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CONTENTS

NEW MEAT PRODUCTS MANUFACTURED WITH THE "KATSUOBUSHI" PROCESS, AND THE CHEMICAL NATURE AND ORGANOLEPTIC ACCEPTABILITY OF THE PRODUCTS

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ABSTRACT

New meat products were developed from beef using the process of dried-skipjack (katsuobushi) manufacturing, which employs boiling, smoke drying and molding. Boiling and molding affected the constituent nitrogen compounds of the meat. These changes affected the flavor of the new meat products. Lipid constituents were altered in the molding process, where lipase produced from the mold increased the amount of free fatty acids, which produced a mild flavor in the new product. Differences in the processing method produce a difference in the organoleptic acceptance and flavor.

In particular, the molding process was responsible for production of a mild sourness and acceptable flavor.

INTRODUCTION

The increasing demand for animal protein products in Japan has heightened interest in developing new meat products. One area where there has been little

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or no work conducted is the development of new meat products with favorable properties similar to katsuobushi marine products in Japan (Wada 1969).

Katsuobushi, made from skipjack fillet, is a traditional marine product made in Japan, and has been used since ancient times to prepare soup stock because of its very mild and acceptable flavor (Kohnosu and Hashimoto 1959; Fujita and Hashimoto 1959; Yamanishi et al. 1966; Kim et al. 1971; Fuke et al. 1989). Various steps are used in the manufacture of katsuobushi such as boiling, drying, smoking, and molding. The process of smoking and molding is repeated several times to obtain the adequate dryness and flavor, which is a unique procedure, since it is not commonly used in the manufacture of other foods. The processes of boiling and smoking remove the fishy odor and provides substances that inhibit the deterioration of the fish meat, increasing the stability (Ohta 1984). For instance, formation of natural antioxidant and synergistic effects of tocopherol from the katsuobushi smoking process have been investigated (Ishikawa 1985). Molding of the fillet decreases the lipid content (Suyama 1949a,b, 1950) and gives it not only a pleasant flavor, in addition to the fish flavor, but also produces a clear stock, which is utilized in making soup.

The objective of this work was to combine the katsuobushi manufacturing process with the process used to manufacture smoked animal meat products such as ham, bacon, sausage (Numata et al. 1987) and jerky in an effort to develop katsuobushi-like meat products. This study focuses on the development of new meat products with application of the katsuobushi manufacturing process. In addition, the effects of this process on the chemical composition and organoleptic properties of the katsuobushi-like meat products were evaluated.

MATERIALS AND METHODS

Frozen Beef Rump

Frozen beef rump was imported from Australia and stored at $-25C$ for 2 months until it was used in the manufacturing of katsuobushi-like products.

Preparation of Katsuobushi-like Products

The different stages of the process used to prepare the new meat product are shown in Fig. 1. The frozen beef was cut at $-25C$ to $20 \times 15 \times 3$ cm, weighing approximately 1 kg, and was defrosted by refrigerator at 5C for ca. 20 h. The meat was designated as sample No. 1. The meat was then divided into two portions. One was processed by boiling, smoking, curing/drying, chipping, and drying or molding, while the other was processed with the same procedures, but no boiling. As shown in Fig. 1, samples of No. 1, 2, 3, 4, 5, and 6 were obtained at different stages throughout the process, and each sample prepared was 700 g.
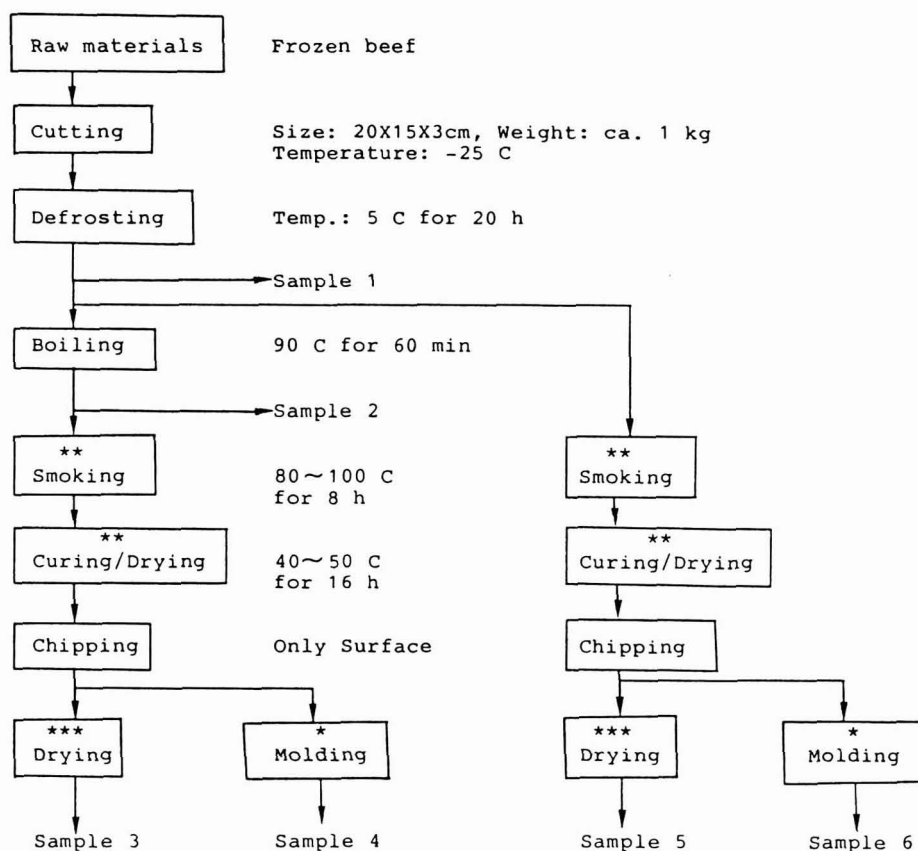
FIG. 1. PRODUCTION METHODS FOR KATSUOBUSHI-LIKE MEAT PRODUCTS
*Temperature: 30C, Humidity: 80%, for 30 days.
**Smoking treatment 8 h/day, Curing/Drying treatment, for 6 days (16 h/day).
***Drying for 10 days (10 h/day).

Boiling and smoking were done by using the conventional steam batch and smoke house, respectively. Temperature and duration of boiling and smoking were 90C, 1 h, and 80–100C, 8 h, respectively. Smoking was repeated at 6 days. Chipping means to knife-cut about 2 mm deep on the surface of the meat for ease of molding. Molding was performed for 30 days in the humidity of 80% at 30C by spraying 1 mL/kg of meat the spore *Asp. repens* dissolved in the salt solution at 15% concentration. Samples (3) and (5) were not molded and samples (5) and (6) were not boiled to compare the difference concerning the acceptability related to the materials of extract.

Figure 2 shows the methods of sample preparation, because each sample had a different hardness. Samples (1) and (2) were soft and, therefore, could be

(Samples 1 and 2)   (Samples 3, 4, 5 and 6)

3 Chunks	Size: 10X10x2cm Weight: ca.250g/chunk

↓

Cutting	ca. 3cm cubes with knife

↓

Homogenizing	Meat chopper (repeat 3 times)

3 Chunks	Size: 8X8X2cm Weight: ca.150g/chunk

↓

Chipping	Katsuobushi-slicer

↓

Shattering	Smashing the slices by mixer
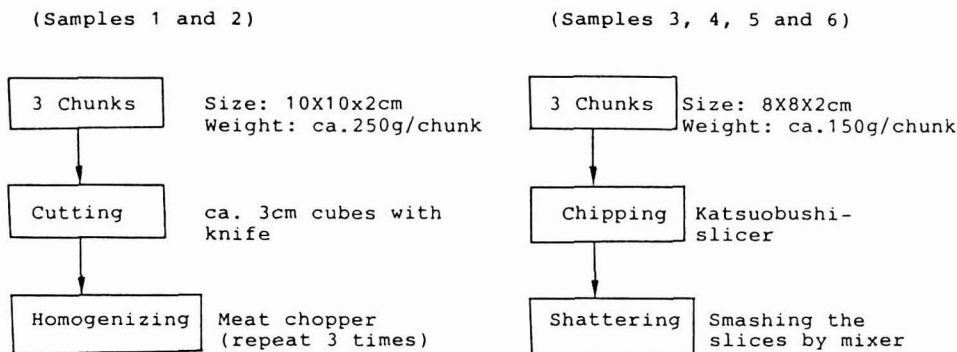
FIG. 2. METHODS OF SAMPLE PREPARATION
Sample treatment temperature 5C.

homogenized by meat chopper to obtain a homogeneous sample, while samples
(3), (4), (5), and (6) were hard. They were shattered by the Katsuobushi slicer,
and then were mixed into powder with a mixer.

All processes for the sample's preparation was performed at 5C, and all samples
were stored at $-25C$ in a polyethylene container until they were prepared for
analyses and organoleptic evaluation.

Analyses

Each sample was prepared for compositional analysis, as outlined in Fig. 1
and 2, and was tested for

(1) Moisture: Aliquots (approx. 2 g) of the samples were weighed in crucibles
and dried at 100C for 5 h in a forced air vacuum oven. The percent of moisture
was determined by:

$$\frac{\text{(Original sample weight)} - \text{(Dried sample weight)}}{\text{(Original sample weight)}} \times 100$$

(2) Nitrogen constituents: (a) Total nitrogen: The amount of nitrogen was deter-
mined by the Kjeldahl method. (b) Water soluble nitrogen, mono-amino and di-
amino nitrogen: Water soluble nitrogen was extracted by boiling a 20 g sample
in 150 mL of distilled water for 3 h. The liquid was concentrated and filtered
with TOYO No. 5A filter paper. The filtrate was diluted to 50 mL with distilled
water and a 2 mL sample was used for quantitative soluble nitrogen analysis
(Kjeldahl method). Five mL of distilled filtrate was acidified with 5 mL of 10
w/w% sulfuric acid and then phosphotungstate acid. Precipitates were filtrated
with TOYO No. 5C filter paper. The precipitates were fractionated as di-amino

nitrogen and the filtrate was fractionated as di-amino nitrogen and the filtrate was fractionated as mono-amino nitrogen (Shimizu 1949; Kashiwada *et al.* 1953; Pharmaceutical Society of Japan 1965). The total nitrogen content of each fraction was determined quantitatively by the Kjeldahl method.

(3) Creatine and creatinine content: Determined quantitatively according to the AOAC (1984) method.

(4) Lipid content, acid value and iodine value: Lipids were extracted with chloroform and methanol and the lipid content was determined by Bligh and Dyer (1959) method. Acid and iodine values were determined according to the Japan Oil Chemists' Society's (1971) method.

(5) Lipid class: Lipid class composition was evaluated by thin layer chromatography (TLC). The TLC developer was a mixture of petroleum ether, diethyl ether and acetic acid (80:20:1, v/v). TLC plate (Silicagel G) used was obtained from E. Merck, AG., and the thickness of the coating was 0.25 mm. After the sample was spotted and developing, a liquid of saturated potassium dichromate in 75% sulfuric acid was sprayed on the TLC plate and was activated at 130C for 5 min. The spot sample was analyzed by using a Shimadzu high speed TLC scanner CS-9200 to determine the lipid class composition quantitatively.

(6) Sensory evaluation: Methods of stock preparation and sensory evaluation were performed as indicated in Fig. 3. For the relative comparison, stocks of samples 3, 4, 5, and 6 were prepared and the quantity of 100 mL solution at temperature of 60C in dishes was served to 8 panelist for the evaluation of aroma, palatability, sourness, and acceptability (total flavor evaluation). Acceptability was scored with the points from 10 to 0 in order of assessments with extremely sweet (10), normal (5), and extremely unpalatable (0). Other evaluations of aroma, palatability, and sourness were done by the score of 5 points assessed with strong (point: 5) or weak (point: 1), or like (point: 5) or dislike (point: 1).

Statical analysis was adapted to the evaluations between samples 3 and 4, samples 3 and 5, and samples 5 and 6, respectively, by t-test of relative comparison.

RESULTS AND DISCUSSION

Moisture and Nitrogen Compounds

The moisture level and various nitrogenous constituents in the katsuobushi-like meat products are shown in Tables 1 and 2. The moisture was decreased throughout the process from 66.8% to less than 20%.

As indicated in Table 2, change in the ratio of di-amino-N(DN)/mono-amino-N(MN) increased throughout the process from the boiling to the drying stage of the material; however, the drying and molding process caused a decrease in the ratio. It is believed the change in the increasing ratio of DN/MN that occurred,

```
┌─────────────────┐
│     Sample      │    Samples 3,4,5 and 6. Each 10g(on dry basis)
└─────────────────┘    in beaker.  Distilled water 100ml
        │
        ▼
┌─────────────────┐
│    Heating      │    3 hours in boiling water
└─────────────────┘
        │
        ▼
┌─────────────────┐
│   Filtration    │    TOYO No.5A
└─────────────────┘
        │
        ▼
┌─────────────────┐
│    Cooling      │
└─────────────────┘
        │
        ▼
┌─────────────────┐
│  Volume adj.    │    Adjust to 100ml with distilled water
└─────────────────┘    Add.   sugar 1g. Salt 1g
        │
        ▼
┌─────────────────┐
│    Stock        │
└─────────────────┘
        │
        ▼
┌───────────────────────┐
│  Sensory evaluation   │
└───────────────────────┘
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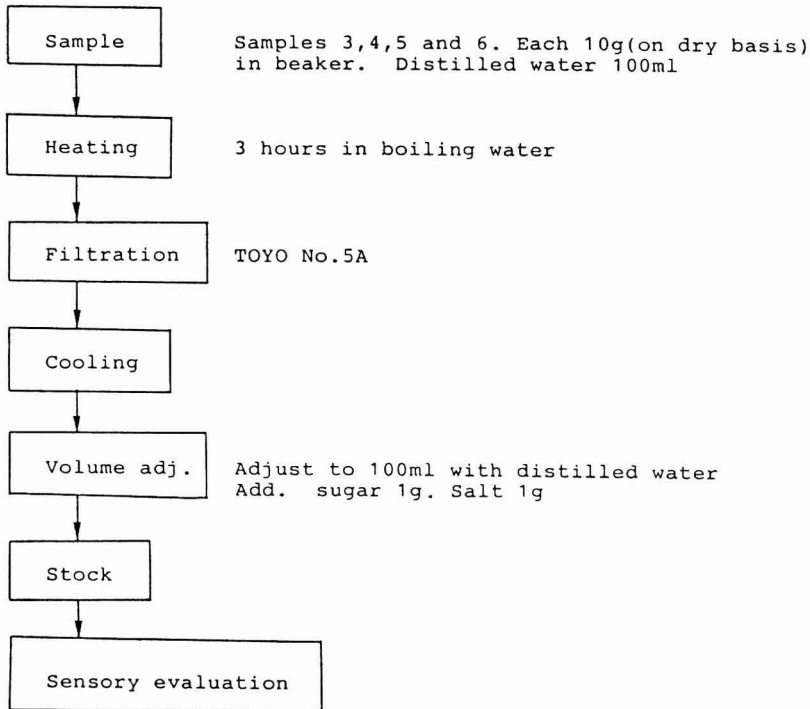
FIG. 3. METHOD OF STOCK PREPARATION
AND SENSORY EVALUATION
Sample: Stocks of smaples 3, 4, 5, and 6 (relative comparison).
Quantity: 100 mL, Temperature: 60C (in dishes).
Panel: 8 panelists. Head: Aroma, palatability, sourness, flavor.

during the boiling and drying process, resulted from the removal of water solu-ble compounds, i.e., low molecular amino acid in the water used. During the molding process the peptides on the surface of the meat were enzymatically broken down into amino acids, since molds on the meat can produce protease, subse-quently decreasing the ratio.

The ratio of CNN/CN increased rapidly when dried after the process of boil-ing. However, the samples processed by molding have less of an increase than those processed by drying. This variation can be explained in this way: creatine in the sample after boiling was converted to creatinine during the process of dry-ing; however, creatinine was changed to creatine by the process of molding.

Changes in the Lipid

The analytical results of lipid content, acid value, iodine value and lipid class composition of the katsuobushi-like meat products are shown in Tables 3 and

TABLE 1.
MOISTURE AND VARIOUS NITROGENOUS CONSTITUENTS[a]

Sample number		1	2	3	4	5	6
Moisture (%)		66.8	61.1	6.26	15.9	11.5	18.2
Total-N[b] (%)	(TN)	9.89	12.1	12.5	12.4	11.4	12.0
Soluble-N[b] (%)	(SN)	1.64	1.48	1.19	1.26	2.05	1.96
Mono-amino-N[b](%)	(MN)	0.47	0.34	0.18	0.23	0.38	0.39
Di-amino-N[b](%)	(DN)	1.14	1.10	1.00	1.02	1.66	1.59
Creatine-N[b](mg%)	(CN)	170	103	44.3	61.3	88.8	110
Creatinine-N[b](mg%)	(CNN)	177	110	120	133	230	257

a, Means of triplicate values
b, On dry basis

TABLE 2.
RELATIVE COMPARISON OF VARIOUS NITROGENOUS CONSTITUENTS[a]

Sample number		1	2	3	4	5	6
(SN/TN)X100	(%)	16.6	12.2	9.52	10.2	18.0	16.3
(MN/TN)X100	(%)	4.75	2.81	1.44	1.85	3.33	3.25
(DN/TN)X100	(%)	11.5	9.09	8.00	8.23	14.6	13.3
(CN/TN)X100	(%)	1.72	0.85	0.35	0.49	0.78	0.92
(CNN/TN)X100	(%)	1.79	0.91	0.96	1.07	2.02	2.14
DN/MN		2.43	3.24	5.56	4.43	4.37	4.08
CNN/CN		0.89	0.92	2.33	1.87	2.24	2.00

a, Means of triplicate values

4. The lipid content in the samples was around 20% on dry basis. The acid and iodine values decreased through the smoking process. After the molding process, the iodine value was similar to the initial level. As indicated in Table 4, free fatty acids increased to around 12% after drying and reached more than 40% after

TABLE 3.
AMOUNT OF CRUDE FAT, ACID VALUE AND IODINE VALUE[a]

Sample number	1	2	3	4	5	6
Amount of crude fat(%)	9.5	7.1	13.8	14.9	21.9	16.5
(On dry basis %)	28.7	18.4	14.7	17.8	24.8	20.2
Acid value	11.7	14.8	9.1	28.5	9.8	29.7
Iodine value	59.7	62.6	30.4	63.2	25.6	61.6

a, Means of triplicate values

molding. On the other hand, phospholipids and triglycerides decreased from the drying process to the molding process. These changes indicated that the rapid increase of free fatty acids caused an increase in the acid value index, since free fatty acids are produced from phospholipids and glycerides. In the molding process stages, it is clear that the mold produces lipase which releases the fatty acids from the glycerides. The production of secondary compounds derived from the lipid oxidation and cleavage of double bonds in the lipids are not apparent in this process, since there was little change in the iodine values, except for samples 3 and 5, which were not treated with the molding process. The decrease of iodine value in samples 3 and 5 was considered to be based on oxidation of the lipid during the process of drying for 10 days.

Organoleptic Evaluation and Acceptability of the Sample

It is important that these new katsuobushi-like meat products have the favorable flavors similar to katsuobushi. Therefore, a sensory evaluation of soup stock prepared from the meat product samples was performed. Dishes using the four different stocks were served in random order to eight trained panelists for organoleptic evaluation. Aroma, palatability (umami) and sourness were compared amaong samples 3, 4, 5, and 6, using the index numbers. The index numbers were defined from 5 to 1, where 5 represented strong or like, and 1 represented weak or dislike. The total evaluation scoring used numbers from 10 to 0, with 10 representing an extremely sweet flavor and 0 representing extremely unpalatable (see Table 5). Samples 4 and 6 received favorable responses in the total assessment. Whether the samples underwent the boiling process or not seemed to influence the degree of organoleptic intensity (strong or weak) among the four stock samples. It is assumed from the results that the weak and/or mild flavor is dependent upon the molding process. In particular, sourness was extremely affected by

TABLE 4.
PERCENTAGE OF LIPID CONSTITUENT IN EACH SAMPLE[a]

Sample number	1	2	3	4	5	6
Phospholipid	3.7	9.9	19.3	10.8	20.7	11.1
Sterol & diglyceride	1.5	2.9	11.1	4.6	8.8	6.3
Free fatty acid	3.9	0.9	11.4	40.7	12.0	42.7
Triglyceride	90.8	86.3	58.1	43.8	58.4	39.7
Total	99.9	100.0	99.9	99.9	99.9	99.8

a, Means of triplicate values

TABLE 5.
RESULTS OF SENSORY EVALUATION[a]

Sample number		3	4	5	6
Aroma	Strong or Weak[b]	3.5	3.1	3.8	3.3
	Like or Dislike[c]	3.0	3.5	3.2^{*f}	3.5^{*f}
Palatability (Umami)	Strong or Weak[b]	3.2	3.2	3.6	3.5
	Like or Dislike[c]	3.0^{*g}	3.7^{*g}	3.1^{*h}	3.6^{*h}
Sourness	Strong or Weak[b]	3.1^{*i} $(5.50)^e$	3.0 $(5.75)^e$	3.9^{*i} $(5.45)^e$	3.4 $(5.65)^e$
	Like or Dislike[c]	3.1	3.3	2.7	3.3
Acceptability (Total evaluation)[d]		5.4	6.7	4.9	6.6

a, Means of scores by 8 panelists
b, Strong or Weak:(5)Strong--(3)Neither strong nor weak--(1)Weak
c, Like or Dislike:(5)Like--(3)Neither like nor dislike--(1)Dislike
d, Flavor:(10)Extremely sweet flavor--(5)Normal--(0)Extremely
          unpalatable
e, pH
*f,g,h,i, Significantly p<0.05

the molding process; in this case the strong sour flavor, which is undesirable,
was diminished in the molding process.

Consequently, the meat obtained favorable properties from the molding pro-
cess, resulting in a mild flavor, which is more widely accepted and preferred,

especially in palatability (significantly p > 0.05). The significant differences were found on the aroma between samples 5 and 6, on the palatability (Umami) between samples 3 and 4 and between samples 5 and 6, and on the sourness between samples 3 and 5. These results indicate that increased acceptability and mildness in flavor depends upon the molding and boiling process. Especially, samples having the process of molding received high scores on acceptability as total-flavor evaluation. These different stages in the katsuobushi process are thus related to producing a preferable flavor.

ACKNOWLEDGMENTS

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EFFECTS OF DIFFERENT STORAGE CONDITIONS ON PRESERVATION OF COCONUT (*Cocos nucifera*) WATER

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ABSTRACT

To determine proper storage conditions for preservation of green coconut (Cocos nucifera) water the effects of different temperatures (4, 12, 22 and 28C), time and packing type (with and without polyethylene) on coconuts were investigated for five weeks. A total of 133 dwarf fruits were used. On day 1 (zero time) and on weeks, 2, 3, 4 and 5 of the experiment, the water was taken at random from six wrapped and six unwrapped coconuts for physicochemical (°Brix, total acidity, pH and weight), microbiological and sensory analyses. Treatments were repeated twice for precise data. Statistical differences were determined by the analysis of variance. Our data show that the treatment of choice for a proper storage is: temperature: 12C; packing type: polyethylene; time, four weeks.

INTRODUCTION

The coconut palm (*Cocos nucfera*) is the most important and widely distributed of cultivated palm-trees (CNPCo). Brazilian production has been estimated in 603.175 million fruits (IBGE 1987); about 75% of this production is used by industries (CEBRAE 1979). More than 100 products are directly or indirectly

prepared with coconuts; from these the desiccated coconut, copra coconut oil and copra meal cake are the most important for international trade.

The fruit is ovoid in shape and the husk is about the size of a football. It consists of four parts: the husk, shell, meat and water.

The coconut water, technically the liquid endosperm, is approximately 25% by weight of the whole nut, and the amount of coconut water that can be derived from each nut is about 420 mL/nut. This water is a luxury to some, but to others it is a common everyday beverage. It is more palatable about 7 months after the nuts are pollinated, and the total solids are around 5% by weight. The desirable flavor is sweet and slightly astringent, with a pH about 5.6 (Jasper 1979; Pandolina 1983). Its consumption is increasing in a range of 20% per year (CEBRAE 1979), which is attributed to the many healing qualities of the water. Because of the high content of salines and albumin it is said to check cholera, combat intestinal worms and relieve stomach troubles (Jasper 1979). The main sugar fractions of young coconuts are glucose and fructose, while sucrose predominates in mature meat (Pandolina 1983). Minerals, amino acids, vitamins and auximic, or growth promoting properties, are found in the coconut water. Vitamin C ranges from 2.2 to 3.7 mg/100 mL (Jasper 1979; Pandolina 1983; Pinto 1983). Alanine, arginine, cystine and serine values in the proteins are higher than those in cow's milk (Jasper 1979; Dias 1983). Its caloric value is 17.4 kcal/100g (Jasper 1979).

Coconut water is easily absorbed by the human organism and is used in the treatment of dysentery and for infant feeding. During the Second World War it was given orally or intravenously for rehydration of Japanese soldiers. Experiments in Bangkok, Thailand, St. Louis (Jasper 1979), and in Recife (Pinto 1983) have demonstrated the possibilities of using coconut water for feeding patients through the veins; since the water is sterile, only filtration is required before use.

The proper storage of coconuts has been a concern for processors and shippers. Jasper (1979) and Bleinroth (1986) have shown that mature coconuts may be stored at low temperatures (about 2.5C) with relative humidity between 45 and 55% for a period of two years. But too little is known about storage conditions for green coconuts to preserve the coconut water. The purpose of this investigation was, therefore, to determine proper storage conditions for green coconuts to preserve the coconut water.

MATERIALS AND METHODS

Product

Green coconuts of the cultivar dwarf were harvested from a plantation in Pernambuco, Brazil. Picked seven months after nut pollinization, 134 dwarf coconuts were used.

Treatments

The coconuts were weighed and half were wrapped in polythylene (thickness 14 μ and density 1.3 g/cm³). Equal groups of each were held at controlled temperatures of, 4, 12, 22 and 28C. The relative humidity ranged between 80–85%, except for the samples held at 22C which were kept at 60–65% R.H. Two experiments were performed. In the first, the coconuts were held at temperatures of 4 and 12C for a period of five weeks. In the second, the coconuts were held at temperatures of 4, 12, 22 and 28C for three weeks.

The overall experiment period lasted five weeks. Analyses were started at week 2, because preliminary studies had shown no differences at all from the first week. On day 1 (zero time) and on weeks 2, 3, 4 and 5, six wrapped and six unwrapped coconuts were taken at random and their water analyzed for physicochemical (°Brix, total titratable acidity, pH and weight), microbiological and sensorial data. The complete experiments were repeated to verify precise data.

Physicochemical Analysis

The composition of the coconut water was analyzed in triplicate for all parameters. Total solids and ash determinations followed AOAC (1970) procedure. Total sugars and reducing sugars were determined by the Luff-School method (IFJU 1968). Calcium, phosphorus and chlorine content were determined by precipitation with ammonium molybdate, and by titration with $AgNO_3$, respectively (IFJU 1968). The contents of sodium and potassium were read directly in a flame-photometer digimed NK 2000.

°Brix was measured using a refractomer, Jean Model I-375320. Total acidity was measured by titration, with 0.1N NaOH and phenolfthalein as indicator. A FANEN, Mod. 302, pH meter at 25C was used for pH determination. The weight differences were obtained compared to weight values at zero time. Microbiological analyses (aerobic plate count) (Speck 1976) were performed. Statistical differences were determined by the analysis of variance on factorial designs in a randomized complete block design, where blocks were storage time and variable factors were temperature and type of packing.

Sensory Evaluation

Using 6-point scales (6 = excellent, 1 = very bad), twelve trained judges were asked to evaluate the overall acceptability of the coconut water and the external appearance for green coconuts. At each session, judges were served with a 50 mL white plastic cup (art plast) containing about 25 mL of coconut water, and the green coconuts were exposed on a table for observation. An incomplete-block design was employed, and an analysis of variance on judgments and treatments was conducted for each attribute of each treatment.

RESULTS AND DISCUSSION

Physicochemical Results

The composition of coconut water is shown in Table 1. However, the coconut water is a relatively dilute system with a total solids content of 5% and total sugars of 2.1%. It is a nutritive beverage, furnishing fluid plus potassium chloride, phosphate, calcium and sodium (salt ingredients). Jasper (1979) has cited Child's statement that the coconut water nutritive value is due almost entirely to its sugar content. Therefore, coconut water is suggested as a good drink in cholera cases, stomach troubles and diarrhea because of its composition of inorganic minerals, amino acids and vitamin C (Jasper 1979; Pinto 1983).

The mean values determined for °Brix, total acidity, pH and weight difference in the coconut water stored in green coconuts unwrapped, and wrapped with polyethylene, during five weeks at 4, 12, 22 and 28C are given in Tables 2, 3, 4 and 5. The chemical parameters determined at zero time are used as reference values for coconut water during this work. Microbiological data were discarded because they showed no significant differences, proving one more time that coconut water is sterile. The green coconuts deteriorated; cleavings and water loss were observed at the fourth week when stored at 28C and at the fifth at 22C. The mean values for °Brix decreased little during the time storage. The pH mean values increased together with the decrease of the total acidity mean values for the same period of time. This variation probably may contribute to the flavor-loss of the

TABLE 1.
CHEMICAL COMPOSITION OF COCONUT WATER[a]

Parameters	
Total solids (%)	5.0
Total sugars(%)	2.1
Reducing sugars(%)	1.9
Ash(%)	0.6
Calcicum (mg/%)	59.6
Phosphorus (mg/%)	10.2
Chlorine(%)	0.3
Na (mg/1)	38.0
K (mg/1)	21.4

[a]Each value is the average of three samples determination.

TABLE 2.
MEAN VALUE OF °BRIX DETERMINED IN COCONUT WATER STORED
IN GREEN COCONUTS UNWRAPPED AND WRAPPED WITH POLYETHYLENE
DURING FIVE WEEKS AT 4, 12, 22 AND 28C

Temperature and packing			Storage time, week			
		Zero time	$2nd^c$	$3rd^d$	$4th^d$	$5th^d$
4 C	W^a	5.75	3.47	5.33	5.07	5.33
	Unw^b	5.75	5.45	5.53	5.73	5.93
12 C	W	5.75	5.20	5.40	5.27	5.10
	Unw	5.75	5.43	5.27	5.33	5.97
22 C	W	5.75	5.33	5.40	4.47	-
	Unw	5.75	5.32	4.87	5.03	-
28 C	W	5.75	4.87	4.63	-	-
	Unw	5.75	4.85	4.60	-	-

a - Wrapped with polyethylene, b - Unwrapped, c - Mean of six values,
d - Mean of three values.

TABLE 3.
MEAN VALUES TOTAL ACIDITY IN MEQ/100G CALCULATED FROM
COCONUT WATER STORED IN GREEN COCONUTS UNWRAPPED AND
WRAPPED WITH POLYETHLENE DURING FIVE WEEKS AT 4, 12, 22 AND 28C

Temperature and Packing			Storage time, week			
		$Zero\ time^c$	$2nd^c$	$3rd^d$	$4th^d$	$5th^d$
4 C	W^a	1.23	0.94	0.53	0.76	0.48
	Unw^b	1.23	0.86	0.70	0.63	0.71
12 C	W	1.23	1.09	0.67	0.83	0.76
	Unw	1.23	1.19	0.89	0.93	0.75
22 C	W	1.23	1.25	0.74	0.98	-
	Unw	1.23	1.08	0.77	0.89	-
28 C	W	1.23	0.78	0.64	-	-
	Unw	1.23	0.76	0.52	-	-

a - Wrapped with polyethylene; b - Unwrapped; c - Mean of six values;
d - Mean of three values.

TABLE 4.

MEAN VALUES FOR pH DETERMINED IN COCONUT WATER STORED
IN GREEN COCONUTS UNWRAPPED AND WRAPPED WITH POLYETHLENE
DURING FIVE WEEKS AT 4, 12, 22 AND 28C

Temperature and Packing		Storage time, week				
		Zero time[c]	$2^{nd[c]}$	$3^{rd[d]}$	$4^{th[d]}$	$5^{th[d]}$
4 C	W[a]	4.70	6.17	6.07	5.43	5.96
	Unw	4.70	6.45	5.80	5.30	5.40
12 C	W	4.70	5.71	5.53	5.24	5.11
	Unw	4.70	4.98	5.28	5.27	5.45
22 C	W	4.70	5.77	5.47	5.03	-
	Unw	4.70	5.47	5.36	4.90	-
28 C	W	4.70	6.20	5.27	-	-
	Unw	4.70	5.93	5.80	-	-

a - Wrapped with polyethylene, b - Unwrapped, c - Mean of six values,

d - Mean of three values.

coconut water at the last weeks. Galic acid is the major organic acid found in coconut water, together with shikimic and quinic acid according to Pinto (1983); other studies in coconut water organic acids are scarce. The increase of the weight difference values according to storage time was expected, especially for the unwrapped coconuts, because of the water loss during the storage.

In experiment 1, temperature and time had no significant effects on °Brix (Table 6); packing, however affected ($P < 0.05$) this variable, lowering it. °Brix values were better for unwrapped coconuts regardless of temperature and time. The mean values for total acidity (Table 6) were significantly affected ($P < 0.05$) by two temperatures, 4 and 12C, and time. Regardless of the time and type of packing, 12C was the best temperature for acidity. Packing and time had no significant effect on the mean values for pH (Table 6), but the effects of temperature on pH were highly significant ($P < 0.05$). The temperature of choice was 12C. The mean values for weight difference were significantly affected ($P < 0.05$) by packing and time, although the weight loss of polyethylene-wrapped coconuts was lower. The longer the storage time, the higher the weight loss.

In experiment 2, the mean values for °Brix were not significantly affected by packing, time and temperature until 22C (Table 7). The coefficient of variation was very low (2.9%). The °Brix value, however, was lower at the temperature

TABLE 5.
MEAN VALUES FOR WEIGHT DIFFERENCE (G) DETERMINED FROM
GREEN COCONUTS STORED UNWRAPPED AND WRAPPED WITH
POLYETHLENE, DURING FIVE WEEKS AT 4, 12, 22 AND 28C

Temperature and Packing		Storage time, week			
		2^{nd}[c]	3^{rd}[d]	4^{th}[d]	5^{th}[d]
4 C	W[a]	17.3	24.3	25.3	29.0
	Unw[b]	112.2	173.0	211.0	260.0
12 C	W	15.3	24.7	43.3	43.0
	Unw	111.2	145.0	202.7	233.3
22 C	W	66.8	59.0	112.0	-
	Unw	223.2	363.0	367.3	-
28 C	W	63.8	103.0	-	-
	Unw	304.8	414.7	-	-

a - Wrapped with polyethylene; b - Unwrapped; c - Mean of six values;

d - Mean of three values.

of 28C. The mean values for total acidity (Table 7) were significantly affected ($P < 0.05$) by temperature and time, the best values for total acidity were detected in the samples stored at 12 and 22C for three weeks. Only temperature significantly affected ($P < 0.05$) the mean values for pH (Table 7), the best values being detected when the samples were stored at 4 and 22C. The mean values for weight differences (Table 7) were significantly affected ($P < 0.05$) by temperature, packing and time. Wrapped coconuts stored at 4 and 12C for three weeks showed the best values.

Coconut Water

Coconut water overall acceptance scores were not affected ($P < 0.05$) by the storage system for two weeks. The scores for coconut water acceptability were higher ($P < 0.01$) for coconut water in wrapped coconut at 12 and 22C for three weeks of storage than those at 4C for three weeks. At the fourth week of storage the coconut water overall accceptance scores received higher values ($P < 0.01$) for those stored wrapped at 22C, and those stored unwrapped at 4C, than other storage systems. The acceptability of the coconuts at the fifth week was fair ($P < 0.05$) for both storage systems at 4 and 12C.

TABLE 6.
EFFECT OF STORAGE CONDITIONS ON PHYSICOCHEMICAL PARAMETERS
OF COCONUT WATER (EXPERIMENT 1)

Storage conditions		Physicochemical parameters			
		°Brix	Total acidity meq/100g	pH	Weight difference (g)
Temperature, °C	4	5.47a	0.70a	5.82a	106.5a
	12	5.37a	0.89b	5.32b	102.3a
LSD[1] (5%)		0.25	0.35	0.35	33.3
Packing[2]	Unw	5.57a	0.83a	5.32a	181.0b
	W	5.27b	0.76a	5.65a	27.8a
LSD (5%)		2.25	0.10	0.35	33.3
Time, week	2nd	5.39a	0.45c	5.83a	63.9b
	3rd	5.83a	0.54bc	5.67a	91.7ab
	4th	5.35a	0.79a	5.31a	120.6ab
	5rd	5.55a	0.67ab	5.48a	141.3a
LSD (5%)		0.48	0.19	0.69	65.0
CV[3] (%)		4.0	10.7	5.6	28.2

The mean values of the same column followed by similar letter do not differ statistically at a probability level of 5% (Tukey test).
[1]LSD Least significant difference by Tukey's procedure.
[2]Unw Unwrapped; W — Wrapped
[3]CV Coefficient of variation.

Green Coconut

Polyethylene-wrapped green coconuts stored at 4, 12, 22 and 28C for two weeks received higher external appearance scores ($P < 0.01$) than the unwrapped ones stored at the same temperatures and times of storage. The external appearance was scored "good" up to five weeks at 12C ($P < 0.01$) when the green coconuts were wrapped. The polyethylene showed once more that it can protect better the physical characteristics of green coconuts. However, external appearance remained "good" for up to five weeks as 12C wrapped; the coconut water rating was fair.

TABLE 7.
EFFECT OF STORAGE CONDITIONS ON PHYSICOCHEMICAL PARAMETERS
OF COCONUT WATER (EXPERIMENT 2)

Storage conditions			Physicochemical Parameters			
			$^\circ$Brix	Total acidity meq/100g	pH	Weight difference (g)
Temperature, C		4	5.44a	0.75ab	5.37a	81.7a
		12	5.32a	0.96	6.12b	74.0a
		22	5.23a	0.96a	5.37a	178.0b
		28	4.74b	0.67b	6.12b	221.6b
LSD[1] (5%)			0.35	0.21	0.60	86.1
Packing[2]		Unw	5.16a	0.85a	5.63a	230.2b
		W	5.20a	0.82a	5.87a	46.8a
LSD (5%)			0.18	0.11	0.30	43.5
Time, week		2nd	5.24a	0.99a	5.83a	114.3a
		3rd	5.13a	0.86b	5.67a	163.4b
LSD (5%)			0.18	0.11	0.30	43.5
CV[3] (%)			2.91	10.98	4.47	26.51

The mean values of the same column followed by similar letters do not differ statistically at a probability
level of 5% (Tukey test)
[1]LSD Least significant difference by Tukey's procedure
[2]Unw Unwrapped; W — Wrapped
[3]CV Coefficient of variation.

Our data lead to the conclusion that polyethylene-wrapped coconuts stored at
12C for 4 weeks were in better condition than those exposed to the other
treatments, supporting Bleinroth's finding; that is, that the physicochemical
characteristics of coconuts, like almost all tropical fruits, are better preserved
at moderate temperatures, 7–12C (Bleinroth 1986).

Our conclusion was based especially on sensory data, since a low coefficient
of variation was shown for physicochemical results, except for weight difference.
Once more, the importance of sensory analyses to evaluate proper storage condi-
tions for foodstuffs is supported.

ACKNOWLEDGMENTS

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MATHEMATICAL ANALYSIS OF VARIATION OF DENSITY AND VISCOSITY OF APPLE JUICE WITH TEMPERATURE AND CONCENTRATION

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ABSTRACT

The effect of temperature and concentration on some of the thermophysical properties of apple juice was studied. Density and viscosity of apple juice at different sugar concentrations and temperature were utilized to derive a multiparameter model. The derived model satisfactorily represented the variation of density and viscosity of apple juice in the concentration and temperature ranges 14–39° Brix, 20–80C, respectively.

INTRODUCTION

Food industry today is very rapidly developing. There are many parameters that have importance in the food industry. The thermophysical properties, such as viscosity and density, are of importance and used in the clarified fruit juice industry.

The main items in a clarified juice production plant, the pipes, the chillers, the mixers, the agitators, the heat exchangers and all the others, require this thermophysical information to be well constructed and well operated for optimum production.

This necessary information can be available experimentally, but this is not always convenient. These kinds of experimental procedures can take a long time and can be expensive. The best way is to use the already available information as the data for determination of the required information. This can be done by using the appropriate model derived for the necessary objectives.

The aim in this study was to derive a multiparameter model for density and viscosity with temperature and concentration variation.

MATERIALS AND METHODS

Apple juice was prepared from a local variety of apple. The apples contained no injured or blemished items.

Apples were washed, peeled and diced prior to extraction. The extraction was done with a simple commercial fruit juice extractor. The extraction was followed by a two stage filtration where cheese cloth was used for prefiltration and a mechanical filter was used for the filtration. The main part of the filter was a 2.5 L stainless steel storage vessel and was stirred vigorously with a common magnetic laboratory stirrer (Bayindirli *et al.* 1989). Filter aid was flux calcined diatomaceous earth (Turkish Sugar Factories Inc., Ankara) of particle size 20 μm and was used on the 30.2 cm² filtration membrane surface to increase the efficiency of the operation. 0.5 kg/cm² gauge pressure was applied during filtration.

The next step was the concentration of apple juice. This was done in a rotary evaporator, in which the evaporation chamber was rotating at a constant rotational speed in water bath at 40C to produce a mild heat effect.

The solutions were concentrated to 14, 27 and 39°Brix. The total soluble solids were measured by a hand refractometer (Tajiri Ind. Co. Ltd., Japan). The viscosity and density values were measurd at these soluble solids within a temperature range of 20–80C. All the experiments were done at least in triplicate.

The viscosity was measured by Ostwald-Cannon-Fenkse viscometer (Schott and Gen. Mainz, Germany) placed in a water bath to keep the desired temperature constant. Soluble solids for apple juice were 14, 27 and 39°Brix. The temperature values at which the measurements done were 20, 30, 40, 50, 60, 70 and 80C.

Pycnometric method was used to determine the density of the apple juice. Pycnometers of 25 mL capacity were used. Water bath was used for controlling temperature. The apple juice samples of 14, 27 and 39°Brix were used for density determination at 20, 30, 40, 50, 60, 70 and 80C.

The statistical analysis for the modelling depends on the available data obtained from the experiments and is done by use of statistical software, which allows the determination of the proper fit for multiparametric models, and the significance of the regression was used to analyze the experimental data of viscosity and density (Constenla *et al.* 1989).

Studies for the further development of models for thermophysical properties of clarified fruit juices were based on this primary analysis. GWBASIC and LOTUS 123, were used for the modification of the models and curve fitting, respectively, on a microcomputer.

RESULTS AND DISCUSSION

The results obtained experimentally for the density of apple juice is represented in Fig. 1. Different types of models have been used to correlate density of sugar solutions and liquid foods, many of them resulting in complex polynomials in temperature and concentration (Choi and Okos 1983; Maxwell *et al*. 1984). The object of the statistical analysis made by the software was to correlate the sugar content and temperature of clarified apple juice to the concerned thermophysical property. The current work is proposed to find the variation of the desired thermophysical property of clarified apple juice (primarily density and viscosity of apple juice) with temperature and soluble sugar concentration by a similar multi-parameter model. The GWBASIC was used to create programs for modification of the models with respect to the experimental data. A main program was written that allowed the modification of models statistically developed. The subprograms were also used for minor shifts in the models.

The following equation resulted as the most suitable model for the variation of density of apple juice with concentration and temperature as it fits to the data with minimum error within the equations sorted.

$$\rho = 0.83 + 0.35 \exp(0.01\ X) - 5.64 * 10^{-4} * T$$
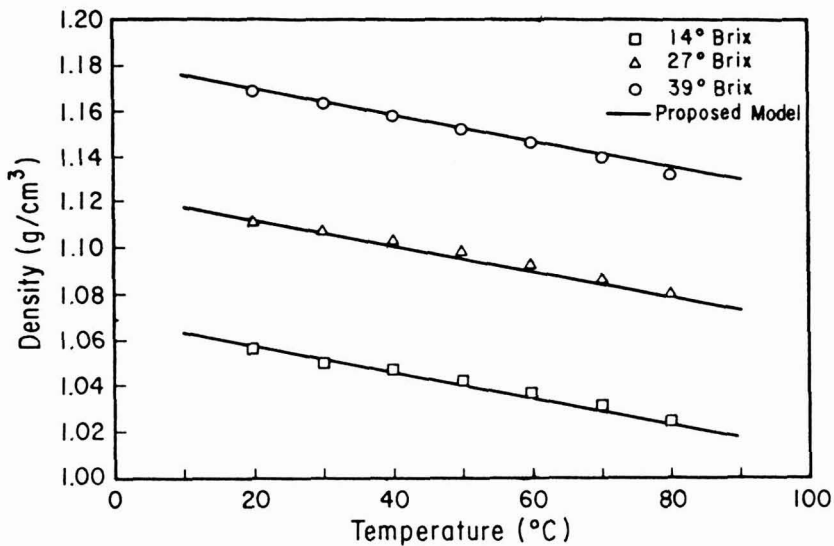
FIG. 1. VARIATION OF DENSITY APPLE JUICE
WITH TEMPERATURE AND CONCENTRATION

where ρ is the density in g/cc, X is the concentration in °Brix and T is the temperature in K.

As a theoretical approach, sugars, organic acids and different macromolecules interact with a substantial number of water molecules, resulting in a nonideal solution behavior. In the dilute limit of a solution, the specific volume of water has contributions mainly from structured free solvent regions, while the specific volume of a solid is affected by hydration and water-solution interactions. In the concentrated limit specific volume of water is defined by water solute aggregations; i.e., hydrogen bonded to hydroxyl groups. For these reasons density is a function of both temperature and concentration.

Viscosities of clarified fruit juices increased as the sugar concentration increased, and decreased as temperature is increased. The intermolecular forces are also a matter of fact in viscosity. As the dissolved sugar concentration increases the viscosity increases, depending on the hydrogen bonds with the hydroxyl groups. The viscosity is also dependent upon the intermolecular distances. As the temperature is increased, the intermolecular distances increase and therefore the viscosity will decrease. For these main reasons, the viscosity is a function of temperature and the dissolved solid concentration.

The Arrhenius equation to a great extent explains the relationship between the temperature and viscosity.

$$\mu = \mu o \exp (Ea/RT)$$

Where μ (cP) is the viscosity at temperature T (K) nad μo is the viscosity of water at that temperature. Ea (kcal/gmol) is the activation energy of flow and R is the gas constant.

The effect of concentration on viscosities of fruit juices at constant temperature can be represented by either an exponential or a power type relationship (Rao et al. 1984; Ibarz et al. 1987).

It is found in the studies for viscosity modeling that any soluble solid concentration change in the solution caused severe differences in the viscosity expression. When the concentration term was introduced into the Arrhenius equation, a complex expression was obtained. To eliminate this, a different approach was used.

The following theoretical relation was derived for viscosity of suspensions (Mooney 1951)

$$\ln(\mu/\mu wo) = 2.5*\emptyset/(1 - K\emptyset)$$

Where $\emptyset$ denotes the volume fraction of solids and K is a coefficient that takes into account the interaction between the particles.

In order to express on a weight basis, as °Brix, and to take into account the effect of temperature, the above equation was modified to the following expression:

$$\ln(\mu/\mu wo) = A*X/(100 - B*X)$$

where A and B are expressed for apple juice as:

$$A = -0.24 + (917.92/T)$$
$$B = 2.03 - 2.67*10^{-3}*T$$

Experimental data and fitted curves for viscosity of apple juice are given in Fig. 2.

The procedure of the modelling of viscosity and density of apple juice can be expressed under three main topics:

(1) Construction of the skeleton of the model.
(2) Statistical determination of the coefficients.
(3) Fitting the model to the experimental data as suitable curves.

The coefficients of the models were determined by using a software named GWBASIC. A program written in basic was used to set the values of the coeffi-
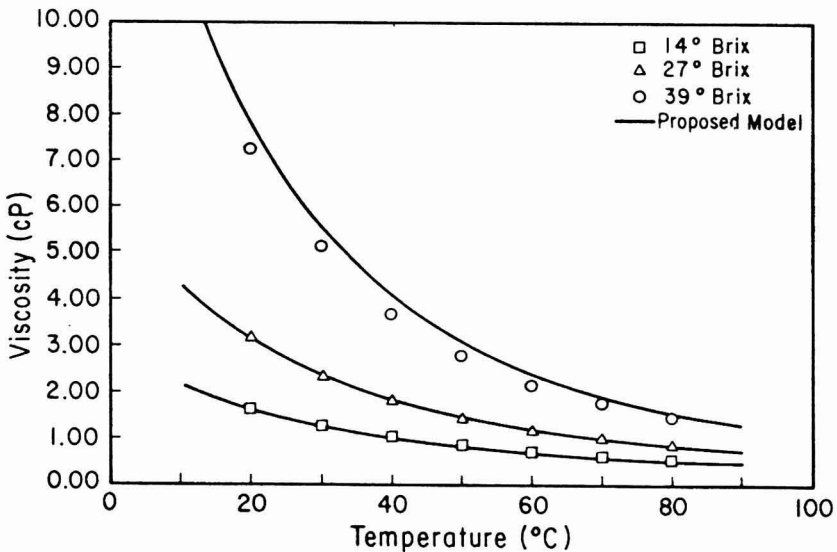
FIG. 2. VARIATION OF VISCOSITY OF APPLE JUICE
WITH TEMPERATURE AND CONCENTRATION

cients of the model within an estimated range of values. All the coefficients were investigated in conjugated basic loops. The coefficients for each parameter were determined with approximately 0.0001% error. The arithmetic and geometric means of the obtained coefficients were taken for a unique multiparameter model for one property. This approximation yielded an estimated error of 0.01–0.1% and was tolerable.

The variation of the parameters was matched so well that several two-dimensional graphs indicating one multiparameter model were drawn. One of the parameters was kept constant, while the variation of the other with the concerned property was drawn. The same approach was applied to several other values of the parameter that was kept constant and many curves were obtained.

As a result, it can be said that the proposed models describe the density and viscosity variation of clear apple juice within the temperature and concentration range studied, which suits various applications in fruit juice industry.

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FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENT DETERMINATION OF HETEROGENEOUS FOODS: A REVIEW

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ABSTRACT

The importance of the fluid-to-particle convective heat transfer coefficient (h_{fp}) in thermal processing of heterogeneous foods, i.e., foods comprised of a liquid (brine, sauce) and particles, is stressed in this review. Methods to determine h_{fp} and problems encountered upon their application are discussed. An overview of experimental approaches to quantify this parameter is given for processing of heterogeneous foods, both in traditional canning and in aseptic processing. The wide range of previously determined h_{fp}'s suggests reliable methods should be developed and extensive studies carried out to determine the fluid-to-particle heat transfer coefficient unambiguously in different processing systems under a variety of processing conditions.

INTRODUCTION

Mathematical modelling constitutes a major contribution to design, optimization and validation of thermal processing of foods (Clark 1978). In processing conditions which are not readily accessible for physical experimentation, such

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as the heating of heterogeneous foods in rotating retorts or aseptic systems, models are of utmost importance to reduce number and cost of experiments required to optimize product safety and quality. However, an adequate theoretical model can only be applied properly if accurate physical input parameters are available. One of the greatest challenges to food technologists today is the determination of these parameters for liquid foods containing particulates. Especially the limited information in open literature on particle-fluid flow phenomena on the one hand (Sastry and Zuritz 1987; Rao and Anantheswaran 1988) and values for the convective fluid-to-particle heat transfer coefficient (h_{fp}) on the other hand (Chandarana and Gavin 1989a) are restricting the applicability of numerical models.

At present, design of thermal processes for canned heterogeneous foods requires heat penetration data. When exact heat transfer rates can not be easily gathered, e.g. for liquid foods containing particles heated by forced convection in rotating retorts, the uncertainty of delivering an adequate thermal treatment to the particles is answered by applying factors-of-safety (Pflug 1987) to processes which have proven their effectiveness under more conservative conditions. Models that can be used with finite and variable surface heat transfer coefficients to optimize products heat-treated under these processing conditions are scarce (Tucker and Holdsworth 1991) because heat transfer by convection is governed by fluid motion beside temperature differences, being far more difficult to describe than conduction heating (ev. with negligible surface heat resistance). Also, physical and thermal properties of foods can be function of position and time. Therefore, it has become customary to study convective heat transfer to (the liquid part of) heterogeneous foods in terms of heat penetration parameters (f_h, j) or dimensionless groups (Anantheswaran and Rao 1985a,b). However, the fluid-to-particle heat transfer coefficient as such is often preferred as an essential input parameter in models describing in-pack thermal processing of heterogeneous foods (Rumsey 1984). Validation of the designed, optimized process can be done using inoculated pack techniques (Yawger 1978) or biological indicator units (Pflug et al. 1980).

Recently developed technologies such as the aseptic processing of liquid foods containing particulates in tubular heat exchangers, scraped surface heat exchangers (SSHE) (Taeymans et al. 1985), ohic heaters (Skudder 1988) or systems where liquid and solids are separately heated (Hersom and Shore 1981; Hermans 1988; Sawada and Merson 1986), have to cope with similar problems. Here also, particle centre temperature can not be monitored experimentally using conventional techniques (thermocouples) without disturbing its real dynamic flow behavior. Such aseptic processes are designed with the conservative assumption that the particle moves only concurrently and with the same velocity as the liquid (Dignan et al. 1989). Although thermal treatments determined under these conditions will satisfy their primary and primordial goal, i.e. produce a microbiologically safe product, product quality retention may be unacceptably low. Oversterilization of both liquid and particles can only be minimized by determining an adequate

heat process on a trial and error basis, illustrating the desperate need of a more fundamental approach, describing relative particle-to-fluid velocity, including residence time distributions studies, and determining fluid-to-particle heat transfer coefficients. Thus, a minimum of microbiological tests (Gaze et al. 1990) will be needed to validate the adequacy of the proposed process.

To predict heat penetration data, to fully understand and mathematically describe the mechanisms of heat transfer, knowledge of the fluid-to-particle convective heat transfer coefficient is essential (Deniston et al. 1987). Yet, because of the practical impossibility to monitor the time-variable temperature history of a particle moving in a flowing liquid, h$_{fp}$ is one of the important gaps in our knowledge on heat transfer. The limited data and the range of fluid-to-particle heat transfer coefficients previously determined (cfr. infra) suggests that further work should be carried out to develop a reliable method for h$_{fp}$ determination (McKenna et al. 1990). This review discusses the present state of the art on the convective fluid-to-particle heat transfer coefficient in relation to thermal processing of particulated foods.

DEFINING THE FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENT

The heating rate of a particle in any thermally processed heterogeneous food is function of a boundary layer, surrounding the particle, which causes a "thermal lag" between particle surface temperature and heating fluid temperature. The most fundamental way to quantify this boundary layer is by expressing it as the "Fluid-to-particle Convective Heat Transfer Coefficient" (h$_{fp}$). h$_{fp}$ represents the proportionality factor between heat transferred by convection to a body immersed in a (flowing) liquid and the temperature difference between particle surface and immersion fluid, as given by it's defining equation (Newton's law of cooling).

$$q = h_{fp}.A_p.(T_{ps} - T_f) \tag{1.1}$$

where
- q = heat flux (W)
- h$_{fp}$ = fluid-to-particle heat transfer coefficient (W/m^{2}C)
- A$_p$ = heat transfer area (m^2)
- T$_{ps}$ = particle surface temperature (C)
- T$_f$ = heating medium temperature (C)

When heat transfer occurs during immersed flow, the flux is dependent upon geometry of the body, its position (front, side, back) (Burfoot and James 1988), proximity of other bodies (Gunn and Narayanan 1986), flow rate and fluid properties. This implies tht the heat-transfer coefficient will vary over the body

(Geankoplis 1978). Bird *et al.* (1960) stress that the transfer area and the temperature difference must be clearly described before h_{fp} is unambiguously defined. Quite often, this is not straightforward since even the microstructure of the surface area determines heat transfer (Achenbach 1976). The magnitude of h_{fp} mainly depends on particle-to-fluid relative velocity and particle surface-to-volume ratio (Chandarana *et al.* 1988). All properties influencing these factors (system geometry, surface structure, temperature difference, fluid rheology, flow velocity) should be taken into consideration when determining h_{fp}.

EXPERIMENTAL PROCEDURES TO DETERMINE H_{FP}

The fluid-to-particle convective heat transfer coefficient traditionally is determined from physical measurements of the temperature response of the particle under well characterized initial and boundary conditions. Thermocouples are used to monitor particle and heating fluid time-temperature data. In the food processing systems previously mentioned (rotating retorts, aseptic processing installations), the particulate portion of the heterogeneous food is not expected to be stationary in the moving liquid, due to centrifugal, gravitational, drag and buoyancy forces when processed in (rotating) cans (Deniston *et al.* 1987) and to drag, buoyancy forces, Magnus lift and Saffman lift under dynamic flow conditions (aseptic processing; Dutta and Sastry 1990a). A thermocouple attached to the particle will restrict its free motion, causing erroneous temperature measurement interpretations which will lead, in turn, to deviations of the calculated heat transfer coefficient from its real value. Recently, some attempts are mentioned in literature by which h_{fp}'s could be determined without measuring directly the particle temperature, leaving the particle-fluid motion pattern undisturbed. An overview of methodologies used to determine h_{fp} is given here. Because of the analogies in the mathematical treatment of h_{fp} determination in canned liquid foods containing particles and aseptically processed heterogeneous foods, both food processing systems are taken into consideration. In Tables 1–5, most of the experimental values — by our knowledge — of h_{fp} published, are given with their method of determination.

H_{fp} Determination from Direct Particle Temperature Measurements

The convective fluid-to-particle heat transfer coefficient has to be determined by applying solutions of the particle differential equations, describing heat transfer from a fluid to a particle. Experimental input data needed for this analysis are the time-variable temperature measurements of both particle and heating fluid. Although the most obvious location to measure particle temperature would be the particle surface (suggested by Eq. 1.1), quite often thermocouples are imbedded at a well defined location in the particle. Prediction of surface temperature and heat flux is then accomplished by inverting the temperature as measured by a probe located

interior to the surface of the solid material (''Inverse Problem''; Chen and Thomsen 1975). Exact localization of the thermocouple sensing tip impinged in the food or model particle is more convenient after the heating step. Large errors that can be expected from thermocouple misplacement (Deniston et al. 1987) are avoided, the surface condition and flow process adjacent to it is less disturbed.

The temperature distribution in a spherical particle is described by the heat conduction equation as

$$\frac{\delta(r_p T_p)}{\delta t} = \frac{k_p}{\rho\, c_p} \frac{(\delta^2 r_p T_p)}{\delta r_p{}^2} \tag{2.1}$$

for the initial condition

$$T_{(r,to)} = T_{ip} \tag{2.2}$$

and the varying boundary condition

$$k_p d\, T_p/d\, r_{p(r = R)} = h_{fp}(T_f\text{-}T_{ps}) \tag{2.3}$$

or its equivalent

$$m_p c_p (d < T_p > /dt) = h_{fp} A_p (T_f\text{-}T_{ps}) \tag{2.4}$$

stating that heat transferred through the particle surface is accumulated in the particle. Uniform initial particle and fluid temperature, constant fluid and particle physical and thermal properties and a constant finite heat transfer coefficient are assumed throughout these equations.

When the Biot number (= $h_{fp}.R/k_p$) is low (< 0.1), i.e. when the resistance to conduction within the solid particle is negligible compared to the resistance to convection across the fluid boundary layer, exact location of the thermocouple to measure the particle temperature becomes unimportant since its temperature distribution will be homogeneous and instantaneously equlibrated. For such a particle immersed in an isothermal heating medium, Eq. (2.4) can readily be integrated to give

$$\ln(T_p\text{-}T_f) = \ln(T_f\text{-}T_{ip}) - (h_{fp} A_p/m_p c_p)t \tag{2.5}$$

From a plot of the left hand side of (2.5) vs. time, h_{fp} is then determined as the product of the slope of the straight line(s) and $(m_p c_p/A_p)$. Several researchers (Chau and Snyder 1988; Sastry et al. 1989a,b; Zuritz et al. 1990; Alhamdan et al. 1990; Lima et al. 1990) used metal particles to satisfy the low Biot number

requirement for this "slope" or "lumped capacitance" method. Lenz and Lund (1978) solved the differential Eq. (2.4) numerically for a lead sphere after demonstrating that the particles equilibrated fast to one temperature at all points. Because of the varying heating medium temperature in their Steritort processing equipment, neither an analytical solution nor Eq. (2.5) could be used to determine h_{fp}. A numerical solution, using a fourth order Runge-Kutta scheme, was proposed to solve the heat transfer equations. The h_{fp} selected was the one for which the sum of the squared deviations between measured and predicted particle surface temperature profile was minimal (LSTD-method). This approach was also followed by Sastry (1984) and Fernandez et al. (1988), using aluminum particles (mushroom- and bean-shaped). In Tables 1–5, (A1) is used to indicate where a metal particle with negligible internal heat resistance is used to determine h_{fp}.

In real food systems however, the heating particle Biot number is more likely to range between 0.1 and 40. Neither internal nor external resistance to heat transfer is negligible (Heldman and Singh 1981). Heat conduction within the particle and therefore the exact location of the particle temperature measuring thermocouple(s) is of major importance. Thermal conductivity of the particle should be accurately known. An estimate of the heat channelling through the measuring thermocouple wires should be made and an appropriate correction of this conduction performed. Insulated thermocouple wires can also be used. However, this insulation may not interfere with the normal flow pattern of the liquid surrounding the particle.

Hassan (1984) derived a correlation for h_{fp} determination when performing dimensional analysis on steam heated liquid canned food containing particulates. He found that

$$h_{fp} = \frac{\rho_p V_{ce} \cdot \epsilon \cdot c_p (<T_p>_{final} - <T_p>_{initial})}{A_p \int_o^t (T_f - T_{ps}) dt} \qquad (2.6)$$

where ϵ is the volume fraction occupied by the solid particles. To solve this equation, average final and initial particle temperatures as well as fluid and particle surface temperature have to be measured accurately. In Tables 1–5, (A2) refers to this approach. Also Deniston et al. (1987) used this equation to determine h_{fp}'s in axially rotating cans. Average initial particle temperature was set equal to the initial measured particle surface temperature, assuming that liquid and particles are initially at equilibrium. Processing times had to be taken long enough to assure that the particles again approach a uniform temperature so that final average particle temperature could be set equal to the final particle surface temperature. The extreme importance of exact particle surface temperature measurement was recognized: erroneous thermocouple placement, only 0.4 mm below the (potato) particle surface would reduce h_{fp} calculated by 10%. Conduction error in the

thermocouple measuring particle surface temperature was negligible because in this experimental set-up, no net heat transfer would occur from one side of the particle to the other.

Chang and Toledo (1989) inserted thermocouples at three different locations in food cubes immersed in an isothermal heating fluid. Heat conduction through the fine (36 ga.) insulated thermocouple wire was considered to be negligible, referring to Uno and Hayakawa (1980). The partial differential equations for heat transfer were solved analytically. They used a four term approximation of the exact solution for temperature in a finite slab, given as a Fourier series.

$$\frac{(T_f-T_t)}{(T_f-T_i)} = \sum_{n=1}^{\infty} C_n.[\cos(\gamma_n x/l)] \tag{2.7}$$

$$\text{where } C_n = [4\sin \gamma_n \exp(-\gamma_n^2 \alpha t/l^2)]/[\gamma_n + \sin(2\gamma_n)]$$

$$\text{and} \quad \gamma_n = \text{positive roots of } \gamma_n \tan(\gamma_n) = (h_{fp} l)/k_p.$$

A multiplicative superposition technique was used to obtain the dimensionless temperature at a specific point for the box shaped particle. The time-temperature profile was calculated iteratively, until the h_{fp} was found for which calculated temperatures at three points inside the particle best fitted the experimental results. In Tables 1–5, (A3) indicates where the temperature measurements at several locations inside the particle are used to determine h_{fp}, (A4) indicates where single point temperature, measurements inside the particle are used to calculate the fluid-to-particle convective heat transfer coefficient. Stoforos (1988) advocated caution when h_{fp} is calculated from temperature measurements other than particle surface temperature. He feared misleading results might be obtained from a time-variable temperature profile measured inside the particle, especially for particles with low thermal conductivity. In such cases, temperature, e.g. at the particle centre, becomes mainly a function of the particulate conductivity rather than of the fluid-to-particle convective heat transfer coefficient. The higher the contribution of particle conductivity (k_p) to the total fluid-internal particle heat transfer resistance ($= 1/h_{fp} + R_p/k_p$), for a spherical particle where temperatures are measured at the center), the less sensitive h_{fp} can be determined. This implies that when the effects of surface roughness, diffusion of hot fluid into the particle, gravity (particle density), . . . are disregarded, temperature data from high conductivity materials will yield the most accurate h_{fp}'s that can be determined. Lenz and Lund (1978) proved that the time-temperature history predicted for an epoxy plastic particle (thermal diffusivity 0.001 cm^2/s), using h_{fp} determined from lead sphere temperature measurements (thermal diffusivity 0.24 cm^2/s), coincided well. Heat transfer coefficients determined from aluminum particles were used by Chau

and Snyder (1988) to model correctly the temperature distribution in shrimps, heated in an agitated waterbath.

Since applying the analytical solution of Eq. (2.1) for transient boundary conditions can be quite tedious, stable, consistent and convergent numerical solutions have been proposed (Chandarana *et al.* 1989a). Stoforos (1988) indicates that numerical methods are not subject to additional assumptions or restrictions, in contrast to analytical or a combination of analytical and numerical methods. The versatility of a numerical solution, e.g., upon varying heating medium temperature, compared to the analytical solution was recognized by Rumsey (1984) when modelling heat transfer in cans containing liquid and particles. Several other authors (Chandarana *et al.* 1989a,b; Chang and Toledo 1990; Weng *et al.* 1991a,b) used an explicit finite difference scheme to solve the heat transfer equations. The analytical solution (using Fourier series solutions or Heisler charts) was used under isothermal processing conditions to validate the numerical model they proposed to use later for variable boundary conditions. Chandarana *et al.* (1989a,b) imbedded a fairly long portion of the thermocouple measuring particle centre temperatures in the particle to minimize heat conduction errors. Chang and Toledo (1990) considered heat conduction errors to be negligible.

All methodologies quoted above are unsteady-state approaches, i.e., approaches where the particle surface temperature varies with time. The experimental studies carried out to determine h_{fp} from liquids to particles which are included in this discussion, all used this unsteady-state approach. For reasons of completeness, we mention the possible use of steady-state techniques, more frequently used to determine heat transfer coefficients for bodies immersed in a gas flow (Ansari 1986). Here, h_{fp} is determined by monitoring the heat flux, e.g., from a heating wire, needed to maintain particle surface temperature constant (Clary and Nelson 1970).

H_{fp} Determination from Liquid Temperature Only

Recently, Stoforos and Merson (1990) proposed a mathematical procedure to estimate h_{fp}'s for solid particles, heated in rotating cans, using liquid temperature as the only input parameter. They solved an energy balance for a can, neglecting heat accumulation in the can walls,

$$UA_c(T_{st}-T_f) =$$

$$\rho_f V_{ce}(1-e)c_f(dT_f/dt) + h_{fp}(3\epsilon V_{ce}/R_p)(T_f-T_{ps}) \qquad (2.8)$$

with $T_f(t=0) = T_{fi}$

and the differential equation for temperature distribution in a spherical particle (Eq. 2.1), assuming uniform fluid temperature, constant heat transfer coefficients,

uniform initial temperatures for particle and fluid, a finite h$_{fp}$, equal diameter spherical particles and constant physical and thermal properties for both fluid and particles. Since fluid temperature depends on both U and h$_{fp}$, a multiple regression scheme (in the Laplace transform plane) and liquid temperature measurements only were needed to estimate both coefficients. Thermocouple wires, restricting free particle movement and leading to erroneous interpretation of particle surface temperature, can be avoided in this approach. Fluid temperatures can be measured more easily and accurately than particle temperatures. However, the estimation of 2 parameters from 1 input parameter remains subject to uncertainty since a number of combinations of these 2 might yield the same solution. In Tables 1–5, (B) indicates where liquid temperatures only are used to determine h$_{fp}$. Calculated h$_{fp}$'s did not coincide with the ones determined from direct particle surface temperature measurements. Predicted h$_{fp}$'s for potato spheres in deionized water (233 W/m^2 C), Teflon spheres in deionized water (696 W/m^2 C) and aluminum spheres in silicone fluid (128 W/m^2 C) were significantly different from the values experimentally determined by Hassan (1984) (142, 75 and 204 W/m^2 C, respectively). Stofoross and Merson (1990) hold misplacement of thermocouples partially responsible for the differences between experimental and predicted h$_{fp}$-values. Because the processing times chosen by Hassan (1984) were only to meet the requirement that $T_f - T_p < 1$ C, lack of experimental data towards the end of the heating contributed to the error in Stoforos' mathematical approach.

H$_{fp}$ Determination from Indirect Particle Temperature Measurement

The same Eq. (2.8) (and a simplified solution) derived by Stoforos and Merson (1990) to determine heat transfer coefficients from liquid temperature only, was used to calculate h$_{fp}$ when particle surface temperatures were known. The particle surface temperatures were monitored with liquid crystal coating which changes color upon changing particle surface temperature. Color changes were videotaped and surface particle temperatures obtained by comparison with standard color charts after proper calibration. In Tables 1–5, (C1) refers to h$_{fp}$ determination using liquid crystals. The necessity to visualize the particle surface limits the applicability of this method in practical processing situations.

An ingenious approach for determination of the average fluid-to-particle heat transfer coefficient in real processing conditions is the one outlined by Hunter (1972), later followed by Heppell (1985) and Weng et al. (1991c). These authors accept that free movement of the particle prohibits direct measurement (using conventional techniques) of the changing temperature in the solid. The combined use of a Time Temperature Integrator (TTI) (Taoukis and Labuza 1989a,b; Hendrickx et al. 1991) and a mathematical model was proposed to determine h$_{fp}$. The processing value F, calculated from reading the TTI's initial (No) and final (N) status according to

$$F_{TTI} = D_{ref}.\log (No/N)$$

was used as matching criterion for the processing value

$$F_{model} = {_0}\!\int^t L.dt$$

(Ball and Olson 1957) calculated from a time-temperature profile generated by a mathematical model for which the recorded heating medium temperature was an essential input parameter. By using the heating fluid temperature and assuming a constant h_{fp}, a unique F_{model} could be found. The estimated h_{fp} for which the F-value generated from the mathematical model (F_{model}) deviated the least from the value given by a Time-Temperature Integrator incorporated in the particle (F_{TTI}), was considered to be the most exact heat transfer coefficient. Weng et al. (1991c) called this approach a 'Least Absolute Lethality Difference' (LALD) method. (C2) indicates in Tables 1–5 where this method has been used. Whereas Hunter (1972) and Heppell (1985) used this technique in aseptic processing of particulated foods, Weng et al. (1991c) proposed to use it in liquid canned foods containing particles. Micro-organisms were used as a TTI by Hunter (1972) and Heppell (1985) (*Bacillus anthracis* and *Bacillus stearothermophilus* respectively). Weng et al. (1991b) used an enzymatic TTI (immobilized peroxidase in dodecane). The accuracy of the enzymatic TTI (maximum error 5%; Weng et al. 1991a) gives this measuring system a significant advantage over the innate inaccuracy of classical methods of quantitative microbiology (Jason 1983) needed by Hunter (1972) and Heppell (1985). Hunter (1972) solved the heat transfer equations analytically, using the Heisler charts, for particles which were injected in an isothermal heating fluid. Heppell (1985) and Weng et al. (1991c) used numerical finite difference equations to solve variable boundary temperature heating of the particles under study. Weng et al. (1991c) compared h_{fp}'s determined with this LALD-approach ($h_{fp-LALD}$) to values calculated with the LSTD-method ($h_{fp-LSTD}$) (*cfr. supra*, Lenz and Lund 1978). Fair agreement between these values was found (Table 2), although $h_{fp-LSTD}$ tended to be higher than $h_{fp-LALD}$. The (relatively small) difference in h_{fp} resulting from these approaches can be accounted for by the different contribution of the entire time-variable temperature profile to the objective function used to estimate h_{fp}: in the LSTD-approach, each temperature registered has an equal importance in minimizing the difference between predicted and experimental temperatures, whereas in the LALD-approach, the weight of higher, more lethal temperatures is more pronounced than the weight of lower temperatures in their respective contribution to the final processing value.

The use of time-temperature history indicators to determine heat transfer coefficients is restricted to reliable, reproducible systems whose kinetic properties are accurately known. All integrator systems (microbiological, enzymic or others (e.g., Thermal Memory Cell, NC State)) will require proper calibration. Since

the method is based upon integrated values over a well-defined time period, h_{fp}'s varying with the fluid-particle temperature difference (Alhamdan *et al.* 1990) can not be determined. Certain TTI's only integrate over a fraction of the experienced temperature history (e.g., lethal temperatures have to be reached before inactivation of spores in a bioindicator (Pflug *et al.* 1980) occurs). Because physical (ρ) and thermophsical properties (k, c) of the TTI-carrier are needed in the heat transfer model, they will have to be accurately determined. For reasons of convenience, well characterized food model systems hence are preferred. The range of fluid-to-particle heat transfer coefficients that can be distinctively determined with this approach will be confined to the lower Biot numbers. If the TTI is located internally in a high Biot number system, it will be ill-conditioned because the integrator then responds to thermal diffusivity rather than h_{fp}. The same processing value F_{TTI} will be obtained in all conditions where fluid-particle interactions are described by Biot numbers higher than a critical value. For each TTI in/on any carrier material (real food or food model system), the restraints on h_{fp}'s that can be determined will have to be checked.

Although subject to more severe initial restrictions and limited working range compared to direct particle temperature measurement methods, the use of a temperature history indicator in fluid-to-particle heat transfer coefficient determination probably is, to our knowledge, the only approach possible that will allow to integrate the effect of both the time varying temperature profile and free particle movement in heterogeneous foods processed in rotating cans. In continuous aseptic processing systems, it will even include the effect of residence time distribution on the food particulates. A feasibility study, identifying possibilities and inherent restrictions to this method, has not yet been performed.

EXPERIMENTAL STUDIES RELATED TO H_FP DETERMINATION: FACTORS INFLUENCING H_FP IN LIQUID CANNED FOODS CONTAINING PARTICULATES

Few studies have dealt with the determination of fluid-to-particle heat transfer coefficients as such in thermal processing of liquid canned foods containing particles. The majority of the investigations of convective heat transfer in the presence of particulate matter focussed their attention on the liquid portion of the canned food (Conley *et al.* 1951; Hiddink 1975; Berry *et al.* 1979, 1980, 1981, 1982). Manson and Cullen (1974) indicated that heat transfer in a liquid-particulate systems depended upon amount, size and shape of the particles present. An overview of these studies and of the dimensionless correlations proposed to describe heat transfer in these cases, can be found in Stoforos (1988).

Exact knowledge of h_{fp}'s magnitude is less critical in classical canning processing conditions than it is for dynamic flow conditions (aseptic processing),

because in 'traditional' canning, commercial sterility can be assured by reliable heat penetration data and when needed conformed by inoculated pack studies (Lee et al. 1990b). Process-value calculations for in-can sterilization use retort temperature and temperature at the coldest spot in the liquid or even in a particle centre and combine them in an apparent thermal diffusivity or in an empirical paramter f_h, characterizing the heating rate of the product to determine an appropriate processing value (Chang and Toledo 1990) which still can be obtained from physical measurements. These physical means to verify commercial sterility experimentally are at this moment not available for aseptic processing of heterogeneous foods. As a surplus, particle residence time distribution does not have to be taken into account for in-pack sterilization. In order to predict and optimize product safety however, exact knowledge of h_{fp} is recommended (Rumsey 1984; Silva et al. 1991).

Influence of Rotation

The impact of rotation on increase of heat transfer rates and the resulting decrease of sterilization times was already documented early in literature (Conley et al. 1951). Predicting time-temperature profiles of particles processed in axial or End-Over-End (EOE) rotating cans, still is restricted by among others lack of information on the film coefficient h_{fp}.

Chang and Toledo (1990) determined h_{fp} by measuring the time-variable temperature history at the 2 cm potato cube centre, heated at 75C in a stationary retort. The average h_{fp}-value they found under these nonrotating processing conditions was 400 W/m^2C (Table 1), which is higher than h_{fp}'s found by other authors for potato particles of comparable equivalent diameter. h_{fp} from water to spherical polyacetal and nylon particles, also in a static retort, was determined by Weng et al. (1991c). The center of 2.5 cm diameter nylon and polyacetal spheres was loaded with a TTI and the processing value determined from it was compared to the processing value determined from a finite difference model for varying boundary conditions. For the spheres in a stationary can, processed in a heating medium at 80C, h_{fp} averaged 103 W/m^2C (Table 1).

Lenz and Lund (1978) studied heat transfer and lethality in liquid canned foods containing particles processed in a Steritort (reel-type retort-axial can rotation) at 250F (121.1C). Convective fluid-to-particle heat transfer coefficients were determined by numerically solving Eq. (2.4) for spherical lead particles, immobilized in the centre of a rotating can. Changing the reel speed from 3.5 to 8 RPM resulted in an average increase of h_{fp} by 150 W/m^2C (Table 3). Convective heat transfer to Teflon, aluminum and potato spheres in a single can axially rotating process simulator was studied by Hassan (1984) from measurements of the particle surface temperature. Varying the can rotation speed from 9.3 over 55.5 to 101 RPM, had less effect on h_{fp} than on the overall heat transfer coefficient. A slight in-

crease in h_{fp} upon increasing the rotating speed could be noticed, except for 3.49 cm diameter potato spheres with 0.3 particle volume fraction and for 2.54 diameter Teflon spheres with 0.2 volume fraction, both immersed in water; h_{fp} was highest at the lowest rotation speed (9.3 RPM), intermediate at the highest rotation speed (101 RPM) and lowest at the intermediate rotation speed (55.5 RPM) (Table 3). The equations derived by Hassan (1984) were used by Deniston *et al.* (1987) to determine heat transfer rates to steam heated, axially rotating cans containing potato spheres in water. The h_{fp}'s determined were rather insensitive to varying can rotation speed (9.3-29.1-101 RPM). The authors attributed this to small relative particle-to-fluid velocity: (i) density of the potato particle (1063 kg/m³) was close to that of water, so that particle settling due to gravity was minimal, (ii) stiffness of the thermocouple wire hindered particle motion, (iii) since the particle was located at the can centre, centrifugal force acting on it was small (Table 3). Stoforos (1988) indicated that increasing the rotating speed would yield higher h_{fp}'s as long as the increasing RPM were reflected in the relative particle-to-fluid velocity. At high rotational speeds, the can contents in his experiments was noticed to behave as a solid body, due to centrifugal forces. From Table 3, it can be seen that a tremendous drop in h_{fp} occurs when Teflon spheres, heated in silicone fluid (350 CST) at about 50C were rotated at 100 RPM in stead of at 54.5 RPM (from 2071 to 410 W/m²C).

Lekwauwa and Hayakawa (1986) determined fluid-to-particle convective heat transfer coefficients for aspheroidally potato particles in water during End-Over-End rotation. By matching the centre time-temperature profile of a potato particle predicted from a computer model, developed to simulate thermal responses of a packaged liquid-solid food with measured data, h_{fp} could be determined. It ranged widely between 60 and 2613 W/m²C, the statistically most frequent value being 261 W/m²C.

Influence of Viscosity

Lenz and Lund (1978) found significant lower h_{fp} values for particles processed in a 60% aqueous sucrose solution than for solids processed in water. Hassan (1984) demonstrated that under equal processing conditions, the heat transfer coefficient to Teflon particles was lowered when more viscous fluids (silicone oils, 1.5, 50 and 350 centiStokes) were used in stead of water. The same trend was noticed for aluminum particles, immersed in silicone oils, except for the largest particles (3.17 cm diameter) where larger h_{fp}'s appeared upon increasing fluid viscosity. These results are in line with the intuitive idea that relative particle-to-fluid velocity, and thus h_{fp}, decreases upon increasing fluid viscosity. In contrast to these observations, Stoforos (1988) visualized an increase in particle-to-fluid relative velocity upon increasing the heating fluid viscosity (from water to silicone oils, 1.5, 50 and 350 CST). Higher h_{fp}'s occurred in less viscous fluids. The

TABLE 1.
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS
FOR 'NATURAL' CONVECTION CONDITIONS

Particle	Dim. (cm)	Fluid	h_{fp} $(W/m^2 \ C)$	T_f-T_{pi} (C)	Meth.	Ref.
Cube (potato)	3.8	water	239	75-25	(A3)	(1)
		sucrose (35 %)	146			
Cube (silicone)	2.54	water	51.1	135-/	(A4)	(2)
		starch	35.9 35.9 32.8 18.3 16.1 8.1			
Cube (silicone)	-	water	50.96-62.61	(133-144)-/	(A4)	(3)
		starch	18.0-65.24			
Cube (carrot)	-	water	388.87	(133-144)-/		
Cube (potato)	-	starch	84.3-99.35	(133-144)		
Mushroom (aluminum)	2.81	water	652 777 786 674 811 850	/ - 20 / - 20 / - 20 / - 40 / - 40 / - 60	(A1)	(4)
Aluminum Shrimp	Jumbo Medium	water	1073 1276	95- /	(A1)	(5)

(1) Chang and Toledo, (1989)
(2) Chandarana et al. (1989a)
(3) Chandarana et al. (1989b)
(4) Alhamdan et al. (1990)
(5) Chau and Snyder (1988)

overall heat transfer coefficient decreased with increasing viscosity. Since in a canned heterogeneous food the brine or sauce is also heated and cooled, h_{fp} is not expected to be constant throughout the whole process, due to temperature effects on fluid viscosity. A typical example of this can be seen when using li-

Particle	Dim. (cm)	Fluid	h_{fp} (W/m^2 C)	T_f-T_{pi} (C)	Meth.	Ref.
Shrimp (Aluminum)	Jumbo Medium	water	5472 3478	95 - /	(A1)	(1)
Sphere (polyacetal)	2.5	water	125.81 123.12 180.26 227.70 152.81	80 - 20	(A4)	(2)
			122.62 127.06 149.44 233.71 150.20	80 - 20	(C2)	

(1) Chau and Snyder (1988)
(2) Weng et al. (1991)

quids containing thickening agents such as starch. Upon heating the starch will gelatinize and change the rate of heat transfer (resulting in broken-heating curves).

Influence of Particle Interaction

The presence of particulate matter during agitated processing will alter the flow pattern of the pure fluid (Rao and Anantheswaran 1988). The amount of solid matrix in the can will influence the relative particle-to-fluid velocity and thus heat transfer rates.

Lenz and Lund (1978) reported that adding real food (peas, carrots or radish) particles of equal diameter as the test system (lead sphere) and thus simulating more closely velocities and "wiping conditions" of particles and fluids under real processing conditions, had no significant effect on h_{fp}. However, from their data, a higher particle volume fraction seemed to cause a decrease in h_{fp}. As an exception to this, for the smallest size particles (0.95 cm diameter), average h_{fp} was lower for a single immobilized particle than when other particles were present. A remark that could be made here is that the authors immobilized the particle for which they determined h_{fp} in the rotating can, what might have caused

particle to particle interactions different from real processing conditions. Increasing the particle volume fraction by adding peas of different size to the liquid also decreased the overall heat transfer coefficient. A reduced relative viscosity due to the drag force exerted by the particles on the liquid was considered to be the main cause of lowering the overall heat transfer coefficient. From the results of Hassan (1984), h_{fp} for 2.54 cm diameter Teflon spheres seemed to increase when ϵ was increased from 0.2 to 0.31. Little difference in h_{fp} for increasing particle volume fraction (0.293–0.506) was found by Deniston et al. (1987). h_{fp} slightly decreased with increasing particle volume fraction from $\epsilon = 0.107$ to 400 but was suddenly lowered for higher particle contents. The authors remarked that for the higher particle volume fractions, free particle movement was impossible because of the tight packing in the can. Stoforos (1988) mentioned that the mixing effect by moving particulates highly contributed to a homogeneous temperature distribution in the can, especially for highly viscous products.

Influence of Particle Size

Fluid-to-particle heat transfer coefficients were determined for lead particles of 0.95, 2.065 and 3.015 cm diameter by Lenz and Lund (1978). When using water as the immersion fluid, h_{fp} increased with increasing particle dimensions. In a 60% aqueous sucrose solution no straightforward relation could be found: the medium size particle (2.06 cm diameter) showed the lowest h_{fp}, followed in increasing order by the 3.01 cm and the 0.95 cm diameter particles in the absence of additional particles and followed by the smallest (0.95) and the largest (3.01) particle in the presence of additional food particles. Hassan (1984) found that h_{fp} was larger for smaller size (2.22 cm diameter) potato spheres than for larger (2.86 or 3.49) diameter particles, processed in water. Little difference between the medium (2.86) and large (3.49) size particles was noticed. Teflon (1.27 and 3.81 cm diameter) and aluminum (1.27 and 381 cm diameter) particles in silicone fluids exhibited the same trend. The data of Deniston et al. (1987) show that potato particle size (2.22, 2.86 or 3.5 cm diameter) did not influence h_{fp} very much. A slight tendency of increasing h_{fp} upon decreasing particle size was noted.

Influence of Particle Properties

As long as specific properties of the particle under study (such as density or surface shape (roughness)) do not affect the particle-fluid motion pattern, the nature of the particle will not be reflected on the convective particle-to-fluid heat transfer coefficient. For solids immobilized in a can, particle density will not influence relative particle-to-fluid motion. This might explain the conformity between experimental and modelled temperature profiles in immobilized epoxy spheres used (Lenz and Lund 1978) and real immobilized shrimps (Chau and Snyder 1988) using surface heat transfer coefficients determined from aluminum particles of

identical shape. When particles are allowed to move freely in the can, their different density will influence their behavior in the fluid and thus altered h$_{fp}$'s will be found. Fluid-to-particle heat transfer coefficients determined by Hassan (1984) were higher for potato than for Teflon particles (processed in water). Upon processing in silicone fluids, Teflon particles exhibited higher h$_{fp}$'s than aluminum particulates of the same size. Aluminum spheres also exhibited lower h$_{fp}$'s than Teflon particles according to Stoforos (1988). Because of the different Biot number (different conductivity), other time-temperature profiles in the particles were noted. Higher thermal diffusivity of the aluminum particle resulted in faster heat conduction in the sphere, thus keeping the particle surface temperature lower as compared to the Teflon spheres.

EXPERIMENTAL STUDIES ON H$_{FP}$ IN DYNAMIC FLOW CONDITIONS (ASEPTIC PROCESSING)

Since it is not yet possible to continuously register the temperature of a particle moving through the heating, holding and cooling section of a heat exchanger, a number of researchers have proposed mathematical methods to predict heat transfer to particles, being sterilized in aseptic processing systems (de Ruyter and Brunet 1973; Manson and Cullen 1974; Kessler and Fiedler 1980; Dail 1985; Sawada and Merson 1985; Sastry 1986; Åström et al. 1988; Chang and Toledo 1989; Larkin 1989; Chandarana and Gavin 1989b; Lee et al. 1990a; McKenna and Tucker 1990) to gain insight in the critical factors for these processes (Lee et al. 1990b) and to minimize the number of microbiological tests (Dignan et al. 1989), indispensable for process validation. In most of these models, the fluid-to-particle convective heat transfer coefficient is needed as an essential input parameter. Whereas early researchers in the field assumed the fluid-to-particle heat transfer coefficient in aseptic processing systems of heterogeneous foods to be infinite (de Ruyter and Brunet 1973; Manson and Cullen 1974), later work has shown that h$_{fp}$ was finite and could be quite low. Ramaswamy et al. (1982) indicated that the erroneous assumption of an infinite h$_{fp}$ could cause spherical particle centre temperature predictions to be wrong by 30% if the actual Biot number was 50. Therefore, an accurate methodology for h$_{fp}$ determination that can be used under these continuous processing conditions is desirable. Combined with particle residence time distribution (RTD-Taeymans et al. 1985, 1986; Defrise et al. 1988; Dutta and Sastry 1990a,b) and thermophysical properties, realilstic predictions regarding sterilization adequacy, necessary in process and installation design, will come within reach. The experimental work done on h$_{fp}$ thus far, has been oriented towards determination of the heat transfer rates from fluids to particles in the (almost) isothermal holding section of aseptic processing equipment. Modelling studies (e.g. Lee et al. 1990a) indicate that the main contribution to particle lethality occurs in this holding section. Regulatory agencies

TABLE 3.

FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS FOR LIQUID CANNED FOODS CONTAINING PARTICLES

Particle	Dim. (cm)	Fluid	Rotation mode	rpm	h_{fp} (W/m^2 C)	Meth.	Ref.
sphere (lead) (no other particles present)	0.95	water	ax.	3.5	522	(A1)	(1)
				5.5	488		
				8.0	534		
	2.065		ax.	3.5	1527		
				5.5	1340		
				8.0	1175		
	3.015		ax.	3.5	2084		
				5.5	2049		
				8.0	1811		
	0.95	sucrose (60%)	ax.	3.5	948		
				5.5	817		
				8.0	1175		
	2.065		ax.	8.0	539		
	3.015		ax.	3.5	698		
				5.5	658		
				8.0	761		

TABLE 3. (CNTD)
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS FOR LIQUID CANNED FOODS CONTAINING PARTICLES

Particle	Dim. (cm)	Fluid	Rotation mode	Rotation rpm	h_fp (W/m² C)	Meth.	Ref.
sphere (lead) (food particles present)	0.95	water	ax.	3.5 5.5 8.0	341 749 659	(A1)	(1)
	2.065		ax.	3.5 5.5 8.0	1260 1266 1453		
	3.015		ax.	3.5	1550		
	0.95	sucrose (60%)	ax.	3.5 5.5 8.0	534 517 818		
	2.065		ax.	3.5 5.5 8.0	431 414 488		
	3.015		ax.	3.5 5.5	1198 1096		

TABLE 3. (CNTD)
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS FOR LIQUID CANNED FOODS CONTAINING PARTICLES

Particle	Dim.	Fluid	Rotation		h_{fp}	Meth.	Ref.
	(cm)		m-le	rpm	(W/m^2 C)		
sphere (potato)	2.22	water	ax.	9.3	142 - 145	(A2)	(2)
				55.5	154 - 138		
				101	165 - 145		
	2.86			9.3	126 - 126		
				55.5	115 - 106		
				101	98 - 103		
	3.49			9.3	120 - 107		
				55.5	104 - 94		
				101	115 - 105		
sphere (Teflon)	2.54	water	ax.	9.3	86 - 84		
				55.5	73 - 73		
				101	80 - 75		
sphere (Teflon)	1.27	silicone oil (50 CST)	ax.	9.3	66 - 56		
				55.5	101 - 95		
				101	108 - 103		
sphere (Teflon)	1.27	silicone oil (350 CST)	ax.	9.3	57 - 54		
				55.5	98 - 101		
				101	105 - 99		
sphere (Teflon)	3.81	silicone oil (50 CST)	ax.	9.3	40 - 37		
				55.5	37 - 37		
				101	38 - 39		

TABLE 3. (CNTD)
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS FOR LIQUID CANNED FOODS CONTAINING PARTICLES

Particle	Dim. (cm)	Fluid	Rotation		h$_{fp}$ (W/m^2 C)	Meth.	Ref.
			mode	rpm			
sphere (Teflon)	3.81	silicone oil (350 CST)	ax.	9.3 55.5 101	33 - 32 34 - 33 34 - 31	(A2)	(2)
sphere (Aluminium)	1.905	silicone oil (1.5 CST)	ax.	9.3 55.5 101	367 - 307 375 - 421 523 - 735		
sphere (Aluminium)	1.905	silicone oil (50 CST)	ax.	9.3 55.5 101	154 - 139 297 - 268 362 - 349		
sphere (Aluminium)	1.905	silicone oil (350 CST)	ax.	9.3 55.5 101	103 - 103 190 - 167 246 - 275		
sphere (Aluminium)	2.54	silicone oil (1.5 CST)	ax.	9.3 55.5 101	204 - 205 334 - 297 468 - 433		
sphere (Aluminium)	2.54	silicone oil (50 CST)	ax.	9.3 55.5 101	- 263 227 - 263 280 - 266		
sphere (Aluminium)	2.54	silicone oil (350 CST)	ax.	9.3 55.5 101	123 - 100 175 - 237 242 - 198		

TABLE 3. (CNTD)
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS FOR LIQUID CANNED FOODS CONTAINING PARTICLES

Particle	Dim. (cm)	Fluid	Rotation mode	rpm	h_{fp} (W/m^2 C)	Meth.	Ref.
sphere (Aluminium)	3.17	silicone oil (1.5 CST)	ax.	9.3 55.5	286 – 277 448 – 464	(A2)	(2)
sphere (aluminium)	3.17	silicone oil (50 CST)	ax.	9.3 55.5	263 – 354 387 – 287		
sphere (aluminium)	3.17	silicone oil (350 CST)	ax.	9.3 55.5	416 – 308 329 – 480		
aspheroidal (potato)		water	EOE	13	60 –2613	(A2)	(3)
sphere (aluminium)	2.54	water	ax.	52.6	1155	(C1)	(4)
sphere (aluminium)	2.54	silicone oil (1.5 CST)	ax.	52.9	1191–1296		
sphere (teflon)	2.54	water	ax.	53.1	1406		
sphere (teflon)	2.54	silicone oil (1.5 CST)	ax.	54.1	1826–1933		

TABLE 3. (CNTD)
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS FOR LIQUID CANNED FOODS CONTAINING PARTICLES

Particle	Dim. (cm)	Fluid	Rotation mode	rpm	h_{fp} (W/m^2 C)	Meth.	Ref.
sphere (teflon)	2.54	silicone oil (350 CST)	ax.	54.5	2071	(C1)	(4)
sphere (teflon)	2.54	silicone oil (350 CST)	ax.	100	410		
sphere (potato)	2.54	water	ax.	9.3	232.9	(B)	(4)
sphere (Teflon)	2.54	water	ax.	9.3	711.5		
sphere (aluminum)	2.54	silicone oil (1.5 CST)	ax.	9.3	128.7		
sphere	2.50	water	none	/	122 132	(A4)	(5)
					106 110	(C2)	

(1) Lenz and Lund, (1978) (rpm= reel rotation speed)
(2) Hassan, (1984) (rpm= can rotation speed)
(3) Lekwauwa and Hayakawa, (1986) (rpm= reel rotation speed)
(4) Stoforos, (1988) (rpm= can rotation speed)
(5) Weng et al., 1991

are rather reluctant to take lethality acquired in the cooling section into considera-
tion (Dignan *et al.* 1989; Chandarana *et al.* 1989b), because from the microbial
safety point of view, lethality acquired in the cooling section can only be accepted
if particle integrity is guaranteed (Heldman 1989).

Influence of Fluid Flow

From the experiences with processing of canned foods, higher heat transfer
rates are expected upon higher relative particle-to-fluid velocity, at least as long
as particle conductivity is not rate limiting. Therefore, several studies considered
the influence of flow rate and turbulence on h_{fp}. Particles have been immobilized
in a liquid, flowing at a specified rate on the one hand, and have been subjected
to dynamic flow conditions, i.e., allowed to move concurrently in a heating fluid,
on the other hand.

Chang and Toledo (1989) inserted thermocouples at three different locations
in 3.8 cm sweet potato cubes immersed in an isothermal (75C) heating fluid (water
and 35% sucrose solution). With the time-temperature data from these points,
the h_{fp} was determined from the analytical solution of the partial differential equa-
tions for heat transfer to the immobilized particle (equation 2.7). Upflow velo-
city was varied between 0 and 0.86 cm/s. Values of h_{fp} were lowest for zero
flow rate (146 W/m²C in the 35% sucrose solution and 239 W/m²C in water).
Upon increasing water flow velocity, heat transfer coefficients increased as well
(from 239 to 303 W/m²C) (Table 5). Chandarana *et al.* (1988) determined in
a specially designed process simulator for high temperatures h_{fp} from both starch
solutions (non-Newtonian fluid, 2–3% starch) and water to particles in an im-
mobilization chamber. Thermocouples were carefully located at the particle cen-
tre and in the surrounding fluid. Heat transfer coefficients were determined by
iteratively solving the heat transfer Eq. (2.1) until the sum of squared deviations
between the experimental time-temperature profile and the one generated for a
chosen h_{fp} with the measured fluid temperatures, was minimized. For silicone
cubes (12.7 mm) in a static fluid at 135C, h_{fp} was 51.1 W/m²C in water and
ranged from 8.1 to 35.9 in the non-Newtonian starch solution. In real food par-
ticles, h_{fp}'s determined were higher: 84.3–99.35 W/m²C for diced potatoes in
static starch and 388.87 W/m²C for a diced carrot in static water (Table 4). For
water flowing past silicone cubes at increasing flow rate (0.26–0.88 cm/s) heat
transfer coefficient values increased from 64.67 to 107.11 W/m²C (depending
on Reynolds number). In starch solutions, h_{fp}'s under the same flow rate condi-
tions ranged between 55.63 and 89.5 W/m²C, depending on Reynolds and Prandtl
numbers (Table 5). Zuritz *et al.* (1990) investigated the effect of fluid flow rate
on h_{fp} from a power-law pseudoplastic liquid (carboxyl-methylcellulose-solution,
71C) to a stationary mushroom-shaped aluminum particle. Heat transfer coeffi-

cients were determined using a lumped capacitance method. Increasing fluid flow rate (0.089 to 0.267 kg/s) resulted in increased heat transfer coefficients. For their experimental conditions, h_{fp} magnitudes were 548 to 1175 W/m²C (Table 5). Particle-to-fluid heat transfer coefficients were determined during sterilization of carrot dices in a packed bed by Chang and Toledo (1990). The authors used basically the same finite difference program they validated previously (Chang and Toledo 1989) with fluid temperature and the temperatures in the particle center and at a point midway the geometrical centre and particle surface as input parameters. For carrot cubes, higher h_{fp}'s were found for increased superficial flow velocity (from 0 to 1.58 cm/s) (Table 5). Gaze *et al.* (1990) immobilized a Sylgard cube (1.5 cm) in a controlled flow and found higher heat transfer rates for increasing flow velocity.

Hunter (1972) incorporated *Bacillus anthracis* spores in polymethylmethacrylate beads (0.31 cm diameter) and injected these in the holding tube (at about 100C) of an aseptic process simulator, allowing the particles to move freely in the liquid solution. Heisler charts were used to solve the unsteady-state heating of a spherical particle iteratively, until the processing value (F-value) calculated, equalled the processing value determined from the spore reduction count. For the higher flow rate (60 cm/s), h_{fp} was lower 1760 W/m²C) than for the lower flow rate (53 cm/s − 2800 W/m²C). Heppell's approach (1985) was essentially the same. He used *Bacillus stearothermophilus* spores, immobilized in 3.1 mm diameter alginate beads as TTI and determined the processing value that resulted in the observed spore reduction for the liquid temperature measured from a finite difference mathematical model. Fluid-to-particle heat transfer was noted to increase upon increasing flow rate (Table 5). Sastry *et al.* (1989) proposed a technique to evaluate h_{fp} under realistic flow conditions from direct time-temperature measurements. A 2.39 cm hollow aluminum particle, attached to a thermocouple wire was introduced in a holding tube test section and the particle was allowed to move at the same velocity as a free particle. The heat transfer coefficient was calculated using a lumped capacitance method. Water flow rate through the 3.05 cm diameter tube was varied from 2.694×10^{-4} to 6.68×10^{-4} cm³/s. In water as a carrier fluid, experimental h_{fp}'s increased from 2039 to 2507 W/m²C upon increasing flow rate (Table 5). The approach outlined here is limited by the thermocouple wire attached. Even when all precautions possible are taken, particle dynamics as compared to a free moving (unwired) particle will be disturbed. Especially free rotation of the particle will be restricted.

Influence of Fluid Viscosity

Chandarana *et al.* (1988) noticed that in water (Newtonian fluid) flowing past silicone cubes heat transfer coefficient values were larger (64.67 − 107.11

TABLE 4.
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS, DETERMINED FOR PARTICLES IMMOBILIZED IN A FLOW

Particle	Dim. (cm)	fluid	relative particle to fluid flow rate (cm/sec)	hfp (W/m² C)	Re	Pr	Nu	T_f-T_{pi} (C)	Meth.	Ref.
Cube (potato)	3.8	water	0	239	-	-	-	75-25	(A3)	(1)
			0.38	239	-	-	-			
			0.55	244	-	-	-			
			0.75	274	-	-	-			
			0.86	303	-	-	-			
		sucrose (35%)	0	146	-	-	-			
Cube (silicone)	2.54	water	0.43	64.67	761.30	-	2.04	129-/	(A4)	(2)
			0.66	83.64	1174.60	-	4.01			
			0.78	85.72	1391.25	-	2.86			
			0.97	89.87	1726.26	-	3.03			
			1.07	95.60	1910.37	-	2.85			
			1.21	107.11	2144.32	-	3.36			
		starch (2-3%)	0.44	67.62	106.20	40.77	15.91			
			0.52	67.44	53.95	94.54	15.87			
			0.68	74.47	75.35	88.5	17.52			
			0.85	85.47	41.84	58.54	20.11			
			0.93	80.86	35.07	258.44	19.03			
			1.16	89.50	126.67	89.46	21.06			
			0.44	55.63	41.98	107	13.09			
			0.63	61.01	8.16	764.16	14.35			
			0.77	65.43	21.70	349.84	15.39			
			0.88	63.98	5.57	1564.04	15.05			

TABLE 4. (CNTD)
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS, DETERMINED FOR PARTICLES IMMOBILIZED IN A FLOW

Particle	Dim. (cm)	fluid	relative particle to fluid flow rate (cm/sec)	hfp (W/m2 C)	Re	Pr	Nu	T_f-T_{pi} (C)	Meth.	Ref.
Aluminum Mushroom (Cap diam)	2.065	water		548	0.123	4.778	17.22		(Al)	(3)
				669	0.164	5.814	21.03			
				701	0.227	6.159	22.04			
				586	0.136	3.685	18.41			
				731	0.463	2.724	22.96			
				777	0.636	2.648	24.41			
				694	0.347	1.201	21.77			
				753	0.941	1.145	23.62			
				806	1.503	1.262	25.82			
	2.484			664	0.125	5.735	25.10			
				751	0.178	6.400	28.40			
				862	0.241	7.219	32.60			
				710	0.136	4.438	26.83			
				826	0.539	2.712	31.21			
				900	0.685	3.077	34.00			
				752	0.380	1.296	28.37			
				866	0.974	1.232	32.68			
				937	1.660	1.259	35.36			
	2.817			700	0.139	5.995	30.01			
				853	0.209	6.593	38.58			
				1006	0.293	6.746	43.14			
				734	0.171	3.997	31.45			
				928	0.505	3.016	39.76			
				1058	0.829	2.851	45.33			
				779	0.435	1.285	33.33			
				948	1.037	1.278	40.57			
				1175	1.943	1.239	50.29			

(1) Chang and Toledo (1989)   (2) Chandarana et al. (1989a)   (3) Zuritz et al. (1990)

W/m^2C) than in starch solutions (non-Newtonian fluid) under the same conditions (55.63 − 89.5 W/m^2C). Upon varying the fluid temperature between 133 and 145C, h_{fp} values for silicone cubes in static water ranged from 50.96 to 62.61 W/m^2C and in static starch solution from 18.0 to 65.24 W/m^2C, due to the temperature effect on fluid viscosity and turbulence. Also Zuritz et al. (1990) mentioned higher fluid-to-particle heat transfer coefficients for decreased mean apparent viscosity of the carboxymethylcellulose solution (power-law pseudoplastic liquid) they used. At the same processing temperatures (30–50C, lower h_{fp}'s were found by Gaze et al.* (1990) in a 5% starch solution than in water. Dutta and Sastry's data (1990b) suggested that the most critical factor affecting particle velocity and therefore h_{fp} is fluid viscosity. Higher viscosity of the fluid in which the particulate is immersed, hampers heat transfer, at least when the lower turbulence decreases the effective relative particle-to-fluid velocity at the interface.

Influence of Particle Size

Zuritz et al. (1990) reported an increase in fluid-to-particle heat transfer coefficient with increasing particle dimension (2.06 − 2.82 cm equivalent spherical diameter). Chandarana et al. (1988) argued that in the experimental set-up of Zuritz et al. (1990), increasing particle dimension resulted in decreasing the effective flow cross section area of the holding tube which increased the relative particle-to-fluid motion. From the data of Chandarana et al. (1988), h_{fp}'s increase with decreasing cube dimensions (2.5 to 1 cm cubes). The authors drew attention to the fact that increasing the surface area to volume ratio enhances heat transfer. Whereas the first authors performed their experiments in a small tube (of realistic commercial dimensions), the latter used a flow chamber where the fluid pattern was not limited by the presence of the tube walls and/or its size and obtained thus results in correspondence with the classical heat transfer correlations (Kramers 1946). Again, the magnitude of the fluid-to-particle heat transfer coefficient will be determined by the *in situ* fluid-to-particle relative velocity, i.e., by the flow pattern of the particles in the heating fluid. Sastry and Zuritz (1990) review the different types of particle behavior in tube flow. McCoy et al. (1987) illustrated differences in particle motion (rolling, sliding, free flow) and particle-wall interactions as a function of particle diameter. Dutta and Sastry (1990a,b) visualized particle-particle interactions and particle velocity distributions in holding tube flow. Under certain circumstances, a large number of particles moved slowly over the bottom of the tube, thus reducing the effective cross-section of the tube and causing 'channelling' of fluid through the remaining free portion of the tube. The increased relative fluid-to-particle velocity then will be translated into an increase in h_{fp} with increasing particle size. h_{fp}-values will not only depend on particle size, but also on their position and flow behavior.

Influence of Particle Properties

Chandarana *et al.* (1989) reported heat transfer coefficients from water and starch solutions to silicone, potato and carrot dices. Higher h$_{fp}$'s were noted for the heating food particles, which the authors attributed to diffusion of hot fluid into intercellular spaces.

Sastry *et al.* (1989) recognized that metal transducer particles, flowing concurrently in the immersion fluid, could only be used to determine h$_{fp}$ if the particle moved at the same velocity as a free food particle. Therefore, they constructed a hollow aluminum particle and made sure the density was about the same as a real food particle's.

QUANTITATIVE CORRELATIONS FOR H$_{FP}$

Since only few researchers tried to determine fluid-to-particle heat transfer coefficients, relatively little is known about how and to which extent particle properties, fluid properties and processing conditions influence h$_{fp}$. Empirical, dimensionless equations are used to describe the complex influence of all these factors on h$_{fp}$. Although h$_{fp}$ might vary over the body and during the process, in empirical relationships, an average h$_{fp}$ is given (Geankoplis 1978). Most of the dimensionless correlations for in-pack thermal processing of heterogeneous foods, describe the overall heat transfer rate or heat transfer rates from heating medium to the liquid and do not give specifications for the particulate portion. Fernandez *et al.* (1988) proposed several correlations to describe heat transfer from water and sugar (30 and 60%) solutions to (immobilized) aluminum bean-shaped particles processed in 303 × 406 cans in a Steritort in terms of Nusselt, Stanton (St)-number or Colburn-j factor (J$_{Colburn}$) as a function of Reynolds and Prandtl number. A shape factor Ω and the viscosity of the fluid was included. Bean diameter was chosen as the characteristic length. Physical and thermal properties of the solutions were evaluated at bulk temperature. Including void volume (ratio of liquid to the can volume) was found not to improve the correlation and viscosity effect was left out of the dimensionless relation because it was highly correlated to the Prandtl number. The best correlation was obtained when the system (reel rotation speed 2, 4, 6, or 8 RPM) was treated as a packed bed. Heat transfer rates were best described by the dimensionless equation

$$J_{Colburn} = 26900 \ Re^{-0.706} \ \Omega^{6.98} \tag{3.1}$$

Thus far, the influence of particle-to-fluid relative velocity on h$_{fp}$ is the most important factor studied for aseptic processing of liquids containing solid par-

TABLE 5.
FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS
DETERMINED FOR PARTICLES MOVING CONCURRENTLY IN A FLOW

Particle	Dim. (cm)	fluid	fluid flow rate (cm/sec)	hfp (W/m² C)	Re	Pr	Nu	T_f-T_{pi} (C)	Meth.	Ref.
sphere (polymethyl-methacrylate)	0.3	water	53.03	2808	40700	-	13.1	101.1-10	(C2)	(1)
			60.6	1759	42900	-	8.2	92.4-10		
sphere (alginate)	0.3-0.34	water	-	7870	50000	-	-	-	(C2)	(2)
			-	2180	5250	-	-	-		
		starch (5%)	-	930	30	-	-	-		
Mushroom (aluminium)	2.39	water	36.87	2039	-	-	76.07	/-0	(A1)	(3)

(1) Hunter (1972)
(2) Heppell (1985)
(3) Sastry et al. (1989)

ticles. In dimensionless correlations proposed, the heat transfer coefficient is expressed as a Nusselt number (= $h_{fp}.D_p/k_f$), a function of Reynolds (= $2R.V.\rho_f/\mu_f$) and Prandtl ($c_f.\mu_f/k_f$) number which quantify the effects of rotational speed and fluid properties. Chandarana et al. (1988) related their experimental results to thermophysical properties of the fluid and the fluid flow dynamics. In water they expressed the heat transfer from the controlled flow rate heating fluid to the immobilized particle as

$$Nu = 0.95\ Re^{0.434}$$

or more direct as

$$h_{fp} = 3.69\ Re^{0.434} \tag{3.2}$$

and in starch solutions they correlated

$$Nu = 0.55\ Re^{0.438}\ Pr^{0.349}$$

or in terms of the convective heat transfer coefficient

$$h_{fp} = 2.33\ Re^{0.438}\ Pr^{0.349} \tag{3.3}$$

Chang and Toledo (1989) compared their experimental results with those obtained from published correlation equations for h_{fp}. For free convection heating, their experimental values compared favorably with predicted ones, but for the different flow conditions tested, experimental results were lower than those from the reported correlations. Zuritz et al. (1990) included in their correlating equation for simulated food particles of irregular geometry immersed in a non-Newtonian fluid also the particle to tube diameter ratio ($D_p/D_{tube} = R_p/R_{tube}$).

$$Nu = 2 + 28.37\ Re^{0.233}Pr^{0.143}\ (R_p/R_{tube})1.787 \tag{3.4}$$

According to this relation, increasing particle diameter would cause an increase in h_{fp}. Zuritz et al. recognized that an increasing particle diameter decreased the available pipe cross-section for flow thus increasing the effective fluid velocity around the particle. The same tendency to decrease the thermal boundary layer around the particle was found upon increasing fluid velocity and decreasing mean apparent fluid viscosity. Chandarana et al. (1989) on the other hand found that particle dimension and h_{fp} were inversely related: decreasing the particle (cube) dimensions would increase the surface area to volume ratio of the particle (SAV) and thus increase h_{fp}. They established the correlation

$$h_{fp} = 1.14 \ 10^{-4}(SAV)^{1.94}Re^{0.07} \qquad (3.5)$$

For real dynamic flow conditions these correlations are hard to use as long as the relative particle-to-fluid velocity is not known. In packed bed heating conditions they might be used to yield indicative h_{fp}'s but when particles are processed in e.g., scraped surface heat exchangers, knowledge on residence time distribution is needed to determine the appropriate dimensionless numbers. Thus far, no realistic attempts — except for the one by Heppell (1985) — have been made to study the effect of real fluid dynamics, particle interactions, particle rotation and/or migration, particle dimensions shape and orientation on (average) h_{fp}. It is however, desirable to know the magnitude of these parameters since they will determine to a great extent the heat and thus the processing value delivered to a particle in a flowing heating medium.

Regarding the diversity of the h_{fp} and dimensionless correlations reported, we would like to emphasize that all results are valid under the limited to the specific conditions investigators tested them for (Tables 1–5). Differences in quantitative and qualitative results thus should be mainly attributed to differences in experimental conditions.

CONCLUSIONS

From Tables 1 and 3 where h_{fp}'s are listed for in-pack heating of liquid food containing particulates, Table 2 where some values are listed determined in agitated heating media and Table 4 and 5 where they are reported for dynamic flow conditions, it is clear that experimental determined h_{fp}'s vary widely. Direct comparison of the methods used to determine h_{fp} or validation of their magnitude is hardly possible, since all of the reported investigations available in the open literature differ in their experimental conditions. All researchers agree that exact determination of the fluid-to-particle convective heat transfer coefficient is very difficult and extreme care should be taken when determining its value. The relative particle-to-fluid velocity, given by (induced) particle motion and rotation, seems to be the most important factor influencing the magnitude of h_{fp}. Quantifying this velocity probably is beyond current (experimental and/or mathematical) possibilities. Several factors such as particle properties, viscosity, rotation, temperature, . . . can not be considered independently, rendering mathematical analysis of this problem and prediction of h_{fp} impossible.

Adequate experimental procedures have to be proposed and validated for different processing conditions in order to determine h_{fp} unambiguously. A direct comparison between methods using real food particles or model solids (e.g., metal transducers) should reveal the importance of particle thermophysical properties (esp. particle thermal conductivity). Applying several mathematical techniques

(analytical, numerical, dimensionless) to the same data could indicate the importance and adequacy of their intrinsic assumptions to h$_{\text{fp}}$-accuracy. Recent developed methodologies such as the combined use of a TTI and a mathematical model have to be validated against the more traditional and accepted techniques. Other methodologies, e.g., using a very small wireless time-temperture data transmitter that can be incorporated in real food particulates, should be looked for. However, with the current level of technology, this ideal solution still is out of reach.

From the engineering standpoint, an accurate easy-to-use method that will allow to determine relevant average h$_{\text{fp}}$'s under a variety of realistic processing conditions without restricting particle movement would represent a major contribution to process design. Besides relying on direct temperature measurements, the combined use of a mathematical model and a Time Temperature Integrator to determine the fluid-to-particle heat transfer coefficient should be further tested, because of its versatility towards practical heating conditions in classical and aseptic sterilization of foods where free motion of the particles prohibits the use of thermocouples.

A more fundamental insight in fluid-to-particle heat transfer has to be obtained from studying particulates under well controlled and known conditions. In this way, h$_{\text{fp}}$ can be related to the other properties of the system and one of the major gaps in our knowledge on heat transfer will be filled.

LIST OF SYMBOLS

Abbreviations:
LALD : Least Absolute Lethality Difference
LSTD : Least sum of Squared Temperature Deviations
RTD : Residence Time Distribution
SAV : particle Surface Area to Volume ratio
SSHE : Scraped Surface Heat Exchanger
TTI : Time Temperature Integrator

Methods used to determine h$_{\text{fp}}$ as listed in the tables:
A : direct particle temperature measurements
   A1   : using metal transducer particles
   A2   : temperatures measured at the particle surface
   A3   : temperatures measured at several locations inside the particle
   A4   : single point temperature measurements inside the particle
B : Liquid temperatures only used to determine h$_{\text{fp}}$
C : Indirect particle surface temperature measurements
   C1   : Liquid crystals used to monitor particle temperature
   C2   : TTI's used to evaluate particle temperature

LIST OF SYMBOLS (Continued)

A : surface area (m²)
c : heat capacity (J/kg, C)
C : constant
D : decimal reduction time (min)
F : processing value (min)
f : heating rate parameter (min)
g : gravitational acceleration (m/s²)
h : convective heat transfer coefficient (W/m², C)
j : lag factor to describe the heating of a product
k : thermal conductivity (W/m,K)
L : Lethal rate (= $10^{(T - T_{ref})/z}$)
l : slab thickness (m)
m : mass (kg)
q : heat flux (W)
R : radius (m)
r : distance from centre (m)
S : radius of reel in agitated retort (m)
T : temperature (C)
t : time (s)
U : overall heat transfer coefficient (W/m², C)
V : heating fluid flow rate (m/s)
x : distance (m)
z : temperature change needed to change the D-value with 90% (C)
α : thermal diffusivity (= $k_p/\rho c_p$, m²/s)
β : volumetric expansion coefficient (1/K)
ϵ : particle volume fraction
ρ : density (kg/m³)
μ : viscosity (Pa s)
Ω : shape factor, ratio of surface area of a sphere of volume equal to that of the particle to the surface area of the particle = $[\pi(6V_p/\pi)^{2/3}/A_p]$

Dimensionless numbers:

Bi : Biot number   : = $h_{fp}.R_p/k_p$
Nu : Nusselt number   : = $h_{fp}.2R_p/k_f$
Re : Reynolds number   : = $2R.V.\rho_f/\mu_f$
Pr : Prandtl number   : = $c_f.\mu_f/k_f$
Gr : Grashof number   : = $g(2R)^3 \rho_f^2\beta(T_{ps} - T_f)/\mu_f^2$
St : Stanton number   : = $Nu/(Re\ Pr)$
$J_{Colburn}$: Colburn j-factor   : = $(Nu\ Pr^{2/3})/(RePr)$

Subscripts:

c : can
e : effective
f : heating medium, fluid
h : heating
i : initial
p : particle
ref : at a chosen reference temperature
s : surface
t : time (s)
t0 : time zero
< > : average

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BOOK REVIEWS

Sensory Science Theory and Applications in Foods. Edited by Harry T. Lawless and Barbara P. Klein. Marcel Dekker, Inc., New York. 456 pages. $69.75 (U.S. and Canada).

Sensory science is a rapidly growing area of food science and technology. Current trends indicate that sensory evaluation will continue to play an ever expanding and critical role in the product development sequence. The purpose of this book is to bridge the gap between the basic science of sensory perception and its practical applications in food and consumer product testing. Contributors include academic as well as industrial-based scientists who are noted in their respective disciplines. This book summarizes the proceedings of the Fourteenth Annual Basic Symposium, "Advances in Sensory Science" presented at the Institute of Food Technologists Annual Meeting in Anaheim, California, June 15–16, 1990.

The first chapter serves as an introduction to the book and sets the tone for subsequent chapters. Chapter 1 proposes that sensory practice should not be viewed merely as a collection of testing methods but should be connected to basic perceptual principles. Understanding these principles is likely to lead to more sensitive tests and aid the product developer in optimizing the perceived attributes of his/her products. The logic of this approach is revealed using clear-cut examples.

Chapters 2–4 discuss physiological mechanisms of taste and odor perception. Chapter 2 is a lengthy 60 pages. It examines the temporal tracking of taste intensity and quality in aqueous taste mixtures. The concept of "chemethesis" is presented in Chapter 3, which describes the perception of chemical irritants such as chili pepper and menthol. The effects of time and temperature on chemical irritation are also examined. Chapter 4 discusses specific anosmias or odor blindness and their effects on individual variation in odor intensity and quality judgments.

Individual differences are considered again in Chapter 10 in regard to flavor perception. Often, individual variation in data is treated as a nuisance and source of experimental error. The author proposes that identifying the sources of these differences and studying them could lead to a greater understanding of sensory phenomena or product differences.

Chapters 5–7 examine sensory perception and information processing. Chapter 5 reinterprets the laws of sensation in terms of an information theory and attempts to explain such sensory phenomena as adaptation and threshold perception via this model. Chapter 6 discusses the unity of the senses and the relationship between seemingly independent sensory modalities (e.g., sight and hearing) to overall perceptual experience. Chapter 7 introduces the reader to neural networks, a computer modeling approach which might provide links between multidimensional stimuli and complex human response patterns.

Chapters 8–9 and 11–13 discuss the use of language as a fundamental tool of sensory evaluation. The idea of concept formation and alignment is discussed in Chapter 8 as a way of calibrating panelists. The selection and use of terms by expert and nonexpert wine tasters is explored in Chapter 9 and might provide hints for understanding how language development arises. Chapter 11 provides a well-organized overview of current descriptive analysis techniques and their uses. A technique for the selection of appropriate terms for descriptive analysis is presented in Chapter 12 using the author's experience with whiskeys as an example. The method of free-choice profiling is presented in Chapter 13. Free-choice profiling departs from traditional descriptive analysis methods in that panelists choose their own terms without forming a consensus. The use of procrustes analysis to interpret these data are also discussed.

Chapter 14 describes the branch of consumer testing known as qualitative research. The author makes a clear distinction between qualitative testing which probes consumer beliefs, expectations and habits to better understand their behavior and quantitative testing which examines the acceptance of specific product attributes.

Finally, statistical analysis of sensory data is critical to interpretation of results. In many applications, establishing a sensory difference is the project goal. However, support of advertising claims requires the affirmation of sensory equivalence. Chapter 15 presents statistical approaches to claim substantiation.

This volume fulfills its goal of bridging the gap between basic research and applications very well. Wherever possible, the authors attempt to put the theoretical into practical perspective. Although the work of many authors, the book is consistent in style and content and each chapter is thoroughly referenced. This book fills a very important niche in the food science literature and would be a welcome addition to any personal library. It is valuable not only to the sensory scientist but to anyone involved in any aspect of product development or testing.

<div style="text-align: right">BEVERLY TEPPER</div>

Fish Quality Control by Computer Vision (Food Science and Technology Series, #43). L.F. Pau and R. Olafsson. Marcel Dekker, Inc., New York. 312 pages. $115 (US and Canada).

This book attempts to summarize the current state of affairs (or at least the current state of affairs at the time the book was actually written), mainly in the Scandanavian countries but also in Britain, Europe and the U.S. with respect to using computers and advanced vision techniques both in the fish plant and at sea. Although no meeting is acknowledged, the papers read as if they were the proceedings of a conference on the subject. Some are clearly laboratory reports. They are quite disjointed, some are poorly edited and proof-read, and the material is often difficult to follow for a "fish" person who is not a com-

puter vision specialist. It is never clear who the intended audience is. Some of the papers are clearly designed for the fish industry — or at least to give the outsider an idea of the problems the fishing industry needs solutions for, while others are quite technical and highly jargon-based computer vision concepts. One chapter is obviously a lab manual for a hands-on workshop session. One or two papers are clearly focused on a company's or laboratory's particular commercial favorite equipment. Despite all the limitations, the book can give a quick overview of where this potential significant concept is at this time and what might be possible in the near future. Some of the problems that have been solved and those that still need to be solved are clearly laid out. The major sections suggest the scope of the book: I. Introduction: Computer Vision Opportunities for the Fish Industry; II. Biological and Optical Properties of Fish for Vision Applications. III. Lighting and Vision Techniques. IV. Remote Sensing and V. Computer Vision Technology for the Fish Industry. I was glad for the opportunity to read the book, but would recommend to most fish technologists that they borrow a library copy and read it quickly. Hopefully, in a year or two someone will write a more comprehensive and useful update.

JOE M. REGENSTEIN

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PUBLICATIONS IN
FOOD SCIENCE AND NUTRITION

Journals

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Page one should contain: the title which should be concise and informative; the complete name(s) of the author(s); affiliation of the author(s); a running title of 40 characters or less; and the name and mail address to whom the correspondence should be sent.

Page two should contain an abstract of not more than 150 words. This abstract should be intelligible by itself.

The main text should begin on page three and will ordinarily have the following arrangement:

Introduction: This should be brief and state the reason for the work in relation to the field. It should indicate what new contribution is made by the work described.

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

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Discussion: The discussion section should be used for the interpretation of results. The results should not be repeated.

In some cases it might be desirable to combine results and discussion sections.

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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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Description of experimental work or explanation of symbols should go below the table proper.

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