_{13} = 13 min, PA_{19} = 19 min at 95 °C, specified in the text for other membranes

PVA and PES membranes were cast on nonfabric cloth. Other membranes were cast on a smooth glass plate.

CA = cellulose acetate, PA = aromatic polyamide, PVA = polyvinyl alcohol, PES = polyethersulfone, DMSO = dimethyl sulfoxide, DMA = dimethyl acetamide, PVP = polyvinyl pyrrolidone

[a] Na_2SO_4, 20 g, H_2SO_4, 1 mL, and glutaraldehyde, 0.1 mL in 100 g of water

The membrane thickness was 254 μm. The cast film was left in the casting atmosphere for 30 s for the partial evaporation of the solvent before it was immersed in the gelation bath. The pore size of the membrane was controlled either by changing the ethanol content of the gelation bath or by changing the temperature of the shrinkage that followed the gelation step.

Aromatic polyamide membranes were prepared from poly-m-phenylene-iso(70)-co-tere(30)-phthalamide polymer synthesized in the laboratory. The membranes were prepared according to the method outlined in the literature (Nguyen *et al.* 1987). The details of the film preparation conditions are given in Table 1. The casting solution was cast on a smooth glass plate.

Then, the cast film together with the glass plate was placed in a preheated oven. Solvent was partially evaporated in the oven at 95 °C for a period specified in Table 1 before it was immersed in ice cold water for gelation. The membrane was kept in the gelation bath for more than 8 h.

Polyvinyl alcohol membranes were prepared according to the method outlined in the literature (Korsmeyer and Peppas 1981). The composition of the casting solution is given in Table 1. Polyvinyl alcohol was dissolved into either aqueous solution of dimethylsulfoxide or water. The solution was then stirred at 100 °C for 4 h to dissolve the polymer completely and subsequently kept at 23 °C for 2 weeks to ensure that no air bubbles were present in the solution. The casting solution was cast on a nonfabric cloth in the ambient atmosphere (24 °C < 60 RH%). The cast film was left in the ambient atmosphere for one minute for the partial evaporation of solvent and then immersed into an aqueous solution including Na_2SO_4, H_2SO_4 and glutaraldehyde for 12 h for cross-linking. The membranes were then placed into pure water until they stood apart from glass plates naturally.

Polyethersulfone membranes were prepared according to the method outlined in the literature (Miyano *et al.* 1990). The compositions of the casting solution are given in Table 1. The membrane pore size was controlled by changing the casting solution composition. The casting solution was cast on a nonfabric backing cloth to a thickness of 254 μm in the ambient atmosphere (20 - 23 °C, < 60 RH%). After the cast film was left in the ambient atmosphere for 20 s the cast film together with the backing material was immersed into ice cold water for gelation. The membranes were kept in the gelation bath for more than 20 min.

Preparation of the Feed Tea Juice Solution

Green tea powder was weighed and dissolved in distilled water at 90 °C. Then, the solution was centrifuged at 6000 rpm to remove the sediment.

Reverse Osmosis Experiment

Two types of reverse osmosis cells were used in this study. One is the continuous type cell that was used for the characterization of membranes by sodium chloride separation or by polyethylene glycol (molecular weight 6,000) separation when the pore sizes of the membranes were those of ultrafiltration membranes. The testing of membranes for the separation and fractionation of the tea juice components at the TDS (total dissolved solid) of 1000 ppm was also performed by the continuous cell. The other is the static cell that was used for the testing of the tea juice concentration at much higher tea powder concentrations (TDS of 1% and above). The details of both continuous and static cells are described in Sourirajan (1970). The primary difference of both cells is that strong turbulence of the feed solution is created in the continuous cell by a rapid flow of the solution parallel to the membranes surface, while the turbulence is created by rotation of a magnetic stirrer in the close vicinity of the membrane in the case of the static cell. The effective membrane areas of the continuous cell and the static cell are 13.2 cm^2 and 9.6 cm^2, respectively. The details of the experimental method were also given by Sourirajan (1970). All experiments were of short run type and they were carried out at the laboratory temperature under specified operating pressures. The product rate (PR) and pure water permeation rate (PWP) were corrected to 25 °C using the relative viscosity and density data for water. The term "product" and "product rate" refer to membrane permeated solution when solute is present in the feed solution. The fraction solute separation obtained in each experiment was calculated from the equation

$$f = \frac{solute\ ppm\ in\ feed - solute\ ppm\ in\ product}{solute\ ppm\ in\ feed} \qquad (19)$$

In each experiment, PWP and PR in grams per hour per given area of film surface (13.2 cm^2 for the continuous cell and 9.6 cm^2 for static cell) were determined at the operating conditions employed.

Analysis of Tea Components

Analysis of caffeine, polyphenols and amino acids was performed by spectrophotometry following the method described in *Tea Plant Physiology and Biochemistry Handbook* (1983). According to the method, caffeine content was determined by ultraviolet spectrometry at 274 nm after adding lead acetate and sulfuric acid into the sample solution. The concentration of polyphenols was determined by ultraviolet spectrometry at 540 nm after adding ferrous tartarate into the sample solution and then diluting with buffer solution. The amino acids content was determined also by ultraviolet spectrometry at 570 nm after adding ninhydrin solution and buffer solution to the sample and heating at 100 °C. The Varian Cary 210 spectrophotometer was employed for the spectrophotometric measurement.

The total organic carbon (TOC) content was determined by Beckman Total Carbon Analyzer, Model 915B. Total dissolved solid (TDS) was determined by gravimetric method. The concentration of aqueous sodium chloride solution was determined by conductivity method. The concentration of aqueous polyethylene glycol solution was determined by Total Carbon Analyzer using a calibration curve betwen TOC and polyethylene glycol concentration. The pH value of the solution was determined by pH Meter, Fisher Model 630. The pH of the feed solution was adjusted by adding 1 M sodium hydroxide solution or by adding 1 M hydrochloric acid solution.

RESULTS AND DISCUSSION

Relationship Between TDS and Other Tea Juice Components

The following linear relationship was obtained between TOC (ppm) and TDS (ppm) values in feed tea juice samples.

$$TOC = 0.400\ TDS \tag{20}$$

While TDS is reported as the feed tea powder concentration to include all tea juice components, the separation was determined on the basis of TOC. Therefore, the separation data for the solutes which involve all tea juice components are reported hereafter as TOC separation. In the feed tea juice sample the following relationship was found between TDS and tea juice components:

Caffeine 6.8% of TDS
Polyphenols 15.2% of TDS
Amino acids 5.6% of TDS

Reproducibility of the Data

Each membrane listed in Table 1 was at least triplicated to examine the reproducibility of the data from different membrane coupons. A typical example is shown in Table 2 for a cellulose acetate membrane. It is clear that the standard deviation of the permeation rate data is ± 10%, whereas that of the solute separation is ± 1.3%.

Membrane Characterization

All the membranes used for the tea juice concentration experiments were characterized by reverse osmosis experiments with 3500 ppm sodium chloride under the operating pressure of 1724 kPa gauge. The results are summarized in Table 3. The table shows that the sodium chloride separation increases and the product permeation rate decreases as the shrinkage temperature of cellulose acetate membrane increases. All aromatic polyamide membranes show sodium chloride separation greater than 93%, but the permeation rate is about one half of the cellulose acetate membrane of comparable sodium chloride separation. Polyvinyl alcohol membranes show 2 levels of sodium chloride separations, one 44.2% and the other 5.0%. The pure water permeation rate of the latter membrane is two orders of magnitude higher than that of the former membrane, indicating that the cross-linking is more effective in the former membrane and the cross-linking decreases the permeation rate enormously. In both membranes a significant decrease from the pure water permeation rate to the product rate is observed. This is probably due to the membrane compaction. Polyethersulfone

TABLE 2.
REPRODUCIBILITY OF THE EXPERIMENTAL DATA[a]

	Sodium chloride experiment[b]			Tea juice experiment[c]				
	PWP	PR	NaCl sep.	PR	TOC	Caffeine	Polyphenols sep.	Amino acids
	g/h	g/h	%	g/h	%	%	%	%
Film 1	132.19	117.15	54.01	79.74	90.42	58.39	90.29	98.56
Film 2	139.45	122.71	50.13	80.85	90.31	55.83	90.09	99.71
Film 3	160.64	140.70	51.47	91.70	90.70	51.46	89.94	96.92
Film 4	138.87	120.55	51.06	81.14	89.66	54.48	88.50	99.71
Film 5	103.41	89.96	52.14	62.40	90.72	51.88	92.12	99.62
Average	134.91	126.56	51.76	65.46	90.36	54.41	90.51	98.90
Standard deviation	18.43	19.30	1.30	15.27	0.39	2.57	1.28	1.08

[a] Membrane, $CA_{u,}$; effective film area, 13.2 cm^2; operating pressure, 1724 kPa gauge; [b]feed NaCl concentration, 3500 ppm; [c]feed TDS, 1000 ppm.

membranes were characterized by polyethylene glycol, PEG 6,000 and PEG 20,000, solutes. The feed PEG concentration was kept at 100 ppm and the experiment was performed under 345 kPa gauge. As expected, polyethersulfone membranes showed reasonably high separations to both PEG solutes.

Effect of the Pore Size on the Performance of Cellulose Acetate Membranes

Figure 2 summarizes the data on the effect of the pore size of cellulose acetate membranes on the separation of various tea juice components and on the product rate. As expected, as the membrane pore size decreases the sodium chloride separation increases and the product rate decreases. The separation of typical tea juice components, such as amino acids, polyphenols and caffeine, increases with an increase in sodium chloride separation. The separation data based on TOC also increases with an increase in sodium chloride separation. The order in the separation of various tea juice components is as follows:

$$amino\ acids > TOC \simeq polyphenols > caffeine \qquad (21)$$

TABLE 3.
MEMBRANE CHARACTERIZATION[a]

Film No.	PWP g/h	PR g/h	NaCl separation, %
CA_{35}	143.09	127.77	49.92
CA_{40}	214.92	186.98	33.78
$CA_{u.s}$	134.91	126.56	51.76
CA_{60}	63.84	60.77	82.53
CA_{80}	23.77	19.24	96.03
CA_{85}	15.53	12.22	95.70
PA_{11}	9.98	8.32	93.73
PA_{13}	8.54	7.05	93.83
PA_{19}	7.48	6.14	97.50
PVA_1	2.11	1.63	44.17
PVA_2	763.8	465.5	4.99
PES_1^b	24.86		77.2[c], 92.6[d]
PES_2^b	117.86		36.1[c], 86.5[d]

[a] Experimental data collected with 3500 ppm NaCl feed solution, at 1724 kPa gauge, and with effective film area of 13.2 cm^2
[b] Experiment conducted with polyethylene glycol (PEG) solute at 345 kPa gauge
[c] With PEG 6,000
[d] With PEG 20,000

One of the objectives of this study is to find a membrane that enables the removal of caffeine into the permeate while retaining polyphenols and other tea juice components in the retentate. The unshrunk cellulose acetate membrane which shows 52% sodium chloride separation seems to be the best for this purpose among all cellulose acetate membranes studied, and therefore extensive investigations were further performed on this particular membrane.

Effect of Membrane Materials on the Separation Pattern of Various Tea Juice Components

The data for the separation of tea juice components by membranes other than cellulose acetate membranes are summarized in Table 4. All data were obtained by experiments with 1000 ppm TDS in the feed solution under the operating

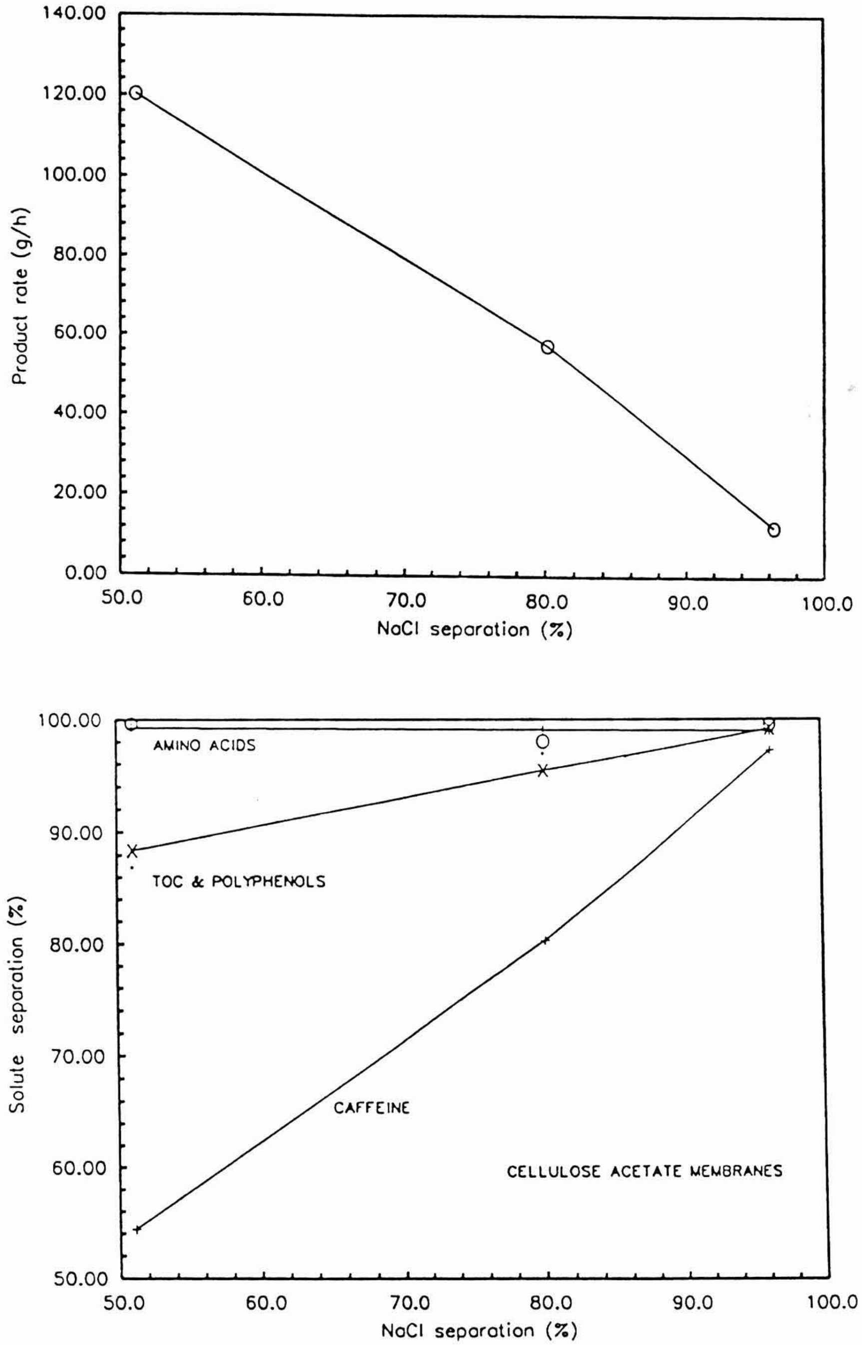

FIG. 2. SEPARATIONS OF VARIOUS TEA JUICE COMPONENTS AND PRODUCT RATE VERSUS SODIUM CHLORIDE SEPARATION

TABLE 4.
RESULTS OF TEA JUICE CONCENTRATION BY MEMBRANES OTHER THAN CELLULOSE ACETATE MEMBRANES[a]

Film No.	PR	Solute separation, %			
	g/h	TOC	Caffeine	Polyphenols	Amino acids
PA_{11}	7.91	97.74	95.58	98.18	98.68
PA_{13}	6.89	97.13	95.70	97.57	95.28
PA_{19}	6.13	97.00	98.65	96.15	99.99
PVA_1	0.77	75.20	-	98.97	-
PVA_2	7.80	44.80	10.73	59.76	-
PES_1	21.41	55.58	-1.71	57.78	3.02
PES_2	82.63	48.75	13.45	39.28	2.31

[a]Feed TDS 1000 ppm; operating pressure, 345 kPa gauge for PES films and 1724 kPa gauge for other films; effective film area, 13.2 cm^2

pressure of 1724 kPa gauge unless otherwise specified in the Table. Since all polyamide membranes show very high sodium chloride separations (above 95%), separation data for all tea juice components are also very high. The average separations for amino acids, TOC, polyphenols and caffeine are 98.68, 97.73, 98.18 and 95.58%, respectively, for PA_{11}. Therefore, the order in the separation for various tea juice components given to the cellulose acetate membranes is still valid.

The above order is also valid for polyvinyl alcohol membranes, although no data was obtained for amino acids solutes. It is also interesting to note that a significant drop in the product rate took place during the tea juice treatment by polyvinyl alcohol membranes.

The materials effect on the pattern of the separation of the tea juice components is seen most evidently in the experiment with polyethersulfone membranes. The patter general to all other polymeric materials; i.e.

$$\text{TOC} \simeq \text{polyphenols} > \text{caffeine} \tag{22}$$

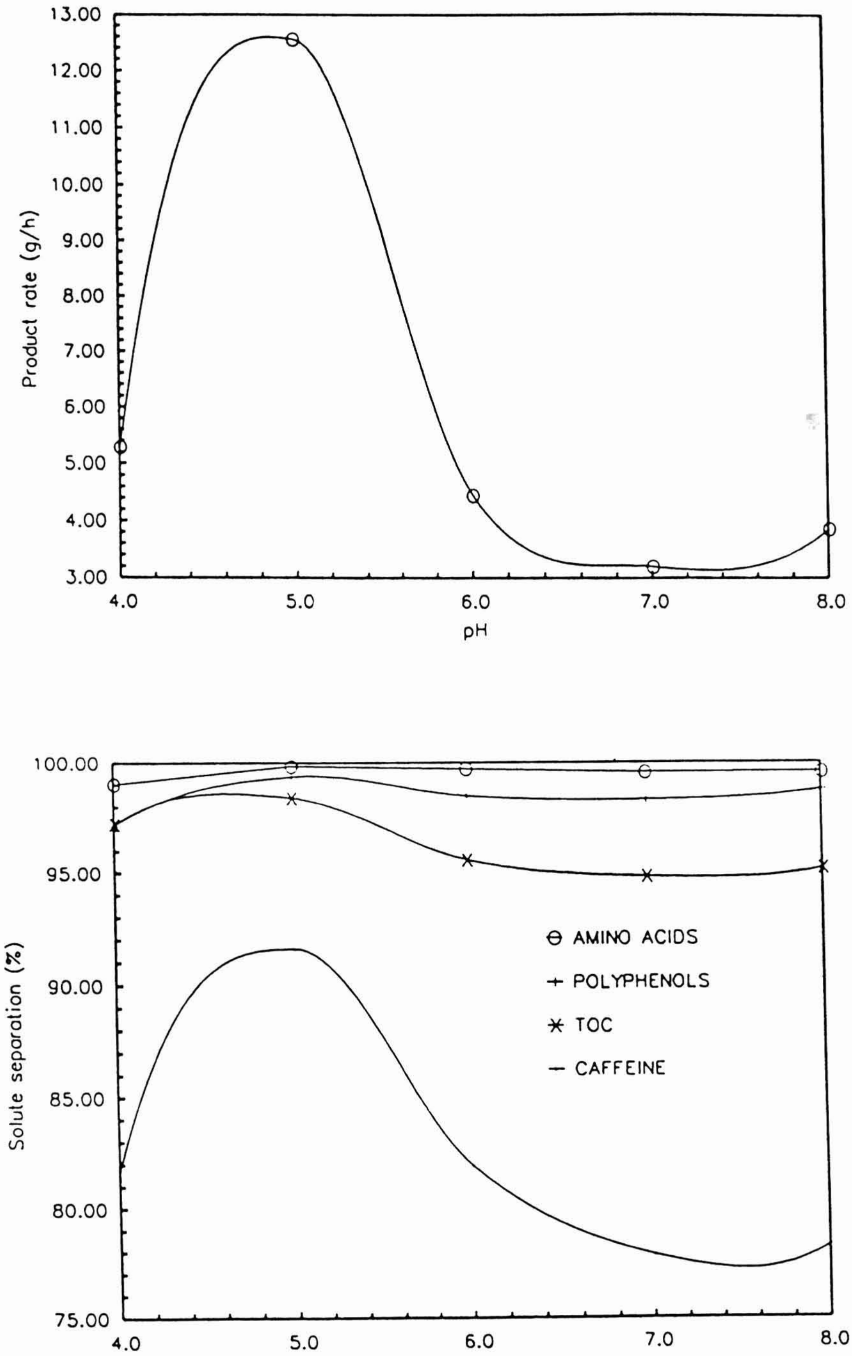

FIG. 3. SEPARATIONS OF VARIOUS TEA JUICE COMPONENTS AND PRODUCT RATE FOR DIFFERENT FEED pH

is also valid for polyethersulfone membranes. However, the separation of amino acids was the lowest among all juice components studied. Apparently, the repulsive force exerted from the membrane material due to the ionic charge of amino acids molecules was not enough to prevent the nearly free passage of the amino acids molecules. The reasons for the poor separation of other unionized tea juice components, such as polyphenols and caffeine, is unknown. A more comprehensive study is needed on the contributions of the solute/membrane interaction and the pore size and the pore size distribution of the membrane.

Effect of pH of the Feed Solution on the Membrane Performance

The effect of pH of the feed tea juice was studied using a cellulose acetate membrane shrunk at 85 °C at the operating presssure of 1724 kPa gauge. The TDS of feed tea juice was 1000 ppm. The experimental results are illustrated in Fig. 3. Both caffeine separation and the product rate show a maximum at pH 5. The separation based on TOC also shows a maximum at pH 5. However, the separations of amino acids and polyphenols remain above 97% in the entire range of pH. That the caffeine separation increases with a decrease in pH when the pH value is more than 5 is understandable considering that caffeine has the nature of both secondary and tertiary amines. At lower pH values the molecule tends to be more dissociated, resulting in stronger rejection from the membrane surface and less blocking of the pore by solute adsorption. The presence of polyphenols and tea components other than caffeine may also intensify the fouling when pH is more than 5. It is difficult to explain, however, why the caffeine separation and the product rate decreased with a further decrease of feed pH.

Effect of the Feed Concentration on the Membrane Performance

Reverse osmosis concentration of tea juice was performed with the static cell at feed concentrations of 1.09, 2.83 and 4.71 × 10 kg/m^3(about 1,3, and 5%), as shown in Fig. 4. The membrane used for the experiment was a CA_{us} film, i.e., a cellulose acetate membrane without any shrinkage, since that membrane was the best for the fractionation of polyphenols and caffeine (Fig. 2). Solute separations were higher in this case than shown in Fig. 2 due to higher feed concentration. Both TOC and polyphenols separations were more than 98%. The separation was more than 90% in most cases for caffeine in contrast to the 52% value when the feed TDS was 1000 ppm. Caffeine separation increases with an increase in the operating pressure. This membrane is, therefore, not effective for the fractionation of polyphenols and caffeine when the feed TDS is higher than 1%. Figure 4 also shows that the product rate levels off with an increase in the operating pressure and the asymptotic value decreases with an increase in the feed TDS. The pattern observed in the product rate data is similar to ultrafiltration data where the gel model is applicable. Together with the separation data of

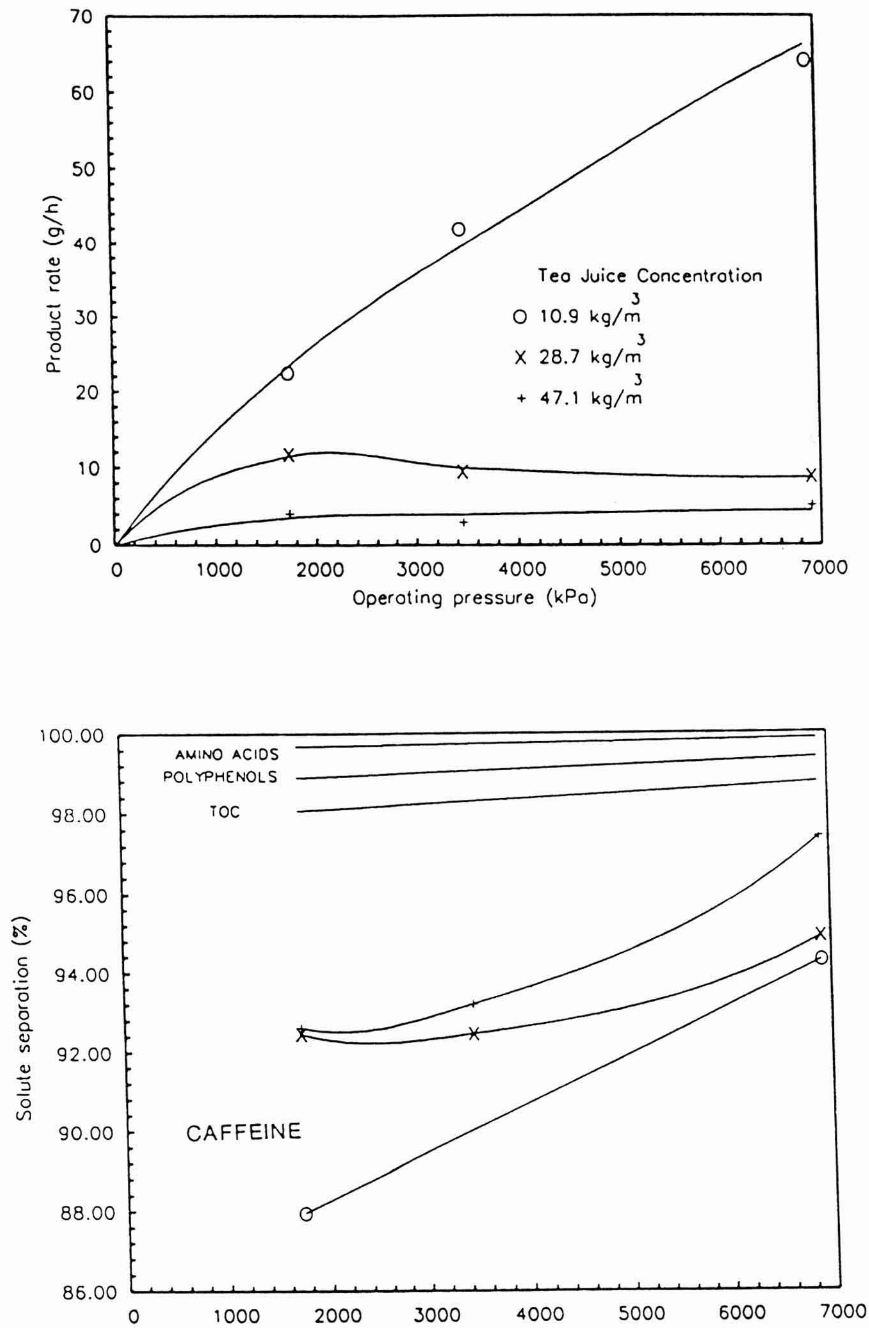

FIG. 4. SEPARATIONS OF VARIOUS TEA JUICE COMPONENTS AND PRODUCT RATE FOR DIFFERENT FEED TDS VALUES AND OPERATING PRESSURES

the caffeine solute that has increased significantly with an increase in the feed concentration, we have concluded that a concentrated layer formed at the membrane/solution boundary contributed to the reduction in flux and an increase in solute separation.

Effect of the Membrane Material and the Feed Solution Turbulence on the Membrane Fouling

The green tea juice concentration was conducted at different feed TDS to study the fouling effect. Two different membranes were used for the experiment, one was CA_{60} membrane and the other was PES_2 membrane. It is known that organic solutes are more strongly attracted to polyethersulfone polymer due to the stronger hydrophobicity of the latter polymeric material. The operating pressures were 1724 kPa gauge and 690 kPa gauge for CA and PES membranes, respectively. Experiments were conducted in a static cell with two degrees of turbulence of the feed tea juice; one when the magnetic stirrer was vigorously rotated in the close vicinity of the membrane surface and the other when the rotation of the stirrer was completely stopped. Since high feed concentrations were involved in this experiment, the separation of the solute based on TOC was almost complete. The product permeation rates are plotted versus logarithm of the feed concentration in Fig. 5. These product permeation rate data are the asymptotic values obtained in the plot, product rate versus operating pressure (see Fig. 4), and therefore correspond to the limiting permeation velocity, u_{inf}. Following Eq. 16 there is a linear relationship between the product permeation rate and the logarithm of the feed tea juice concentration. The slope of the straight line is less when the rotation of the stirrer was stopped, since the mass transfer coefficient k becomes smaller corresponding to less turbulence of the feed solution. A significant decrease in observed in the feed the juice concentration that corresponds to zero product permeation rate when the membrane material is changed from cellulose acetate to polyethersulfone. This is expected from Eq. 18, since the interaction between the solute and the membrane material is stronger for polyethersulfone than for cellulose acetate due to higher hydrophobicity of polyethersulfone material. This was confirmed by the results from liquid chromatography experiments (Taketani *et al.* 1982). The effect of the turbulence on c_1 corresponding to $u_{inf} = 0$ is not so spectacular, yet small decreases in such c_1 values are observed for both membrane materials when the rotation of the stirrer in the cell is stopped. Thus, the experimental results testify to the validity of the theory for the fouling established in this paper. The theory includes parameters related to the solute-membrane interaction force. It would be very useful if these parameters could be predicted.

It should be noted that the entire approach is based on the gel model. Attempts are currently being made to analyze the experimental data on the basis of the osmotic pressure effect.

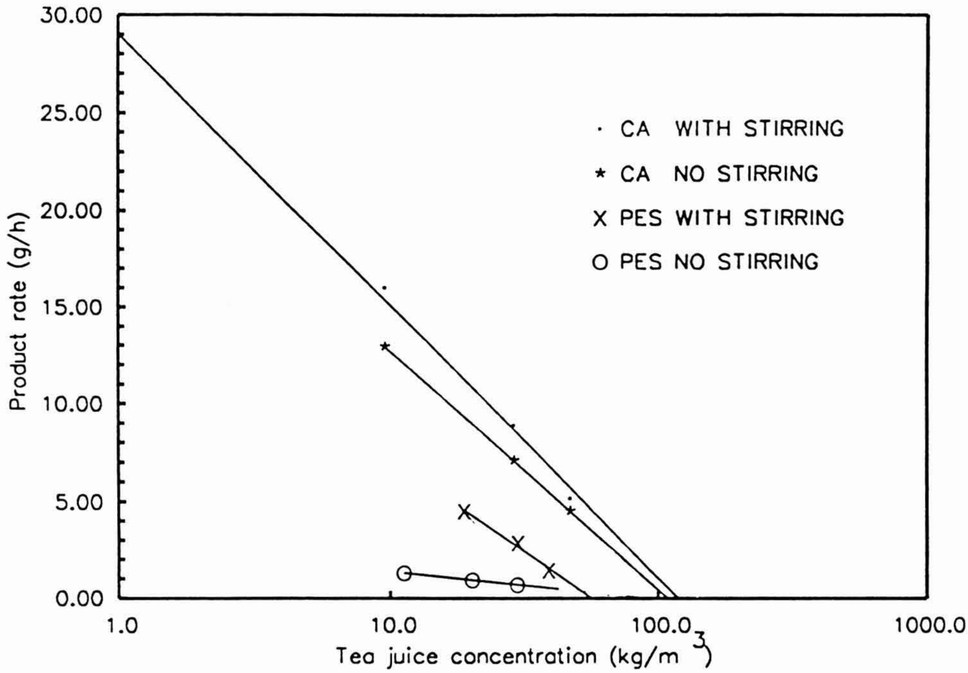

FIG. 5. PRODUCT RATE VERSUS LOG (FEED TDS)

Films, CA_{60} and PES_2; Operating pressure, 1724 kPa gauge for CA film and 690 kPa gauge for PES film.

CONCLUSIONS

The following conclusions were drawn from the experimental results of this work.

(1) The concentration of green tea juice can be performed effectively by reverse osmosis membranes prepared from cellulose acetate and aromatic polyamide materials.

(2) Though the fractionation of caffeine (in the permeate) and other tea juice components (in the retentate) can be achieved by cellulose acetate membranes without shrinkage at low feed concentrations, the fractionation becomes less effective at high tea juice concentrations.

(3) There is an optimum value of pH for the separation of the tea juice components and for the product rate.

(4) The modified gel model proposed appears to fit the experimental data. A more detailed study is called for to justify the proposed model.

REFERENCES

BLATT, W.F., DRAVID, A., MICHAELS, A.S. and NELSEN, L.M. 1970. Solute polarization and cake formation in membrane ultrafiltration: causes, consequences, and control technique. In *Membrane Science and Technology,* (J.E. Flinn, ed.) Plenum, New York.

BONNEAU, M. 1981. Removing harmful components from vegetable extracts by filtration on semipermeable membranes. French Patent FR 2,499,369.

BUHLER, M. and OLOFSSON, M. 1981. Process for the preparation of concentrated extracts of coffee, tea or substitutes therefore. UK Patent GB 2,057,849.

CHERYAN, M. 1986. *Ultrafiltration Handbook,* Technomic, Lancaster, PA.

CHUA, H.T., RAO, M.A., ACREE, T.E. and CUNNINGHAM, D.G. 1987. Reverse osmosis concentration of apple juice: flux and flavor retention by cellulose acetate and polyamide membranes. J. Food Process Eng. *9,* 231–245.

GAN, L.H., BLAIS, P., CARLSSON, D.J., SPRUNCHUK, J. and WILES, D.M. 1975. Physicochemical characterization of some fully aromatic polyamide. J. Appl. Polym. Sci. *19,* 69.

HIDDINK, J., DE BOER, R. and NOOY, P.F.C. 1980. Reverse osmosis of dairy liquids. J. Dairy Sci. *63,* 204.

KORSMEYER, R.W. and PEPPAS, N.A. 1981. Effect of the morphology of hydrophilic polymetric matrices on the diffusion and release of water soluble drugs. J. Membrane Sci. *9,* 211–227.

MATSUURA, T., BAXTER, A.G. and SOURIRAJAN, S. 1973. Concentration of fruit juices by reverse osmosis using porous cellulose acetate membranes. Acta Alimentaria *2,* 109–150.

MERSON, R.L. and MORGAN, A.I. 1968. Juice concentration by reverse osmosis. J. Food Technol. *22,* 97.

MIYANO, T., MATSUURA, T. and SOURIRAJAN, S. 1990. Effect of polymer molecular weight, solvent and casting solution composition on the pore size and the pore size distribution of polyethersulfone (Victrex) membrane. Chem. Eng. Comm. (In Press.)

NGUYEN, T.D., MATSUURA, T. and SOURIRAJAN, S. 1987. Effect of nonsolvent additives on the pore size and the pore size distribution of aromatic polyamide RO membranes. Chem. Eng. Comm. *54,* 17–36.

NOGY, A.S. 1985. Long-life drink, e.g., fruit juice prepn., by ultrafiltration using synthetic resin membrane followed by sterilization by heating. Japanese Patent 60,110,271.

PORTER, M.C. 1972. Concentration polarization with membrane ultrafiltration. Ind. Eng. Chem. Prod. Res. Dev. *11,* 234.

SCHREIER, P. and MICK, W. 1984. Uber das Aroma von schwarzem Tee: Herstellung eines Teekonzentrates mittels Umgekehrosmose und dessen analytische Charakterisierung. Zeit. fur Lebensmittel-Untersuch. Forsch. *179*, 113–118.

SOURIRAJAN, S. 1970. *Reverse Osmosis*, Academic, New York.

SOURIRAJAN, S. and MATSUURA, T. 1985. *Reverse Osmosis/Ultrafiltration Process Principles*, pp. 513–517, National Research Council of Canada, Ottawa.

TAKETANI, Y., MATSUURA, T. and SOURIRAJAN, S. 1982. Use of liquid chromatography for studying reverse osmosis and ultrafiltration. Sep. Sci. Technol. *17*, 821.

TAMAKI, Y., YAMAMOTO, K. and YASUDA, T. 1986. Processing of tea extract. Japanese Patent 6,336,745.

VASSILIS, G. and OLUND, K. 1988. Mass transfer in the membrane concentration polarization layer under turbulent cross flow. II. Application to the characterization of ultrafiltration membranes. J. Membr. Sci. *37*, 145–163.

WIJMANS, J.G., NAKAO, S. and SMOLDERS, C.A. 1984. Flux limitation in ultrafiltration: osmotic pressure model and gel layer model. J. Membrane Sci. *20*, 115–124.

WUCHERPFENNIG, K. and ZUERN, F. 1980. Concentration of wine by hyperfiltration. Wein Wissen. *35*, 342.

ZHANG, S.Q. 1987. Separation and concentration of fresh green tea juice by ultrafiltration and reverse osmosis, MS Thesis submitted to Zhejiang Agricultural University.

PRODUCTION PLANNING WHEN BATCHING IS PART OF THE MANUFACTURING SEQUENCE

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ABSTRACT

Batching is a routine part of food production, even in many manufacturing sequences which have continuous components. Determining the correct number of batches to be produced in the face of continuous demand for final product and multiple demands on the batches from many products is a computationally complex problem. An organizational and computational scheme for tracking the impact of the batching decision is presented. The structure provides means for determining resource use patterns and for costing those patterns for a given production plan. The data necessary to drive this system are the costs, the batch formulation and yields and the other resources required by the product. The scheme is suited for electronic computation and can be rendered in a straightforward way on a microcomputer. An example illustrating how the data are organized is provided.

INTRODUCTION

Batching is an inevitable part of many food manufacturing sequences. While a ''continuous process may be the ideal, batching is a regular reality of food production because of capital investment in batching equipment and because the ''continuous process'' technology is not always available to produce the same output as a batch system. A ''batch'' of product is created when a discrete quantity of material, usually a mixture or a formula, is made available at specific, discrete times. The output from a batch is then available for continued processing or packaging into products.

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Planning production is done to meet anticipated demand for products. While producing exactly the amount of final product demanded may be most efficient, this amount is seldom the amount that will be manufactured from a discrete number of batch outputs intrinsic to the manufacturing system. The difference between the production target and the amount implied by a batch formula introduces an imprecision in planning that may have important financial consequences, especially in a low margin industry. Idle equipment and labor may occur due to production bottlenecks. Excessive materials in inventory ties up capital, ingredients and finished products. Insufficient product amounts may reduce customer satisfaction because of untimely delivery.

A strategy to overcome these difficulties is to supply the production manager with information useful for making batching decisions (how many batches and in what sequence) which make efficient use of resources. Without such information the batching decisions are made based on experience, intuition or guess work. With the correct information, the impact of these decisions on company resource use can be revealed and evaluated. These batching decisions are further complicated by allowing for "partial batches" which require the same equipment, processing time and labor, but result in smaller volumes of output, hence increasing the overall unit cost for that facility. The yield from a batch may be intrinsically variable, depending upon the quality attributes of the inputs, while the demand for batch outputs may come from many products, or these outputs may be inputs to yet other batches. Managing information for hundreds of products, formulas and resources means that making batching decisions without accurate, timely information risks many inefficiencies.

Effective production planning information in batching situations can be provided by combining the Matrix Data Structures (MDS) approach with the "Gozinto" procedure. These approaches organize information for access and manipulations by computer, so the production planner/controller can quickly determine the financial impact and the resource requirements to produce partial or whole batches of a formula.

This paper will provide a discussion of batching and its inherent problems and will suggest how information to support batching decisions can be generated and used. An example of how MDS and the Gozinto procedure can be applied to a production process for Spaghetti Sauce products illustrates these methods.

BATCHING PROBLEMS

Typical

Batching is a process during which an established quantity of a formula is prepared in a single operation. Many food production systems use batches for various technological or economic reasons. Typical problems associated with batches are enumerated below. A generalization that encompasses these problems is that it is convenient to produce some intermediate manufacturing materials in very large quantities, for example batches of 10,000 lb, but it is not convenient to sell end product this way, but rather as cases of product. These two facts of the food business, production in large quantities but sales in small ones, tend to cause difficulties for the decision makers.

(1)Actual Versus Planned Production Variance. Making discrete production processes respond to continous demand implies a variation in the actual volume of product produced from the volume planned. Such variations in batch yield may be due to attributes of the contituents of the batch or even the efficiency of labor making the batch, but these variations in yield complicate planning and product costing. (Yield is the ratio of the expected volume of a formula and the volume actually produced.)

(2)Batch Process Equipment Contributes to Bottlenecks. Batching constrains a manufacturing sequence because output from a batch is only available at specific times. The resulting bottleneck which occurs waiting for the availability of batch output may leave labor and machinery idle. Because batching equipment tends to be large scale, it is costly to expand capacity both in initial investment and in labor and support for that investment. Eliminating batch equipment causing production bottlenecks is not always feasible.

(3)Competition for the Same Resources Complicates Planning. One of the advantages that batching can provide is that output from the same batch may be used in several products. This competition for batch output provides planning alternatives that must be managed. Production targets (specified in cases) must be matched to the batch output in some efficient and appropriate way. Overproduction or underproduction implied by the yield from the batch must be distributed among the competing products which use the batch output.

(4)Multi-staged Processes Add Complexity to Planning. When batches are part of the production sequence for intermediate and final products, costing and resource allocation become difficult. An intermediate product like spaghetti sauce, may be used in several products, or it may be used as a final product. Determining the assignment of batching costs requires untangling a complicated flow of materials.

(5) Partial Versus Whole Batch Policies Effect Planning. When the option to produce a partial batch exists, the manager may theoretically produce just enough of a formula for the desired production target. Although some of the materials required would be adjusted to this lower amount, many resource inputs, especially labor and equipment time, remain the same. Rescaling the batch size may also require special expertise regarding the amounts of ingredients that must be used, since the impact on product qualities may not scale linearly. Also, equipment performance of critical process steps may be a function of batch size, e.g., mixer time as affected by percent fill. Resulting changes in sensory perception of the product may damage sales and future demand for the product. The resources necessary to insure uniform qualities in output product would then need to be balanced against the advantages of the partial batch.

Practical Responses to Batching and Production Planning

''Real world'' responses to planning in the face of inadequate information especially include looking for a ''satisfactory'' response to the planning problem at hand. Left on his own without other information or incentives, the production planner minimizes his own problems rather than evaluating production alternatives. This often results in excess inventories on hand, regular overproduction of finished goods or other costly customs. The impact of these methods ripple through the organization causing difficulties in inventory management and pricing of goods. Over time a manager may develop an intuition about the problems related to batching, what works and what does not, but it does not mean that the methods and procedures that evolve are efficient.

What is missing from these intuitive approaches is a way to evaluate alternatives to determine which of the ones being considered is the best. Manual approaches to the required calculations for such evaluations are too tedious to even consider. But with the information organized properly, a computer based decision support system can be devised which can portray the appropriate facts quickly and reliably for the production planner. The requirements of such a structure are that it must be able to dynamically manage the batch production process, varying batching policies and expected yield variations. It must also support multiple processing stages and products competing for the same resources. MDS organization provides ways to develop planning information and product costs, while the Gozinto procedure provides the means to determine resource use in multistaged production processes. These organizational structures can be manipulated to provide the information necessary to manage batching. Suggestions for the use and development of these procedures can be found in Norback and Matthews (1981, 1982) and in Rice and Norback (1987). Details about the Gozinto procedure can be found in Vazsonyi (1958) and Mize, *et al.* (1971).

The Gozinto Matrix is created through a procedure which organizes production information into a lower triangle invertible matrix. When manipulated, resource requirements information is derived for every stage of a multistaged production process. Further manipulations of the Gozinto Matrix can provide feedback on the effect of batching and suggest ways to manage and control the production plan. The following is an example on how to apply the Gozinto procedure to determine the production requirements for producing a production plan. The example is of two products competing for the formula Spaghetti Sauce. The products are Spaghetti Sauce with noodles (SS w/N) and Spaghetti Sauce without noodles (SS). This example shows how to manipulate and organize the structures to get product resource requirements, product costs, and establish the cost and resource impact of producing product under the both partial and full batch production policies.

The Gozinto Procedure

Step. 1. Define the amounts of the resources, formulas, byproducts, weight conversions, and intermediate products directly required to produce the products in the production plan (Tables 1 and 2).

TABLE 1.
PER CASE REQUIREMENTS

Final product		S.S.	S.S. w/N
Spaghetti Sauce per case requirement:	Unit of Measure	Amount without Noodles	Amount With Noodles
32 ounce glass jars	each	12	12
Caps	each	12	12
Label for 32 oz./w noodles	each	12	0
Label for 32 oz. w/noodles	each	0	12
Carton for 32 ounce	each	1	1
Spaghetti Sauce	pound	24	0
Spaghetti Sauce w/noodles	pound	0	24

The Production Plan:

130 cases of 12, 32 ounce jars of Spaghetti Sauce
180 cases of 12, 32 ounce jars of Spaghetti Sauce with Noodles

Step 2. Diagram the production processes for the products required in the production plan. This diagram should show direct relationships between the intermediate products, formulas, byproducts, and resources required for the production of each finished product. An example is given in Table 3.

TABLE 2.
PER BATCH REQUIREMENTS

Formula- Spaghetti Sauce with Noodles Per Batch Requirements:	Unit of Measure	Amount
Spaghetti Sauce Formula	pound	800
Dry Noodles	pound	320
Water	pound	320
TOTAL: Pounds/Batch		1,440

Formula- Spaghetti Sauce Per Batch Requirements:	Unit of Measure	Amount
Water	pound	1,190.0
Acid, citric	pound	3.0
Beet color	pound	4.6
Textaid	pound	10.0
Starch	pound	45.0
Oil, soybean	pound	12.5
Spaghetti seasoning	pound	9.4
Cheese flavor	pound	0.4
Mushrooms, diced	pound	22.0
Fructose	pound	67.5
Salt, liquid	pound	18.5
Tomato paste	pound	116.2
Tomato flavor	pound	0.9
TOTAL: Pounds/Batch		1,500.0

Step 3. From the diagram, create a list with units of all finished products, intermediate products, formulas, byproducts and resources. Organize this list in order such that each item is listed above its required intermediary products and resources, i.e., nothing required by that item should appear above it in the list. (See Table 4).

TABLE 3.
REQUIREMENTS DIAGRAM

Spaghetti Sauce Without Noodles 32 ounce case	Spaghetti Sauce With Noodles 32 ounce case
Jars Caps Label Carton Spaghetti Sauce (batch)	Jars Caps Label w/noodles Carton Spaghetti Sauce w/noodles (batch)
	Spaghetti Sauce w/noodles (batch)
Spaghetti Sauce (batch)	Dry Noodles Water
Water Acid, citric Beet color Textaid Starch Oil, soybean Spaghetti seasoning Cheese flavor Mushrooms, diced Fructose Salt, liquid Tomato paste Tomato flavor	

Step 4. Create a square matrix of dimension the number of items in the list created from step 3, call this matrix N. Going from top to bottom and left to right, enter the row and column headings starting at the upper left of the matrix

TABLE 4.
GOZINTO ORDERING

Item Number	Item Descriptions	Unit of Measure
1	Spaghetti Sauce with Noodles	case
2	Spaghetti Sauce	case
3	Spaghetti Sauce with Noodles	batch
4	Spaghetti Sauce	batch
5	Spaghetti Sauce with Noodles	pound
6	Spaghetti Sauce	pound
7	Label with Noodles	each
8	Label	each
9	Cap	each
10	Jar	each
11	Carton	each
12	Dry noodles	pound
13	Water	pound
14	Acid, citric	pound
15	Beet color	pound
16	Textaid	pound
17	Starch	pound
18	Oil, soybean	pound
19	Spaghetti seasoning	pound
20	Cheese flavor	pound
21	Mushrooms, diced	pound
22	Fructose	pound
23	Salt, liquid	pound
24	Tomato paste	pound
25	Tomato flavor	pound

N. Each column represents an item unit produced by a combination of the row resource, intermediate, byproduct required to produce a single unit of each column item. Properly entered values result in a matrix that is square and lower triangular. For example, 3 lb of citric acid is required to produce a single batch of Spaghetti Sauce Formula. Columns 7 through 25 are not shown because they have no nonzero entries. This matrix is shown in Table 5.

Step 5. Create an identity matrix I of the same size as the matrix N. The inverse of the difference between the identity matrix I and matrix N will be the Gozinto matrix T.

$$T = (I - N)^{-1}$$

TABLE 5.
THE MATRIX N

Resource Requirements Descriptions			S S w/N cases 1	S S w/N pound 2	S S w/N batch 3	S S cases 4	S S pound 5	S S batch 6
S S w/N	cases	1						
S S w/N	pound	2	24					
S S w/N	batches	3		1/1,440				
S S	cases	4						
S S	pound	5			800	24		
S S	batches	6					1/1,500	
label w/N	each	7	12					
label	each	8				12		
cap	each	9	12			12		
jar	each	10	12			12		
carton	each	11	1			1		
N - noodles	pound	12			320			
Water	pound	13			320			1,190.0
Citric Acid	pound	14						3.0
Beet Color	pound	15						4.6
Textaid	pound	16						10.0
Starch	pound	17						45.0
Oil	pound	18						12.5
S. season	pound	19						9.4
Cheese flavor	pound	20						0.4
Mushrooms	pound	21						22.0
Fructose	pound	22						67.5
Salt	pound	23						18.5
Tomato Paste	pound	24						116.2
Tomato Flavor	pound	25						0.9

The matrix N is lower triangular and by definition is invertible when it is subtracted from the identity matrix (Anton 1981). A computer package can quickly invert the difference of these matrices to derive the matrix T. The following represents the T matrix, the Gozinto Matrix:

$T_{i,j}$ = the amount of i required to produce 1 unit of j. The result for an inversion is shown in Table 6.

The entries in matrix T will be the amount in detail of each row item required to produce each unit of column item. For example, to produce one case of Spaghetti Sauce with Noodles requires 0.027 lb of Citric Acid.

The matrix T offers planning information in the form of production resource requirements. Having resource unit costs in hand permits the calculation of product unit costs. The production plan allows the computation of the total resource requirements and the total cost of the plan. The following computations will support the application of the partial batch production policy. Once presented, there will be a discussion of how the production could change the plan to support the whole batch production policy.

TABLE 6.
THE MATRIX T = $(I - N)^{-1}$

Resource Requirements			S S w/N cases	S S w/N pound	S S w/N batch	S S cases	S S pound	S S batch
Descriptions			1	2	3	4	5	6
S S w/N	cases	1	1.					
S S w/N	pound	2	24.000	1.				
S S w/N	batches	3	0.017	1/1441	1.			
S S	cases	4				1.		
S S	pound	5	13.320	0.555	800.000	24.000	1.	
S S	batches	6	0.009	1/2703	0.534	0.016	1/1499	1.
label w/N	each	7	12.000					
label	each	8				12.000		
cap	each	9	12.000			12.000		
jar	each	10	12.000			12.000		
carton	each	11	1.000			1.000		
T - noodles	pound	12	5.330	0.222	320.000			
Water	pound	13	15.910	0.663	954.980	19.050	0.794	1,190.0
Citric Acid	pound	14	0.027	0.001	1.601	0.048	0.002	3.0
Beet Color	pound	15	0.041	0.002	2.455	0.074	0.003	4.6
Textaid	pound	16	0.089	0.004	5.336	0.160	0.007	10.0
Starch	pound	17	0.400	0.017	24.010	0.720	0.030	45.0
Oil	pound	18	0.111	0.005	6.670	0.200	0.008	12.5
S. season	pound	19	0.084	0.003	5.016	0.150	0.006	9.4
Cheese flavor	pound	20	0.004	1/6757	0.213	0.006	1/3745	0.4
Mushrooms	pound	21	0.196	0.008	11.740	0.352	0.015	22.0
Fructose	pound	22	0.600	0.025	36.020	1.081	0.045	67.5
Salt	pound	23	0.164	0.007	9.872	0.296	0.012	18.5
Tomato Paste	pound	24	1.033	0.043	62.000	1.860	0.078	116.2
Tomato Flavor	pound	25	0.008	1/3003	0.480	0.014	1/1667	0.9

Calculating Costs

To derive unit costs for each stage in production requires the creation of a resource unit cost vector p. The vector p would be the number of rows in the matrix T in length, with the entries being the resource unit costs. Note that only *resource* costs are required as shown in Table 7.

TABLE 7.
THE COST MATRIX

Resource Unit Costs Descriptions			Unit Cost ($)
S S w/N	cases	1	
S S w/N	pound	2	
S S w/N	batches	3	
S S	cases	4	
S S	pound	5	
S S	batches	6	
label w/N	each	7	0.0112
label	each	8	0.0112
cap	each	9	0.0269
jar	each	10	0.1093
carton	each	11	0.2123
P - Noodles	pound	12	0.5215
Water	pound	13	0.0000
Citric Acid	pound	14	0.7591
Beet Color	pound	15	0.7041
Textaid	pound	16	0.6944
Starch	pound	17	0.4595
Oil	pound	18	0.3441
S. season	pound	19	1.7174
Cheese flavor	pound	20	6.1775
Mushrooms	pound	21	0.5446
Fructose	pound	22	0.0693
Salt	pound	23	0.0299
Tomato Paste	pound	24	0.3851
Tomato Flavor	pound	25	3.5104

Product Unit Costs

Product unit costs provide managers with an idea of how much they can expect a production plan to cost. To get the resource unit costs for each stage of production, take the dot product of the vector p and the matrix T. The new matrix C would be of the same dimension as T; the entries would be the resource costs for each stage of production. The column totals would be the total unit production stage cost. The matrix C may be represented by the following:

$$C = p \cdot T$$

Table 8 shows the costs of our example.

TABLE 8.
PRODUCT UNIT COSTS

Resource Requirements Descriptions			S S w/N cases 1	S S w/N pound 2	S S w/N batch 3	S S cases 4	S S pound 5	S S batch 6
S S w/N	cases	1						
S S w/N	pound	2						
S S w/N	batches	3						
S S	cases	4						
S S	pound	5						
S S	batches	6						
label w/N	each	7	0.134					
label	each	8	0.000			0.134		
cap	each	9	0.323			0.323		
jar	each	10	1.312			1.312		
carton	each	11	0.212			0.212		
C-noodles	pound	12	2.780	0.116	166.880	0.000		
Water	pound	13	0.000	0.000	0.000	0.000	0.000	0.000
Citric Acid	pound	14	0.020	0.001	1.215	0.036	0.002	2.277
Beet Color	pound	15	0.029	0.001	1.729	0.052	0.002	3.239
Textaid	pound	16	0.062	0.003	3.705	0.111	0.005	6.944
Starch	pound	17	0.184	0.008	11.033	0.331	0.014	20.678
Oil	pound	18	0.038	0.002	2.295	0.069	0.003	4.301
S. season	pound	19	0.144	0.005	8.614	0.258	0.010	16.144
Cheese flavor	pound	20	0.025	0.000	1.316	0.037	0.000	2.471
Mushrooms	pound	21	0.107	0.004	6.394	0.192	0.008	11.981
Fructose	pound	22	0.042	0.002	2.496	0.075	0.003	4.678
Salt	pound	23	0.005	0.000	0.295	0.009	0.000	0.553
Tomato Paste	pound	24	0.398	0.017	23.876	0.716	0.030	44.749
Tomato Flavor	pound	25	0.028	0.000	1.685	0.049	0.004	3.159
Column Totals			5.844	0.159	231.533	1.935	0.081	121.174

The C matrix offers managers production information regarding the resource costs for each stage of production. From this matrix, one can see that the cost of tomato flavor per pound of Spaghetti Sauce with and without noodles is negligible. The cost contribution per batch and case of product is evident; the cost of tomato flavor per batch of Spaghetti Sauce is $3.159.

Production Plan Costs

To get information for the planned production schedule, the scheduled information must be organized in a matrix, named S. The matrix S would have the dimension of the number of required finished products by the total number of production plans. The entries of $S_{i,j}$ represent the number of units of product as required in plan j. The current plan is to produce 180 cases of spaghetti sauce with noodles and 130 cases without noodles. The matrix S is represented by the following:

		Plan
S =	Spaghetti Sauce 32 oz with noodles/cases	180
	Spaghetti Sauce 32 oz/cases	130

Organize a product unit cost vector c of length the number of products in the production plan, the number of rows in the matrix S. The entries would be the sum of columns 1 and 4 in the matrix C. The dot product of the vector c and the matrix S is the total cost to produce each product. The resulting matrix V would be of size total number of products by the total number of production plans. For this example, the vector c is represented by the following:

		S S w/N	S S
C	=	5.844	3.916 $/case

The dot product of the vector c and the matrix S would be the matrix V.

$$V = c \cdot S$$

V = Spaghetti Sauce 32 oz with noodles/cases		$1,075.86
Spaghetti Sauce 32 oz/case		509.08
	Total	$1,584.94

The total costs to produce each production plan is the sum of each column. To produce the plan would cost the manufacturer $1,584.94.

Production Plan Resource Requirements

The production plan concerns itself with the production of the finished products. The columns of the T matrix provides unit resource requirements for each stage of production that is represented by the columns. Create a matrix named T′ consisting of only those columns of finished products required in the production plan. For this example, columns 1 and 4 represent the product unit resource requirements. These columns are used to make up the matrix T′ and are presented by columns 1 and 4 of Table 6.

To define the resource requirements of the production plan, take the product of the matrices T′ and S, let the new matrix be R. The entries of the matrix R represent the resources required to produce the production plan.

$$R = T' \times S$$

Table 9 shows the result of this multiplication.

TABLE 9.
PRODUCTION PLAN REQUIREMENTS

Plant Resource Requirements:

Descriptions			S.S. w/N	S.S.	Total
S S w/N	cases	1			
S S w/N	pound	2	4,320.00		4,320.00
S S w/N	batches	3	3.06		3.00
S S	cases	4			
S S	pound	5	2,397.60	3,120.00	5,517.60
S S	batches	6	1.62	2.08	3.70
Label w/N	each	7	2,160.00		2,160.00
Label	each	8		1,560.00	1,560.00
Cap	each	9	2,160.00	1,560.00	3,720.00
Jar	each	10	2,160.00	1,560.00	3,720.00
Carton	each	11	180.00	130.00	310.00
R - Noodles	pound	12	959.40		959.40
Water	pound	13	2,863.80	2,476.50	5,340.30
Citric Acid	pound	14	4.86	6.24	11.10
Beet Color	pound	15	7.38	9.62	17.00
Textaid	pound	16	16.02	20.80	36.82
Starch	pound	17	72.00	93.60	165.60
Oil	pound	18	19.98	26.00	45.98
S. season	pound	19	15.12	19.50	34.62
Cheese flavor	pound	20	0.72	0.78	1.50
Mushrooms	pound	21	35.28	45.76	81.04
Fructose	pound	22	108.00	140.53	248.53
Salt	pound	23	29.52	38.48	68.00
Tomato Paste	pound	24	185.94	241.80	427.74
Tomato Flavor	pound	25	1.44	1.82	3.26

To produce the production plan requires 3.70 batches of Spaghetti Sauce, 3.06 batches of Spaghetti Sauce with noodles, and 11.10 lb of citric acid. The material requirements presented in the R matrix reflect the partial batch production policy. The manager would respond by producing just enough of each batch to make the planned volume of product. Defining the production requirements for producing whole batches of product requires further manipulation. Depending on the accounting procedure, the costs generated by this matrix manipulation could be used as a "standard cost." This standard cost suggested by Horngren (1981) may be thought of as "a budget for the production of a single unit." It provides a means to control direct material and direct labor, a way to monitor performance.

Deriving Whole Batch Production Information

The whole batch policy requires answers to a few questions. How much flexibility is required to modify the production plan? Is a shortage or excess acceptable? Can batches be rounded up or down? Once these answers are provided, a MDS could calculate how many more or less of each product would be produced and the cost.

The manger must decide based on the number of batches defined in matrix R whether or round up or down, since whole batches are desired. If there is a rounding up, more products would result. A system of linear equations can help determine the impact of rounding up batches.

A portion of the T′ matrix provides the batch requirements to produce each unit of product. With 2 products and 2 constraints of batches of formulas, the matrix is of size 2 × 2.

$$
\begin{aligned}
T_1 &= 0.017 \qquad 0 \qquad\quad S_1 1 \\
T_1 &= 0.009 \qquad 0.016\ ,\ 2 = S_{21}
\end{aligned}
$$

This matrix is named T_1. Another matrix is required of the same size as the matrix S with entries representing variables $S_{1,1}$ and $S_{2,1}$, the name of this matrix is S′. The product of these matrices must be less than or equal to the batch constraints imposed by the production manager. Let the constraint matrix be named A with the size of the number of batches of formulas by the number of production plans. Let the entries of A be taken from the matrix T but rounded. The effect of rounding down the number of batches of Spaghetti Sauce with Noodles to 3.0 and rounding up the number of batches of Spaghetti Sauce to 4.0 is shown in the following computation:

$$T_1 \times S' \leq A$$

Solving the system of linear equations we get the following:

$$(0.017)S_{1,1} + \qquad < \; = 3.0$$
$$(0.009)S_{1,1} + (0.016)S_{2,}{}^{1} < \; = 4.0$$

With rounding, the solution is $S_{1,1} = 176$ cases, and $S_{2,1} = 150$ cases. A production manager following the whole batch production policy can expect to produce 176 cases of spaghetti sauce with noodles and 150 cases of spaghetti sauce. The effect would be 4 cases under the planned volume of spaghetti sauce with noodles. For the product spaghetti sauce, 20 cases more than planned would be produced. By taking this revised production plan, and recalculating the MDS, the production manager can expect the total production cost to be \$1,615.94. The difference in costs between the original and revised plans is \$31.00. The price difference may be considered reasonable. However, the price difference will be bigger if the batch size is bigger. The production manager may choose the whole batch production policy for a smoother production operation. To determine the resource requirements of this revised plan requires the revised plan to be entered in the matrix S. The product of the matrices T and S would be the resource requirements defined by the matrix R.

With more complex production plans, this system of linear equations can expand to contain an objective function, say for example to maximize profit or minimize cost. Defining a system of linear equations provides for the addition of the constraints of labor, machinery and raw materials inventory. The addition of a constraint would be an additional row in the matrices of A and T_1. With both partial and full batch production policies, a system of linear equations can be developed to provide feedback on production planning, capacity and budgetary control.

Resolution

The batch process suggests a lack of precision in production planning. The inability to get accurate product unit costs suggests the inability to evaluate the profit margins. A manager should know if a particular product is unprofitable, so a decision could be made to either stop or continue processing it. MDS provide a flexible way to organize and manipulate information to assist in supporting management decisions. By themselves, MDS have proven useful for single-staged production processes. Through the application of the Gozinto procedure, MDS prove useful for complex multistaged food processing production environments. A comparison between the partial and full batch production processes is easily made by using MDS and solving a system of linear equations. An objective function could be applied to suggest an improved production plan keeping costs or profits in mind. The matrix manipulations suggest computer programmability. The use of computers to store, retrieve and manipulate information quickly suggests that a manager could extract information in a timely manner. With a proper Management Decision Support System, managers can better control production rather than just manage it.

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REFERENCES

ANTON, H. 1981. *Elementary Linear Algebra*, pp. 34–37. John Wiley & Sons, New York.

CHASE, R.B. and AQUILANO, N.J. 1981. *Production and Operations Management*, 3rd ed. p. 35. Richard Irwin, Inc., Homewood, Ill.

ELLIS, P. 1985. Ingredient-Blending Problems with Chemical Reactions. Production and Inventory Management, Third Quarter, 1985.

GOVINDARAJAN, V. 1983. How firms use cost data in price decisions. Management Accounting, July 30-36.

HORNGREN, C.T. 1981. *Introduction to Management Accounting*, 5th ed., p. 178, Prentice-Hall, Inc., Englewood Cliffs, NJ 07632.

MIZE, J.H., WHITE, C.R. and BROOKS, G.H. 1971. *Operations Planning and Control.* Prentice Hall, Englewood Cliffs, NJ.

NORBACK, J.P. and MATTHEWS, M.E. 1981. Data structures for integrating quality and cost factors in a food service operation. J. Food Protect. *44*(5), 364–368.

NORBACK, J.P. and MATTHEWS, M.E. 1982. Computer implementation of matrix data structures for controlling food formulation and manufacture. Food Technol., April, 77–82.

RICE, J.W. and NORBACK, J.P. 1987. Process Industries Production Planning Using Matrix Data Structures. Prod. Inventory Management Rev., APICS, 2nd Quart., 15–23.

TSUBONE, H., MURAMATSU, R. and SOSHIRODA, M. 1983. Designing an Effective Production System for Processing Agricultural Products. Int. J. Prod. Res. *21*(1), 17–30.

VALENTA, J.R. 1984. Managing effective productivity decision support systems. Manag. Plan. Jan/Feb., 33–36.

VAZSONYI, A. 1958. *Scientific Programming in Business and Industry*, p. 258–267. John Wiley & Sons, New York.

PARTICLE RESIDENCE TIME DISTRIBUTIONS IN A MODEL HORIZONTAL SCRAPED SURFACE HEAT EXCHANGER[1]

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ABSTRACT

Residence times and their distribution characteristics of potato cubes with aqueous solutions of sodium carboxymethyl cellulose (CMC), simulating non-Newtonian fluid foods, in a horizontal scraped surface heat exchanger (SSHE) were investigated. Minimum and maximum normalized particle residence times (NPRTs) and standard deviations of mean values were not significantly affected by the particle concentration while mean NPRTs of up to 10% particle concentration were signficantly lower than those of 20–40% particle concentrations (P < 0.05). Mean NPRTs were significantly influenced by process parameters including concentration of carrier, viz., viscosity, mutator speed and particle size (P< 0.001) as well as 2-way interactions among flow rate, mutator speed and particle size (P< 0.05 or 0.001). Furthermore, most of the individual particle residence time distributions in a horizontal SSHE flow could be described by either normal or gamma distribution models.

INTRODUCTION

The continuous flow thermal sterilization has been favorably used as an economical and efficient means for destruction of microorganisms in a variety of foods. Its advantages include less damage to the medium, shorter processing periods, uniform and improved product quality, reduced energy consumption, and ready adaptability to automatic control. Despite its advantages, development of this technology to processing of particulate foods has been somewhat limited due to the problems that have to be solved prior to performing successful treatments (Defrise and Taeymans 1988).

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One of the most important parameters affecting the heat transfer and thus subsequent sterilization efficiency in aseptic (continuous) processing of liquid foods with or without particulates is connected to the existence of residue time distribution (RTD). Conceivably, different elements spend different lengths of time in the processing system (heat exchanger or holding tube); thus, each fluid element receives a different degree of sterility. Especially for the processing of foods containing large particulates, this may result in considerable disparity between and lethality (or cook value) accumulated in the liquid fraction and the particulates.

From a public health standpoint, it is of great importance to identify the residence time of the fastest moving particle in the heating and holding sections of the aseptic processing system (Dignan *et al.* 1989). In addition, it is equally important to determine average (or mean) and maximum particle residence times to predict quality changes in the whole product so that possible overprocessing of the product can be avoided. It is impossible, however, to identify the fastest particle in a commercial operating system. Therefore, the particle residence time distribution must be measured and then it can be predicted statistically with a high degree of confidence (Berry 1989).

Recently, a great interest has developed towards aseptic processing of heterogeneous food products (i.e., fluids containing discrete particulate food matter). The introduction of particulates into the fluid significantly complicates the flow conditions which influence the residence time distribution. A few studies related to the residence time distribution in a SSHE for processing liquids containing particulates have been published (Alcairo and Zuritz 1990; Defrise and Taeymans 1988; Sastry 1986; Taeymans *et al.* 1985 a,b).

Taeymans *et al.* (1985 a,b) used calcium alginate beads suspended in water as a model system. Coomassie® blue and spores of *Bacillus stearothermophilus* were used as color and microbiological tracers, respectively. Results indicated that the flow patterns diverged from the ideal plug flow. It was also indicated that an increase of rotational speed increased the mean residence time of solid particles, which directly impacts the lethality. It is obvious that the tangential component of the velocity of the solid particle becomes more important when the scrapers rotate rapidly. They also reported that when the flow rate of the liquid increased, the mean residence time of the particles decreased and approached the value of the mean residence time of the liquid phase. It was observed that the residence time of paticles decreased with increase of concentration up to 8%, probably due to the fact that the centrifugation of the solid particles was restrained by the presence of other solid particles; thus the path of a solid particle was reduced.

Sastry (1986) developed a quantitative methodology for evaluating thermal process schedules for low-acid foods containing particulates of any shape using a finite element method. Simulation was conducted to study situations involving unusually fast or slow-moving particles using values of Heat Exchanger Residence Time Ratio (HXRTR) ranging from 0.2 to 2.5. The HXRTR was defined as the ratio of particle residence time to the mean particle residence time within the SSHE. He indicated that the range was sufficient for the purpose of his study, even though Taeymans *et al.* (1985a) observed wider range of residence times. He concluded that the effect of heat exchanger residence time distribution on attaining commercial sterility was highly significant. The fast moving particles greatly increased the required process schedule. The same dramatic effects have been presented in a number of modeling studies (Lee *et al.* 1990 a,b; Defrise and Taeymans 1988; Manson and Cullen 1974). Dail (1985) also indicated that the fastest moving particle should be used for process calculations in any case, since it represented the worst case in terms of accumulated lethality; however, a systematic study on the residence time distribution of particulates was not given.

More recently, Alcairo and Zuritz (1990) presented a study of the residence times of a single spherical particle suspended in a non-newtonian fluid flowing through a SSHE. They concluded that an increase in particle diameter, blade speed or flow rate decreased the standard deviation of the residence times and narrowed the RTD but was unaffected by the change of viscosity. They also found that no effect of viscosity, blade speed and particle diameter levels on the minimum and mean particle residence times. Mean particle residence times were only 16% shorter than mean fluid residence times at the higher flow rate, whereas they were equal at the low and medium flow rate levels. In addition, it was assumed that their RTDs were normal probability distribution functions; however, this may not represent the actual characteristics of the observed distributions.

It is evident from the literature review that information available on the RTD of foods containing particulates in a non-Newtonian fluid flowing through a SSHE is scarce. Especially, the one variable at a time experimental approach would fail to take into account of the important interaction effects, if any. Therefore, this study was designed to investigate the flow phenomena in the SSHE, which would allow more accurate predictions of sterility and quality, and help to design (or optimize) more adapted apparatus.

The objectives of present study were: (1) to study the effects of process and product conditions such as fluid viscosity, product flow rate, SSHE mutator speed, particle size, particle concentration, and their 2-way interactions on residence time and RTD, and (2) to determine characteristics of the observed distributions.

MATERIALS AND METHODS

Experimental Design

A 3^{4-1} factorial design in 3 blocks, confounded in 3 blocks of 9 runs each, as described by Montgomery (1984) was employed to determine the effects of individual factors on particle residence time and their interactions. The block represents the concentration of carrier medium, therby viscosity, and other variables include flow rate, mutator speed and particle size. To avoid bias, the experiment runs were conducted in a random order. Using this confounding scheme, information on all the main effects and two-factor interactions is available. The remaining components of the three-factor interaction are combined as an estimate of error. The levels and coded values of each variable (factor) are given in Table 1.

TABLE 1.
VARIABLE LEVELS AND CODED VALUES USED IN THE 3^{4-1} FACTORIAL DESIGN IN 3 BLOCKS WITH AB^2C^2 CONFOUNDED

Variables	Symbol		Level	
	Uncoded	Coded	Uncoded	Coded
Concentration (%)	C	AB^2C^2	0.4	0
			0.8	1
			1.2	2
Flow rate (mL/s)	$\dot{V}$	A	453	0
			534	1
			599	2
Mutator speed (rpm)	$\dot{r}$	B	60	0
			110	1
			160	2
Particle size (cm)	d	C	1.0	0
			1.5	1
			2.0	2

Model Aseptic Processing System

A schematic of the experimental setup is illustrated in Fig. 1. The model aseptic processing system consisted of a transparent SSHE (Contherm Division, Alfa-Laval, Inc., Newburyport, MA), connected with a holding tube to represent the condition of those used in the commercial practice. The model SSHE was composed of an 0.6223-m long and 0.1524-m I.D. acrylic outer shield, so

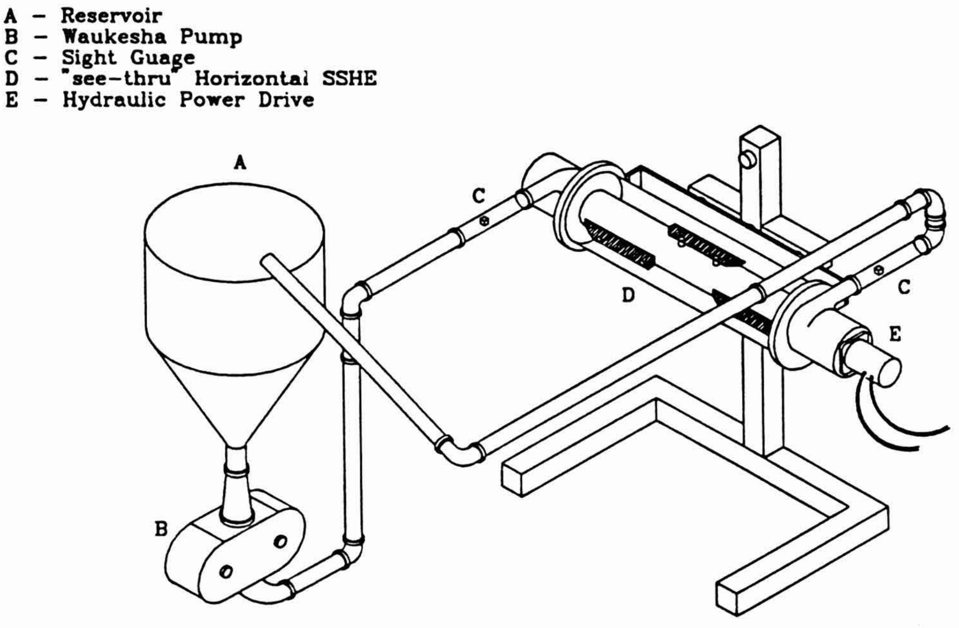

FIG. 1. SCHEMATIC DIAGRAM OF A MODEL HORIZONTAL SSHE

that it was possible to observe the particle flow pattern inside the SSHE. The mutator (0.073-m diameter) inside the SSHE was driven by a variable speed hydraulic power drive (Vickers Div., Sperry Rand Corp., Troy, MI). A 0.0762-m I.D. inlet/outlet port Waukesha positive displacement pump (AMCA International, Waukesha, WI) with a 7.46-kW variable speed motor (Syncrogear Module, U.S. Electrical Motors, St. Louis, MO) was used to pump the product through the system. A 0.0445-m I.D. (0.0635-m O.D.) pipe was used to connect the pump and SSHE, and the product was circulated through a 56.78 stainless steel reservoir connected to inlet port of the pump. Two 0.0445-m I.D. and 0.3048-m long sight gauges (SaniTech, Sparta, NJ) were connected just before the inlet and after the outlet of SSHE so that the residence time of tracer particles could be visually determined. The returning product was tangentially introduced to the reservoir and the SSHE to minimize the formation of air bubbles and to avoid bridging of the particles, respectively.

Model Food Systems

Fresh potatoes were brought from a local grocery store and cut into desired cube sizes just prior to the experiment, except for the samples used for the effect of particle concentration studies. Those samples were brought from Purdue

Food Store and were precut in 12.7-mm cubes. In addition, aqueous solutions of sodium carboxymethyl cellulose (CMC; Aqualon Company, Wilmington, DE) were used to simulate non-Newtonian pseudoplastic fluid foods.

A total of 252-L aqueous solution of CMC was prepared one day before the experiment in a creamery pot with a mixing blade. The CMC powder was slowly added while blade was on for about 4 h which was sufficient to dissolve most of the powder. The solution was left overnight to remove air and further dissolution. A fresh solution was used for each run to minimize the decrease in viscosity with time of shearing. Rheological properties (consistency coefficients and flow behavior indices) of CMC solutions were determined using a Brookfield digital viscometer (Model DV-I, Brookfield Engineering Laboratory, Inc., Stoughton, MA) at room temperature. All rheological properties were checked before and after each test run to determine whether or not significant decrease in viscosity had occurred. The properties of potato cubes and CMC solutions are given in Table 2.

TABLE 2.
DENSITY AND RHEOLOGICAL PROPERTIES OF MODEL FOODS SYSTEM AT ROOM TEMPERATURE

Model System	Density (Kg/m^3)	Consistency Coefficient ($Pa \cdot s^n$)	Flow Behavior Index (-)
Potato cube	1074.9 ± 4.0		
CMC			
0.4%	999.2 ± 0.4	0.286	0.888
0.8%	1001.0 ± 0.2	3.457	0.668
1.2%	1003.3 ± 0.1	9.567	0.418

Experimental Procedure

The experiments were performed in two stages. First, the effect of particle concentration (single particle to 40%, w/v) was investigated to determine whether the effect of particle concentration (particle-particle interaction) on the particle residence times and distributions was significant. Second, the effect of process variables (viz., flow rate, mutator speed and particle size on residence time and its distribution) was examined using 1–3 tracer particles.

All experiments were conducted under isothermal conditions (at room temperature) at zero heat flux. A 26.5-L prepared CMC solution was filled in the reservoir and pump was turned on to circulate for about 5 min for removing the air bubbles from the system. Meanwhile, mutator speed and flow rate were set according to the specified conditions (Lee and Singh 1990). A Hasler tachometer (Hasler-Tel Co., Inc., New York, NY) with visual calibration was used to determine the mutator speed. The flow rate was adjusted by measuring the volume of the returning fluid and time.

Once all the process variables were set, the specified amount or size of particles was added in the reservoir and circulated for about 5 min to achieve a steady-state condition. Tracer particles (1–3) dyed with food colors (Durkee-French Foods, Inc., Wayne, NJ) were introduced and their individual residence times spent between the inlet and the outlet port of the SSHE were recorded manually. Data were collected at least 100 times consecutively, resulting in a total of 2700 data points in addition to 600 data points from the particle concentration studies. Occasionally, broken tracer particles were replaced by new ones.

Statistical Analyses

A total of 2700 residence time data from 27 treatments in addition to 600 data from particle concentration studies were normalized by dividing their respective average bulk fluid residence time to avoid any artifact of flow rate on the RTD. Statistical analyses were performed using the General Linear Model Program (SAS 1986) to test the effect of viscosity of carrier medium, flow rate, mutator speed, particle size and their partial 2-way interactions, as well as particle concentration. Duncan's multiple range test was used to estimate significant difference among means at the 5% probability level (Duncan 1955; O'Mahony 1986).

The frequency distribution of particles having residence times within certain time intervals was plotted for 27 conditions in addition to 6 conditions for particle concentration study using 10 time intervals to describe the distribution. It is unlikely that any one known distribution would exactly fit the experimental data because of the severe skewness exhibited by some of the distributions. The best candidate for those kind of distributions would be the gamma distribution which is skewed to the right.

The characteristic parameter for tank-in-series model, $r = \bar{x}^2/s^2$, where $\bar{x}$ and s are the mean normalized particle residence time (NPRT) and standard deviation, respectively, was also used to characterize the distribution. If r is greater than or close to 50, the distribution approaches a normal distribution; thus, it was tested for its fit to the normal distribution. Otherwise, it was done for the gamma distribution.

Pearson's x^2 goodness of fit test was used to examine both distributions (Bickel and Doksum 1977). The statistic is,

$$\chi^2 = \sum_{i=1}^{k} \frac{(N_i - nP_{io})^2}{nP_{io}} \qquad (1)$$

where P_{io} is a probability of occurrence in the "ith" interval under the theoretical distribution. Chi-square is a measure of the departure of the observed N_i from their expectation "n P_{io}" under the null hypothesis H_o: distribution is a Gamma (θ, r) or Normal ($\bar{x}$, s^2) against the alternative H_1: distribution is not a Gamma (θ, r) nor Normal ($\bar{x}$, s^2), where $\theta = \bar{x}/s^2$ and $r = \bar{x}/s^2$, respectively.
The probability

The probability that a particle possesses a NPRT between x_1 and x_2 is given by the following probability density function (PDF):

$$P\{X \le x_2\} - P\{X \le x_1\} = F(x_2) - F(x_1) \quad (2)$$

where cumulative distribution function (CDF), F, for the normal distribution is given by:

$$F(x) = P\{X \le x\} = P\left\{z \le \frac{x - \bar{x}}{s}\right\} \quad (3)$$

and F for the gamma distribution is given by:

$$F(x) = P\{X \le x\} = \int_0^y \frac{y^{r-1} e^{-y}}{\Gamma(r)} dy \quad (4)$$

where $y = x \cdot \theta$. The required probability can be obtained from a standard normal distribution table with x = 0 and s^2 = 1 or using the PROBNORM Program or PROBGAM Program of statistical analysis system (SAS 1986).

RESULTS AND DISCUSSION

Normalized Particle Residence Time (NPRT)

Effect of Particle Concentration. Table 3 presents the effect of particle concentration on the normalized particle residence times (NPRTs) in a horizontal SSHE. Although one specific operating condition was chosen to study the effect of particle concentration (single particle to 40%, w/v), this should provide an insight into the influence of particle concentration on the residence time and its distribution.

The particle concentration up to 40% did not significantly affect the minimum and maximum NPRTs and standard deviation of mean NPRTs ($P < 0.05$). All

TABLE 3.
NORMALIZED PARTICLE RESIDENCE TIMES* AS INFLUENCED BY PARTICLE CONCENTRATION IN A HORIZONTAL SSHE

Particle Concentration (%, w/v)	Minimum	Maximum	$\bar{x}$	s	r**
single***	0.687 a†	1.393 a†	0.975 a†	0.140 a†	48.50 a†
5	0.639 a	1.444 a	0.929 a	0.174 a	28.51 a
10	0.711 a	1.506 a	0.950 a	0.163 a	33.97 a
20	0.728 a	1.944 a	1.042 b	0.193 a	29.15 a
30	0.711 a	1.580 a	1.041 b	0.166 a	39.33 a
40	0.625 a	2.023 a	1.068 b	0.190 a	31.60 a

* Measured at 534 mL/s flow rate, 110 rpm mutator speed and 1.5 cm potato cube as a tracer particle in 0.8% CMC solution as a carrier.
** Characteristic parameter for tanks-in-series model, $r = \bar{x}^2 / s^2$, where $\bar{x}$ and s are mean normalized particle residence time and standard deviation, respectively.
*** Only the tracer particle was used.
† Determined from 2 sets of 100 observations.
a–b Means with the same superscript are not significantly different (P<0.05).

the minimum NPRTs represent the situation where the tracer particles stayed shorter than the average bulk fluid in the horizontal SSHE. No minimum NPRT below 0.625 was observed, indicating that no particle traveled faster than 1.60 times the average bulk fluid velocity. It is interesting to note that the lowest minimum NPRT was observed when 40% particle concentration was used, while the highest value was observed with 20% particle concentration. This indicates that particle-particle interactions due to its concentration does not seem to always interfere the path of the tracer particles in the same way even at as high as 40% particle loading. On the contrary, the maximum NPRTs represent those particles that stayed longer than the average bulk fluid in the system. Although they were not significantly different from each other ($P < 0.05$), they seemed to increase as particle concentration increased except for the 30% particle concentration. It was found that some particles stayed about twice as long as the average bulk fluid when 20 or 40% particle concentrations were introduced.

The mean NPRTs may be important to determine the overall quality of the product after processing. It can be seen that the mean NPRTs for up to 10% particle concentration are significantly lower than those of 20–40% particle concentrations ($P < 0.05$). It is also interesting to note that the mean NPRTs for up to 10% particle concentration are less than 1, whereas they are greater than 1 for particle concentrations of 20–40%. This implies that particles spent relatively shorter times as compared to the average bulk fluid when 10% or less particle concentration was used. However, particles stayed for relatively longer times in the system when particle concentrations of 20–40% were introduced. This may indicate that a distinctive particle-particle interaction which restrained the path of the trace particle existed with the particle concentration of 20–40% compared to that at 10% or less.

The characteristic parameter (r) for tanks-in-series model was also calculated and compared for each experimental condition. It was found that r was not significantly different from condition to condition ($P < 0.05$), although it was higher when a single particle and 30% concentration were used than that for the remaining conditions. This parameter will be further discussed in terms of distribution characteristics.

Effect of Process Parameters. Table 4 presents analysis of variance of mean NPRTs as influenced by the process parameters in a horizontal SSHE. It can be seen that all the main effects ($P < 0.001$), except for flow rate as well as 2-way interactions among flow rate, mutator speed and particle size, are significant ($P < 0.05$ or 0.001). Results of analysis of variance for minimum and maximum NPRTs and standard deviations or mean NPRTs are not given since their respective main and interaction effects were not significant. The summary of the main effects of process parameters on the NPRTs is given in Table 5.

TABLE 4.
ANALYSIS OF VARIANCE OF MEAN NORMALIZED PARTICLE RESIDENCE TIME AS INFLUENCED BY PROCESS PARAMETERS IN A HORIZONTAL SSHE

Source	DF	Sum of Squares	Mean Squares	F
Concentration (C)	2	7.24	3.62	96.44***
Flow Rate ($\dot{V}$)	2	0.10	0.05	1.29^{NS}
Mutator Speed ($\dot{r}$)	2	3.52	1.76	46.85***
Particle Size (d)	2	7.68	3.84	102.30***
$\dot{V} * \dot{r}$	4	1.60	0.40	10.67***
$\dot{r} * d$	4	0.48	0.12	3.20*
$\dot{V} * d$	4	1.59	0.40	10.62***

NS Not significant at P<0.05.
* Highly significant at P<0.05.
*** Highly significant at P<0.001.

TABLE 5.
NORMALIZED PARTICLE RESIDENCE TIMES AS INFLUENCED BY PROCESS PARAMETERS IN A HORIZONTAL SSHE

Process Parameters	Minimum	Maximum	$\bar{x}$	s
CMC concentration (%)				
0.4	0.759[a]	1.552[a]	1.059[a]	0.158[a]
0.8	0.670[a]	1.721[a]	0.960[b]	0.168[a]
1.2	0.649[a]	1.593[a]	0.941[c]	0.179[a]
Flow rate (mL/s)				
453	0.667[a]	1.523[a]	0.978[a]	0.166[a]
534	0.699[a]	1.544[a]	0.991[a]	0.166[a]
599	0.712[a]	1.799[a]	0.990[a]	0.173[a]
Mutator speed (rpm)				
60	0.660[a]	1.892[a]	0.964[a]	0.194[a]
110	0.707[a]	1.393[a]	0.958[a]	0.134[a]
160	0.711[a]	1.581[a]	1.037[b]	0.177[a]
Particle size (cm)				
1.0	0.633[a]	1.673[a]	0.929[a]	0.180[a]
1.5	0.673[ab]	1.572[a]	0.973[b]	0.164[a]
2.0	0.771[b]	1.621[a]	1.057[c]	0.161[a]

[a–c] Means in the same column within a process parameter with the same superscript are not significantly different ($P<0.05$).

Concentration. The concentration of CMC, viz., viscosity, does not significantly influence the minimum and maximum NPRTs and standard deviations of mean NPRTs ($P< 0.05$). However, it can be seen that minimum NPRT and standard deviation of mean NPRTs tend to increase as the concentration of CMC increases. On the other hand, mean NPRT significantly decreases as CMC concentration increases. It is interesting to note than mean NPRT is greater than 1 (i.e., particle stayed longer than the average bulk fluid in the system) with 0.4% CMC carrier, while it is less than 1 when 0.8 or 1.2% CMC were used. This can be explained by the fact that higher concentration of CMC provided more lifting force to the particles so that particles traveled faster, adjusting for other process conditions such as flow rate, mutator speed and particle size. At low viscosity conditions, where the majority of particles lag the fluid, a fastest-particle design strategy would lead to overprocessing of majority of particles in a SSHE. It may be expected that there exists an interaction between CMC concentration and other process parameters, however, it could not be tested due to the design constraint.

Flow Rate, Mutator Speed, Particle Size. The minimum and maximum NPRTs and standard deviations of mean NPRTs are not significantly affected by the flow rate of carrier medium, mutator speed nor particle size ($P < 0.05$). Nevertheless, similar trends of increase in minimum and maximum NPRTs and standard deviations of mean NPRTs as flow rate increases are noted. It is also noted that an increase in mutator speed or particle size seems to increase minimum NPRT while standard deviation of mean NPRTs seems to decrease as particle size increases.

Mean NPRTs are significantly influenced by the mutator speed and particle size ($P < 0.05$). However, effect of flow rate on the meanNPRTwas not significant. As flow rate increases, the mean particle residence time seems to approach the average bulk fluid residence time.

Increase in mutator speed from 60 to 110 rpm to 160 rpm significantly increases the mean NPRT, and increase in particle size by each level also significantly increaes the mean NPRT ($P < 0.05$). This indicates that mutator speed of 160 rpm may provide a distinctive tangential force applied to the particles as compared with 60 or 110 rpm, so that the particles stayed longer in the system. In fact, average particles stayed longer than the average bulk fluid when mutator speed was 160 rpm, whereas they traveled faster than the average bulk fluid when the speed was 110 rpm or less. In addition, particles stayed longer in the system as their size increased due to the increase in their weight. Again, average particles stayed longer than the average bulk fluid when particle size of 2.0 cm was used, while they stayed shorter when the particle size was 1.5 cm or less.

Effect of Two-Way Interactions. It is important to realize that there also exist significant interactions among flow rate, mutator speed and particle size. This indicates that the combination of process conditions of flow rate, mutator speed and particle size contributed to a significant effect on themean NPRT, whereas the flow rate alone did not.

Tables 6 and 8 summarize the NPRT as influenced by 2-way interactoins between flow rate and mutator speed, flow rate and particle size and mutator speed and particle size in a horizontal SSHE, respectively. As mentioned earlier, the interactions for the minimum and maximum NPRTs and standard deviations of mean NPRTs are not presented, since they were not significant ($P < 0.05$). Only the mean NPRTs were significantly affected by the interactions ($P < 0.05$).

Flow Rate × Mutator Speed. Significantly higher mean NPRTs were observed when flow rates of 453 and 534 mL/s and a mutator speed of 160 rpm were used ($P < 0.05$)(Table 6). In fact, they are greater than 1, indicating particles stayed longer in the system than the average bulk fluid. This supports a significant main effect of mutator speed in the sense that higher mutator speed prevented the particles from moving forward, since the higher mutator speed means more tangential force applied to the particles. This agreed with the results of Taeymans *et al.*

TABLE 6.
NORMALIZED PARTICLE RESIDENCE TIME AS INFLUENCED BY TWO-WAY INTERACTION BETWEEN FLOW RATE AND MUTATOR SPEED IN A HORIZONTAL SSHE

Flow Rate	Mutator Speed	$\bar{x}$
0	0	0.937 [d]
0	1	0.936 [d]
0	2	1.061 [a]
1	0	0.962 [bcd]
1	1	0.954 [cd]
1	2	1.057 [a]
2	0	0.994 [b]
2	1	0.983 [bc]
2	2	0.993 [b]

[a–d] Means with the same superscript are not significantly different (P<0.05).

(1985a). At a higher flow rate of 599 mL/s and a mutator speed of 160 rpm, the mean NPRT is less than 1, indicating particles traveled faster than the average bulk fluid despite the same mutator speed due to higher pushing power induced by the higher flow rate. The same trends were found at lower mutator speeds of 60 and 110 rpm, although some of them were not significantly different from each other, and values were less than 1.

It was also noted that an increase in mutator speed while maintaining the flow rate did not always increase the mean NPRT. This confirmed the interaction between flow rate and mutator speed. The mean NPRTs were not significantly different among others when flow rate was 599 mL/s regardless of mutator speed and when flow rate and mutator speed were 534 mL/s and 60 rpm, respectively ($P < 0.05$). In addition, no significant difference in mean NPRTs was found when flow rate of 599 mL/s and mutator speed of 110 rpm, 534 mL/s and 60 rpm and 534 mL/s and 110 rpm were used ($P < 0.05$). It was also found that the mean NPRTs were significantly lower when flow rate was 453 mL/s and the mutator speed was 60 or 10 rpm, whereas it was significantly higher when the mutator speed was 160 rpm at same flow rate ($P < 0.05$). This indicates that mutator speed did not have a significant influence on the mean NPRT when the flow rate was 599 mL/s. Also, a mutator speed of 60 or 110 rpm did not affect the mean NPRTs regardless of flow rate. This indicates that mutator speed up to 110 rpm did not exert a significant tangential force to the particles regardless of the flow rate. However, the mutator speed of 160 rpm induced tangential force significant enough to keep the particles longer than the average bulk fluid in the system except when the flow rate was 599 mL/s, whereas the effect of mutator speed was not significant as mentioned earlier.

Flow Rate × Particle Size. Table 7 presents a significant interaction between flow rate and particle size on the NPRT. The mean NPRT was significantly higher when a flow rate of 534 mL/s and particle size of 2.0 cm were used. Descending levels of significance for mean NPRT were found when flow rates of 599 and 453 mL/s with particle size of 2.0 cm were used (P< 0.05). This indicated that particles stayed longer (than the average bulk fluid) in the system when 2.0 cm particles were introduced regardless of flow rate supporting the main effect of particle size. It is interesting to note that the value was significantly higher when the flow rate was 534 mL/s than when it was 453 mL/s. When particle size of 1.5 cm or less was used, particles stayed for a shorter time than the average bulk fluid regardless of the flow rate. Particles of 1.5 cm size flowing at 453 mL/s traveled significantly slower than those particles at 534 mL/s while speed of the same size particles flowing at 534 or 599 mL/s, and that of 1.0 cm particles at 599 mL/s were not significantly different from each other (P < 0.05). In addition, 1.0 cm particles at 534 and 453 mL/s represented the faster moving particles among other process conditions. It may be concluded that the effect of particles of less than 1.5 cm size was significant for flow rate 534 mL/s or less but not for 599 mL/s (P< 0.05). This may be due to high enough momentum to overcome the weight differences between 1.0 and 1.5 cm particles at higher flow rates.

TABLE 7.
NORMALIZED PARTICLE RESIDENCE TIME AS INFLUENCED BY TWO-WAY INTERACTION BETWEEN FLOW RATE AND PARTICLE SIZE IN A HORIZONTAL SSHE

Flow Rate	Particle Size	$\bar{x}$
0	0	0.903^{e}
0	1	0.996^{c}
0	2	1.035^{b}
1	0	0.917^{e}
1	1	0.958^{d}
1	2	1.098^{a}
2	0	0.967^{cd}
2	1	0.964^{cd}
2	2	1.039^{b}

a–e Means with the same superscript are not significantly different (P<0.05).

Mutator Speed × Particle Size. A significantly higher mean NPRT was observed when mutator speed and particle size were 160 rpm and 2.0 cm, respectively. The next highest means occurred when 1.5 cm particles at 160 rpm, 2.0 cm particles at 110 rpm as well as 2.0 particles at 60 rpm were used, while means were not significantly different among others (P< 0.05)(Table 8).

TABLE 8.
NORMALIZED PARTICLE RESIDENCE TIME AS INFLUENCED BY TWO-WAY INTERACTION BETWEEN MUTATOR SPEED AND PARTICLE SIZE IN A HORIZONTAL SSHE

Mutator Speed	Particle Size	$\bar{x}$
0	0	0.909 [d]
0	1	0.960 [c]
0	2	1.023 [b]
1	0	0.919 [d]
1	1	0.928 [cd]
1	2	1.026 [b]
2	0	0.958 [c]
2	1	1.030 [b]
2	2	1.124 [a]

[a–d] Means with the same superscript are not significantly different (P<0.05).

The mean NPRTs were greater than 1 for those conditions, indicating that larger particles stayed for relatively longer times in the system as compared to the average bulk fluid due to their weight. In addition, 1.5 cm particles at 160 rpm mutator speed stayed for relatively the same time due to higher tangential force applied to the particles by higher mutator speed. It was also found that 1.5 cm particles at mutator speeds of 60 and 110 rpm, and 1.0 cm particles at 160 rpm stayed for relatively the same time in the system while 1.0 cm particles at the mutator speeds of 60 and 110 rpm and 1.5 cm particles at 110 rpm traveled much slowly through the model SSHE. This indicates that an increase in mutator speed and particle size increased tangential and gravitational forces applied to the particles, which worked against the particle flow. However, effect of particle size up to 1.5 cm was not significant for the mutator speed of 110 rpm.

Distribution Characteristics

Effect of Particle Concentration. Table 9 presents the residence time distribution characteristics in terms of P-values of x^2 test along with distribution characteristic parameters as influenced by the particle concentration in a horizontal SSHE. As indicated earlier, r value was close to 50 when a single particle was used, therefore, it was tested for the normal distribution. The remaining distributions were tested for the gamma distribution. There was insufficient evidence to reject H_0 except for the distribution when 40% particle concentration was used ($P < 0.01$). Most of the distributions were described by gamma model except when only the tracer particle was used. This indicates that the distributions were skewed to the right because the particles stayed for relatively long

TABLE 9.
RESIDENCE TIME[a] DISTRIBUTION CHARACTERISTICS AS INFLUENCED BY PARTICLE CONCENTRATION IN A HORIZONTAL SSHE

Particle Concentration (%, w/v)	$\bar{x}$	s	θ^b	r^c	Distribution Characteristic	P-value[d]
single[e]	0.975†	0.140†	49.74†	48.50†	normal	0.6899
5	0.929	0.174	30.68	28.51	gamma	0.6818
10	0.950	0.163	35.76	33.97	gamma	0.0591
20	1.042	0.193	27.97	29.15	gamma	0.0190
30	1.041	0.166	37.78	39.34	gamma	0.5839
40	1.068	0.190	29.58	31.60	gamma	0.0023

[a] Measured at 534 mL/s flow rate, 110 rpm mutator speed and 1.5 cm potato cube as a tracer particle in 0.8% CMC solution as a carrier.
[b] $\theta = \bar{x} / s^2$, where $\bar{x}$ and s are mean and standard deviation, respectively.
[c] Characteristic parameter for tanks-in-series model, $r = \bar{x}^2 / s^2$.
[d] P-value used for Pearson's χ^2 goodness of fit test.
[e] Only the tracer particle was used.
† Determined from 2 sets of 100 observations.

times as compared to the average bulk fluid. This might be due to particle-particle interactions. In addition, there was no evidence to affect the shape of distribution by the particle concentration.

Comparisons were made between the experimental and theoretical values of the CDF or NPRT for each condition. Results indicated that the model did fit the data well (Fig. 2 and 3). Nevertheless, the reason for low P-value when 40% particle concentration was used was mainly because of severe "tailing" effect, probably due to the particle-particle interaction. Some limited number of tracer particles, not enough to cause significant difference in the mean NPRT, stayed for longer times in the system, resulting in a skewed distribution to the right.

Effect of Process Parameters. Tables 10 through 12 present the residence time distribution characteristics as influenced by process parameters in a horizontal SSHE when 0.4, 0.8 and 1.2% CMC was used, respectively. Individual distribution was tested using Pearson's x^2 goodness of fit test and CDFs to compare the experimental and theoretical values. It was rather difficult to isolate the single effect of process parameter on the distribution characteristics. However, it can be found that the number of distributions described by the normal distribution seemed to decrease as CMC concentration increased but increased as the flow rate and particle size increased. This indicates that the "tailing" of particles increases with the increase of CMC concentration, decrease of flow rate and particle size; thus, the distribution was skewed to the right approaching the gamma distribution.

TABLE 10.
RESIDENCE TIME DISTRIBUTION CHARACTERISTICS AS INFLUENCED BY PROCESS PARAMETERS IN A HORIZONTAL SSHE WHEN 0.4% CMC WAS USED

Flow Rate	Mutator Speed	Particle Size	$\bar{x}$	s	θ	r	Distribution Characteristic	P-value
0	0	0	0.940	0.092	111.06	104.40	normal	0.5596
0	1	2	1.061	0.115	80.23	85.12	normal	0.8805
0	2	1	1.224	0.302	13.42	16.43	gamma	0.4268
1	0	1	0.995	0.091	120.16	119.55	normal	0.8211
1	1	0	0.924	0.095	102.38	94.60	normal	0.7204
1	2	2	1.309	0.308	13.80	18.06	gamma	0.5879
2	0	2	1.085	0.132	62.27	67.56	normal	0.1253
2	1	1	0.953	0.074	174.03	165.85	normal	0.7792
2	2	0	1.039	0.210	23.56	24.48	gamma	0.3383

The number of gamma distributions having $P < 0.001$, thus rejecting the gamma distribution, seemed to increase with an increase of CMC concentration and decrease of mutator speed. Especially for the mutator speed of 60 rpm when 0.8 or 1.2% CMC solution was used as a carrier, the distributions could not be represented by gamma model due to severe skewness to the right. In such cases, some tracer particles were found to reach an equilibrium of forces and stayed as long as 4 min and 54 s when a flow rate of 599 mL/s, mutator speed of 60 rpm and particle size of 1.5 cm were used with 1.2% CMC solution as a carrier. It is interesting that the equilibrium only occurred where the blades overlap. However, it is less likely to happen in actual practice where a single particle is usually not processed. Particle-particle interactions may well have existed in such cases, as indicated earlier.

Occassionally, tracer particles were observed flowing backward, which confirms the back-mixing occurring inside the SSHE. This all contributed to the "tailing" of the distribution to the right which was the reason to reject the gamma distribution. Comparisons between the experimental and theoretical values of the CDF of NPRTs for each condition indicated that the model did fit the data well when $P > 0.01$ (Fig. 2 and 3).

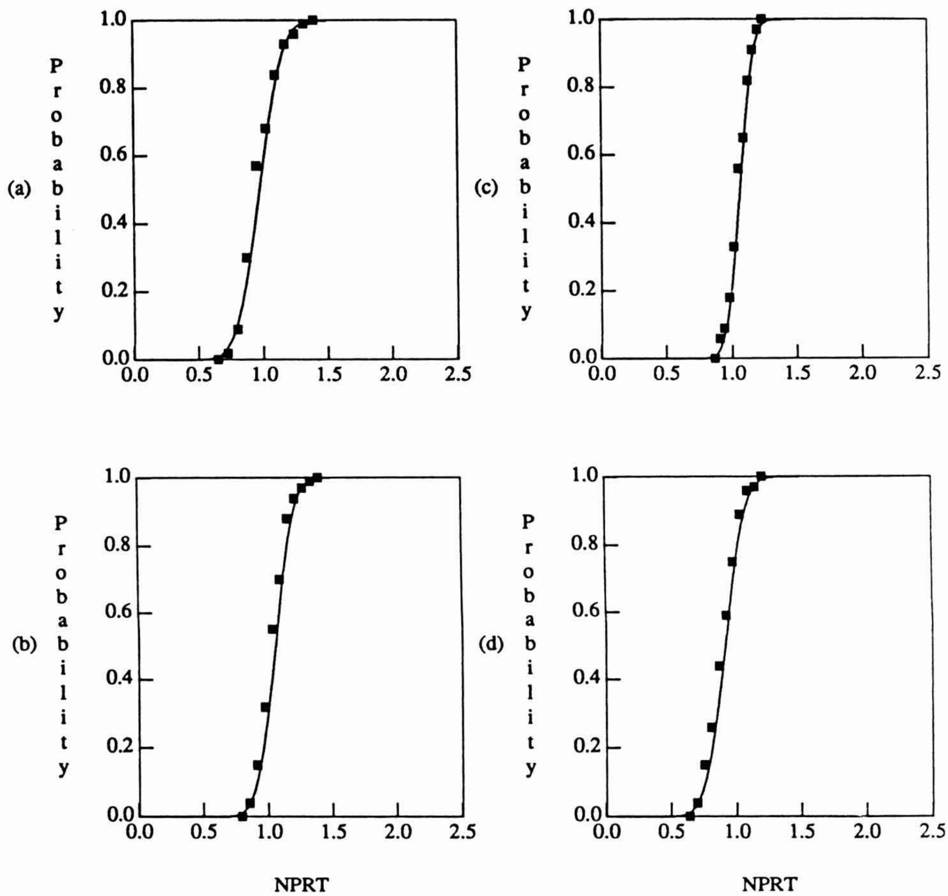

FIG. 2. NORMAL CUMULATIVE DISTRIBUTION FUNCTION OF NORMALIZED PARTICLE RESIDENCE TIME IN A HORIZONTAL SSHE

(a) 534 mL/s, 110 rpm and 1.5 cm potato cubes as tracer particles in 0.8% CMC solution as a carrier. (b) 453 mL/s, 110 rpm and 2.0 cm potato cubes in 0.4% CMC solution. (c) 453 mL/s, 160 rpm and 2.0 cm potato cubes as tracer particles in 0.8% CMC solutions as a carrier. (d) 534 mL/s, 160 rpm and 1.5 cm potato cubes as tracer particles in 1.2% CMC solutions as a carrier. Legend: ■ experimental, — theoretical.

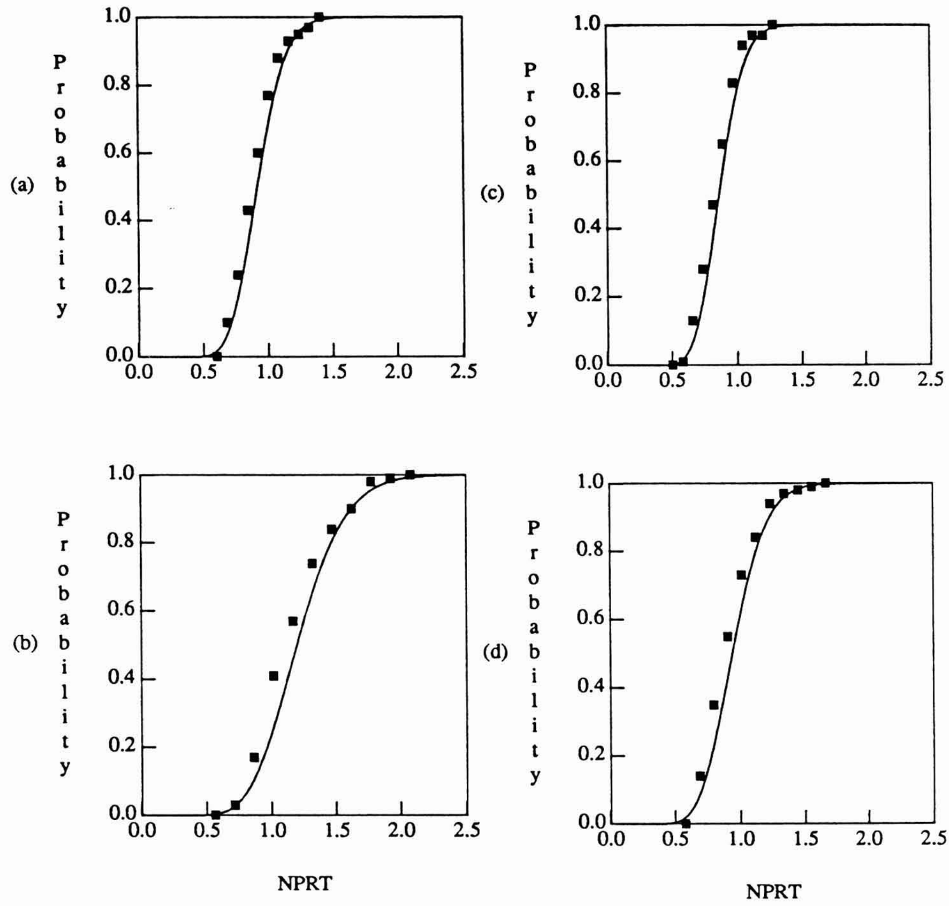

FIG. 3. GAMMA CUMULATIVE DISTRIBUTION FUNCTION OF NORMALIZED PARTICLE RESIDENCE TIME IN A HORIZONTAL SSHE

(a) 534 mL/s, 110 rpm and 1.5 cm potato cubes as tracer particles in 5% (w/v) 1.27 cm potato cubes in 0.8% CMC solution as a carrier. (b) 453 mL/s, 110 rpm and 1.5 cm potato cubes in 0.4% CMC solution. (c) 453 mL/s, 110 rpm and 1.0 cm potato cubes as tracer particles in 0.8% CMC solutions as a carrier. (d) 599 mL/s, 110 rpm and 1.0 cm potato cubes as tracer particles in 1.2% CMC solutions as a carrier. Legend: ■ experimental, — theoretical.

TABLE 11.
RESIDENCE TIME DISTRIBUTION CHARACTERISTICS AS INFLUENCED BY PROCESS PARAMETERS IN A HORIZONTAL SSHE WHEN 0.8% CMC WAS USED

Flow Rate	Mutator Speed	Particle Size	$\bar{x}$	s	θ	r	Distribution Characteristic	P-value
0	0	1	0.893	0.218	18.79	16.78	gamma	0.2270
0	1	0	0.875	0.153	37.29	32.64	gamma	0.9884
0	2	2	1.068	0.083	153.50	163.90	normal	0.5776
1	0	2	1.007	0.229	19.27	19.41	gamma	0.0001
1	1	1	0.960	0.138	50.72	48.71	normal	0.7227
1	2	0	0.943	0.160	36.94	34.84	gamma	0.8656
2	0	0	0.905	0.369	6.66	6.03	gamma	0.0000
2	1	2	1.038	0.139	53.88	55.94	normal	0.0115
2	2	1	0.947	0.098	97.79	92.60	normal	0.1150

TABLE 12.
RESIDENCE TIME DISTRIBUTION CHARACTERISTICS AS INFLUENCED BY PROCESS PARAMETERS IN A HORIZONTAL SSHE WHEN 1.2% CMC WAS USED

Flow Rate	Mutator Speed	Particle Size	$\bar{x}$	s	θ	r	Distribution Characteristic	P-value
0	0	2	0.976	0.254	15.13	14.77	gamma	0.0000
0	1	1	0.872	0.150	38.76	33.80	gamma	0.0078
0	2	0	0.892	0.188	25.24	22.51	gamma	0.3210
1	0	0	0.883	0.216	18.93	16.71	gamma	0.0040
1	1	2	0.979	0.134	54.52	53.38	normal	0.3213
1	2	1	0.920	0.124	59.83	55.05	normal	0.4110
2	0	1	1.184	1.934	0.32	0.38	gamma	0.0000
2	1	0	0.958	0.208	22.14	21.21	gamma	0.6171
2	2	2	0.994	0.117	72.61	72.18	normal	0.0682

CONCLUSIONS

Within the range of process parameters investigated, minimum and maximum NPRTs and standard deviation of mean NPRTs were not significantly affected by the particle concentration. However, a distinctive difference was found among mean NPRTs between up to 10% particle concentration and 20–40% ($P < 0.05$). The concentration of CMC, viz., viscosity, mutator speed and particle size ($P < 0.001$) as well as 2-way interactions among flow rate, mutator speed and particle size ($P < 0.01$ or 0.001), showed a significant impact on the mean NPRTs. However, these processing conditions did not significantly influence the minimum and maximum NPRTs and standard deviation of mean NPRTs ($P < 0.05$).

Pearson's x^2 goodness of fit test indicated that most of the individual particle residence time distributions in a hortizontal SSHE flow could be described by either normal or gamma models. Particle-particle interactions caused "tailing" of some particles, resulting in skewed distributions to the right. The "tailing" of the particles increased with the increase of CMC concentration, decrease of flow rate and particle size' thus, the distribution was skewed to the right approaching the gamma distribution. Comparisons between the experimental and theoretical values of the CDF or NPRTs for each condition indicated that the model did fit the data well when $P > 0.01$. Caution must be exercised in application of the results presented here unless the conditions and the apparatus design are similar to those used in these experiments.

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REFERENCES

ALCAIRO, E.R. and ZURITZ, C.A. 1990. Residence time distributions of spherical particles suspended in non-Newtonian flow in a scraped-surface heat exchanger. Trans. ASAE. *33*, 1621–1628.

BERRY, M.R. 1989. Predicting fastest particle residence time. Presented at the First International Congress on Aseptic Processing Technologists. Indianapolis, IN, March 19–21.

BICKEL, P.J. and DOKSUM, K.A. 1977. *Mathematical Statistics*. Holden-Day, Inc., San Francisco, CA.

DAIL, R. 1985. Calculation of required hold time of aspectically processed low acid foods containing particulates utilizing the Ball method. J. Food Sci. *50*, 1703–1706.

DEFRISE, D. and TAEYMANS, D. 1988. Stressing the influence of residence time distribution on continuous sterilization efficiency. *Proc. Int. Symp. on Progress in Food Preservation Processes,* pp. 171–184. CERIA, Brussels, Belgium.

DIGNAN, D.M., BERRY, M.R., PFLUG, I.J. and GARDINE, T.D. 1989. Safety considerations in establishing aseptic processes for low-acid foods containing particulates. Food Technol. *43*(3), 118–121, 131.

DUNCAN, D.B. 1955. Multiple range and multiple F tests. Biometrics *11*, 1–42.

LEE, J.H. and SINGH, R.K. 1990. Particle residence time distributions in a scraped surface heat exchanger. ASAE Paper No. 90-6520, American Society of Agricultural Engineers, St. Joseph, MI.

LEE, J.H., SINGH, R.K. and CHANDARANA, D.I. 1990a. Sensitivity analysis of aseptic process simulations for foods containing particulates. J. Food Proc. Eng. *12*, 295–321.

LEE, J.H., SINGH, R.K. and LARKIN, J.W. 1990b. Determination of lethality and process time in a continuous sterilization system containing particulates. J. Food Eng. *11*, 67–92.

MANSON, J.E. and CULLEN, J.F. 1974. Thermal process simulation for aseptic processing of foods containing discrete particulate matter. J. Food Sci. *39*, 1084–1089.

MONTGOMERY, D.C. 1984. *Designand Analysis of Experiments,* 2nd ed. John Wiley & Sons, New York.

O'MAHONY, M. 1986. *Statistics for Sensory Evaluation.* Marcel Dekker, Inc., New York.

SAS. 1986. *SAS User's Guide: Statistics,* Version 5 ed. SAS Institute, Inc., Cary, NC.

SASTRY, S.K. 1986. Mathematical evaluation of process schedules for aseptic processing of low-acid foods containing discrete particulates. J. Food Sci. *51*, 1323–1328.

TAEYMANS, D., ROELANS, E. and LENGES, J. 1985a. Residence time distribution in a horizontal SSHE used for UHT processing of liquids containing solids. Presented at the Fourth International Congress on Engineering and Food, Edmonton, Alberta.

TAEYMANS, D., ROELANS, E. and LENGES, J. 1985b. Influence of residence time distribution on the sterilization effect in a scraped surface heat exchanger used for processing liquids containing solid particles. Presented at the IUFoST Symposium on Aseptic Processing and Packaging of Foods, Tijlosand.

SIMULATION BASED PERFORMANCE ANALYSIS OF CRAWFISH PROCESSING OPERATIONS[1]

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ABSTRACT

A detailed model of crawfish processing operations was developed using the SLAM II simulation language. The simulation model was used to compare overall plant performance for two crawfish cooking schemes, boiling water and steam infusion, and to evaluate processing parameters for different plant capacities. For all the range of operating levels included in this study (2,400–19,000 lb of live crawfish/day or 360–2,900 lb of tail meat/day), the steam infusion cooking scheme rendered shorter processing times than those required by the boiling water cooking scheme. Moreover, the batch sizes and amount of resources used are smaller for the steam infusion cooking scheme. The simulation model is a valuable tool to analyze the performance of crawfish plants as well as to determine the impact of changes in technology on the overall process.

INTRODUCTION

Crawfish, *Procambarus* sp., is a lobster-resembling crustacean of economic and cultural importance in Louisiana. Commercial processing of crawfish started in St. Martin Parish, Louisiana, in the 1950s (Morse 1977). Currently, Louisiana produces approximately 90% of the crawfish consumed in the United States (Marshall *et al.* 1987), as well as crawfish exported to European countries.

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The steps in the processing of crawfish depend on the type of crawfish product demanded by the consumers. Some of these crawfish products are as follows:

(1) whole, live crawfish
(2) whole, cooked, and frozen crawfish
(3) cooked, peeled, and deveined crawfish meat (crawfish tail meat)

Among these, the cooked, peeled and deveined crawfish requires the greatest number of processing operations. A schematic diagram of the processing for crawfish tail meat is shown in Fig. 1.

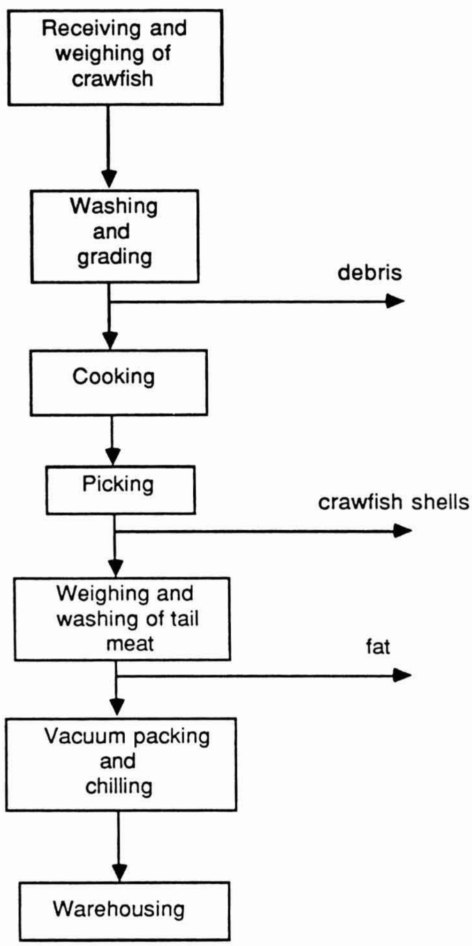


FIG. 1. FLOWCHART OF CRAWFISH PROCESSING OPERATIONS

A crawfish processing plant for the production of cooked, peeled, deveined, and frozen crawfish was simulated using the SLAM II simulation language. SLAM II is a process-oriented language that can be used for the simulation of discrete and continuous processes. This simulation language can be interfaced with FORTRAN subroutines, allowing the implementation of network models that cannot be readily represented using the built-in SLAM II routines.

The processing capacity of commercial crawfish plants ranges from 900 to 19,800 lb of live crawfish/day (Moody 1989). The simulation program in this study was run for plant capacities ranging from 2,400 to 19,000 lb of live crawfish/day, which covers most of the commercial range.

A fundamental problem in the processing of crawfish is that picking or peeling or crawfish is carried out manually. Therefore, the picking operation, being the slowest, is the bottleneck of the processing line. Moreover, manual handling of the product at this stage of the process can cause its contamination when appropriate sanitary practices are not followed.

Another problem is the relatively low processing rate obtained with the conventional boiling water cooking method. In this cooking method, water is added to a pot, and heat is applied until the water begins to boil. Then, a basket containing the crawfish to be cooked is immersed in the pot. The temperture of the boiling water decreases due to the fact that some amount of energy is consumed to heat the product during the initial contact. The product is allowed to boil for several minutes, and then the basket is removed from the pot. As this operation is repeated several times, the pot has to be cleaned after every fifth batch in order to maintain sanitary conditions. This particular step causes a delay in the cooking operation, since a resource (cooking pot) is out of service for some period of time.

An alternative cooking method, the steam infusion cooking scheme, has also been employed in a pilot scale experiment (Baskin and Wells 1990) and in some commercial crawfish processing applications. In this cooking scheme, crawfish are loaded into an empty kettle, which is then closed. Pressurized steam is injected into the kettle, the product is rapidly cooked, the steam is released when the kettle is opened, and the cooked crawfish are dumped into the chute. This cooking scheme does not require periodic cleaning.

The specific objectives of this research are:

(1) The modeling and simulation of all the stages of a crawfish plant for the production of cooked, peeled, and deveined crawfish.
(2) The comparative evaluation of the impact of using two cooking schemes, boiling water and steam infusion, on plant throughput, processing times, and labor needs.
(3) The extension of the evaluation of cooking schemes for different batch sizes and plant capacities.

METHODOLOGY

Many authors have used modeling and simulation for sound evaluation of food processing plants (Shah *et al.* 1985; Starbird and Ghiassi 1986). A model is an abstraction of a real system on which some simplifications and assumptions are usually made (Jenson and Jeffreys 1977). Thus, modeling can be approached from different views and using different methods based on the nature of the process. Simulation is the design and implementation of an experiment involving a model. Together, modeling and simulation can be used to evaluate the impact of changes in process technology and to estimate optimal design capacities in planned facilities.

Some processes can be suitably represented using differential equations in which the independent variable is time. In those processes the variables that describe the state of the system change continuously with time, and they are categorized as continuous processes. Other processes, however, are discrete in nature, and appreciable changes in the process variables occur only at time intervals (e.g., in a flexible manufacturing system). In discrete-type systems, attention must be focused on the events that alter the state of the system. Keeping track of those events and states over time will give an adequate representation of the process. Also, some processes exhibit both discrete and continuous natures.

There are situations in which a processing plant must be studied using either a discrete or a continuous model depending on the parameters of interest or the precision desired. For instance, in a crawfish processing operation, the use of a discrete model is needed if average processing times, average labor needs, and average plant throughputs are to be estimated. On the other hand, a continuous model is required when changes of temperature over time during the cooking operation are to be modeled.

Both discrete and continuous processes can be successfully simulated using computers. Several computer languages are available to accomplish that purpose (e.g., BASIC, FORTRAN, C, etc.). Moreover, a variety of simulation languages and software packages are available to simulate specific types of processes (e.g., SLAM II, PROCESS, ASPEN PLUS, DYNAMO, etc.).

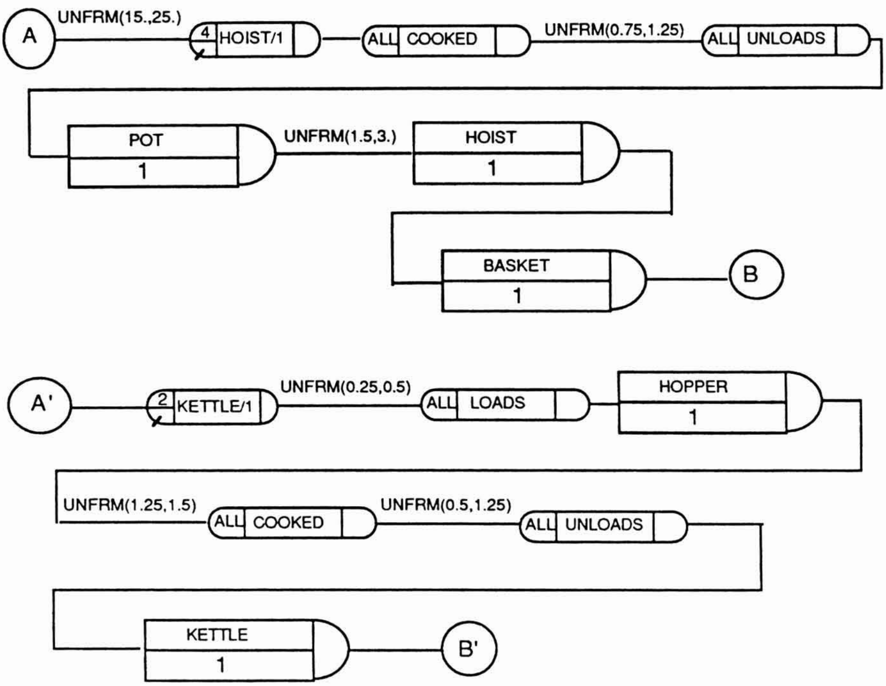
In this research, SLAM II, a process-oriented simulation languague, is used to simulate crawfish processing operations. SLAM II can be used for the simulation of both continuous and discrete process models. Several SLAM II nodes, blocks, and arcs are available to simulate equipment, activities, and other processing operations such that a process flowchart can be converted into a network-type model. A complete description of the capabilities of this simulation software package is given by Pritsker (1986).

Two network models of a crawfish plant for the production of crawfish tail meat using the boiling water and steam infusion cooking scheme were the tools for the study of crawfish processing operations. Numerous experimental runs of the SLAM II network models were run on an IBM 3084 mainframe computer under the VM/CMS operating system. The process equipment and labor needed in the processing plant were simulated using resources as described in SLAM II. Both the boiling water and steam infusion cooking schemes are batchwise operations, and a batch node was utilized to simulate this part of the process. The batch node groups a specified number of entities into a single entity. In this particular case, the batch size corresponded to the amount of crawfish cooked using either cooking scheme. The entities continue to flow independently through the process after cooking is completed. That step is accomplished using an unbatch node.

A segment of the SLAM II network model used to simulate the cooking schemes is shown in Fig. 2. Different activity durations (such as cooking and chilling/freezing times, peeling rates, loading, unloading, and cleaning times) are typical of local crawfish processing plants. Those activity durations and their distributions are shown in Table 1. The cooking times for the steam infusion and boiling water cooking schemes are the same as those reported by Baskin and Wells (1989). The peeling rate used in this study includes downtime and was estimated based on a 4 lb/h average picking rate as reported by Moody (1980). A triangular distribution was used for the picking operation based on its nature. The picking operation has a lower limit based on minimum rates determined through motion and time studies. There is not a specific higher limit, but the probability of having picking rates much greater than the mode is very low. Thus, a skewed normal distribution or an asymmetric triangular distribution can be used to model this particular activity.

It should be noted that the entity in this simulation study was one pound of tail meat. Thus, after the 40-pound sacks of crawfish (Moody 1980) reach the plant, their weight is expressed as pounds of tail-meat. Huner (1988) states that 85% of the live weight of crawfish is waste; therefore, a 15% yield was assumed for conversion of live crawfish to finished weight of tail meat. The use of pounds of tail meat rather than raw crawfish weight in the simulation helps to reduce the number of entities in the SLAM II files. Thus, the dimension of the arrays needed to run the simulation is smaller, and consequently, the memory requirement is also reduced.

The SLAM II programs used to simulate both the steam infusion and the boiling cooking schemes comprehend all the steps or operations that are needed to obtain cooked, peeled, deveined, and chilled/frozen crawfish tail meat.



Resources used for the cooking operation simulation segments

boiling water

HOIST	2	3	4
BASKET	4	1	
POT	5	2	

steam infusion

HOPPER	1	1	
KETTLE	2	2	

FIG. 2. SEGMENTS OF THE SLAM II NETWORKS USED TO SIMULATE THE COOKING OPERATION IN THE BOILING WATER (A – B) AND STEAM INFUSION (A′ – B′) PROCESS MODELS

TABLE 1.
ACTIVITY DURATIONS AND PROBABILITY DISTRIBUTIONS USED IN THE BOILING WATER (BW) AND STEAM INFUSION (SI) COOKING SCHEMES

Description	Cooking scheme	Probability distribution[a]	Time (minutes) min	mode	max
Receive	BW	UNF	0.25		0.5
Convey	BW	UNF	0.75		1.25
Load pot	BW	UNF	1.5		2.50
Cooking time	BW	UNF	15.0		25.0
Unload pot	BW	UNF	0.75		1.25
Empty chute	BW	UNF	1.5		3.0
Picking time	BW	TRIAG	10.0	14.5	15.0
Packing time	BW	UNF	3.0		4.0
Chilling time	BW	UNF	30.0		35.0
Receive	SI	UNF	0.5		1.0
Convey	SI	UNF	0.75		1.25
Load kettle	SI	UNF	0.25		0.5
Cooking time	SI	UNF	1.25		1.50
Unload kettle	SI	UNF	0.50		1.25
Empty chute	SI	UNF	1.25		2.5
Picking time	SI	TRIAG	10.0	14.5	15.0
Packing time	SI	UNF	3.0		4.0
Chilling time	SI	UNF	30.0		35.0

[a]The notation UNF and TRIAG indicates the uniform and triangular probability distributions, respectively.

RESULTS AND DISCUSSION

Estimation of Resources

In order to cover the range (2,400–19,000 lb of live crawfish/day) considered in this work, different batch sizes were utilized in the boiling water cooking scheme. The batch sizes, baskets, pots, and plant throughputs (expressed in pounds of tail meat/day) for the boiling water cooking scheme are presented in Table 2. In the boiling water cooking scheme, the shift length is constant (8 h/day). For the steam infusion cooking scheme a fixed batch size, 60 lb, was used, and in order to obtain plant throughputs within the aforementioned range, the shift length was varied according to the desired plant capacity. The number of kettles, pickers, and plant throughputs are included in Table 3. The results reported in Tables 2 and 3 correspond to simulation runs that use a number of resources so that the processing line is balanced and a near optimal utilization of resources is obtained.

TABLE 2.
BATCH SIZES, BASKETS, POTS, AND PLANT THROUGHPUTS FOR THE BOILING WATER COOKING SCHEME ACCORDING TO THE SIMULATION RUNS

Run number	Tail meat (lb/day)	Batch size (lb)	Number of Baskets	Pots
1	360	200	1	2
2	690	200	2	2
3	810	200	2	3
4	1200	200	3	4
5	1620	200	4	5
6	2130	200	6	7
7	2610	200	7	8
8	2940	200	8	9

An example of how a near optimal number of pickers was obtained for a fixed number of pots and baskets is shown in Table 4. A given number of pots and baskets (6 and 7, respectively in this study) can be used to obtain different plant throughputs depending on the number of pickers working in the plant. However, processing should be scheduled so that after an 8-h period, there is no material left in the processing line (in the water boiling cooking scheme). Another factor considered in the estimation of the number of pickers needed for a given plant throughput is the utilization of the picker. It can be seen from Table 4 that as the number of pickers increases, their average utilization decreases. Additionally, the average time in the system decreases as the number of pickers increases.

As discussed above, the optimal number of pickers for a fixed number of baskets and pots depends on several parameters. In the example shown in Table 4, 85, 94 and 110 pickers are required to obtain plant throughputs of 2,580, 2,610 and 2,580 lb of tail meat with average time in the system of 102.0, 85.0 and 78.0 minutes and percent of line balances of 0.69, 0.68, and 0.69, respectively. It can be seen from these simulation results that there is a compromise between the foregoing parameters. For instance, although the percent of line balance is approximately the same in the three simulation results, plant throughput, picker utilization and average time in the system are affected by the number of pickers selected for the peeling operation. In this particular case, and

TABLE 3.
PICKERS, KETTLES, HOPPERS, SHIFT LENGTH, AND PLANT THROUGHPUTS (EXPRESSED IN POUNDS OF TAIL MEAT) FOR THE STEAM INFUSION COOKING SCHEME ACCORDING TO THE SIMULATION RUNS

Run number	Tail meat (lb/shift)	Shift length (min)	Pickers	Number of Hoppers / Kettles	
1	360	180	38	1	1
2	522	220	45	1	1
3	702	260	48	1	1
4	873	310	48	1	1
5	1044	360	48	1	1
6	1215	410	49	1	1
7	1422	480	53	1	1
8	1431	300	82	1	2
9	1629	320	82	1	2
10	1818	350	85	1	2
11	1980	370	85	1	2
12	2313	410	90	1	2
13	2646	460	90	1	2
14	2781	480	92	1	2

based on the reported data, 94 pickers for a plant throughput of 2,610 lb of tail meat were considered to be a near optimal combination.

It can be seen from Tables 2 and 3 that the number of kettles required to cook the crawfish in the steam infusion method is always fewer than the number of baskets and pots required to cook the crawfish in the boiling water cooking method for all levels of operation. Moreover, the batch size is smaller in the steam infusion cooking scheme.

TABLE 4.
SAMPLE RUNS SHOWING THE PROCEDURE USED TO DETERMINE THE NEAR OPTIMAL AMOUNT OF RESOURCES NEEDED FOR DIFFERENT PLANT THROUGHPUTS[a]

	Pickers								
	60	70	80	85	94[b]	110	120	130	140
%LB[c]	28.5	17.5	5.63	0.69	0.68	0.69	0.0	0.23	0.0
PTP[d]	1860.0	2160.0	2480.0	2580.0	2610.0	2580.0	2640.0	2550.0	2640.0
%PU[e]	94.0	94.0	89.5	83.2	76.0	64.3	60.3	53.8	51.7
ATS[f]	158.0	136.0	114.0	102.0	85.0	78.0	78.0	78.0	77.0

[a] In these runs, the fixed resources are 7 baskets and 8 pots.
[b] Near optimal number of pickers selected based on performance parameters.
[c] %LB is the percent of line balance=(input-output)*100/input.
[d] PTP is the plant throughput in pounds of tail meat.
[e] %PU is percent picker utilization.
[f] ATS is the average time in the system.

Regression Equations

A plot of the number of 200-lb capacity baskets required for different levels of plant throughput for the boiling water cooking scheme is shown in Fig. 3. The first order regression equation

$$B = -0.06768 + 2.719TM \qquad R^2 = 0.995 \qquad (1)$$

where B is number of baskets of 200-lb capacity
TM are pounds of tail meat

was chosen to estimate the number of baskets for any operation level within the range (2,400–19,000 lb of live crawfish/day or 360–2,900 lb of tail meat/day) covered by the simulation study. As a rule of thumb, the number of pots either equals or exceeds by one unit the number of baskets required. This can be verified by looking at the data in Table 2. A similar result can be drawn from Table 3 concerning the number of kettles required for a given plant throughput in the steam infusion cooking scheme. Moreover, a plot of the shift length in minutes versus plant throughput is shown in Fig. 4. The regression equations

$$PTP(1\ kettle) = -246.18 + 3.5437\ SL \qquad R^2 = 0.996 \qquad (2a)$$

$$PTP(2\ \text{kettles}) = -779.82 + 7.456SL \qquad R^2 = 0.998 \qquad (2b)$$

where PTP is plant throughput in pounds of tail meat
`SL is the shift length in minutes

were calculated based on the data in Table 3 and can be used to estimate plant throughputs within the ranges given in Table 3. Extrapolation of the regression equations (2a) and (2b) indicates that above plants throughputs of 270 lb of tail meat/shift, there is the option to use either 1 or 2 kettles to obtain the desired operation level.

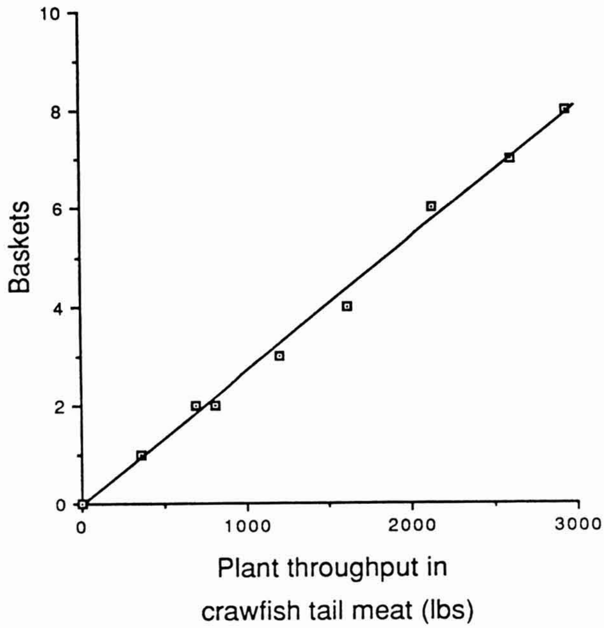


FIG. 3. BASKETS (200-lb CAPACITY) REQUIRED FOR DIFFERENT LEVELS OF OPERATION

Another important aspect of the simulation results is the number of pickers needed to carry out the peeling operation. A plot showing the number of pickers versus pounds of tail meat for the boiling water cooking scheme is shown in Fig. 5. A first order regression equation

$$P = 0.59529 + 0.03268TM \qquad R^2 = 0.98 \qquad (3)$$

where P is number of pickers
TM are pounds of tail meat

that estimates the number of pickers needed for different levels of operation is included in the figure. For the steam infusion cooking scheme, the number of pickers needed for a given plant throughput can be estimated from Table 3.

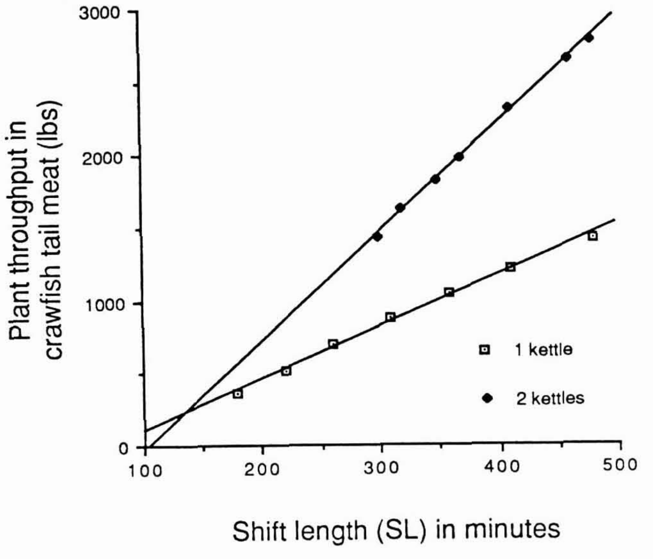


FIG. 4. PLANT THROUGHPUTS CORRESPONDING TO DIFFERENT SHIFT LENGTHS AND NUMBER OF KETTLES

Average Time in the System

Noticeable differences were observed in the average time in the system for the boiling water and steam infusion cooking schemes. In order to illustrate the differences in average time in the system for the 2 cooking methods under study, as well as the use of Fig. 3 and 5 and Table 3 in the estimation of the amount of resources needed to obtain 1,500 lb of tail meat, the following example is presented.

Regression equations shown in Fig. 3 and 5 can be used to estimate the number of baskets and pickers needed for a 1,500-lb plant throughput. These values are 4 and 50, respectively. Five pots can be selected based on the rule of thumb that the number of pots may equal or exceed by one unit the number of

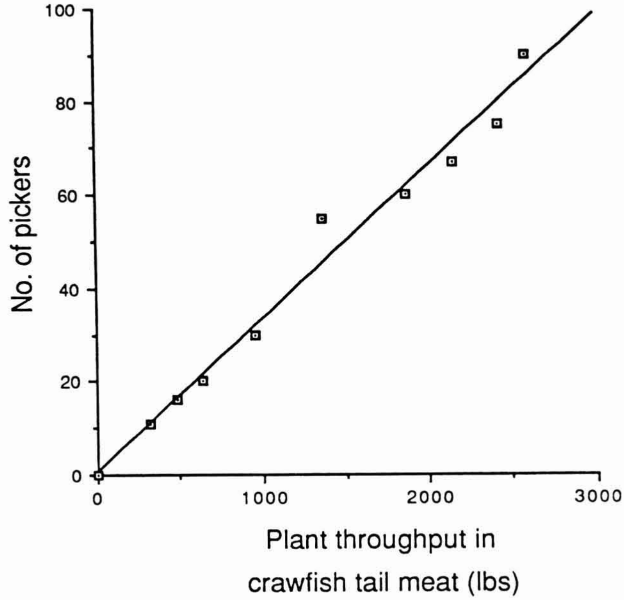


FIG. 5. PICKERS REQUIRED IN BOIL PROCESS FOR DIFFERENT LEVELS OF OPERATION

baskets. The simulation results for the selected resources are a plant throughput of 1,552 lb of tail meat and an average time in the system of 107 minutes with a standard deviation of 15.7.

Similarly, the information in Table 3 is used to estimate that 82 pickers, 2 kettles, 1 hopper, and a shift length of 310 min are needed to obtain 1,500 lb of tail meat for the steam infusion cooking scheme. The simulation results for the selected resources are a plant throughput a 1,494 lb of tail meat and an average time in the system of 60.4 min with a standard deviation of 3.5.

Thus, in this particular example, the boiling water cooking scheme requires a longer time in the system (77% longer) than the time needed in the steam infusion cooking scheme. Moreover, it is important to note the difference in the value of standard deviation of the average time in the system for both cooking schemes. Additionally, the example illustrates that the plant throughputs obtained are very close to the design value of 1,500 lb.

Sensitivity Analysis

Some important factors to be considered in simulation studies are the stochastic nature of the processing data and the robustness of the model to

TABLE 5.
SENSITIVITY ANALYSIS RESULTS FOR CHANGES IN RECEIVING RATE CORRESPONDING TO THE BOILING WATER (BW) AND STEAM INFUSION (SI) COOKING SCHEMES

Run No.	Cooking scheme	Receiving rate (min)	PTP[a] (lb/shift)	Change in PTP (lb/shift)	Change in PTP (%)
6	BW	0.25-0.5	2130		
6A	BW	0.50-1.0	1890	-240	11.26
12	SI	0.50-1.0	2313		
12A	SI	0.25-0.5	2384	71	2.97

[a] PTP is the plant throughput in pounds of tail meat.

changes in processing parameters. The stochastic nature of process data is accounted for in the simulation of the crawfish plant by assuming a probability distribution for all the activities. Thus, processing data can vary within a given range in a random fashion. Some experimental runs to determine the impact of changes in the low and high limits of the triangular distribution assumed for the peeling activity indicated that there are changes in the output of the plant, but the changes were not found to be significant.

Much greater changes in plant throughput were observed, however, when the receiving rate or receiving frequency were changed on the runs corresponding to the boiling water and steam infusion cooking scheme. Changes in the receiving rate for the boiling water (BW) cooking scheme, as indicated in Table 5, caused a change in plant throughput of 11.26%. In the steam infusion (SI) cooking scheme, however, changes in the receiving rate caused a change in plant throughput of only 2.97%. Therefore, the model corresponding to the boiling water cooking scheme is relatively sensitive to changes in the receiving rate, while the model for the steam infusion cooking scheme is relatively stable.

CONCLUSIONS

(1) Two network-based models that simulate crawfish processing operations were implemented using the SLAM II simulation language. Both SLAM II pro-

grams integrate all the resources, activities, and operations required to obtain cooked, peeled, deveined, and chilled/frozen crawfish tail meat. One of the programs simulates a processing plant that uses the boiling water cooking scheme, whereas the other simulates a plant that uses the steam infusion cooking scheme. The programs require distinct resources that are inherent to either technology.

(2) The simulation study covered a wide range of operation levels that characterize the commercial production of crawfish, and it is a valuable aid to estimate the major equipment and labor needs for commercial crawfish plants using the boiling water or the steam infusion cooking schemes. In addition, regression equations were derived to estimate the number of pickers and baskets used in the boiling water cooking method.

(3) A comparative evaluation of the foregoing cooking schemes reveals that the average time in the system is always smaller when the steam infusion cooking scheme is used. Also, the amount of equipment and batch sizes needed to implement the steam infusion cooking scheme is considerably smaller.

(4) An analysis of robustness of both models to variations in processing parameters indicated that the model corresponding to the boiling water cooking scheme is relatively sensitive to changes in receiving rate. Thus, the steam infusion cooking scheme is less sensitive to changes in processing parameters.

NOMENCLATURE

B Number of baskets of 200 lb capacity
P Number of pickers
PTP Plant throughput, lb
R^2 Correlation coefficient
SL Shift length, min
TM Tail meat, lb

REFERENCES

BASKIN, G.R. and WELLS, J.H. 1990. Evaluation of Alternative Cooking Schemes for Crawfish Processing. J. Shellfish Research *9*(2), 389–393.

HUNER, J.V. 1988. Procambarus in North America and elsewhere. Ch. 9. In *Freshwater Crayfish: Biology, Management, and Explotation,* (D.M. Holdich and R.S. Lowery, eds.), p. 239, Timber Press, London.

JENSON, V.G. and JEFFREYS, G.V. 1977. *Mathematical Methods in Chemical Engineering,* 2nd ed. Academic Press, London.

MARSHALL, G.A., MOODY, M.W., HACKNEY, C.R. and GODBER, J.S. 1987. Effect of blanch time on the development of mushiness in ice-stored crawfish meat packed with adhering hepatopancreas. J. Food Sci. *52*(6), 1504–1505.

MOODY, M.W. 1980. Louisiana seafood delight — the crawfish. Louisiana Cooperative Extension Service Publication #LSU-TL-80-002, Louisiana State Univ. Agricultural Center, Baton Rouge, LA.

MOODY, M.W. 1989. Processing of freshwater crawfish: a review. J. Shellfish Res. *8*(1), 293–301.

MORSE, W.P. 1977. Guidelines governing crayfish processing. In *Freshwater Crayfish*, (O.V. Lindqvist, ed.) pp. 483–89, University of Kuopio, Finland.

PRITSKER, A.B.A. 1986. *Introduction to Simulation and SLAM II.* 3rd. ed. Systems Publishing Corp., West Lafayette, IN.

SHAH, S.A., OKOS, M.R. and REKLAITIS, G.V. 1985. A SLAM based computer simulation model of a meat processing plant. Trans. ASAE *28*(5), 1698–1703.

STARBIRD, S.A. and GHIASSI, M. 1986. Simulation Modeling of a Multi Product Tomato Processing Plant. Trans. ASAE *29*(1), 324–330.

GUIDE FOR AUTHORS

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

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

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Tables should be numbered consecutively with Arabic numerals. The title of the table should appear as below:

Table 1. Activity of potato acyl-hydrolases on neutral lipids, galactolipids, and phospholipids

Description of experimental work or explanation of symbols should go below the table proper. Type tables neatly and correctly as tables are considered art and are not typeset. Single-space tables.

Figures should be listed in order in the text using Arabic numbers. Figure legends should be typed on a separate page. Figures and tables should be intelligible without reference to the text. Authors should indicate where the tables and figures should be placed in the text. Photographs must be supplied as glossy black and white prints. Line diagrams should be drawn with black waterproof ink on white paper or board. The lettering should be of such a size that it is easily legible after reduction. Each diagram and photograph should be clearly labeled on the reverse side with the name(s) of author(s), and title of paper. When not obvious, each photograph and diagram should be labeled on the back to show the top of the photograph or diagram.

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Short notes will be published where the information is deemed sufficiently important to warrant rapid publication. The format for short papers may be similar to that for regular papers but more concisely written. Short notes may be of a less general nature and written principally for specialists in the particular area with which the manuscript is dealing. Manuscripts which do not meet the requirement of importance and necessity for rapid publication will, after notification of the author(s), be treated as regular papers. Regular papers may be very short.

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