F
N
P

Journal of FOOD PROCESS ENGINEERING

Edited by

D. R. HELDMAN

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

VOLUME 6, NUMBER 1 QUARTERLY

JOURNAL OF FOOD PROCESS ENGINEERING

All articles for publication and inquiries regarding publication should be sent to Prof. D. R. Heldman, Michigan State University, Department of Food Science and Human Nutrition, East Lansing, Michigan 48824 USA.

All subscriptions and inquiries regarding subscriptions should be sent to Food & Nutrition Press, Inc., 155 Post Road East, Suite 6, Westport, Connecticut 06880 USA.

One volume of four issues will be published annually. The price for Volume 6 is $60.00 which includes postage to U.S., Canada, and Mexico. Subscriptions to other countries are $72.00 per year via surface mail, and $80.00 per year via airmail.

Subscriptions for individuals for their own personal use are $40.00 for Volume 6 which includes postage to U.S., Canada, and Mexico. Personal subscriptions to other countries are $52.00 per year via surface mail, and $60.00 per year via airmail. Subscriptions for individuals should be sent direct to the publisher and marked for personal use.

The *Journal of Food Process Engineering* (ISSN 0145-8876) is published quarterly (March, June, September and December) by Food & Nutrition Press, Inc.—Office of Publication is 155 Post Road East, Suite 6, Westport, Connecticut 06880 USA. (current Issue is March 1982).

Second class postage paid at Westport, CT 06880

POSTMASTER: Send address changes to Food & Nutrition Press, Inc., 155 Post Road East, Suite 6, Westport, CT 06880.

JOURNAL OF FOOD PROCESS ENGINEERING

Journal of
FOOD PROCESS ENGINEERING

VOLUME 6
NUMBER 1

Editor: D. R. HELDMAN

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

ISSN 0145-8876

Printed in the United States of America

CONTENTS

MEETINGS

MAY 1983

May 9-12: Better Process Control School. Cornell University, Rochester, New York. Contact D.L. Downing, Department of Food Science and Technology, Cornell University, Geneva, New York 11456.

May 10-12: 30th Annual Purdue Industrial Waste Conference. Stewart Center, Purdue University, West Lafayette, Indiana. Contact Dr. J.D. Wolszon, Purdue Industrial Waste Conference, Civil Engineering Building, Purdue University, West Lafayette, Indiana 47907.

May 17-19: 1983 National Food and Agriculture Exposition. World Congress Center, Atlanta, Georgia. Contact William C. Rolle, Jr., Bill Rolle and Associates, Inc., 1725 Desales Street, N.W., Washington, D.C. 20036-4468.

May 29-June 1: INATEC International Fair for Food Manufacturing and Processing. Cologne, Germany. Contact Messe-und Ausstellungs-GmbH Koln, Postfach 210760, D-5000 Koln 21, Germany.

JUNE 1983

Jun 19-22: 43rd Annual Meeting of the Institute of Food Technologists and Food Expo. New Orleans, Louisiana. Contact W.C. Willey, Institute of Food Technologists, Suite 2120, 221 N. LaSalle Street, Chicago, Illinois 60601.

Jun 26-29: Summer Meeting of the American Society of Agricultural Engineers. Montana State University, Bozman, Montana. Contact Mark A. Purschwitz, American Society of Agricultural Engineers, P.O. Box 410, St. Joseph, Michigan 49085.

JULY 1983

Jul 11-15: 12th AUMS-ICFMH International Symposium. Budapest, Hungary. Contact Dr. Ira J. Mehlman, Food and Drug Administration, 200 C Street S.W., Washington, D.c. 20204.

Jul 16-23: Workshop on Rapid Methods and Automation in Microbiology. Kansas State University, Manhattan, Kansas. Contact Dr. Daniel Y.C. Fung, Leland Call Hall, Kansas State University, Manhattan, Kansas 66506.

AUGUST 1983

Aug 6-11: Annual Meeting of the International Association of Milk, Food and Environmental Sanitarians, Inc. Marriott Pavilion, St. Louis, Missouri. Contact K.R. Hathaway, Association Executive Secretary, IAMFES, Inc., PO Box 701, Ames, Iowa 50010.

SEPTEMBER 1983

Sept 1-9: The 16th International Congress of Refrigeration. Paris, France. Contact Joseph W. Slavin, American Society of Heating, Refrigeration and Air-Conditioning Engineers, 1791 Tullie Circle N.E., Atlanta, Georgia 30329.

Sept 18-23: 6th World Congress of Food Science and Technology. Dublin, Ireland. Contact Dr. R.L. Joseph, An Foras Taluntais, Dunsinea, Castle Knock Co., Dublin, Ireland.

Sept 26-28: 3rd Annual Congress on Engineering and Food. Dublin, Ireland. Contact ICEF Secretariat, Institute of Engineers of Ireland, 22 Clid Road, Dublin 4, Ireland.

OCTOBER 1983

Oct 22-26: Food and Dairy Expo 83. McCormick Place, Chicago, Illinois. Contact F.G. Greiner, Dairy and Food Industry Supply Association, Inc., 6245 Executive Boulevard, Rockville, Maryland 20852.

ESTIMATING OUTPUT AND POWER OF FOOD EXTRUDERS[1]

LEON LEVINE

The Pillsbury Company
311 2nd Street S.E.
Minneapolis, MN 55414

Received for Publication January 7, 1982
Accepted for Publication March 19, 1982

ABSTRACT

A simplified model of food extruders is proposed. Analysis of this model suggests that extruder output and power consumption can be described by simple relationships of dimensionless groups. Comparison of the theoretical relationships with data obtained by processing a pseudoplastic dough in four different extruders indicates a sound scale-up technique has been established. A method of extending the analysis to more complicated extrusion problems is suggested.

INTRODUCTION

A major problem confronting engineers working with food extrusion is scale-up. The problem arises from the necessity of performing development experimentation on equipment which is much smaller than that used on the commercial scale. For many unit operations scale-up is straightforward, and little difficulty is encountered. Unfortunately for extrusion in general, and food extrusion in particular, there is very little information on how to proceed.

Most of the limited information available on extruder scale-up is found in plastic processing literature. Schenkel (1966) reports some data on predicting extruder output as a function of scale. The same author has also established some rules for scale-up. A correlation between desired extruder geometry and scale has been published by Uhl and Gray (1967) from E.I. Dupont. Wilkinson (1960) suggests complex relationships for predicting pressure profiles and outputs of extruders. Computer simulations are available to analyze plastic extruders (Klein 1973). All of this information is of limited value to the engineer designing or specifying a food extruder.

Information about food extruder performance is very limited. Much of the information that has been published concerns very small laboratory extruders, having diameters on the order of one inch. Recently,

[1] Presented at the August 1981 meeting of the American Institute of Chemical Engineers.

Holay and Harper (1981) have suggested that shear rate and sheer rate history are important factors in determining the quality of extruded product. In order to estimate the effect of scale-up on these parameters, the power and output of the scaled-up extruder must be predictable. Two papers (Bruin *et al.* 1978 and Harper 1979) begin to deal with the issue of scale-up. The Bruin *et al.* (1978) paper attempts to correlate extruder performance through the use of dimensionless numbers. The attempt, had it been successful, would have clearly given us a powerful tool. Unfortunately, the correlations did not work as well as expected. The authors attributed the problems to an inadequate knowledge of the dough being extruded. While this conclusion is correct, it is incomplete.

This paper will illustrate that inadequate knowledge of dough rheology can result in an inadequate definition of the dimensionless numbers.

EXTRUDATE VISCOSITY

Before proceeding with the description of the extruder model, a viscosity model of the extrudate must be establish. Several researchers (Harper 1979; Remsen and Clark 1978; Morgan *et al.* 1978; Cervon and Harper 1978; Jao *et al.* 1979) have determined the rheology of food doughs. In general, most doughs may be described by a power law model,

$$T = m\dot{\gamma}^n \tag{1}^*$$

The fluids are generally found to be pseudoplastics, so the flow index has a value less than unity. In addition, temperature and moisture corrections are required. The corrections take the form,

$$m = m_o e^{A/T} e^{BM} \tag{2}$$

The determination of the various constants is best accomplished through capillary rheometry. Alternatively, the viscosity model may be determined by measuring the pressure drop through a simple die at various conditions. For a power law fluid the pressure drop through a tubular die is given by Shenkel (1966)

$$P = m_o\left(\frac{3n+1}{n\pi R^3}\right)^n\left(\frac{2L}{R}\right)e^{A/T}e^{BM}q^n \tag{3}$$

* To be perfectly general, and dimensionally consistent, the shear stress should be multiplied by the gravitational constant, g_c; the presence of this factor is implied in the equations that follow.

The desired constants, M_o, A, B, and n may be easily determined by multiple regression techniques.

In this work, the extrudate studied was an uncooked hard wheat flour dough. The moisture and temperature ranges studied are given in Table 1.

The correlation for determination of the desired constants used seventy-seven data points and yielded a correlation coefficient (r^2) of 0.87. The adequacy of the model used is illustrated in Fig. 1. The constants obtained are summarized in Table 2.

Table 1. Temperature and moisture ranges used in viscosity determination

$95°F < \text{Temperature} < 125°F$

$27.5\% < \text{Moisture (Wet Basis)} < 32.5\%$

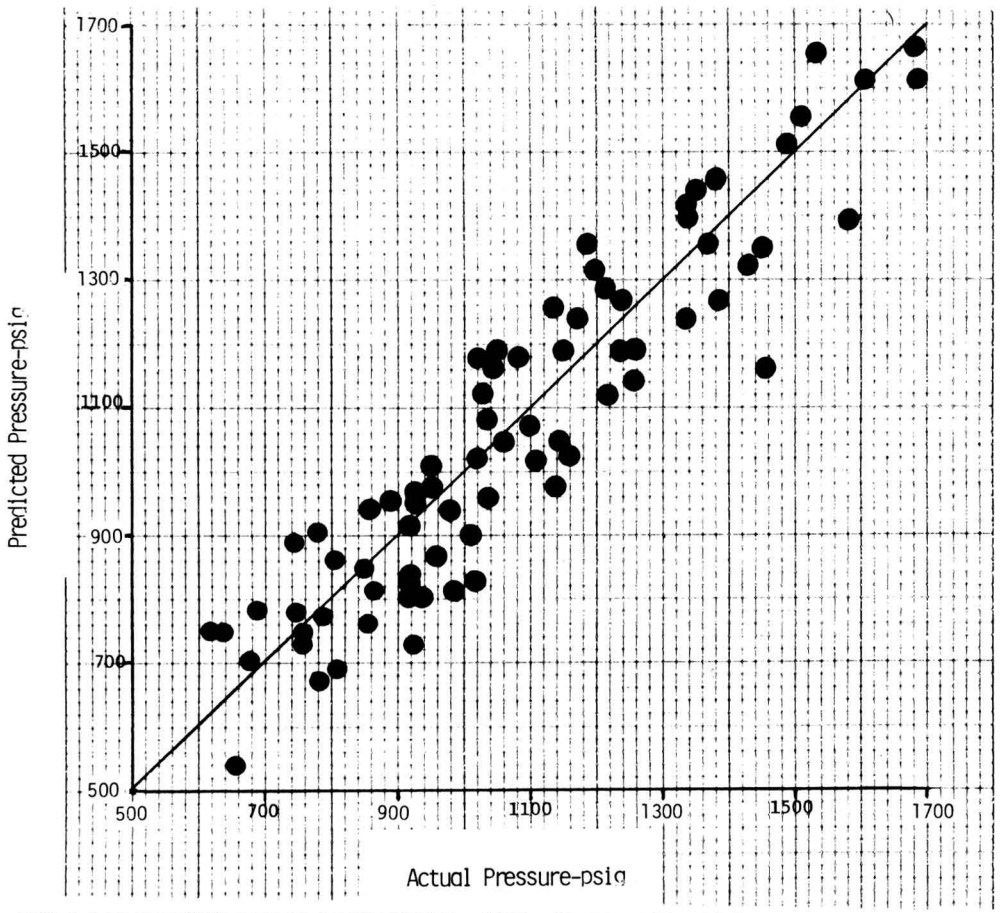

FIG. 1. DIE PRESSURE DROP PREDICTION USING POWER LAW MODEL

Table 2. Constants of viscosity model

Flow index (n): 0.410

Consistency constant (m_o): 7.09×10^4 lb/in-min.$^{1.590}$

Temperature coefficient: 3240 R

Moisture coefficient: −6.80

It follows that the viscosity model is,

$$T = 7.09 \times 10^4 e^{3240/T} e^{-6.80M} \dot{\gamma}^{0.410} \tag{4}$$

Equation 4 indicates the fluid to be pseudoplastic and the consistency to be highly moisture and temperature dependent.

THE EXTRUDER MODEL

The conceptual model of the extruder is illustrated in Fig. 2. This idealized model is composed of three parts:

1. An ideal screw which allows no backflow.
2. A recycle pipe through which all the backflow (pressure flow) travels.
3. A valve which provides the flow resistance of the dies, breaker plates, etc.

Visualized in this manner the extruder is easily analyzed by considering the role of each component.

The output of the system is given by,

$$Q_n = Q_m - Q_r \tag{5}$$

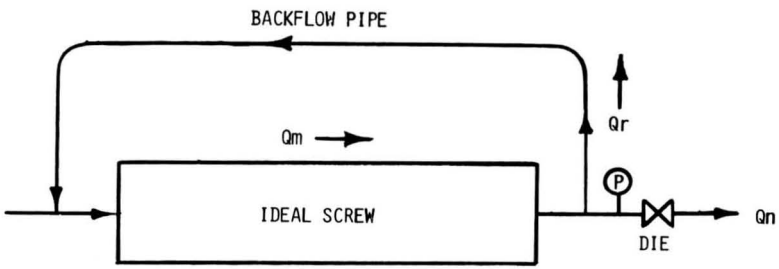

FIG. 2. CONCEPTUAL MODEL

If we consider a section of the screw and barrel as two plates moving relative to each other as shown in Fig. 3, it may be shown that the output of the ideal screw is,

$$Q_m = \pi D t_e h N/2 \tag{6}$$

The output of the extruder, Q_n, can be determined if the backflow, Q_r, can be determined. This may be accomplished by recognizing that the backflow occurs in the helical channel formed by the screw and barrel. The length of the channel is given by,

$$L_{eq} = \frac{\pi D L}{t}\sqrt{1 + \left(\frac{t}{\pi D}\right)^2} \tag{7}$$

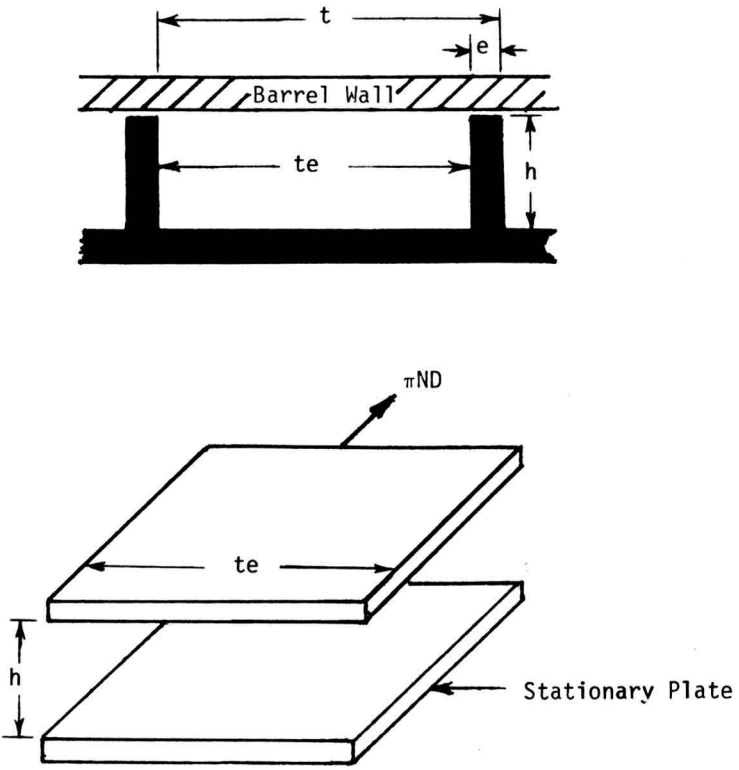

FIG. 3. TWO PLATE VISUALIZATION OF SCREW AND BARREL

The channel has a crossectional area given by,

$$S = ht_e \tag{8}$$

It follows that the average fluid velocity is given by,

$$v = Q_r/S \tag{9}$$

The equivalent diameter is estimated by finding the size of the cylindrical pipe which gives the same pressure drop as the helical channel. The approximate relationship for pressure drop through the slot is given by,

$$P = m_o\left(\frac{2(2n+1)}{nt_e h^2}\right)^n \left(\frac{2L}{h}\right) e^{A/T} e^{BM} q^n \tag{10}$$

Equating Eq. 10 to Eq. 3, and solving for the cylindrical radius yields,

$$D_{\text{eq}} = 2R = 2\left(\frac{3n+1}{2\pi(2n+1)}\right)^{1/3+n} (t_e h^{2+n})^{1/3+n} \tag{11}$$

These calculations allow the helical channel to be viewed as a simple pipe. For laminar flow we may write the familiar relationship between friction factor and Reynolds number (Wilkinson 1960),

$$f = \frac{16}{\text{Re}_f} \tag{12}$$

The friction factor is defined by,

$$f = \frac{D_{\text{eq}}(P/4L_{\text{eq}})}{\rho v_2/2} \tag{13}$$

The Reynolds number is correctly defined, for a power law fluid, by,

$$\text{Re}_f = \frac{D_{\text{eq}}{}^n v^{2-n} \rho}{\frac{m}{8}\left(\frac{6n+2}{n}\right)^n} \tag{14}$$

Equation 14 illustrates why an incomplete knowledge of dough rheology may lead to an inadequate definition of dimensionless numbers.

Assuming the model is correct, the backflow, Q_r, can be easily calculated using Eq. 12, and the extruder output can be determined as a function of back pressure (die resistance). An energy balance around the three components of the model leads to a method of predicting power requirements.

The power required to pump the dough through the backflow pipe is,

$$p_r = Q_r P \tag{15}$$

Similarly, the power to pump the dough through the die is,

$$p_n = Q_n P \tag{16}$$

The power requirement to overcome pressure buildup is obtained by summing Eq. 15 and 16, using Eq. 5 to eliminate Q_r and Q_n, and replacing Q_m with Eq. 6.

$$p_p = \frac{\pi D t_e h N P}{2} \tag{17}$$

The total power required is the sum of power required for pressure buildup and the power required to overcome the ideal screw.

$$p_t = p_s + p_p \tag{18}$$

Considering the two plate model of the screw and barrel, and neglecting the different shear rates between the screw flights and barrel, the power to overcome the friction of the ideal screw can be shown to be,

$$p_s = \frac{m\pi^{2+n} D^{2+n} L N^{1+n}}{h} \tag{19}$$

This may be rearranged to yield,

$$\frac{p_s}{\rho N^3 D^4 L} = \frac{m\pi^{2+n}}{\rho h^n N^{2-n} D^{2-n}} \tag{20}$$

The left hand side of Eq. 20 has the familiar form of the power number encountered in mixing problems (Uhl and Gray 1967). Examination of the right hand side of the equation reveals a similarity to the power law form of the Reynolds number given in Eq. 14. Equation 20 can be written as,

$$N_p = \frac{1}{\mathrm{Re}_s} \tag{21}$$

The Reynolds number of Eq. 20 is defined by,

$$\mathrm{Re}_s = \frac{\rho h^n (ND)^{2-n}}{m\pi^{2+n}} \tag{22}$$

Total extruder power consumption may be calculated through the use of Eq. 17, 18, and 20.

MODEL CONFIRMATION

Output and/or data was obtained on four different extruders. The nominal capacities of these extruders ranged from 20 to 1000 lb/h. All the extruders had simple augers and slotted barrels. The important dimensions of the screws are presented in Table 3.

Various pressures, flowrates, and power consumptions were obtained by varying dough moisture, screw speed, and die resistance. The temperature of the dough was controlled by a cooling jacket around the barrel. The target screw outlet temperature was 120°F. The dugh temperature at the inlet to the screw was maintained at 80°F. To simplify calculations an average dough temperature of 100°F was used in all calculations. The density of the dough, as measured by volumetric extruder output, was found to average 80 lb/ft^3. This value was used for all calculations.

Figure 4 illustrates the correlation of extruder output suggested by Eq. 12. The equation obtained by regression analysis is,

$$f = \frac{3.65}{\mathrm{Re}_f^{1.07}} \tag{23}$$

For a total of 116 data points a correlation coefficient (r^2) of 0.98 was obtained. The correlation fits all sizes of extruder studied, indicating a scale-up procedure has been obtained.

The measured relationship between friction factor and Reynolds number is reasonably close to these suggested by the model in Eq. 12, thus substantiating the conceptual view of the extruder. Some deviation must be expected because of the crude determination of the viscosity model and the simplifying assumptions made in developing the model.

Total screw power was measured with a wattmeter. To obtain net power delivered to the dough, a no load power was measured with a

Table 3. Dimensions of screw used in model confirmation (dimensions in inches)

	A	B	C	D
Diameter	1.75	3.0	4.5	5.5
Length	22.0	26.8	47.0	43.4
Pitch	1.25	1.875	3.5	3.62
Thread Depth	0.3125	0.75	1.375	1.60
Land Width	0.25	0.375	0.5625	0.55
Speed (rpm)	20-35	15-35	10-16	10-22

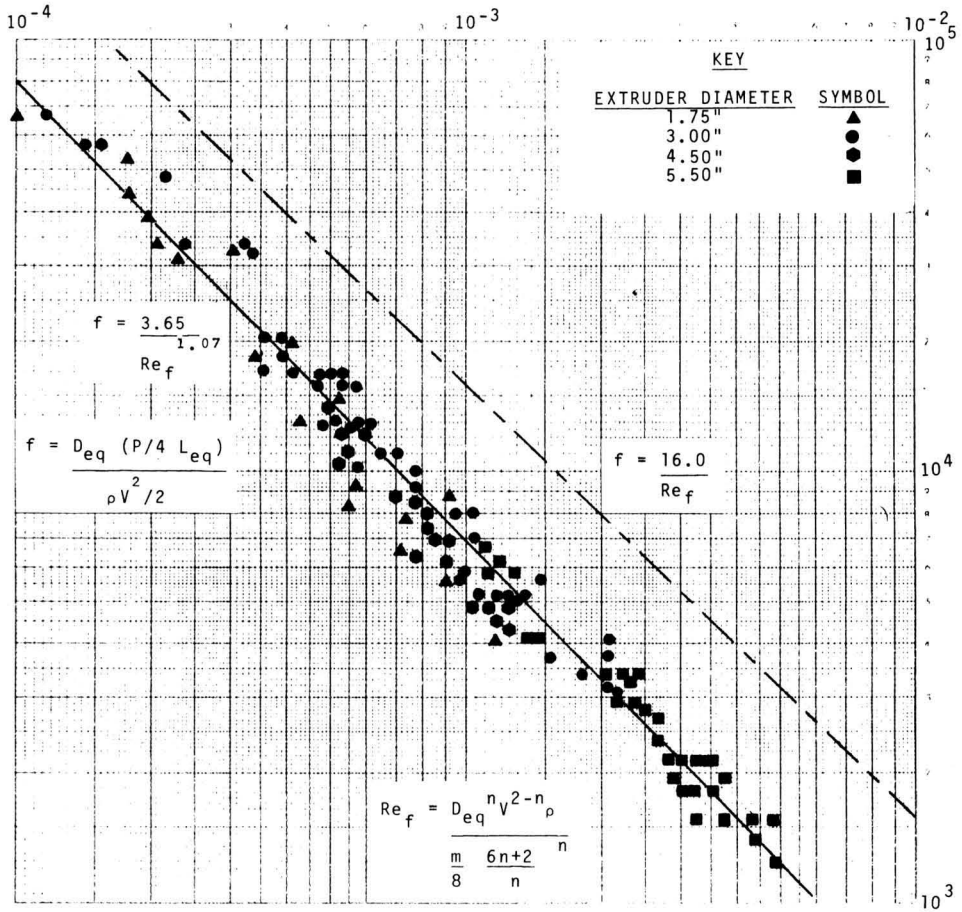

FIG. 4. CORRELATION OF EXTRUDER OUTPUT

clean empty barrel. Power data was correlated in the form suggested by Eq. 20, as illustrated in Fig. 5. The equation obtained by regression analysis is,

$$N_p = \frac{0.252}{Re_s^{1.11}} \tag{24}$$

For a total of sixty-three points a correlation of 0.90 was obtained. Once again, the correlation covers the different extruder sizes reasonably well, again suggesting a valid scale-up method. The data for the three inch extruder deviates somewhat from the prediction. It is believed that this is due to inaccuracies in the measurement of no load power on the small motor.

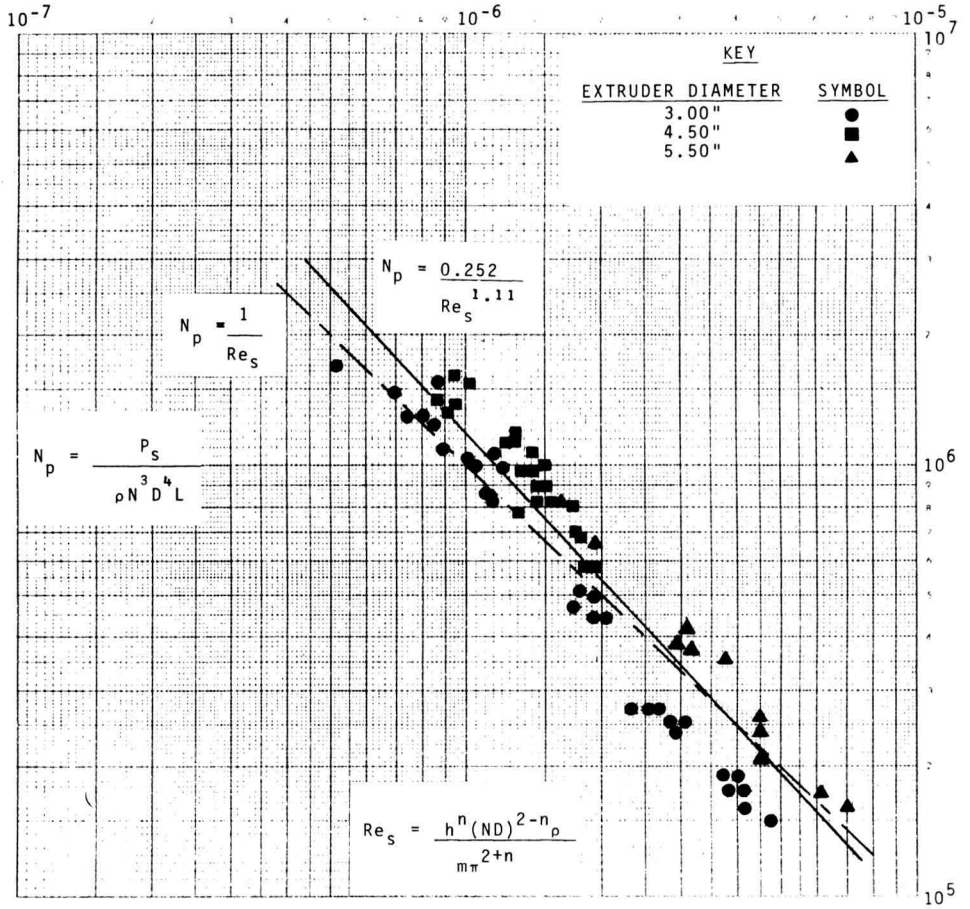

FIG. 5. CORRELATION OF EXTRUDER POWER

Once again, the constants in Eq. 24 are reasonably close to those suggested by the model in Eq. 20, further substantiating the model.

APPLICATION TO MORE COMPLEX EXTRUDERS

This paper has illustrated the application of the model to the simplest possible case, a simple screw and isothermal extrusions temperatures. Most food extrusions are not this simple. For example, in a cooking extruder, the temperature of the extrudate rises continuously and the thread depth varies down the length of the screw.

This more complicated situation can be dealt with in a straightforward, though mathematically cumbersome manner, provided rheological constants are known as a function of temperature. For this situation the complicated screw is broken down into a chain of short screws in series. The model is then applied to the differential screw sections as illustrated in Fig. 6. The performance of the chain is obtained by trial and error on the section discharge pressure. Convergence is attained when,

$$Q_{n1} = Q_{n2} = \cdots . Q_{nj} = Q_n \tag{25a}$$

and

$$\sum_1 P_i - P_{i-1} = P \tag{25b}$$

One difficulty encountered is the possibility that the discharge pressure for one section is lower than that for the previous section. This can occur when the metering zone of the extruder is too short and overrun. In this case the flow through the backflow pipe is opposite to its normal direction and power is delivered to the system by pressure loss, rather than consumed by pressure gain.

CONCLUSIONS

Through the use of a simplified extruder model, dimensionless correlations of extruder output and power have been developed. The experimental results verify the validity of the model. Given rheological constants, these correlations predict extruder performance independent of scale, thus providing a technique for scale-up.

The data presented in this paper considers only the simplest extruder design. A method of application to more complicated extruders has been suggested. Through this method, complicated screw geometry and temperature profiles may be studied, provided adequate viscosity data is available.

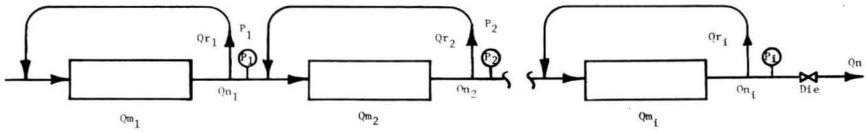

FIG. 6. SERIES VISUALIZATION OF COMPLEX EXTRUDER

NOTATION

A, B, C = constants
D = extruder diameter
D_{eq} = equivalent channel diameter
e = land width
f = friction factor
h = thread depth
L = screw or die length
L_{eq} = helix length
m = flow consistency
m_o = flow consistency constant
M = fractional moisture (dry basis)
n = flow index
N = rotational speed
N_p = power number
P = screw discharge pressure
p_n = power consumed by die
p_p = power consumed by pressure build-up
p_r = power consumed by reverse flow
p_s = power consumed by ideal screw
p_t = total extruder power consumption
q = die flowrate
Q_m = ideal screw output
Q_n = extruder output
Q_r = reverse flowrate
R = die radius
Re_f = flow Reynolds number
Re_s = screw Reynolds number
S = channel crossectional area
t = screw pitch
te = channel width perpendicular to flight
T = absolute temperature
v = average channel velocity

Greek Letters

$\dot{\gamma}$ = shear rate
ρ = density
T = shear stress

ACKNOWLEDGMENT

The author would like to thank Mr. Jeffrey Rockwood for his assistance in the preparation of the figures in this paper.

REFERENCES

BRUIN, S., VAN ZUILIEHEM, D.J. and STOLP, W. 1978. J. Food Proc. Eng. *2*, 1.

CERVON, N.W. and HARPER, J.W. 1978. J. Food Proc. Eng. *2*, 83.

HARPER, J. 1979. CRC Critical Reviews in Food Science and Nutrition, 155.

HOLAY, S.H. and HARPER, J. 1981. *Plant Protein Texturization Under Varying Shear* paper presented at A.I.Ch.E. National Meeting, Aug.

JAO, Y.C., CHEN, A.H., LEWANDOWSKI, D. and IRWIN, W.E. 1979. *Engineering Analysis of Soy Dough Rheology in Extrusion*, paper presented at A.I.Ch.E. National Meeting, Nov.

KLEIN, I. 1973. *Plastics Design and Processing*, Sept., 22.

MORGAN, R.G., SUTER, D.A. and SWEAT, V.E. 1978. J. Food Proc. Eng. *2*, 65.

REMSEN, C.H. and CLARK, P.J. 1978. J. Food Proc. Eng. *2*, 39.

SHENKEL, G. 1966. *Plastics Extrusion Technology and Theory*, American Elsevier Publishing Co., Inc., New York.

UHL, V.W. and GRAY, J.B. 1967. *Mixing Theory and Practice*, academic Press, New York.

WILKINSON, W.L. 1960. *Non-Newtonian Fluids*, Pergamon Press, New York.

MATHEMATICAL SIMULATION OF THE THERMAL BEHAVIOR OF FROZEN MEAT DURING ITS STORAGE AND DISTRIBUTION

NOEMÍ E. ZARITZKY

Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA)
(UNLP-CONICET-CIC).
47 y 116 La Plata (1900).Provincia de Buenos Aires. ARGENTINA.

Received for Publication March 18, 1981
Accepted for Publication December 23, 1981

ABSTRACT

During the various stages of marketing, frozen food products are frequently subjected to changes in temperature which affect their quality.

In the present work, a mathematical model is developed to analyze the thermal behaviour of frozen meat subjected, under different insulation conditions, to thermal step functions and periodic fluctuations in temperature varying in amplitude and frequency.

The heat transfer equation has been numerically solved, since it is a system with physical properties that vary with the temperature, and fluctuating boundary conditions.

At the same time, laboratory experiments were performed to verify that the mathematical model is applicable to one-dimensional and three-dimensional heat transfer problems.

The obtained results were compared with analytical solutions for the heat transfer equation, with constant coefficients, determining the temperature range for which it is possible to use average values in the physical properties.

INTRODUCTION

Frozen meat products can remain in storage for long periods, after which they are transported for distribution. During that situation, a loss in quality occurs which exceeds the losses caused in any other phase of the freezing process (pre-treatment, freezing, thawing). Internationally accepted heat requirements are increasingly strict, indicating temperatures below −18°C for the storage and transportation stages. (Van Ardsel *et al.* 1969).

It is common for frozen meat products to be subjected to changes in temperature that cause physico-chemical changes which alter their quality and shorten their storage life. (Singh and Wang 1977).

Some of these changes include:

a. recrystallization phenomena, which result in an increase in the size of the average ice crystal.
b. increased weight losses while the food is maintained frozen.
c. denaturation of proteins, which causes changes in the texture of the food.
d. oxidation of lipids, which produces rancidity and loss of aroma.

All these changes are accelerated by rises or fluctuations in the storage temperature. Sy and Fennema (1973) reported a remarkable increase in the recrystallization temperature of liver above −7°C. Khan *et al.* (1963) and Awad *et al.* (1968) observed a reduction in protein solubility when the storage temperature was raised from −18°C to −4°C.

Rancidity due to lipid oxidation is higher in meat products stored at −5°C than at −20°C for the same period of time. An increase in lipid oxidation and a consequent decrease in palatability in frozen meat stored at a fluctuating temperature (−18°C to −5°C) has been reported. (Chrystall 1972).

From a microbiological standpoint, storage temperatures below −10°C are considered safe. Consequently, during transportation, temperatures at any point of the meat cuts should not be above −5°C, otherwise the microbial alteration is very great, (Malton 1974; Haughey and Marer 1971).

In general, it may be said that frozen foods are exposed to two types of temperature changes (1) during storage there is generally some fluctuation in the temperature of the freezing chambers, and (2) during transportation there is frequently an interruption in the cold chain during loading and unloading of the vehicle. In both cases, the rise in temperature of the frozen foods can reach undesirable levels. Under these variations in temperature, large cuts of meat will not show the same behaviour in the center as at the edges. The response to different temperature signals will depend on the size of the cut and on the type of wrapping.

In order to predict the thermal behaviour of the system that has been subjected to sharp changes in the ambient temperature (step signal) and to periodic fluctuating temperature of varying amplitude and frequency, a mathematical model has been developed, and a temperature range has been established for which it is possible to applied analytical solutions using average physical properties in the cases of one-dimensional and three-dimensional heat transfer problems.

Using these solutions it is possible to predict:

1. the time required to reach given temperature levels in the edges and centre when the pieces of meat are subjected to different thermal steps;

2. how fluctuations in ambient temperature are atenuated and shifted along the meat cuts in order to establish the real temperature abuses to which they are subjected.

THEORETICAL CONSIDERATIONS

Mathematical Model: Numerical Solution

The mathematical model is based on the solution of the non-stationary unidirectional heat transfer equation of a slab of frozen meat ($0 \leq x \leq L$).

$$\rho \hat{C}_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) \tag{1}$$

with the following conditions:

$$t = 0 \qquad T = \mathrm{Ti} \qquad \forall x \tag{2}$$

$$t > 0 \qquad \frac{\partial T}{\partial x} = 0 \qquad x = 0 \tag{3}$$

$$-k \frac{\partial T}{\partial x} = h(T - T_a) \qquad x = L \tag{4}$$

where Ti is the initial temperature and T_a the ambient temperature.

In the analysis of the response of the system to step-type temperature signals, T_a has been considered constant, while in the case of sinusoidal temperature variation on equation of the following form was used:

$$T_a = T_M + A \sin \Omega t \tag{5}$$

where T_M is the mean temperature of the fluctuation, A its amplitude and Ω its frequency.

In the case in which the thermal behaviour of an object subjected to a fluctuation in the ambient temperature is represented, it must be taken into account that once the transitory period of the response is elapsed (which is short with respect to the time the object remains in that environment), the temperature of the object begins to fluctuate around the mean value of T_a irrespective of the initial temperature it may have had. For this reason, the ambient temperature is usually considered the initial temperature of the meat cut. (Ti = T_M).

The frozen meat can be considered as a multicomponent system made up of water, ice and tissue. Its physical properties, density ρ, specific $\hat{C}_p$ and thermal conductivity k, vary with the temperature in terms of the

water fraction converted into ice ω. An increase in temperature implies a reduction in the ice content and a proportional increase of the liquid aqueous phase.

To determine the fraction of water that is converted into ice ω, a model of cryoscopic descent for meat was used. (Mascheroni and Calvelo 1978).

Through this model, ω is related to the absolute temperature of the system T_K(°K) as follows:

$$\omega = 1 - \frac{x_B}{x_o} + \frac{DRT_K}{1000 L_f x_o} \frac{T_K}{T_K - T_o} \tag{6}$$

where
x_o is the initial content of water on a dry basis adopting as the mean value x_o = 2.8461 Kg water/Kg of dry substance, L_f is the heat of fusion for ice (L_f = 333640. J/Kg), T_o is the melting point of pure water (T_o = 273,16 °K) and R is the general constant of gases. Constants x_B = 0.1965 (content of water bounded on a dry basis) and D = 1.455 (moles of solute per Kg of dry substance) were evaluated using experimental data of Riedel, 1957.

Figure 1 represents the variation of ω with temperature for frozen beef with an initial content of water on a wet basis, Y_o = 0.74 Kg water/total Kg

$$\left(Y_o = \frac{x_o}{1 + x_o}\right).$$

The density ρ of partially frozen meat is determined by assuming the additivity of specific volumes:

$$\rho = \frac{\rho_o}{1 + Y_o \rho_o \omega (1/\rho_h - 1/\rho_w)} \tag{7}$$

where ρ_o is the density of fresh beef (1053 Kg/m^3), ρ_h is the density of ice (ρ_h = 916 Kg/m^3), ρ_w is the density of water (1000 Kg/m^3) and a mean value Y_o = 0.74 Kg water/total Kg has been adopted.

In Eq. (1), $\hat{C}_p$ is the apparent specific heat, which for frozen meat includes the latent heat due to change of phase in accordance with the expression

$$\hat{C}p = \hat{C}p_o - \omega Y_o(\hat{C}p_w - \hat{C}p_h) - \left[L_f + (\hat{C}p_w - \hat{C}p_h)(T - T_o)\right] Y_o \frac{d\omega}{dT} \tag{8}$$

where the specific heat of ice, $\hat{C}p_h$ = 2050. J/Kg°K and of water, $\hat{C}p_w$ = 4180. J/Kg°K are considered constant and where $\hat{C}p_o$ is the specific heat of unfrozen meat ($\hat{C}p_o$ = 3470. J/Kg° K).

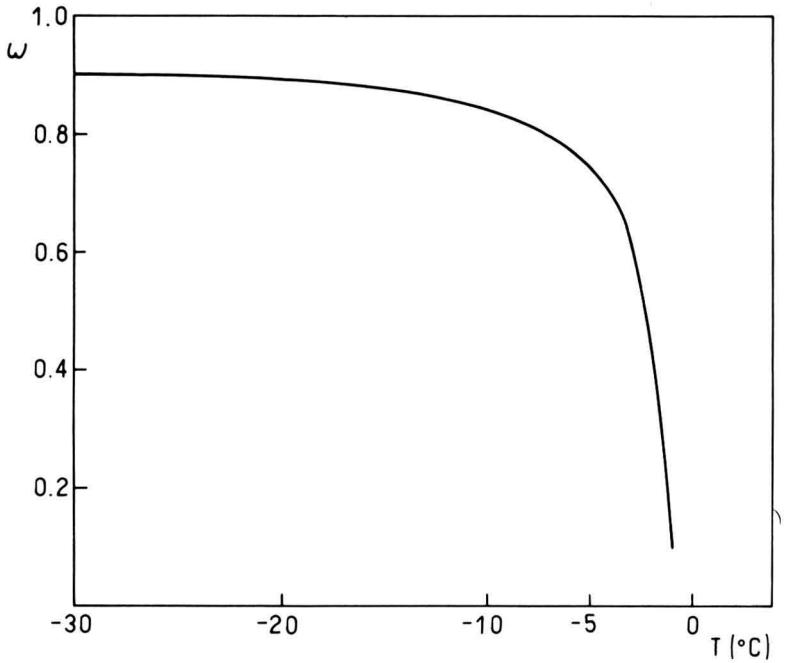

FIG. 1. FRACTION OF FROZEN WATER (ω) VERSUS TEMPERATURE FOR BEEF WITH AN INITIAL MOISTURE CONTENT $Y_0 = 0.74$

The thermal conductivity of frozen meat varies not only with temperature but also according to the direction (Lentz 1961; Miller and Sunderland 1963).

To establish the thermal conductivity of frozen meat in terms of the temperature, the mathematical expressions were those corresponding to a model that makes it possible to evaluate it both parallel and/or perpendicular to the fibres in terms of the ice fraction present ω (Mascheroni *et al.* 1977).

Figure 2 shows the curves for the variation of the thermal conductivity of frozen beef both parallel (k_l) and perpendicular (k_t) to the tissue fibres in relation to the temperature. Values for unfrozen beef are $k_{ol} = 0.505$ W/m°K and $k_{ot} = 0.463$ W/m°K.

The same figure also shows the thermal diffusivity curves ($\alpha = k/\rho\hat{C}p$) parallel (α_l) and perpendicular (α_t) to the fibres, using the expressions of ρ and Cp of equations (7) and (8).

Nonlinear Eq. (1), having variable conditions at the edges over a period of time, was solved using the Douglas Jones method of finite differences (Von Rosenberg 1969). For their numerical solution, the

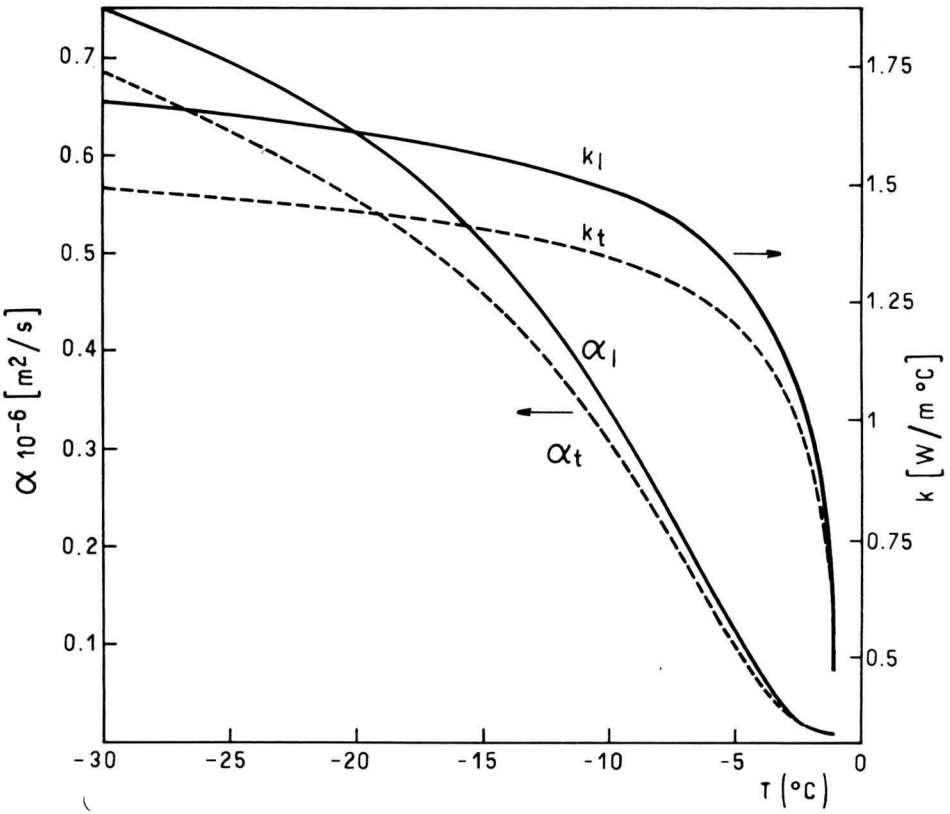

FIG. 2. THERMAL CONDUCTIVITY(k) AND THERMAL DIFFUSIVITY (α) VERSUS TEMPERATURE FOR FROZEN BEEF ($Y_o = 0.74$) l = PARALLEL, t = PERPENDICULAR TO BEEF FIBRES

equations were previously written in dimensionless form using the physical properties of unfrozen beef ρ_o, k_o, $\hat{C}p_o$ and $\alpha_o = k_o/\rho_o \hat{C}p_o$ with the following definitions:

$$T^* = \frac{T - T_i}{T_a - T_i} \text{(step function)} \tag{9}$$

$$T^* = \frac{T - T_M}{A} \text{(sinusoidal signal)} \tag{10}$$

and

$$x^* = x/L;\ t_o^* = \alpha_o t/L^2;\ Bi_o = hL/k_o;\ \Omega^* = \Omega L^2/\alpha_o.$$

Analytical Solutions

The numerical solution of the model, which includes complex changes in the physical properties according to temperature changes, is extremely useful for predicting responses to temperature signals of various types (step and sinusoidal functions) making it possible to simulate extreme situations which are difficult to handle experimentally by changing the parameters governing the system.

However, to obtain the approximate thermal response of a cut of frozen meat to temperature steps and fluctuating conditions in the temperature range between −30°C and −5°C to the dimensionless heat transfer equation

$$\frac{\partial T^*}{\partial t^*} = \frac{\partial^2 T^*}{\partial x^{*2}} \tag{11}$$

using average physical properties of frozen meat with the following conditions:

$$t^* = 0 \qquad 0 \leq x^* \leq 1 \qquad T^* = 0 \tag{12}$$

$$t^* > 0 \qquad x^* = 0 \qquad \partial T^*/\partial x^* = 0 \tag{13}$$

$$x^* = 1 \qquad \partial T^*/\partial x^* = Bi(1 - T^*) \tag{14}$$

or

$$x^* = 1 \qquad \partial T^*/\partial x^* = Bi(\sin \Omega^* t^* - T^*) \tag{15}$$

where the definition of T^* coincides with Eq. (9) or (10) according to the problem and $x^* = x/L$; $t^* = \bar{\alpha}t/L^2$; $Bi = hL/\bar{k}$; $\Omega^* = \Omega L^2/\bar{\alpha}$

The analytical solution of Eq. (11) with conditions (12), (13) and (14) is expressed as follows (Carslaw and Jaeger 1959)

$$T^* = 1 - \sum_{n=1}^{\infty} \frac{2Bi \cos(\lambda_n x^*) \sec \lambda_n}{Bi(Bi + 1) + \lambda_n^2} e^{-\lambda_n^2 t^*} \tag{16}$$

where λ_n are the positive roots of $\lambda_n \tan \lambda_n = Bi$ with $n = 1, 2, 3, \ldots$.

Solutions of three-dimensional problems can be obtained superimposing one-dimensional solutions, Neumann's theorem (Carslaw and Jaeger 1959).

In the case of sinusoidal temperature signals the solution of Eq. (11) with conditions (12) (13) and (15) is obtained using the Dühamel theorem for the transitory part of the solution and the Residue theorem for the stationary part.

The solution is expressed in the following manner:

$$T^* = Bi\frac{A_o}{A_1}\sin(\Omega^* t^* + \phi_o - \phi_1) + 2Bi\sum_{n=1}^{\infty}\frac{\lambda_n 2\Omega^* \cos(\lambda_n x^*)\sec\lambda_n e^{-\lambda n^2 t^*}}{(\lambda n^4 + \Omega^{*2})(Bi(Bi+1)+\lambda_n^2)} \quad (17)$$

with $\lambda n \text{ tg } \lambda n = Bi$ where

$$A_o e^{i\phi o} = \cosh(\theta x^*)\cos(\theta x^*) + i\sinh(\theta x^*)\sin(\theta x^*) \quad (18)$$

$$A_l e^{i\phi l} = \theta(\sinh\theta\cos\theta - \cosh\theta\sin\theta) + Bi\cosh\theta\cos\theta + i\theta(\sinh\theta\cos\theta + \cosh\theta\sin\theta) + Bi\sinh\theta\sin\theta \quad (19)$$

and

$$\theta = \frac{\Omega^*}{2} \text{ natural frequency of the system)} \quad (20)$$

It is interesting to analyze the stationary signal of the response and particularly:

$$Ra = \text{amplitude ration} = \frac{A_o}{A_1}Bi \quad (21)$$

$$\phi = \text{phase lag} = \phi_o - \phi_1 \quad (22)$$

obtained from the modulus and the phase of the vectors represented by Eq. (18) and (19).

In Fig. 3a, b the amplitude ratio (Ra) was plotted in terms of θ for the edges and center respectively, and in Fig. 4 the phase lag of the signals (ϕ) is observed.

EXPERIMENTAL

Beef samples of different sizes and with different insulation conditions were subjected to temperature changes under controlled one-dimensional and three-dimensional heat transfer conditions, recording the thermal response of the system in order to verify experimentally the mathematical models.

One-dimensional heat transfer experiments

Beef cuts of semitendinousus muscle post rigor were used, frozen in such a way that the heat flow was parallel to the muscle fibres in 5 cm diameter acrylic cylinders supported on a heat exchanger, through

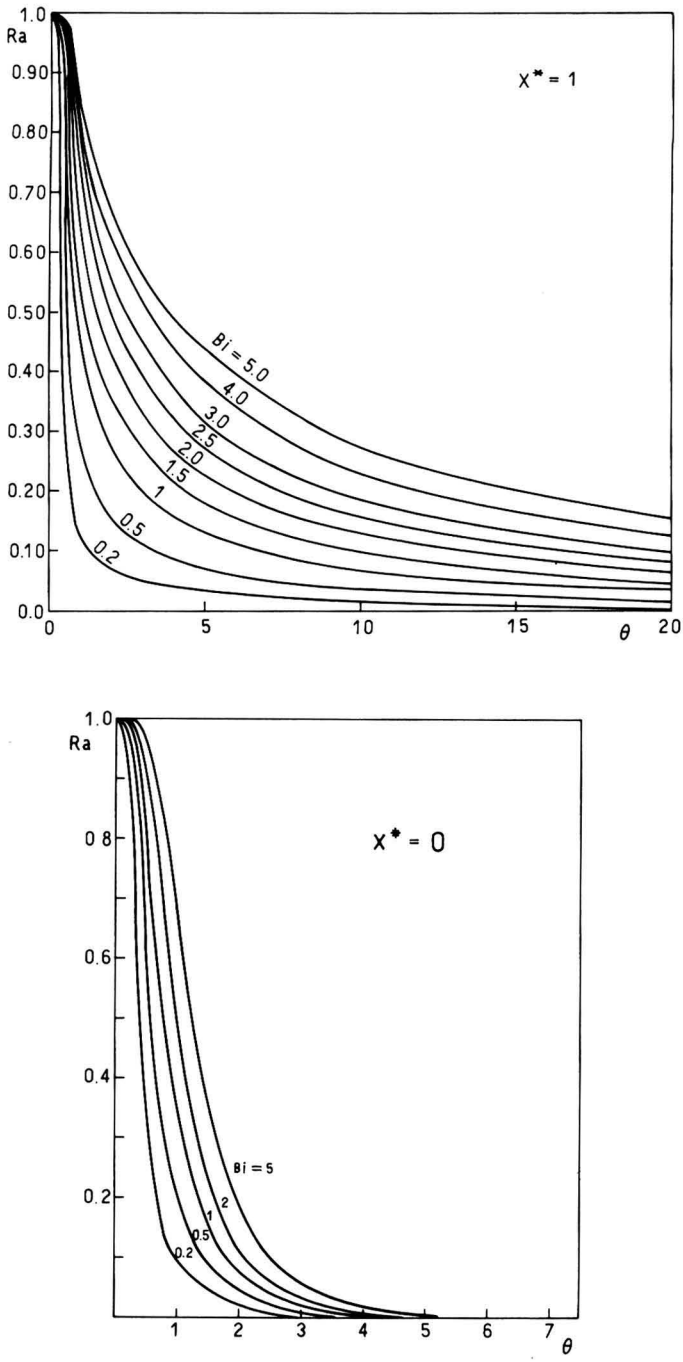

FIG. 3. AMPLITUDE RATIO(Ra) VERSUS NATURAL OSCILLATION FREQUENCY (θ) FOR A SLAB (a) BORDER (b) CENTER (Analytical solution).

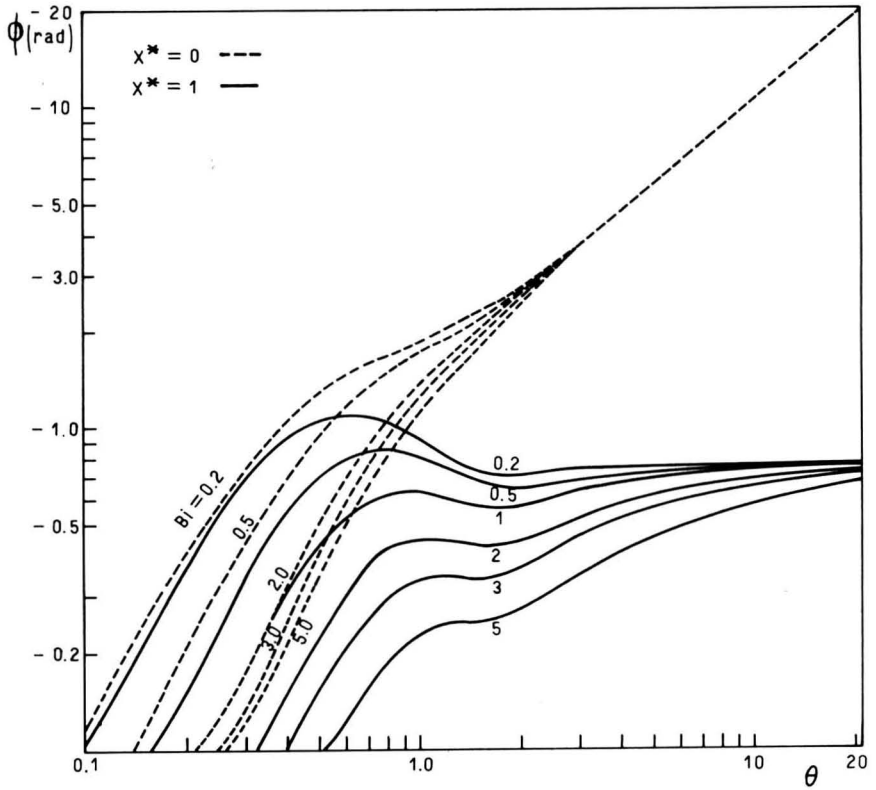

FIG. 4. PHASE LAG (ϕ) VERSUS NATURAL FREQUENCY (θ) FOR THE BORDER($x^* = 1$) AND CENTER ($x^* = 0$) OF A SLAB (Analytical solution).

which alcohol from a Lauda UK 50 DW cryostat circulated; the cylinders being outwardly insulated by a covering of expanded polystyrene, 4 cm thick.

The length, L, of the sample could be varied in each experiment and by means of acrylic slabs of a given thickness (e_a) and known thermal conductivity (k_a) placed between the meat cut and the heat-exchanger, different types of thermal insulation were simulated (Fig. 5). By means of thermocouples (Cu-Co) inserted at the indicated points it was possible to record the thermal history of the meat cuts.

Samples were frozen to a uniform temperature, and, at a given time, cooling fluid was circulated through the heat-exchanger at a different temperature from the final freezing temperature, simulating the temperature steps, while the thermal response was recorded simultaneously using a Rikadenki DB6 six-channel recorder and an electronic sequential switch.

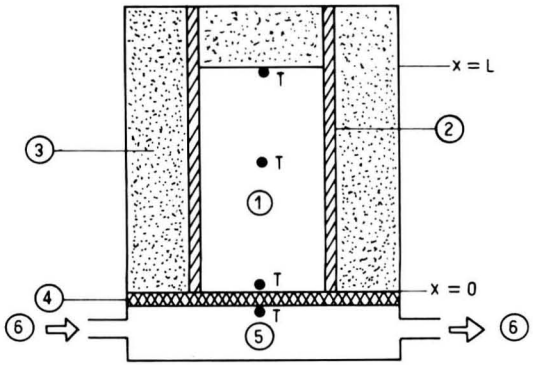

FIG. 5. EXPERIMENTAL ARRANGEMENT FOR UNIDIRECTIONAL HEAT FLUX 1) Beef sample 2) Acrylic cylinder 3) Expanded polystyrene 4) Acrylic slab 5) Heat exchanger 6) Refrigerant *T*) Thermocouples.

The following parameters could be modified in each experiment: the initial temperature of the meat (T_i), the step temperature (T_a), the heat transfer coefficient h and the length of the sample.

Three-Dimensional Heat Transfer Experiments

In order to simulate three-dimensional heat transfer, a cubic box, 8 cm per side, was made of acrylic material having a thickness, e_a, of 0.23 cm, in which the meat was carefully placed, taking care to leave no free spaces. After sealing the lid, this was frozen to an uniform temperature.

The box had thermocouples attached to the vertices (B), in the centre of its faces by its inner (A) and outer (D) surfaces and, through a small hole in the lid, the thermocouples inserted in the geometrical centre of the system (C) were connected.

Once the piece of meat was frozen inside this box in a low-temperature chamber to a uniform temperature, it was quickly introduced in a liquid cryostat bath or placed in another chamber at a controlled temperature, thus simulating the thermal steps.

In this environment the box was kept suspended to achieve a uniform distribution of temperature, recording simultaneously the thermal response of the difference points of the system by means of the multichannel recorder.

To measure the heat transfer coefficient in the different media, similar experiments were performed, but using ice whose physical properties are known, as a solid inside the box. By comparing the

experimental thermal response curves to step-type signals with the analytical solutions valid for constant coefficients, the h values were determined.

RESULTS AND DISCUSSION

Response to Step Signals

Numerical Solution

The numerical model was solved simulating the behaviour of meat cuts of different sizes and under different insulation conditions in the face of temperature steps of variable amplitude, analyzing their response in the −30°C to −5°C temperature range usually involved in storage and transportation problems.

Figure 6a, b shows dimensionless thermal response at the surface and center of a meat cut to the following temperature steps:

I) $T_i = -25°$ C, $T_a = -5°$ C
II) $T_i = -15°$ C, $T_a = -5°$ C
III) $T_i = -20°$ C, $T_a = -10°$ C

and for $1 < Bi_o < 15$

The Bi_o range was established on the basis of the values normally adopted by the heat transfer coefficient, h, during storage in freezing chambers or under loading and unloading conditions of the meat. (Fleming 1974).

Figure 7 shows a comparison of thermal responses obtained in unidirectional heat transfer experiments and those predicted by the numerical solution. The numerical solution predicts actual behaviour with a small margin of error. The maximum error noted for the different experiments was equal to 3.8% calculated as the absolute value of the percentage difference between experimental and estimated temperature with respect to the total temperature change.

Analytical Solution

The analytical solution was used to predict the time required to reach certain temperatures at critical points of the system (for example, the surface of the meat).

In the case of unidirectional heat transfer the estimated times to reach given thermal levels were compared with actual experimental times, (Table 1) wherein t-5, t-10, etc., indicate the time required for the surface of the meat piece to reach −5°C, −10°C, respectively.

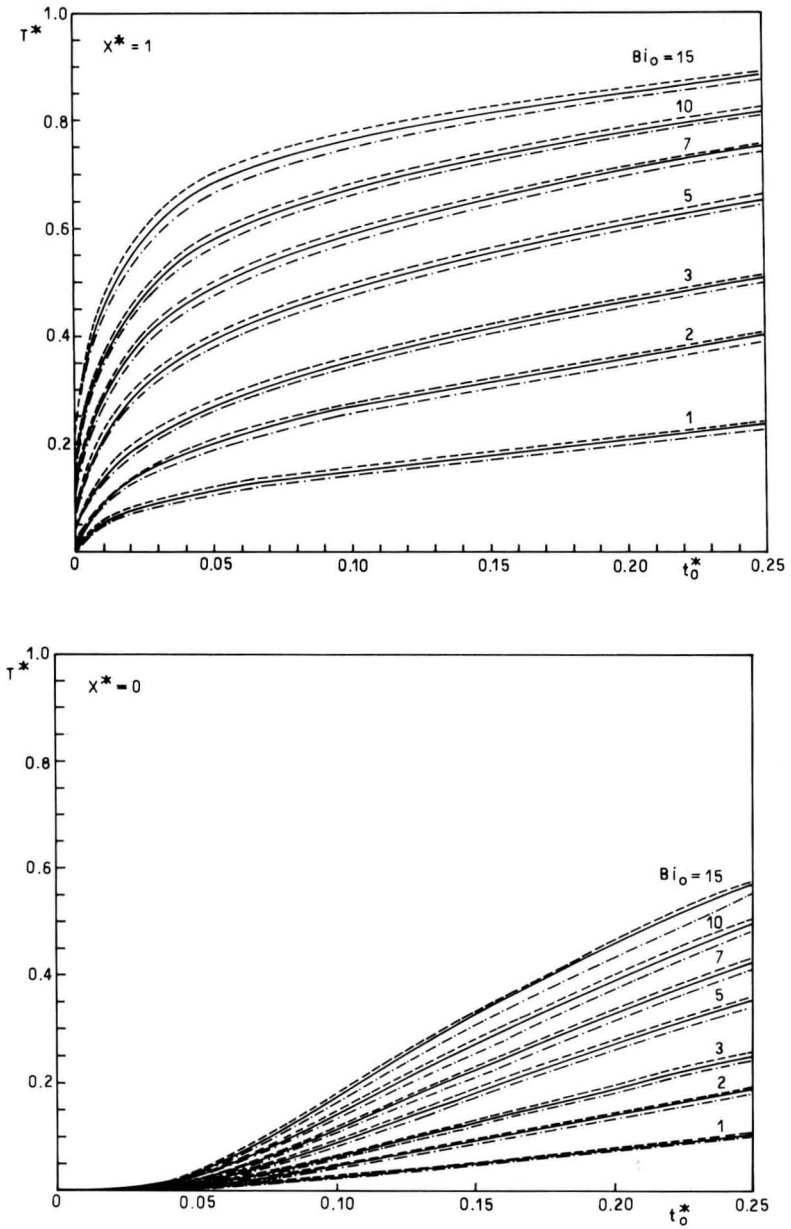

FIG. 6. THERMAL RESPONSE OF A BEEF PIECE TO STEP SIGNALS(a) BORDER (b) CENTER (Numerical solution).

—— $T_i = -25°$ C, $T_a = -5°$ C

—— $T_i = -20°$ C, $T_a = -10°$ C

–.–. $T_i = -15°$ C, $T_a = -5°$ C

Table 1. Unidirectional heat transfer. Comparison of the experimental response times and those predicted by the analytical solution for the border of meat pieces under thermal step functions

h W/m²°K	L (m)	T_i (°C)	T_a (°C)	Experimental Times (min)	Analytical Solution				Error | e | %
					$\bar{\alpha} \times 10^{-7}$ (m²/s)	$\bar{k}$ (W/m°K)	Bi	Estimated Times (min)	
90.28	0.65	−18.5	−5.0	t − 10 = 43.0	4.64	1.55	3.80	39.2	8.8
				t − 8 = 69.0	4.25	1.52	3.85	66.5	3.6
	0.94	−27.0	1.0	t − 10 = 17.0	5.32	1.58	5.37	15.8	7.05
				t − 5 = 58.2	4.19	1.50	5.64	62.4	7.21
	0.53	−33.5	20.0	t − 10 = 8.0	5.46	1.59	3.01	7.3	8.7
				t − 5 = 20.0	4.80	1.52	3.15	18.2	9.0
36.40	0.94	−31.0	−4.0	t − 20 = 21.5	6.87	1.65	2.07	24.0	11.6
				t − 15 = 53.4	6.37	1.63	2.10	55.0	2.9
	0.50	−31.0	−3.0	t − 20 = 18.0	6.87	1.65	1.11	16.5	8.3
				t − 15 = 33.0	6.37	1.63	1.18	30.2	8.4
	0.54	−26.5	4.8	t − 10 = 37.1	5.29	1.58	1.24	36.7	1.1
				t − 5 = 86.5	4.16	1.50	1.29	90.9	5.0
	0.50	−29	17.0	t − 10 = 14.5	5.44	1.59	1.14	16.0	10.3
				t − 5 = 37.5	4.31	1.51	1.20	38.7	3.1
24.11	0.76	−32.0	−4.5	t − 20 = 45.6	6.91	1.66	1.10	48.1	6.1
				t − 15 = 85.0	6.41	1.64	1.12	87.5	2.9
	0.56	−31.0	−3.0	t − 20 = 32.2	6.87	1.65	0.82	29.6	8.0
				t − 15 = 48.4	6.37	1.63	0.74	53.0	9.5
	0.53	−26.5	4.8	t − 10 = 51.3	5.29	1.58	0.81	55.3	7.8
				t − 5 = 95.8	4.16	1.50	0.85	105.2	9.8
	0.53	−29	19.0	t − 10 = 28.0	5.44	1.59	0.80	30.1	7.5
				t − 5 = 61.5	4.31	1.51	0.84	62.0	0.8

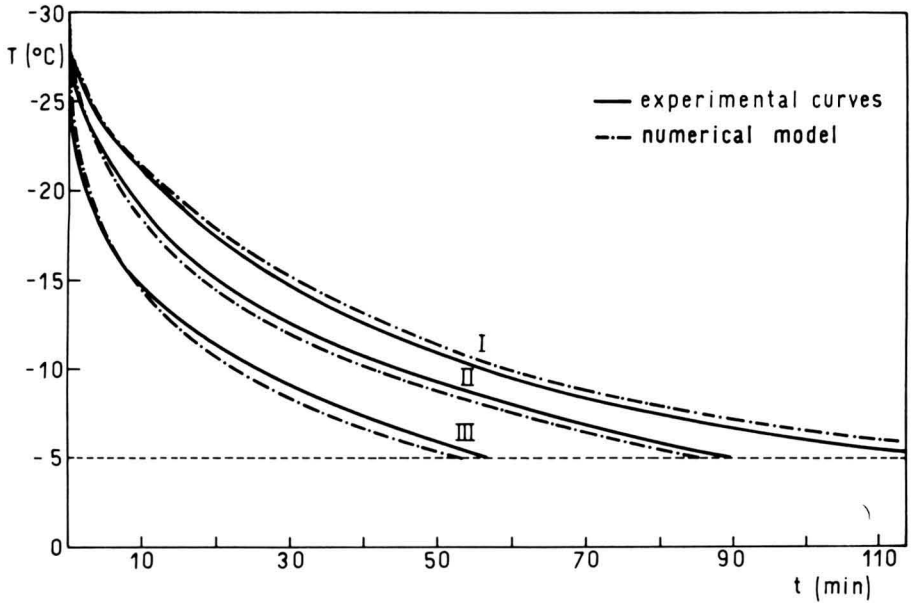

FIG. 7. COMPARISON OF THE EXPERIMENTAL UNIDIRECTIONAL THERMAL RESPONSES TO STEP SIGNALS FOR THE SURFACE OF A MEAT PIECE AND THOSE PREDICTED BY THE NUMERICAL MODEL
$T_i = -26.5°$ C, $T_a = 4.8°$ C
I: $L = 0.53$ m, $h = 24.11$ W/m²°C
II: $L = 0.54$ m, $h = 36.50$ W/m²°C
III: $L = 0.50$ m, $h = 64.87$ W/m²°C

To use analytical solutions it was necessary to determine the most suitable mean values of the physical properties (α and k of frozen beef) involved in the calculation of the Bi and t^*. Comparison of the predicted values and experimental data led to the conclusion that the average values of the properties in the $-30°$C to $-5°$C temperature range, give good results and have the advantage of being simple to calculate. In the case of one-dimensional heat transfer, where the heat flow was kept parallel to the muscle fibres, the data for k_l and α_l (longitudinal) were used. The mean value of the relative errors in estimations taken as absolute value was 6.7%.

Table 2 presents the results obtained in three-dimensional heat transfer experiments. In each case, the initial temperature of the meat (T_i), the ambient temperature (T_a), and the total heat transfer coefficient U, which includes the thermal resistance of the acrylic and that of the environment (water or air), are indicated.

The experimental results of the time required to reach temperatures of $-10°$C and $-5°$C at certain defined points of the system and of the

Table 2. Three-dimensional heat transfer. Thermal response to step functions

T_i (°C)	−23.1		−18.0		−30.0	
T_a (°C)	5.0		23.5		5.6	
U (W/m²°K)	69.0		23.4		66.0	
	Exp.	Analytical Solution	Exp.	Analytical Solution	Exp.	Analytical Solution
t − 10 in A (min)	9.0	8.3	11.5	9.7	13.1	12.9
t − 5 in A (min)	31.3	33.8	28.7	28.0	36.2	39.0
t − 5 in B (min)	5.9	5.0	10.0	7.2	6.9	5.8
Temp in C at t − 10 in A (°C)	−18.8	−18.2	−14.9	−15.3	−18.5	−18.7
Temp in C at t − 5 in B (°C)	−21.5	−22.0	−16.5	−16.8	−24.0	−25.4

temperatures recorded in the geometric center of the system at given times are presented.

The center of the face is designated as A, B represents the vertex and C the geometrical center of the system. Thus, for example, t-5 in A represents the time required for the center of the face to reach −5°C, while Temp_C at t-5 in A indicates the temperature at the geomtrical center of the system when point A reached −5°C.

The experimental results correspond to the average measurements at equivalent points of the system. Predicted values were obtained using average properties evaluated both, parallel and perpendicular to the fibres for the temperature range under analysis.

It is observed that the analytical solution can be used to predict the thermal evolution of the system in the case of three-dimensional heat transfer; the largest errors are recorded for short periods of time and in general are by defect, since in the actual system, heat insulation has a finite specific heat which is not contemplated in the mathematical model.

Response to Sinusoidal Signal

The response of the system to sinusoidal ambient temperature changes was simulated with the numerical model.

Figure 8a, b represents, in terms of

$$T^* = \frac{T - T_M}{A} \text{ versus } t_o^* = \alpha_o t/L^2,$$

the temperature at the surface and center of a cut of frozen meat of semi-thickness L=0.1 m and under different thermal insulation conditions represented by the values of Bi_o, under a sinusoidal ambient temperature variation of $T_M = -18°$ C, $A = 5°$ C and a period of fluctuation $P = 6$ h ($\Omega = 2.9\ 10^{-4}\ s^{-1}$).

It is observed that the surface of the meat responds practically without delay to the ambient temperature fluctuation and with the same frequency, and that the amplitude ratio increases with Bi_o.

The center shows a delay with respect to the external signal, which causes a phase lag, but maintaining the same fluctuation frequency. The temperature oscillation is noticeably attenuated, showing a similar variation with Bi_o as that recorded for the surface.

Results obtained from the numerical solution were compared with those obtained by applying the analytical solution to the same system, as show in Table 3.

In the columns corresponding to the numerical solution, the results of R_a and ϕ at the surface and center of the meat for different values of $Bi_o = hL/k_o$, are presented in accordance with the curves of Fig. 8a, b.

In order to apply the analytical solution the values of θ and $Bi = hL/\bar{k}$ were determined. In the described system, the temperature fluctuates within the range: $-23°C \leq T \leq -13°C$.

Thus:

$$\bar{k} = 1.58 \text{ W/m° K}; \bar{\alpha} = 5.63\ 10^{-7}\ m^2/s; \theta = \frac{\Omega L^2}{2\alpha} = 1.606$$

and the ratio of $Bi_o/Bi = \bar{k}/k_o = 3.14$

With these values, and using Fig. 3 and 4, analytical results were obtained.

The satisfactory agreement between both solutions, remarks the usefulness of the analytical solution to interpret the thermal responses to fluctuations in temperature.

By using this solution it is possible to make a comparative analysis of the influence of Bi and the frequency of ambient temperature fluctuations in the thermal response of the system.

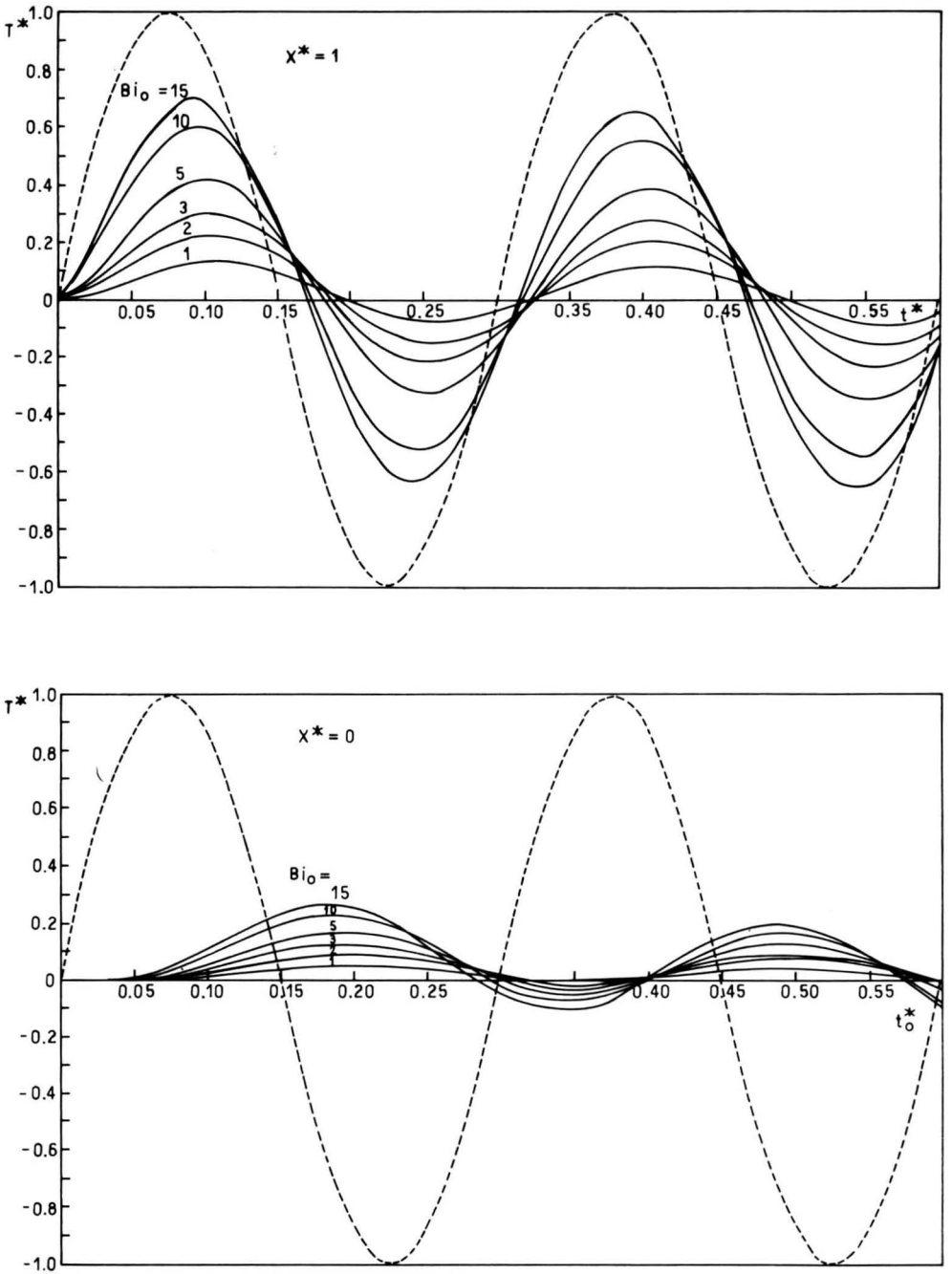

FIG. 8. THERMAL RESPONSE OF A MEAT SLAB TO SINUSOIDAL AMBIENT TEMPERATURE CHANGES(numerical solution)
$L = 0.1$ m, $T_M = -18°$ C, $A = 5°$ C, $\Omega = 2.9\ 10^{-4}\ s^{-1}$ (a) border (b) center

Table 3. Thermal response to sinusoidal signals: Analysis of the amplitude ratio (R_a) and phase lag (ϕ) according to the numerical and analytical solution for a frozen meat piece ($L = 0.1$ m) exposed to a thermal oscillation ($T_M = -18°$ C, $A = 5°$ C, $\Omega = 2.9\ 10^{-4}$ seg^{-1}) under different insulation conditions

Numerical Solution					Analytical Solution				
$Bi_o = hL/k_o$	Border		Center		$Bi = hL/\bar{k}$	Border		Center	
	R_a	$(-\phi)$	R_a	$(-\phi)$		R_a	$(-\phi)$	R_a	$(-\phi)$
1	0.12	0.71	0.05	2.60	0.32	0.13	0.71	0.06	2.45
2	0.21	0.63	0.09	2.48	0.64	0.22	0.64	0.08	2.35
3	0.28	0.58	0.12	2.35	0.96	0.30	0.58	0.13	2.30
5	0.40	0.50	0.17	2.30	1.59	0.43	0.50	0.17	2.25
10	0.58	0.37	0.23	2.12	3.18	0.63	0.31	0.23	2.10
15	0.68	0.29	0.26	2.09	4.77	0.70	0.25	0.29	1.95

Table 4. Response to a sinusoidal signal: influence of the oscillation frequency and the Biot number on the amplitude ratio and phase lag

	$P = 6$ h $\quad \theta = 1.606$				$P = 12$ h $\quad \theta = 1.13$			
	Border		Center		Border		Center	
$Bi = hL/\bar{k}$	5	0.5	5	0.5	5	0.5	5	0.5
Amplitude ratio R_a	0.7	0.19	0.32	0.09	0.8	0.25	0.64	0.18
Thermal fluctuation (°C)	± 3.5	± 0.95	± 1.6	± 0.45	± 4.0	± 1.25	± 3.2	± 0.9
$-\phi$ (rad.)	0.25	0.7	1.8	2.2	0.23	0.75	1.35	1.7
Phase lag (min.)	15	40	102	126	26	86	155	195

Table 4 presents values of R_a and ϕ, corresponding to the simulation of a meat cut of $L = 0.1$ m under temperature fluctuations around $T_M = -18°$ C, with $A = 5°$C and a fluctuation period of 6 and 12 h leading to values of $\theta = 1.606$ and $\theta = 1.13$ respectively, and under two different thermal insulation conditions corresponding to $h = 79.42$ W/m^2°K and $h = 7.942$ W/m^2°K which produce values of $Bi = 5$ and $Bi = 0.5$ respectively.

It is observed that the reduction of the Biot number causes a reduction in the amplitude ratio and an increase in the phase lag, while a long fluctuation period causes larger temperature fluctuations capable of greatly affecting the quality of the product, especially when the temperature is above $-10°$C.

The influence of an increase in the size of meat cuts L is reflected simultaneously in the proportional increase of the Biot number and the quadratic growth of the natural frequency θ. Both effects superimposed lead to a reduction in the amplitude ratio R_a, since the influence of the increase of θ through L is more pronounced than the increase of the Biot number.

NOTATION

A = amplitude of the thermal oscillation, °C
A_o, A_l = modulus of the vectors defined in Eqs. (18), (19)
Bi = Biot number in the analytical solution ($Bi = hL/\bar{k}$)
Bi_o = Biot number in the numerical solution ($Bi_o = hL/k_o$)
C_p = specific heat of beef, J/Kg°K
D = moles of solute/Kg of dry substance
e_a = thickness of acrylic slabs, m
h = heat transfer coefficient, W/m^2°K
k = thermal conductivity of beef, W/m°K
L = semi-thickness of the beef sample, m
L_f = heat of fusion for ice, J/Kg
P = period of the thermal oscillation, s
R = gas constant, 8.314 J/mole°K
R_a = amplitude ratio
t = time, s
T = temperature °C
T_a = ambient temperature °C
T_K = absolute temperature °K
T_M = mean temperature of the oscillation °C
T_o = freezing point of pure water °K

U = total heat transfer coefficient, $W/m^2°K$
x = space coordinate
x_B = initial content of water on a dry basis, Kg of bounded water/Kg of dry substance
x_o = initial water content on a dry basis, Kg of water/Kg of dry substance
Y_o = moisture content of the meat, Kg of water/total Kg.

Greek letters

α = thermal diffusivity, m^2/s
θ = natural frequency of the oscillation
ρ = beef density, Kg/m^3
ϕ = phase lag in Eq. (22)
ϕ_o, ϕ_l = phase of the vectors defined in Eqs. (18), (19)
ω = fraction of frozen water
Ω = frequency of the thermal oscillation, s^{-1}

Subscripts

a = acrylic
h = ice
i = initial value
l = parallel to beef fibres
t = perpendicular to beef fibres
w = water
o = non frozen beef

Superscripts

$*$ = dimensionless value
$\bar{}$ = mean value

REFERENCES

AWAD, A., POWRIE, W.D. and FENNEMA, O.R. 1968. Chemical Deterioration of Frozen Bovine Muscle at −4°C. J. Food Sci. *33*, 227-234.

CARSLAW, H.S. and JAEGER, J.C. 1959. Conduction of Heat in Solids pp. 119-127. Oxford University Press.

CHRYSTALL, B.B. 1972. Influence of Storage Temperature on Quality of Frozen Meat. MIRINZ Publication N°274. Meat Industry Research Institute of New Zealand.

FLEMING, A.K. 1974. The New Zealand Approach to Meat Freezing in the Meat Freezing Why and How. 24.1-24.11. Meat Research Institute Symposium N°3. Langford. Bristol.

HAUGHEY, D.P. and MARER, J.M. 1971. The Softening of Frozen Meat. Criteria for Transportation in Insulated Containers without Refrigeration. J. Food Technol. *6* (2) 119-130.

KHAN, A.W., VAN DER BERG, L. and LENTZ, C.P. 1963. Effects of Frozen Storage on Chicken Muscle. J. Food Sci. *28*, 425-430.

LENTZ, C.P. 1961. Thermal Conductivity of Meat, Fats, Gelatin Gels and Ice. Food Technol. *15*, 243-247.

MALTON, R. 1974. Recent observations on the Commercial Handling and Transport of Frozen Meat. In *Meat Freezing. Why and How?* 37.1-37.15. Meat Research Institute Symposium N°3, Langford. Bristol.

MASCHERONI, R.H. and CALVELO, A. 1978. Modelo de Descenso Crioscópico en Tejidos Cárneos. La Alimentación Latinoamericana. *111*, 34-42.

MASCHERONI, R.H., OTTINO, J. and CALVELO, A. 1977. A Model for the Thermal Conductivity of Frozen Meat. Meat Science *1* (4) 235-243.

MILLER, H.L. and SUNDERLAND, J.E. 1963. Thermal Conductivity of Beef. Food Technol. *17*, 490-492.

RIEDEL, L. 1957. Kalorimetrische Untersuchungen über das Gefrieren von Fleisch. Kaltetechnik *9*, 38-40.

SINGH, R. and WANG, C.Y. 1977. Quality of Frozen Foods. A review. J. Food Pro. Eng. *1*, 97-127.

SY, S.H. and FENNEMA, O.R. 1973. Rates of Recrystallization in Beef Liver Tissue. In *Proceedings of the International Congress of Refrigeration.* 13th Washington *3*, 199-204.

VAN ARSDEL, W.B., COPLEY, M.J. and OLSON, R.L. 1969. Quality and Stability of Frozen Foods. Time-Temperature-Tolerance and its Significance. Wiley Interscience.

VON ROSENBERG, D. 1969. Methods for the Numerical Solution of Partial Differential Equations. Modern Analytical and Computational Methods in Science and Mathematics N°16. New York. American Elsevier.

GENERAL AND KINETIC ASPECTS OF PRE-RINSE AND CLEANING OF A MILK STORAGE TANK

JEAN-PIERRE TISSIER, GEORGE CORRIEU and MARC LALANDE

INRA—Laboratoire de Genie Industriel Alimentaire
Villeneuve d'Ascq (France)

Received for Publication May 14, 1981
Accepted for Publication January 11, 1982

ABSTRACT

With the aim of studying pre-rinsing and cleaning of a milk storage tank, different representative samples are collected during the process and their components (protein, sugar and lipid) analysed. The main conclusions of this study may be summarized as follows: (1) The mean thickness of milk remaining in the tank ranges around 20 μm. It depends on the dropping time and on the possible presence of milk foam. (2) The different main milk components do not exhibit the same removal rate and sugar seems to be completely removable by rinsing only. (3) Pre-rinsing may be characterized by four periods of which one depends on a diffusion mechanism. (4) Pre-rinse is a very rapid process which mainly depends on the pre-rinse solution volume used per unit of soiled surface. (5) Hard water, osmosed water alone or admixed with a surface active agent or caustic soda (1%) lead to the same results.

INTRODUCTION

Many studies were devoted to rinsing and cleaning of food processing equipments 25 years ago, during the setting up of Cleaning-In-Place Systems. The industrial daily utilization of such equipments might suggest that these processes are very well known and controlled. In fact, fundamental knowledge of their kinetics and mechanisms is very poor.

Most scientific research made on cleaning has been based on an empirical approach. This is the case of storage tanks which cannot be filled up with cleaning solution but are treated by spraying and creating a falling film of cleaning solution on the surface. In that case, some authors recommended particular working conditions. This is the case of Radler (1976) who recommended a volumetric flow rate per unit of wetted perimeter ranging from 1.5 to 2.1 m^2/h. Buchwald (1974) considered that a Reynolds number of the falling film between 1600 and 2400 is optimal.

Journal of Food Process Engineering 6 (1982) 37-53.

Contrary to this specific study, the works of Loncin (1977) and Thor and Loncin (1978) about final rinsing of a tubing and a heat plate exchanger are very interesting. This team developed a mathematical model involving the working conditions and were able to predict the duration of the operation according to the desired final rinsing conditions.

According to their results, the rinsing kinetics can be divided into three phases. Until the minimum residence time, the concentration remains constant and equal to the initial concentration Co. In a second phase, a fast exponential decay is observed. The influence of the tracer substance can be seen only in the third phase during which the exponential decay gets slower. This way of studying is well adapted to an optimization of final rinsing. We attempted to use such a method for studying cleaning of storage tanks. In our opinion, such an approach has not been made before.

MATERIAL AND METHODS

Description of the Experimental Equipment

The experimental equipment presented in Fig. 1 was composed of: (1) A 2.6 m^3 stainless steel (Z6 CN 18-10) cylindro conical storage tank whose inside wall is polished (grain 220). (2) A Cleaning-In-Place System including 2 tanks (W1 and RS). (3) A cleaning ball spraying the cleaning solution on the upper part of the tank in such a way that a falling film flows on the soiled surfaces. Rinsing and cleaning depend only on the falling film effect. (4) A sampling device merely fed by gravity is placed at the outlet of the tank. It is composed of a high speed sampler, a container (W2) collecting the soiled effluent and a three-way valve (V2) directing the solution into the (W2) container or into the (RS) tank for recirculation. The high speed sampler provides 60 samples of about 100 ml for 90 s. The collection frequency which changes every 30 s is: one sample every second, one sample every second and a half, one sample every three seconds. Rinsing and cleaning steps and the onset of sampling were controlled by a microcomputer.

Experimental Cleaning Procedure

The experimental tank was filled with raw bulk milk pasteurized in our experimental unit the day before. This milk contains about 125g DM/liter, 36g fat/liter and 36g protein/liter. Its pH value ranges around 6.6. The procedure of each trial may be summarized as follows: (1) *Draining and Dropping of the Milk.* After several hours of storage

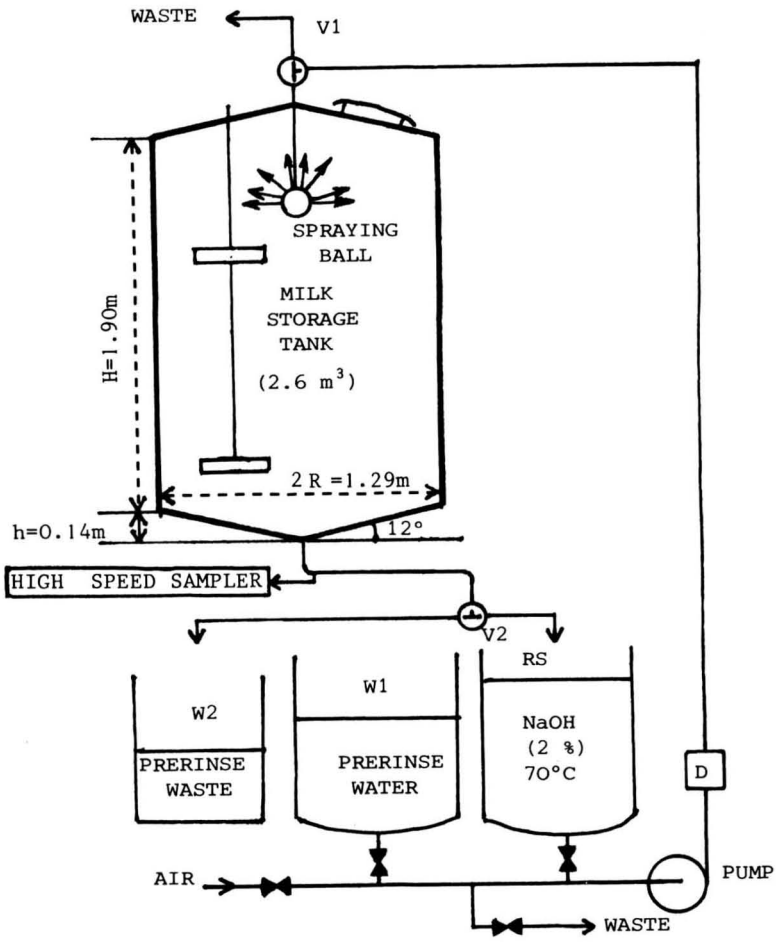

FIG. 1. SCHEMATIC REPRESENTATION OF THE PLATFORM
(D = Diaphram, V1 and V2 = 3 way valves)

at 4°C, the milk was drained (for about 8 min) and the tank was allowed to drop. Generally, no foam remained inside the tank after draining. Yet, a diffuse creamy trail could be shown on the virole and the agitator axis. (2) *Pre-rinsing.* After the upper pipes were rinsed with the water solution the switching of the three-way valve (V1) allowed to feed the spraying ball; simultaneously the sampler was started. The water-milk mixture leaving the tank was distributed between the sampler (about 10% of the total volume) and the container (W2). Measurement of the total volume of rinsing solution allowed to determine the experimental flow-rate. For standard trials, a 90 s pre-

rinsing was made 27 min after the beginning of dropping, by reverse osmosis water at ambient temperature and a flow rate of 5.5 m^3/h. (3) *Caustic Soda Cleaning.* To remove the soil remaining in the tank after pre-rinsing cleaning was performed for 10 min by recirculation of 50 liters of a caustic soda solution (2%, 70°C). Final rinsing and disinfection by means of cold sodium hypochoride represented the final steps of the procedure.

Analytical Methods

The main component of the samples obtained by automatic collection or from different containers were analysed according to Dreywood (1946) for total reducing sugars, Lowry *et al.* (1951) for proteins and Heinemann and Rohr (1950) for lipids. Absorbance measurement at 600 nm was also made because Ashworth (1951) showed that turbidity of the milk solution is closely related to the particle size distribution and total fat concentration. We first determined the correlation between the 600 nm absorbance $(C/Co)_{A600}$ and the lipid analysis $(C/Co)_L$ for 71 effluent analyses from 4 trials in a range area of $(C/Co) < 6 \times 10^{-2}$.

$$(C/Co)_L = 0.82\,(C/Co)_{A600} + 5 \times 10^{-5} \qquad (r = 0{,}993)$$

The constant value, 5×10^{-5}, ranged around the absolute error of the accuracy of the analyses in the concentration area used.

As kinetics was presented in a logarithmic form to calculate the reaction rate constant, we also determined the logarithmic correlation for the 51 data ranging between $(C/Co = 5 \times 10^{-5})$ and $(C/Co = 2 \times 10^{-1})$

$$\log_{10}(C/Co)_L = 0.931 \log_{10}(C/Co)_{A600} - 0.255 \qquad (r = 0{,}985)$$

As the two analyses led to similar results, we gave up the lipid analysis which is long and tedious and the automatic absorbance analysis was then used to study the behaviour of milk fat components.

In additional trials, corresponding to final rinsing, we used a conductimeter in order to study the removal of a 2% caustic soda solution by distilled water.

All the results were expressed in dimensionless concentration (C/Co) which corresponds to the ratio of the concentration of main soil components in the effluent to the concentration of main components in the tank milk.

Mode of Expression of the Results, Definitions

Overall analysis of the Phenomena. From the analysis (absorbance, protein and sugar) made on the samples from W2 and RS containers, we determined the composition and the quantity of different soil types.

We called *total soil* the soil remaining on the tank surface after draining and dropping. This soil which was supposed to be completely removed during the cleaning process, corresponds to the sum of the soil removed by pre-rinsing and that subsequently removed only by soda cleaning.

The tank being unequally filled, the soiled surface is indicated and the results are presented as soil quantity in milk equivalent (obtained by analysis of each main component) per unit of soiled surface (ml/m^2), which corresponds to an equivalent milk film thickness in micrometres. However, this expression does not allow to distinguish between the vertical wall tank and the lower cone which may represent between 15 and 25% of the total soiled surface, according to cases.

Kinetics, Flow-rate Influence, Modeling. Beside the unsteady conditions of the initial phase, the flow-rate of effluent leaving the tank is equal to the ball feeding flow-rate. Soil removal kinetics can therefore be merely studied by analysis of concentration of the different soil components leaving the tank.

The mode of falling film flow is characterized by the Reynolds number (Re) which depends on the ball feeding rate (Q), the tank perimeter ($2\pi R$) and the kinematic viscosity of the solution (ν). To characterize falling film, we used the liquid flow-rate per unit wetted perimeter ($Q/2\pi R$).

$$\mathrm{Re} = 4\left(\frac{Q}{2\pi R}\right)/\nu \tag{1}$$

Weighing of the collected samples allowed to determine the zero time of the kinetics in such a way that the waste volume (V) became proportional to the kinetic time.

$$V = Qt \tag{2}$$

As pre-rinse kinetics is complex, we studied its reproducibility point by point determining some time dependent parameters (i.e. the waste volume used per soiled surface unit).

For stages which can be fitted by a first order reaction, we also determined the reaction rate constant (per second) as defined by the slope (K) of the naperian semi logarithmic plot of the soil concentration (Fig. 2).

We determined an empirical kinetic modeling (3) relating the naperian logarithm of the relative concentration of soil in the effluent and the volume of solution used per soiled surface unit (V/S); the real soiled surface (S) being calculated for each trial.

$$f[\log(\mathrm{C/Co}), (V/S)] = 0 \tag{3}$$

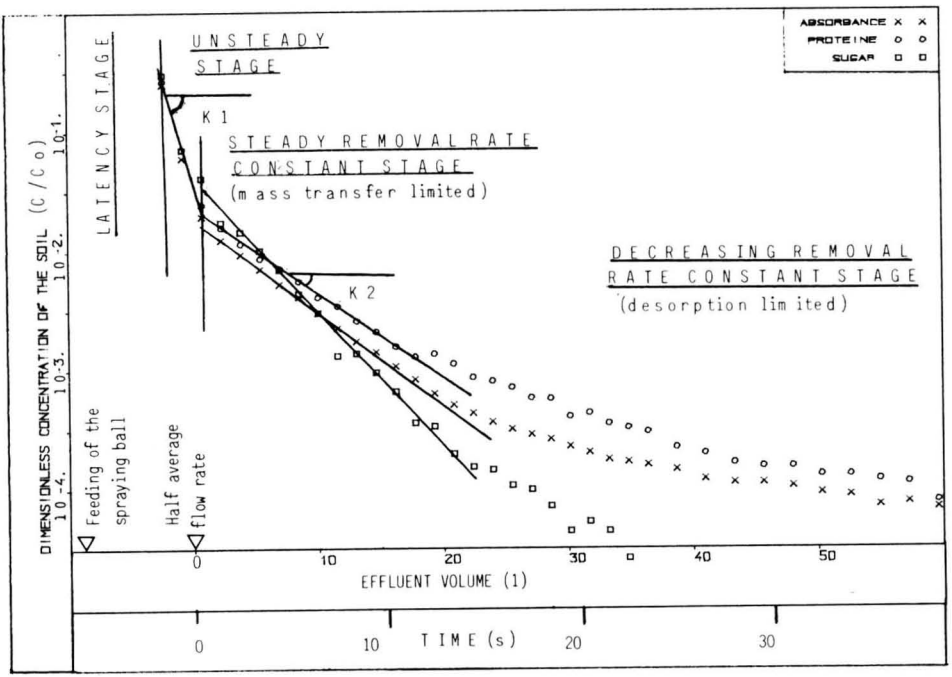

FIG. 2. VARIATION IN THE DIMENSIONLESS CONCENTRATION OF SOIL IN THE EFFLUENT DURING PRE-RINSE OF A TYPICAL STANDARD TRIAL

For cylindro conical tanks the wall surface can be calculated from the height of the lower cone (h), and the soiled surface height of the virole (H).

$$S = 2\pi R\left(H + \frac{1}{2}\sqrt{h^2 + R^2}\right) \tag{4}$$

From these different relations (1, 2, 3 and 4), we may determine the pre-rinse time ($t1$) according to falling-film characteristics (Re, ν), tank geometry (h, H, R) and the soil concentration in the effluent $(C/Co)_1$. Subsequent experiments have to be made to determine whether the results can be extrapolated to different tanks.

$$t1 = \frac{S}{Q} f[(C/Co)_1] = \frac{4\left(H + \frac{1}{2}\sqrt{h^2 + R^2}\right)}{\nu \, \mathrm{Re}} f[(C/Co)_1] \tag{5}$$

Experimental schedule

Primarily, we studied the reproducibility of the overall soil removed and its kinetics by means of seven standard trials: (1) Total soil and soil removed only by soda cleaning were estimated. Some factors affecting

the total amount of soil present on the tank surface before cleaning were evidenced. (2). The pre-rinsing kinetics was divided into different characteristic stages and a mechanistic approach suggested.

Then the flow rate influence was studied using the standard conditions but with a flow rate (Q) ranging from 2.55 m^3/h to 8.15 m^3/h. The flow rate exceeding 8.5 m^3/h could not have be analysed because the tank failed to drain rapidly enough and the samples were not representative.

Thereafter we studied the influence of pre-rinse solution composition on the kinetics in the same conditions as those of the standard trials, but with reverse osmosis water together with caustic soda (1%) or surface active agent[1] (0.06, 0.18 and 0.25%). These surface active agent concentrations were at least equal to the critical micelle concentration in the solution. The corresponding surface tension was about 35 dynes/cm, i.e. lower than the milk surface tension (44 dynes/cm). We also used very hard non treated water (about 400 mg/liter equivalent $CaCO_3$).

RESULTS AND DISCUSSION

The results from the seven standard trials presented in Table 1 concern soil removed only by soda cleaning and total soil. These results may be summarized as follows: (1) The total soil thicknesses calculated

Table 1. Milk equivalent soil thickness removable from the tank by pre-rinsing and soda cleaning, and only by soda cleaning. Determination from main milk component analysis: protein (P) sugar (S) and absorbance determined components (A)

	Soiled Surface (m^2)	Soil Thickness (μm) Removed By					
		Rinsing and Soda Cleaning			Only Soda Cleaning		
		A	P	S	A	P	S
1	9.01	15.6	21.6	18.0	2.6	1.0	0
2	8.98	16.4	20.3	17.6	0.6	3.1	0
3	8.61	20.7	19.0	20.8	1.0	1.8	0
4	8.29	15.1	15.6	15.6	2.6	1.0	0
5	7.76	13.7	14.5	15.2	0.7	0.6	0
6	7.76	16.1	17.8	18.6	1.1	1.5	0
7	7.76	14.3	16.9	12.2	0.6	1.1	0
AV	8.31	15.98	17.96	16.86	1.31	1.44	0
SD	0.57	2.89	2.53	2.78	0.90	0.83	

AV : Average – SD : Standard deviation

[1] (Additive for caustic cleaning solution manufactured by SOPURA (BELGIUM))

from the different analyses were not statistically different. Accordingly, total soil roughly correspond to the milk initially present in the tank. (2) The corresponding milk film thickness was small (17 ml/m^2). It represented less than 1/10,000 of the initial milk contained in the tank. It depended on the dropping time. When this dropping only lasted 2 to 5 min, the mean film thickness slightly increased (20 to 24 ml/m^2). If the dropping time exceeded 1 h, the thickness decreased to about 10 to 12 ml/m^2. These results are in agreement with those of Schlüssler (1980) concerning the pellicular water thickness on different surfaces according to dropping time. However, we have to mention that the mean soil film thickness also depends on foam remaining in the tank. This foam is formed during milk transfer or by air-milk interface stirring. Some of the milk foam not removed during tank draining is still present and contributes to increasing the soil remaining in the tank. In some trials we determined milk film thickness of 30 to 40 ml/m^2 soiled tank surface even after a standard draining and dropping time. The presence of foam traces or of a more or less large creamy trail may account for the film thickness variability in the standard trials (Table 1). (3) The different milk components were not removed in the same way. Thus, all lactose was removed during pre-rinsing and no lactose traces were found in the soda cleaning solution.

On the contrary, soda cleaning still removed a milk equivalent thickness of about 1.4 ml/m^2 for protein and lipid like components determined by absorbance. These results seem to be in good agreement with those of Hierath *et al.* (1974) who using the Oxygen-Chemical-Demand analysis found that after pre-rinse, detergent cleaning can still remove about 1.5 ml/m^2 of milk soil from a milk storage tank.

Irrespective of any kinetic consideration, pre-rinsing appears to be very rapid. Thus a mean pre-rinsing time of 30 s (variation coefficient of 12%) was able to dilute over 10^4 all the soil components in the effluent.

Kinetic Study of Pre-rinsing

The semi-logarithmic plot of the main milk components expressed in dimensionless concentration in the effluent as a function of time is presented in Fig. 2 for a typical standard trial. Considering the overall kinetics, it appeared that the removing rate of each component decreased according to time. However we attempted to divide the kinetics into four specific periods:

Stage zero: A latency stage occurred for about 5 s between the V1 valve switching and the outflow of the effluent from the tank. This stage depended on the design of the equipment and was not of any particular interest.

First stage: Then, during the end of the building-up of the falling film of rinse solution on the walls of the tank, the instantaneous effluent flow-rate increased rapidly for 2 to 3 s before it reached its nominal value. This unsteady stage was too short to allow a precise study, but corresponded to the removal of about 30% of total soil.

It may however by noticed that the different main milk components were not separated during this stage. The slope line (K1) drawn from the first two experimental points of each of the seven standard trials was equal to 1.2 s^{-1} with a variation coefficient of 14%. This stage seemed to correspond to a first order model with a constant rate equal to K1. We assume that during this unsteady stage the falling film and a part of the milk film was mixed together.

Thereafter, the various main milk components in the effluent behaved in different ways.

Second stage: For more than 10 s a first order kinetics whose removal rate constant depended on the milk component was observed. This stage involved a mass transfer mechanism limited by the nature of the component. Using the consideration of Loncin (1977), we assume that this stage is controlled by diffusion. As shown on Table 2, the milk equivalent concentration of 10^{-2} was reached during this stage, with 0.46 to 0.69 liter of solution per soiled surface square meter, according to the analyzed soil component in the effluent. The equivalent standard deviation calculated in time (0.4 to 0.75 s) corresponded to the range of accuracy of the zero time determination. In other respects, the removal

Table 2. Study of the reproducibility of diffusion stage for protein (P), sugar (S) and absorbance determined components (A) of the standard trials

		Soiled Removal Rate of The Diffusion Stage k2 (s^{-1})			Used Water Volume Per Unit Soiled Surface ($1/m^{-2}$) to Reach C/Co = 10^{-2}		
	Flow Rate (m^3/h)	A	P	S	A	P	S
1	5,57	0.272	0.253	0.397	0.38	0.52	0.60
2	5,70	0.283	0.226	0.388	0.41	0.48	0.62
3	5,53	0.298	0.313	0.384	0.70	0.62	0.80
4	5,54	0.306	0.260	0.429	0.57	0.60	0.75
5	5,53	0.332	0.285	0.497	0.50	0.42	0.70
6	5,46	0.289	0.275	0.419	0.38	0.45	0.74
7	6,09	0.320	0.290	0.434	0.27	0.27	0.62
AV		0.300	0.272	0.421	0.46	0.48	0.69
SD		0.021	0.028	0.039	0.14	0.12	0.08

AV : Average – SD : Standard deviation

rate constant depend on the analysed components. It was higher for sugar $k2_S = 0.42\ s^{-1}$) than for protein ($k2_p = 0.27\ s^{-1}$). That of the components determined by absorbance whose behaviour was similar to the fatty phase was located between the two former ($k2_A = 0.30\ s^{-1}$). The variation coefficient of the rate constant was about 10%. Thus, the reproducibility of this second stage was confirmed.

Third stage: The soil removal constant of the different components decreased gradually, but this did not seem to be so marked for sugar. For the seven standard trials, we calculated the pre-rinse effluent volume used per soiled surface unit to reach soil concentration threshold of 10^{-3} and 10^{-4}. These results are also shown in Table 3. It may be noticed that the variation coefficient of these volumes ranged around 7 and 16%, respectively. Therefore, the depletion stage was also reproducible even if it could not be so easily quantified.

Difference in the nature of the main milk components may partly account for the difference of behaviour of the last two stages if a hypothesis of diffusion mechanism is accepted. Reducing sugars analyzed in the effluent were only composed of lactose, a well defined chemical component whose diffusion coefficient is relatively high ($0.49 \times 10^{-9}\ m^2/s$ at 25°C) as mentioned by Schwartzberg *et al.* (1982). On the contrary, milk proteins are solublized in serum, but most of them (about 80%) are present in the form of nonuniform spheric micelles whose diffusion coefficient and removal rate constant are different and always lower than those of lactose. As mentioned by Schwartzberg *et al.* (1982) the diffusion coefficient of goat lactaglobulin at 25°C is $0.0748 \times 10^{-9}\ m^2/s$. The progressive lowering of the depletion rate constant of

Table 3. Study of the reproducibility of the depletion stage for protein (P), sugar (S) and absorbance determined components (A)

	Water Volume Per Unit Soiled Surface (l/m^2) to Reach					
	C/Co = 10^{-3}			C/Co = 10^{-4}		
	A	P	S	A	P	S
1	1.82	2.31	1.59	5.27	6.30	2.91
2	1.85	2.20	1.60	3.30	4.83	2.66
3	2.12	2.51	1.85	4.64	5.40	3.49
4	1.90	2.26	1.75	4.00	5.09	2.86
5	1.86	2.11	1.56	3.66	5.08	2.65
6	1.98	2.24	1.74	4.13	5.88	3.38
7	1.89	2.01	1.77	4.77	5.96	3.43
AV	1.92	2.23	1.69	4.25	5.51	3.05
SD	0.10	0.16	0.11	0.68	0.55	0.37

AV : Average – SD : Standard deviation

the proteins can be explained by the progressive depletion of the more movable protein components. The same argument may explain the depletion stage of the lipid components. However, we have to notice that the diameter of the fat globules is larger (generally 2 to 12 μm) than that of protein micelles (0.1 μm average diameter). Their diffusion coefficient and their removal rate constant should be lower.

Another observation should be pointed out. During final removal of soda by water, the kinetics resembles that of lactose during pre-rinsing; but the removal rate constant of soda is still higher k2 = 1.3 s^{-1}). Calculated from the Nerst equation according to Perry and Chilton (1973) the diffusion coefficient of NaOH is higher (2.13 10^{-9} m^2/s at 25°C) than that of lactose. However both lactose and NaOH are highly soluble whereas fat and casein are insoluble in water. Thus, their behaviour may be different. For instance, the fat globules and protein micelles being electrically charged they may be attached to the metal surface of the tank.

Accordingly, other mechanisms are involved simultaneously, the depletion stage can also be partly explained by a desorption limited mechanism and (or) by the influence of some parameters bound to tank features (lower cone, agitation device...). Nevertheless, we must admit that our system is not well adapted to an accurate study of cleaning mechanisms. We therefore rather attempted to find an empirical approach of the pre-rinse kinetics of the tank.

Influence of Different Parameters on Pre-rinsing Kinetics

Flow Rate Influence. The latency stage time decreased when the flow rate increased. Likewise, the soil removal rate constant of the unsteady stage (K1) increased from 0.7 to 2.9 s^{-1}. The rate constant (K2) of the soil removal diffusion stage also increased, as shown in Fig. 3. The experimental results show a rather substantial dispersion. Thus, for 15 experimental trials, the regression coefficient (r) of the linear relation between this rate constant and the flow rate was equal to 0.83 for absorbance determined components, 0.84 for protein and 0.89 for sugar. Another presentation of the relation (for example $K2 = a\ Q^b$) did not improve the correlation. On the other hand, as we know that the depletion stage cannot be easily described we did not study the influence of this parameter. But, we shall try to investigate the influence of the pre-rinse water volume upon the overall kinetics.

Influence of the Pre-rinse Water Volume, Kinetic Modeling. The concentration of absorbance determined components, protein and sugar of all samples from ten trials (eight flow rate trials and two standard trials) is given in Fig. 4 in relation to pre-rinse volume used per unit of soiled surface. On the considered area ($C/Co > 3 \times 10^{-5}$) it should be

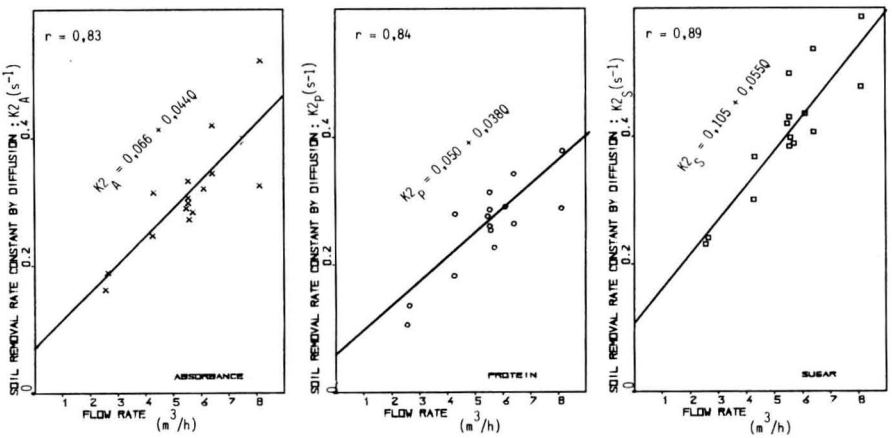

FIG. 3. VARIATION OF THE SOIL REMOVAL RATE CONSTANT BY DIFFUSION (k2) ACCORDING TO FLOW RATE (*Q*)

emphasized that all the experimental points corresponding to each component are located inside a relatively narrow bundle. The enlargement observed in the low concentration area can partly be explained by a relative lower accuracy of analytical determination in this concentration area, which is amplified by this logarithmic presentation. Thus, pre-rinse kinetics are relatively independent of the volume of milk initially contained in the tank and of the pre-rinse solution flow rate (*Q*) when the results are expressed in terms of effluent volume used per soiled surface unit (*V/S*). Consequently, a modeling of the kinetics is possible as shown in Table 4 including all experimental points from two

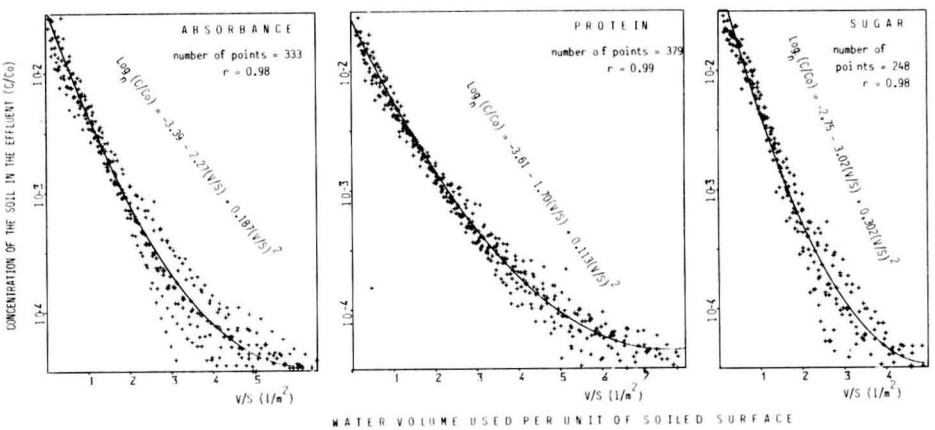

FIG. 4. VARIATION IN THE DIMENSIONLESS CONCENTRATION OF SUGARS AND PROTEINS IN THE EFFLUENT ACCORDING TO WATER VOLUME USED PERm^2 OF SOILED SURFACE

Table 4. Study of the pre-rinse kinetic modeling of the dimensionless concentration for absorbance determined components (A), protein (P) and sugar (S), in the effluent according to used volume per soiled surface unit (V/S) – ($1/m^2$)

	Regression Results								
	For $C/Co > 10^{-4}$ Linear Relation				For $C/Co > 3 \times 10^{-5}$ Quadratic Relation				
		$Log_n (C/Co) = A1 (V/S) + B1$				$Log_n (C/Co) = A2 (V/S)^2 + B2 (V/S) + C2$			
Soil Type	Number of Points	A1	B1	r	Number of Points	A2	B2	C2	r
A	232	−1.49	−3.89	0.96	333	0.187	−2.27	−3.39	0.98
P	296	−1.14	−4.06	0.97	379	0.113	−1.70	−3.61	0.99
S	191	−2.01	−3.29	0.97	2.48	0.302	−3.02	−2.75	0.98

particular dimensionless concentration areas. For dimensionless concentrations above 10^{-4}, a merely linear relation (6) may lead to a correct modeling of the kinetics.

$$\log(C/Co) = A1\,(V/S) + B1 \tag{6}$$

Pre-rinse time (t_1) reducing the soil dimensionless concentration in the effluent to a particular value $(C/Co)_1$ may easily be calculated by the following relation:

$$t_1 = \frac{1}{A1}(\log(C/Co)_1 - B1) \times \frac{S}{Q} \tag{7}$$

In fact, the total pre-rinse time determined from the moment of V1 valve switching is equal to t_1 added to the length of the latency stage. A quadratic relation (8) is required to make a modeling of the kinetics on a larger dimensionless concentration area.

$$A2\left(\frac{V}{S}\right)^2 + B2\left(\frac{V}{S}\right) + \left(C2 - \log\left(\frac{C}{Co}\right)\right) = 0 \tag{8}$$

For the dimensionless concentration above 3×10^{-5} indicated in Fig. 4, this function is correctly located on the experimental plotting. The regression coefficient (r) is at least equal to 0.98. Therefore, this relation may correctly represent the kinetics. Pre-rinse time (t_1) reducing the soil dimensionless concentration in the effluent to a given value $(C/Co)_1$ can be calculated by a little more complex formula (9):

$$t_1 = \left(\frac{S}{Q}\right) f(\log(C/Co)_1) \tag{9}$$

where $f(\log(C/Co)_1)$ is the minimum root of the quadratic Eq. (8).

Observation: The rinsing volumes determined by the simulations or by the experiments are rather low. They are at least four times lower than those obtained by Patel and Jordan (1964) with a turbidimetric method able to detect a soil dilution of 10^4. These authors found that a stainless steel pipe (diameter: 37 mm; length 27 m) completely filled with whole homogenised milk, is correctly rinsed with 22 liters of water per square metre of soiled surface.

Influence of Other Parameters. Rinsing kinetics were studied relative to the effluent volume per soiled surface unit. Thus rinsing kinetics is almost independent of milk volume in the tank and of the flow rate of the pre-rinse solution. Comparison of the rinsing curves of the 7 standard trials shows that they are overlapping each others and are thus identical. Results in Table 5 show that the effluent volume per unit

Table 5. Removal kinetics of various milk components as affected by the composition of the pre-rinse solution, during diffusion and depletion stages

	Trial Number		Volume Per Soiled Surface Unit ($1/m^2$) to Reach								
			$C/Co = 10^{-2}$			$C/Co = 10^{-3}$			$C/Co = 10^{-4}$		
			A	P	S	A	P	S	A	P	S
Osmosed Water	7	AV	0.46	0.48	0.69	1.92	2.23	1.69	4.25	5.51	3.05
		SD	0.14	0.12	0.08	0.10	0.16	0.11	0.68	0.55	0.37
Hard Water	3	AV	0.45	0.43	0.74	2.03	2.31	1.87	4.60	5.02	3.32
		SD	0.02	0.03	0.14	0.16	0.32	0.27	0.62	0.69	0.09
NaOH 1 g/l	3	AV	0.44	0.46	0.68	1.98	2.53	1.94	4.06	5.04	3.78
		SD	0.10	0.06	0.06	0.18	0.07	0.09	0.90	0.64	0.93
Sur-factants	4	AV	0.48	0.50	0.70	1.65	2.06	1.49	3.55	5.01	2.71
		SD	0.07	0.07	0.13	0.18	0.27	0.19	0.57	1.04	0.52

A : absorbance ; P = protein ; S = sugar

of soiled surface reducing the dimensionless concentration of the three types of the soil to 10^{-2} to 10^{-3} and 10^{-4} is not significantly affected by the composition of the pre-rinse solutions studied. Temperature influence of the pre-rinse solution cannot be experimentally studied. Indeed, the stored milk is cooled to about 4°C by means of a glycol solution. The empty tank wall keeps that temperature and cools the water rinse solution at the beginning of pre-rinse. Therefore, the influence of temperature cannot be determined by the experimental equipment.

CONCLUSION

When drawing the conclusions about research on pre-rinse of milk storage tanks it should be emphasized that only the soil removed by cleaning was analyzed and that the presence of remaining soil on the tank walls after cleaning was never verified.

However, it appears that pre-rinsing is essential as it removes most of the milk residues. Although performed at a high velocity it is very reproducible. We therefore described it according to three main stages. The first one, very short, corresponding to the building-up of the film of rinse solution on the walls of the tank and mixing of milk and water. The second stage seems to be controlled by a diffusion mechanism corresponding to a first order mechanism whose rate constant depends on the nature of the milk components. During the third stage, the removal rate of these components decreases gradually. The latter stage is particularly marked for proteins and lipids. We did not find any significant gain in using osmosed water alone admixed with NaOH or a surface active agent in the rinse water. The used rinse solution volume per unit of soiled surface seems to be rather independent of flow rate and working conditions. Accordingly, an empirical mathematical model can be established to determine pre-rinse duration according to spraying flow rate of the cleaning ball, soiled surface and maximum concentration of soil in the effluent at the end of pre-rinsing.

ACKNOWLEDGMENTS

The authors wish to thank Dr. O. Cerf and G. Daufin for helpful discussions and the INRA-CNRZ service of translation.

REFERENCES

ASHWORTH, U.S. 1951. Turbidity as a means for determining the efficiency of homogenization. J. Dairy Sci. *34*, 317-320.

BUCHWALD, B. 1974. Praktishe Einflüsse der mechanischen Komponente. Ernährungswirtschaft. Lebensmitteltechnik, *9*, 590-598.

DREYWOOD, R. 1946. Qualitative test for carbohydrate material. Ind. Eng. Anal. ed *18*, 499.

HEINEMANN, B. and ROHR, M.R. 1950. A micro-method for routine determinations of fat in skimmilk and nonfat dry milk solids. J. Dairy Sci. *33*, 703-309.

HIERATH, D., SCHARF, R. and SCHLÜSSLER, H.J. 1974. Versuche zur quantitativen Bestimmung von Verschmutzungen in Reinigungslösungen.
II. Reinigungslaugen in der Milchwirtschaft. Milchwissenschaft. *29* (7), 385-394.

LONCIN, M. 1977. Modelling in cleaning, disinfection and rinsing. In *Mathematical Modelling in Food Processing*, Proc. Eur. Fed. Chem. Eng. Mini-Symp. pp. 301-335. Lund Institute of Technol. (SWEDEN).

LOWRY, O.H., ROSENBROUGH, N.J., FARR, L.A. and RANDALL, R.J. 1951. Protein measurement with the folin phenol reagent. J. Biol. Chem. *193*, 265-275.

PATEL, S. and JORDAN, W.K. 1964. Rinsing milk residues from stainless steel, glass and tygon pipelines with cold and warm water. J. Milk Food Technol. *27*, 66-68.

PERRY, R.H. and CHILTON, C.H. 1973. *Chemical Engineers Handbook*, fifth Edition, (3-235) McGraw-Hill Book Co.

RADLER, O. 1976. Einfluss der Strömungsgeschwindigkeit auf Reinigungsvorgänge Brauwelt, *116* (26), 847-850.

SCHLÜSSLER, H.J. 1980. Rückstände von Reinigungs und Desinfektionsmitteln auf festen Oberflächen. Chem. Ing. Tech. *52* (3), 246-247.

SCHWARTZBERG, H.G. and CHAO, R.Y. 1982. Solute diffusivities in leaching processes. Food Technol. *36*, 73-86.

THOR, W. and LONCIN, M. 1978. Reinigen, Desinfizieren und Nachspülen in der Lebensmittel–Industrie–Chem. Ing. Tech. *3*, 188-193.

LITERATURE ABSTRACTS

ABSTRACTS FROM TRANS. ASAE

HEAT AND MASS TRANSFER CHARACTERISTICS AND THE EVALUATION OF THERMAL PROPERTIES OF MOIST FOOD MATERIALS. K.B. Narayana, M.V. Krishna Murthy. Trans. ASAE. *24FE*, 789.

This paper presents a mathematical model for predicting time-temperature characteristics of slab shaped food products considering the effects of both heat and mass transfer. The theoretical time-temperature histories are presented in the form of charts in terms of five dimensionless parameters. The experimentation consists of applying a uniform heat flux on one side of the slab and exposing the other side to the ambient where both heat and mass transfer occur under free convection conditions. The thermal properties of some food models consisting of agar-agar, sugar and water are determined using the experimental time-temperature data and the proposed mathematical model through non-linear estimation method. It is observed that for food models thermal conductivity and thermal diffusivity decrease with increase in sugar content.

PACKAGE PRODUCT INTERACTION IN CORRUGATED CONTAINERS FOR FRESH PRODUCE. K. Peleg. Trans. ASAE. *24FE*, 794.

Performance of Full Telescopic and Regular Slotted corrugated containers with internal dividers for fresh produce is defined in terms of top to bottom compressive force at critical deflection, causing unacceptable produce damage, and maximal compressive force, causing containers collapse. Using small sample statistics, typical performance tolerance intervals of shipping containers for Michigan apples were developed whereby performance standards for the different containers tested were set. A similar approach may be used to define performance standards for shipping containers for other types of fresh produce.

The effects of different styles of internal partitions and strength reduction due to handholes are investigated.

Compression tests of apple filled containers were run parallel to tests of empty containers to assess apples' share of bearing stacking loads. It was shown that pattern packed apples caused less bulging than random jumble packs, thereby improving container stacking strength.

REFLECTANCE AS A TOMATO GRADE CATEGORY STANDARD. S. Moini, M. O'Brien. Trans. ASAE. *24FE*, 1066.

Light reflectance characteristics of tomatoes at various stages of maturity, dirt clods, mold and other tomato defects have been found to be sufficiently different to identify them. By using combinations of light reflectances at different wavelengths, several criteria were found which will provide reasonable separation of good tomatoes from green tomatoes, dirt clods, and those having defects.

ANALYSIS OF CALCULATION METHOD FOR PRODUCT GRADE DEFECT PERCENTAGES. S. Prussia, M. O'Brien. Trans. ASAE. *24FE*, 1068.

A method was developed to analyze the probability of error when produce grade defect percentages are based on the custom of using an assumed incoming sample mass in a standard size container. A plot of grade defect mass vs. incoming sample mass yields "isoerror" curves that indicate the level of error for a chosen combination of grade defect and incoming sample masses. Superimposing normal curves representing a range of incoming sample mass distributions permits calculation of the points needed for a 3-D plot of the probability of a correct grade defect percentage as a function of the mean and standard deviation of the incoming sample mass distribution with the grade defect mass and level of error as implicit variables. The method was found reliable for predicting the amount of error at a comercial tomato grading station. The results provided information needed to decide if mass determinations of the incoming sample should be required.

USING WINTER COLDNESS TO PROVIDE REFRIGERATION. R.R. Zall, W.K. Jordan, D.C. Ludington, J.H. Chen. Trans. ASAE. *24FE*, 1073.

Research has been conducted to learn if winter coldness could be used in appropriate climates for reducing energy spent to produce refrigeration. The concept was tried in three different situations: (a) chilling a food storage walk-in cooler; (b) building ice in a solid ice bank; and (c) producing slush ice for storing Btu's by misting water into cold air.

Results show that using winter coldness is feasible; the data also suggest that if seasonal cold air was used to provide refrigeration below certain temperatures that this action would conserve energy.

DESIGNING MIXTURE EXPERIMENTS—A REVIEW. D.R. Thompson. Trans. ASAE. *24FE*, 1077.

Mixture and constrained mixture experiments are a special subset of response surface methodology for studying components in a mixture. This paper reviews the mathematical models, experimental designs and analysis techniques that have been developed for mixture and constrained mixture experiments.

MODELING MICROBIAL POPULATIONS DURING MEAT COOKING AND COOLING. D.R. Thompson, F.F. Busta. Trans. ASAE. *24FE*, 1664.

Clostridium perfringens are a potential cause of food-borne illness from slow cooked meat. This paper extends the applications of a previously reported model for the growth and inactivation of this organism in three respects. Implied mechanisms are evaluated, a simplified prediction procedure is presented and preliminary data on organism re-growth during roast cooling is compared with model predictions.

DEWATERING CANNERY SOLID WASTE. D.J. Hills, H.E. Studer, J.J. Mehlschau. Trans. ASAE. *24FE*, 1671.

A major problem facing the food industry today is proper management of solid wastes. Chemical and physical data are presented on the separation of tomato solid waste from cannery effluent achieved with either an experimental vibrating screen or a commercial hydrasieve. Observation that additional dewatering was achievable with a grape pumace belt press led to development of a tire press prototype to follow in series with the vibratory screen or hydrasieve. This additional device achieved approximately a 50 percent reduction in weight and volume of the tomato solid waste. Muncipal treatment cost for the additional filtrate generated by a full size tire press was calculated to be relatively insignificant.

ENERGY PERFORMANCE OF A HTST CITRUS EVAPORATOR UNDER DIGITAL COMPUTER CONTROL. C.S. Chen, R.D. Carter, W.M. Miller, T.A. Wheaton. Trans. ASAE. *24FE*, 1678.

Computer controls to reduce the energy requirement of a 3-effect pilot evaporator were studied. Energy savings of 17 percent were achieved. Smaller savings are expected as the number of effects increased. Computer control is justified for every savings of 3 to 5 percent for commercial applications.

A NONLINEAR IMPACT MODEL FOR A SPHERE WITH A FLAT PLATE. J.E. Franke, R.P. Rohrbach. Trans. ASAE. *24FE*, 1683.

With the development of the piezoelectric force transducer it has become possible to measure directly the time dependent contact force during impact of a uniform viscoelastic sphere with a solid flat surface. This paper develops the second order nonlinear differential equation,

$$m\ddot{x} + e^{\frac{v_o}{v_t}} - (1 - e^{-t/\tau})\dot{x} + k(x + \gamma(1 - e^{x/\gamma})) = -mg \cdots \quad (1)$$

and proposes it as a model for the motion of the sphere's center of gravity during impact. The seven parameters $(m, k, c, \tau, \gamma, v_o, v_t)$ are determined for a silicone rubber ball. These parameters are then used in a numerical solution of the differential equation and compared with the measured force of the impact.

Three methods of direct measurement of the parameters from the contact force are discussed. The first two methods use formulas for the coefficients of the power series solution for the contact force which contain the parameters as variables. The third method involves a direct least-square fit of the differential equation to the measured force.

F
N
P

JOURNALS AND BOOKS IN FOOD SCIENCE AND NUTRITION

Journals

JOURNAL OF NUTRITION, GROWTH AND CANCER, G. P. Tryfiates

JOURNAL OF FOOD SERVICE SYSTEMS, O. P. Snyder, Jr.

JOURNAL OF FOOD BIOCHEMISTRY, H. O. Hultin, N. F. Haard and J. R. Whitaker

JOURNAL OF FOOD PROCESS ENGINEERING, D. R. Heldman

JOURNAL OF FOOD PROCESSING AND PRESERVATION, T. P. Labuza

JOURNAL OF FOOD QUALITY, M. P. DeFigueiredo

JOURNAL OF FOOD SAFETY, M. Solberg and J.D. Rosen

JOURNAL OF TEXTURE STUDIES, P. Sherman and M. C. Bourne

Books

PRODUCT TESTING AND SENSORY EVALUATION OF FOODS, H. R. Moskowitz

SHELF-LIFE DATING OF FOODS, T. P. Labuza

ANTINUTRIENTS AND NATURAL TOXICANTS IN FOOD, R. L. Ory

UTILIZATION OF PROTEIN RESOURCES, D. W. Stanley, E. D. Murray and D. H. Lees

FOOD INDUSTRY ENERGY ALTERNATIVES, R. P. Ouellette, N. W. Lord and P. E. Cheremisinoff

VITAMIN B_6: METABOLISM AND ROLE IN GROWTH, G. P. Tryfiates

HUMAN NUTRITION, 3RD ED., R. F. Mottram

DIETARY FIBER: CURRENT DEVELOPMENTS OF IMPORTANCE TO HEALTH, K. W. Heaton

RECENT ADVANCES IN OBESITY RESEARCH II, G. A. Bray

FOOD POISONING AND FOOD HYGIENE, 4TH ED., B. C. Hobbs and R. J. Gilbert

POSTHARVEST BIOLOGY AND BIOTECHNOLOGY, H. O. Hultin and M. Milner

THE SCIENCE OF MEAT AND MEAT PRODUCTS, 2ND ED., J. F. Price and B. S. Schweigert

GUIDE FOR AUTHORS

Typewritten manuscripts in triplicate should be submitted to the editorial office. The typing should be double-spaced throughout with one-inch margins on all sides.

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 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.

Results: The results should be presented as concisely as possible. Do not use tables *and* figures for presentation of the same data.

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.

References: References should be given in the text by the surname of the authors and the year. *Et al.* should be used in the text when there are more than two authors. All authors should be given in the Reference section. In the Reference section the references should be listed alphabetically. See below for style to be used.

DEWALD, B., DULANEY, J. T. and TOUSTER, O. 1974. Solubilization and polyacrylamide gel electrophoresis of membrane enzymes with detergents. In *Methods in Enzymology*, Vol. xxxii, (S. Fleischer and L. Packer, eds.) pp. 82—91, Academic Press, New York.

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

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

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

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

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

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

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

Acknowledgments: Acknowledgments should be listed on a separate page.

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

Standard nomenclature as used in the engineering literature should be followed. Avoid laboratory jargon. If abbreviations or trade names are used, define the material or compound the first time that it is mentioned.

EDITORIAL OFFICE: Prof. D. R. Heldman, Editor, Journal of Food Process Engineering, Michigan State University, Department of Food Science and Human Nutrition, East Lansing, Michigan 48824 USA.

JOURNAL OF FOOD PROCESS ENGINEERING VOL. 6 NO. 1

CONTENTS