



ELSEVIER

Journal of Food Engineering 47 (2001) 203–210

JOURNAL OF  
FOOD  
ENGINEERING

www.elsevier.com/locate/jfoodeng

# Heat transfer characteristics of cucumbers during blanching<sup>☆</sup>

O.O. Fasina<sup>\*</sup>, H.P. Fleming

US Department of Agriculture, Agricultural Research Service, and North Carolina Agricultural Research Service, Department of Food Science, North Carolina State University, Raleigh, NC 27695-7624, USA

Received 30 June 1999; received in revised form 3 April 2000; accepted 14 April 2000

## Abstract

The possible use of blanching in combination with controlled fermentation is being considered as a means to reduce the salt levels needed in the storage of brined cucumbers. To be commercially feasible, the use of heat should be optimized for economic and product quality considerations. This study reports basic information on the heat transfer characteristics of cucumbers needed to optimize the blanching process.

Two-dimensional (cylindrical coordinates) heat diffusion equations were used to simulate the heat transfer characteristics of cucumbers during rapid water heating (blanching). The equations were solved by explicit form of the finite difference method. Thermo-physical properties (thermal conductivity, specific heat and density) of cucumbers needed to solve the heat transfer equation were also measured. Temperature (20–95°C) did not significantly affect the thermal conductivity (0.62 W/m K) or specific heat (4.03 kJ/kg K) of cucumber. The maximum standard error of simulated temperatures of the cucumbers from experimental data was 4.5°C. There was no significant change in the moisture level of the cucumber during blanching. Simulation results showed that heat transfer coefficients between 500 and 6000 W/m<sup>2</sup> K had no significant effect on the surface and center temperatures of cucumbers during blanching.

**Keywords:** Cucumber; Thermal properties; Heat transfer; Blanching

## 1. Introduction

The US production of cucumbers (*Cucumis sativus*) for pickling is about 590,000 t, which are preserved by brine fermentation (40%), pasteurization (40%), or refrigeration (20%) (Fleming, Kyung, & Breidt, 1995). Brine fermentation is the oldest method for cucumber preservation and was the only commercial method used before the introduction of pasteurization in the 1940s (Etchells & Jones, 1942, 1944; Monroe et al., 1969).

Brine fermentation remains an important method for temporary preservation of cucumbers because of sensory traits desired in certain products, processing strategies, and economic reasons (Fleming, 1982; Fleming & Moore, 1983). However, the need to use relatively high

concentrations of salt for preservation necessitates removal of some of the salt during processing of the brined cucumbers into finished products, which results in disposal problems associated with both the salt and consequent organic matter. Environmental problems exist within the pickle industry because many companies cannot meet the 230 ppm chloride limit set by the US Environmental Protection Agency for discharge of their wastewater into fresh water bodies (Anonymous, 1987; Humphries & Fleming, 1989).

It is possible that salt levels needed to assure the microbial and textural storage stability of brined cucumbers can be reduced (or even eliminated) by heating the cucumbers before brining to inactivate undesirable microorganisms and softening enzymes on the cucumber surface, followed by the addition of a desired culture of lactic acid bacteria (Fleming et al., 1995). The optimum heat process necessary to adequately preserve cucumbers brined at low levels of salt has not been established.

Considerable research has been done in establishing the optimum heat process necessary to preserve pasteurized cucumbers contained in glass jars and submerged in acidified liquid (Anderson, Ruder, Esselen, Nebesky, & Labbee, 1951; Esselen & Anderson, 1957;

<sup>☆</sup>Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the US Department of Agriculture or North Carolina Agricultural Research Service, nor does it imply approval to the exclusion of other products that may be suitable.

<sup>\*</sup>Corresponding author. Tel.: +1-919-515-2979; fax: +1-919-856-4361.

E-mail address: fasina@unity.ncsu.edu (O.O. Fasina).

Esselen, Anderson, Ruder, & Pflug, 1951; Esselen, Anderson, Fagerson, & Labbee, 1952a; Esselen, Fagerson, Pflug, & Anderson, 1952b; Etchells & Jones, 1942; Labbee, Esselen, & Anderson, 1952; Monroe et al., 1969; Nicholas, Pflug, & Costilow, 1957; Nicholas & Pflug, 1962; Rodrigo & Alvarruiz, 1988). The industry-accepted standard for pasteurization is to heat the cucumbers in acidified cover solutions to an internal (of the cucumber) temperature of 74°C.

Blanching was compared to irradiation and pasteurization as a means of inactivating naturally occurring microorganisms for use in inoculation with pure cultures of selected species of lactic acid bacteria (Etchells, Costilow, Anderson, & Bell, 1964). Blanching of fresh, whole cucumbers is a common commercial practice to increase flaccidity of the cucumbers so as to facilitate their packing into jars. The effect of blanching on the quality of fresh cucumber pickles has been studied (Nicholas & Pflug, 1962). The texture, as measured by a mechanical pressure tester, was significantly lower for the heat-processed pickles than for the raw cucumbers. Blanching was carried out at temperatures of 65.6–95.6°C for 7–166 min. In addition, internal damage, largely carpel separation, was obtained for heating regimes exceeding equivalent temperature and time of 82.2°C and 2 min, respectively.

The possible use of blanching in combination with controlled fermentation has been considered. The pure culture fermentation studies of Etchells et al. (1964) had implications in that direction. However, at the time, heating of cucumbers for bulk fermentation was not considered practical. Salt was inexpensive, and the use of excess concentrations to assure stability of the brine-stock was not as serious a concern as it is today. To be commercially feasible, however, the use of heat should be optimized for economic and product quality considerations. Evidence indicates that, by far, most microorganisms are located on or near the surface of the whole cucumbers (Etchells, Bell, Costilow, Hood, & Anderson, 1973; Breidt & Fleming, 1998), although some occasionally may occur within the fruit (Samish, Etinger-Tulczynka, & Bick, 1963; Meneley & Stanghelin, 1974). Also, most microbially produced softening enzymes are thought to be located on/near the surface, since washing of cucumbers prior to brining has been shown to reduce enzyme activity and result in firm salt-stock cucumber (Etchells, Bell, & Jones, 1955). We wish to determine if a blanching process can be optimized to be commercially applicable to fermentation and storage of whole cucumbers in bulk containers.

To optimize such a blanching process, basic information on the heat transfer characteristics of cucumbers is needed. Although research has been published on heat penetration into cucumbers contained in liquid in glass jars, we are unaware of studies relating specifically to the blanching process. In addition to obtaining a general

understanding of the heat transfer characteristics of cucumbers during blanching, we were particularly interested in quantifying the rate of temperature increase within the first 100 s of heating, since most of the microorganisms are suspected to be located at or near the surface of whole cucumbers (Breidt & Fleming, 1998). The objective of this paper was to simulate the transfer of heat into cucumbers during blanching and to use experimental data to verify the simulation model.

## 2. Materials and methods

### 2.1. Heating experiment

Fresh pickling cucumbers were obtained from local growers or pickle companies. Only hand-washed cucumbers free of obvious physical damage and disease were used. Cucumbers with diameters of about 25, 37, and 45 mm were used for model verification. A digital vernier calipers (Digimatic, model no. CD-S6"CP, Mitutoyo, Japan) with precision of 0.01 mm was used to measure the actual dimension of each cucumber. Two small diameter (0.432 mm) needle probe thermocouples (model 08505-93, Cole Parmer Instrument, Vernon Hills, IL) were inserted into a cucumber from the axial (stem) end. The intent was to have the tip of one of the thermocouples at the geometric center of the cucumber, while the other thermocouple tip resided close to the surface of the cucumber. In most of the cases, these could not be achieved because of the soft nature of cucumber tissue. Therefore, the actual locations of the thermocouple tips were obtained by cutting the cucumbers after heating and measuring with the vernier calipers.

A DaqBook Data Acquisition system (IOtech, Cleveland, OH) was used to collect temperature readings from the thermocouples placed inside the cucumber during heating. The data acquisition system consists of a signal conditioner (DBK 19), an analog to digital converter – ADC (DaqBook 100), and a personal computer.

To carry out a test, a cucumber fruit with the thermocouples inserted was placed in a 10-l heated water bath set to a desired temperature. The temperature of the water in the bath did not deviate from the desired set point by more than 0.5°C. Temperatures from the thermocouples were read and stored by the data acquisition system at every second for 1000 s. The heated fruit was, thereafter, removed from the blanching water, cut and the actual axial and radial locations of the tips of the two thermocouples were measured. Heating of the 37 mm diameter cucumbers was carried out in water heated to constant temperatures of 50°C, 65°C, 80°C, and 95°C. The effect of cucumber size was studied by heating 25 and 45 mm diameter cucumbers in water at

temperatures of 65°C and 80°C. All blanching experiments were done in duplicate.

## 2.2. Thermal and physical properties determination

The thermal and physical properties of cucumbers and the convective heat transfer coefficient ( $h$ ) must be known before modeling heat transfer rates during the blanching of cucumbers. The density of 20 cucumbers was calculated from the ratio of mass of cucumbers to the volume. Cucumber volume was obtained by the fluid (ethanol) displacement method (Mohsenin, 1986).

Specific heat was measured by means of a Perkin-Elmer DSC 7 differential scanning calorimeter equipped with intracooler II refrigeration unit and dry box (Perkin-Elmer, Norwalk, CT). The DSC was calibrated with indium (temperature and enthalpy) and dodecane (temperature) before use. Samples were weighed (30 mg) in the manufacturer's stainless steel pans and run from 20°C to 95°C at a heating rate of 3°C/min using an empty pan as the reference. Specific heat was calculated by the software provided by the DSC manufacturer. To ascertain the accuracy of the measurements, the specific heat of HPLC-grade water was measured and found to be within 2% of published values. The specific heat of the mesocarp, endocarp and whole cucumbers was determined. Duplicate samples for specific heat measurements were obtained by grinding whole, mesocarp or endocarp sections of 20 (10 for each duplicate) cucumbers.

Thermal conductivity was determined by the line-heat source probe method. The probe apparatus, constructed according to the recommendations of Sweat (1986), consisted of a type E thermocouple (0.051 mm diameter), constantan heater wire (0.077 mm diameter), a 23-gauge stainless steel hypodermic needle (houses the heater wire and thermocouple) and a type E thermocouple connector. Thermal conductivity measurements were carried out on intact or cut-out cucumber. The cut-out (cross-sectional) cucumber samples were used for endocarp and mesocarp thermal conductivity measurements. Cucumber samples were heated to the desired temperature by placing in the water bath for at least 25 min. After reaching the desired temperature, the sample was removed from the water bath and thermal conductivity probe was immediately inserted. For average thermal conductivity measurement, the probe was inserted from the cucumber surface to the center, while, for mesocarp and endocarp measurements, the probe was inserted into either the mesocarp or the endocarp. Time and temperature data were recorded by a data-logger (OM-3000, Omega Engineering, Stamford, CT) at the rate of 5 readings per second. Thermal conductivity was calculated from the relation (Sweat, 1986)

$$k = \frac{Q}{2\pi} \frac{\ln(t/t_0)}{T - T_0} \quad (1)$$

The initial time ( $t_0$ ) in the above equation was set equal to the time when the semi-log plot of time-temperature plot starts to become linear. The power level in the heater was 5.5 W/m. For each time-temperature plot, the slope was found using simple linear regression.

The lumped heat capacity analysis method was used to determine  $h$  (Holman, 1996). The method involves measuring temperature changes of objects of known shape and with high thermal conductivity (such as aluminum or copper) and the use of appropriate equations to estimate  $h$  for the process. If Biot number is less than 0.1,  $h$  can be calculated from the relation below for lumped heat transfer (Incropera & Dewitt, 1996).

$$TR = \frac{T_c - T_\infty}{T_i - T_\infty} = \exp\left(-\frac{hA}{\rho cV}t\right), \quad (2)$$

where  $TR$  is the temperature ratio,  $T_c$  the temperature at the geometric center of object (°C),  $T_i$  the initial temperature of object (°C),  $T_\infty$  the temperature of blanching water (°C),  $A$  the surface area (m<sup>2</sup>), and  $V$  is the volume (m<sup>3</sup>).

A plot of natural log of the temperature ratio versus time should give a straight line with a slope of  $hA/\rho cV$ . The value of  $h$  can then be determined from the slope of the line, since the values of all the other parameters are known or can be calculated.

Three sizes (diameters of 25.4, 38.1, and 50.8 mm) of aluminum cylinders with length to diameter ratio of 3 to 1 (based on average of 40 measurements of cucumbers) were made. These sizes are within the diameter range used in the pickle industry. A 1.8 mm diameter hole was drilled from the side to the geometric center of each of the cylinders. A 24-gauge thermocouple was inserted into the hole of each cylinder such that the tip of the thermocouples was at the geometric center of the cylinder. Each hole was sealed with a silicon adhesive to prevent penetration of water during heating. The aluminum cylinders were placed horizontally in heated water (35°C, 50°C, 65°C, 80°C, and 95°C). The temperatures at the geometric centers of the aluminum cylinders were collected every 0.25 s and stored by the data acquisition system.

## 2.3. Heat transfer equations

Cucumbers were approximated to be cylindrical in shape. Since several measurements of the length and diameter of cucumbers indicated an approximate length to diameter ratio of 3 to 1 (see Section 3), a two-dimensional (2-D) heat diffusion equation was used to describe the radial and axial flow of heat into the center of cucumbers during blanching in hot water as follows:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} kr \frac{\partial T}{\partial r} + k \frac{\partial^2 T}{\partial z^2}, \quad (3)$$

where  $T$  is the temperature of cucumbers as a function of position and time ( $^{\circ}\text{C}$ ),  $t$  the time (s),  $r$  the radial coordinate of point of interest expressed as the distance measured along the radius from the center of cucumber (m),  $z$  the axial coordinate of point of interest expressed as the distance measured along the length from center of cucumber (m),  $k$  the thermal conductivity ( $\text{W/m K}$ ),  $c$  the specific heat ( $\text{J/kg K}$ ), and  $\rho$  is the density ( $\text{kg/m}^3$ ).

The initial and boundary conditions to Eq. (3) are given by:

$$T = T_0 \quad t = 0, \quad (4)$$

$$\frac{\partial T}{\partial r} = 0 \quad t > 0, \quad r = 0, \quad (5)$$

$$\frac{\partial T}{\partial z} = 0 \quad t > 0, \quad z = 0, \quad (6)$$

$$-k \frac{\partial T}{\partial r} = h(T - T_{\infty}) \quad t > 0, \quad r = R, \quad (7)$$

$$-k \frac{\partial T}{\partial z} = h(T - T_{\infty}) \quad t > 0, \quad z = L/2, \quad (8)$$

where  $h$  is the heat transfer coefficient ( $\text{W/m}^2 \text{K}$ ), and  $R$  and  $L$  are, respectively, the radius and length of cucumbers in meters. The above set of equations assume that mass transfer is negligible during the blanching of cucumbers and that Biot number ( $hR/k$ ) is greater than 0.1 (Incropera & DeWitt, 1996). Justifications for these assumptions are presented in Section 3. In addition, it is assumed, for simplicity purposes, that cucumbers are homogenous and isotropic. Preliminary experimentation showed that the variation between the thermal properties of endocarp and mesocarp of cucumber is very small (Table 1).

Myers (1971) showed that the solution to multi-dimensional heat transfer problems is expressed as the product of one-dimensional solutions for each of the dimensions of the geometry. Therefore, the solution to the 2-D problem of Eq. (3) is given as

$$\frac{T(r, z, t) - T_{\infty}}{T_i - T_{\infty}} = \frac{T(z, t) - T_{\infty}}{T_i - T_{\infty}} \Big|_{\text{infinite slab}} \times \frac{T(r, t) - T_{\infty}}{T_i - T_{\infty}} \Big|_{\text{infinite cylinder}} \quad (9)$$

## 2.4. Numerical formulation

Eqs. (3)–(9) may be solved analytically or numerically. Exact analytical solutions are in the form of infinite series. Due to the complexities involved in obtain exact solutions, the infinite series is often approximated to a single series term by assuming that the Fourier number (Eq. (10)) is greater than 0.2 (Incropera & DeWitt, 1996).

$$F_0 = \frac{kt}{\rho c_p L^2}, \quad (10)$$

where  $L$  is half thickness for a plane wall or radius for a cylinder. Using the typical values of thermo-physical properties of cucumber (presented later in Section 3), the assumption of  $F_0 > 0.2$  will be valid after the cucumbers have being blanched for more than 15 min. Preliminary experimentation showed that a major part of the transfer of heat from the heated water to the cucumbers occurred during the first 10–15 min.

The numerical approach was, therefore, used to obtain solutions to Eqs. (3)–(9). The equations were written in the explicit form of the finite difference method. Details of the resulting mathematical expressions are given in Fasina and Sokhansanj (1995) and Ozisik (1985). For stability, a time step of 0.5 s was used in numerical formulation. This is much less than the calculated critical time step of 2 s, based on the stability criterion that the Fourier number must be less than 0.5 (Incropera & DeWitt, 1996).

The discretized equations (using 20 nodal points each in the axial and radial coordinates, Fig. 1) were coded in Fortran 90 and solved for temperature at various locations along the radial dimension of the cucumber. The same solution methodology was used to obtain temperature at various locations along the axial dimension of the cucumber. The temperature at a particular location was then evaluated from Eq. (9). This procedure was carried out for the total time duration at which experimental data collection was carried out (usually 1000 s).

The closeness of experimental data to predicted temperature was evaluated by means of standard error of estimate (S.E.) estimated as (Draper & Smith, 1981)

Table 1  
Thermal properties of cucumbers at temperatures of 20–95 $^{\circ}\text{C}$

Sample	Thermal conductivity ( $\text{W/m K}$ )		Specific heat ( $\text{kJ/kg K}$ )	
	Average	S.D. <sup>a</sup>	Average	S.D. <sup>a</sup>
Whole	0.62	0.002	4.03	0.040
Endocarp	0.57	0.003	4.12	0.058
Mesocarp	0.61	0.004	4.13	0.071

<sup>a</sup>S.D. – standard deviation.

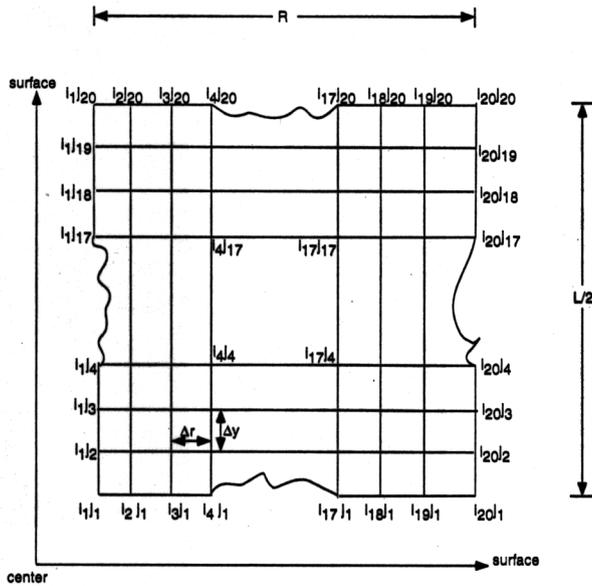


Fig. 1. Schematic diagram of nodal network used in 2-D heat transfer simulation.

$$S.E. = \sqrt{\frac{\sum_{i=1}^{1000} (T_i - \hat{T}_i)^2}{n - 1}}, \quad (11)$$

where  $T_i$  is the experimentally obtained temperature at time  $t$  ( $^{\circ}\text{C}$ ),  $\hat{T}_i$  the predicted temperature at time  $t$  ( $^{\circ}\text{C}$ ), and  $n$  is the number of data points (1000).

### 3. Results and discussion

#### 3.1. Thermal and physical properties

Using the fluid displacement method, the average density of 20 cucumbers was determined to be  $959 \text{ kg/m}^3$ , with a standard deviation of  $2.5 \text{ kg/m}^3$ . There was little influence of temperature on specific heat and thermal conductivity of cucumbers (Table 1 and Fig. 2). Statistical testing at 95% confidence interval (SAS, 1996) showed that the thermal properties of the mesocarp and endocarp of cucumbers were not significantly different from those of whole cucumbers. The average values for specific heat and thermal conductivity of whole cucumbers were found to be  $4.04 \text{ kJ/kg K}$  and  $0.61 \text{ W/m K}$ , respectively.

Fig. 3 shows the rate of temperature ratio change at the center of the aluminum cylinders when exposed to water temperature of  $80^{\circ}\text{C}$ . Similar curves were obtained at the other temperatures. As expected, the temperature-time curves were exponential in nature. Slower heating rates were obtained with increase in cylinder size (diameter and length).

The non-linear regression procedure of SAS package (SAS, 1996) was used to estimate the value of the  $h$  of

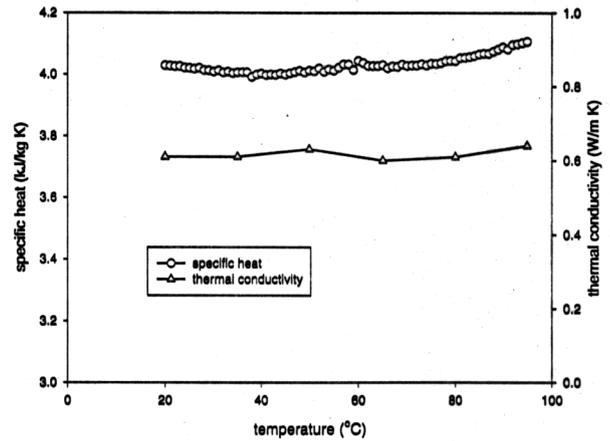


Fig. 2. Temperature effect on the specific heat and thermal conductivity of cucumbers.

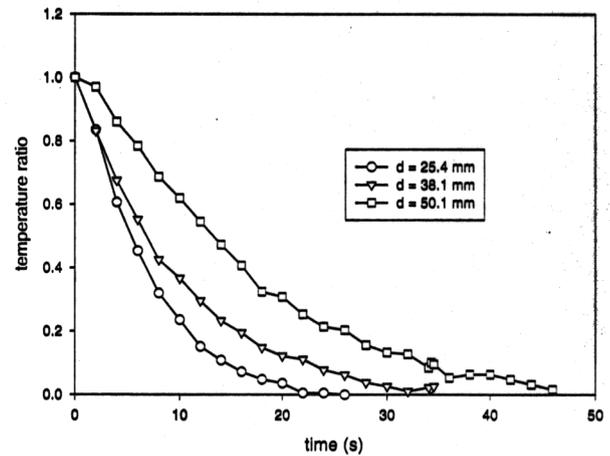


Fig. 3. Influence of diameter ( $d$ ) on the temperature ratio of aluminum cylinders exposed to water temperature of  $80^{\circ}\text{C}$ .

Eq. (2). For all the experimental conditions (five temperature levels and three sizes), the regression coefficients obtained from the fit of Eq. (2) to experimental data were greater than 0.99. In estimating  $h$  from Eq. (2), a specific heat value of  $903 \text{ J/kg K}$  (Incropera & DeWitt, 1996) was assumed for the aluminum cylinders. The average density of the cylinders (mass per unit volume) was measured to be  $2696 \text{ kg/m}^3$ . This is close to the literature value of  $2702 \text{ kg/m}^3$  (Incropera & DeWitt, 1996). The maximum Biot number that was calculated for the aluminum cylinders was 0.086 (using a thermal conductivity value of  $237 \text{ W/m K}$  – Incropera and DeWitt, 1996). This value of Biot number is less than the critical value of 0.1. This validates the suitability of Eq. (2) in estimating the surface heat transfer coefficient during the blanching of cucumbers.

The estimated values of  $h$  were found to be independent of temperature, but decreased with increase in cylinder size. For each cylinder size, the values of  $h$  over the temperature range of  $35\text{--}95^{\circ}\text{C}$  were averaged, and

the average values were related to the cylinder diameter ( $d$ ) by the relation

$$h = 3176.7 - 28.89 d \quad (12)$$

$$R^2 = 0.99,$$

### 3.2. Cucumber blanching

Experimental data on blanching of cucumbers indicate that the surfaces of cucumber approach water temperature in an exponential fashion, thereby indicating the adequacy of the convective boundary condition used in heat transfer modeling (Fig. 4). In most cases, it took less than 60 s for the surface of the cucumber to be within 5°C of the blanching temperature. This indicates

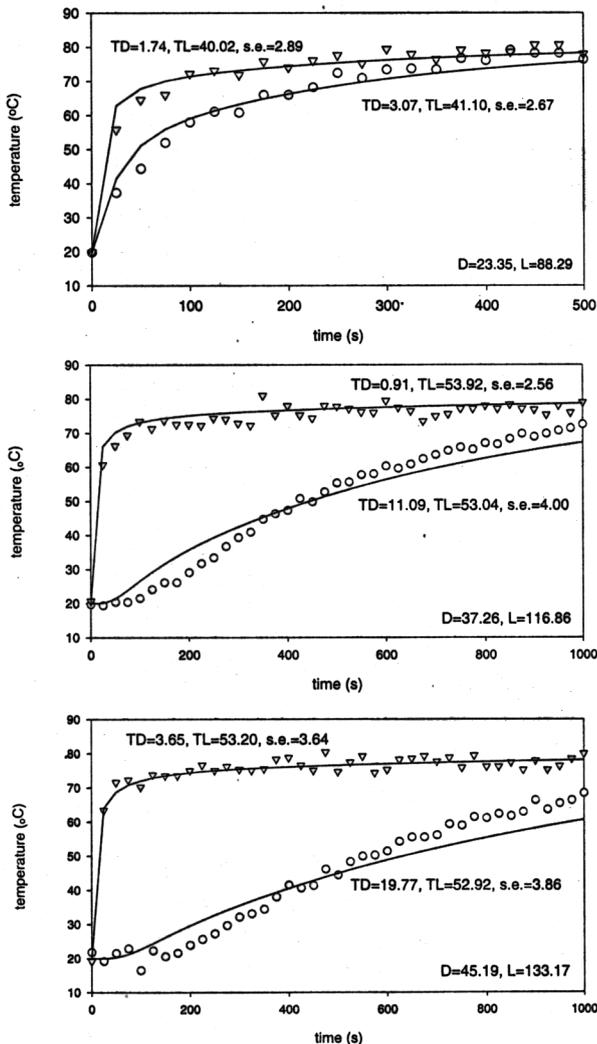


Fig. 4. Experimental and predicted temperatures of cucumbers blanching at 80°C.  $\Delta$ ,  $\circ$  experimental data, (—) predicted.  $TD$  and  $TL$  are the radial and axial locations of the thermocouple tip.  $D$  and  $L$  represent the diameter and length of whole cucumber. Dimensions of  $TD$ ,  $TL$ ,  $D$ , and  $L$  are in millimeters and were measured from cucumber surface.

that blanching times less than 100 s may be adequate for the surface decontamination of whole cucumbers for the purposes of controlled fermentation. Future microbiological and quality studies in conjunction with simulation results from this study will dictate the optimum heating time and temperature.

Using the measured values of thermophysical properties of cucumber, the Biot number ( $Bi$ ) was calculated to be 21, 27 and 29 for cucumber with diameters of 25, 37, and 45 mm, respectively. These values of Biot number are much greater than the critical value of 0.1 (Incropera & DeWitt, 1996). Therefore, Eqs. (3)–(8) are appropriate in modeling the heat transfer characteristics of cucumber during blanching.

Fig. 4 compares predicted temperatures to experimental data for three sizes of cucumbers (diameters of about 25, 37, and 45 mm) blanching at 80°C. Similar results were obtained for cucumbers blanching at 50°C, 65°C and 95°C. In all cases, the standard error of predicted values from experimental data were less than 4.5°C.

At the same distance from the surface of the cucumber, the larger-sized cucumber experienced a slower rate of temperature increase in comparison to the smaller-sized ones (Fig. 5). In applications where heating of the center of cucumber is important, the larger-sized cucumbers, therefore, have to be blanched for a longer time to achieve the same temperature-time equivalency. This information is important in the development of appropriate methodology and equipment for quick blanching of cucumbers.

To verify the assumption of negligible mass transfer during blanching of cucumbers, samples of known weight (about 600 g) were blanched for 25 min in water at temperatures between 50°C and 95°C. The weights of the samples were taken after blanching. Although the percent change in weight increased with blanching temperature (Fig. 6), statistical testing using ANOVA

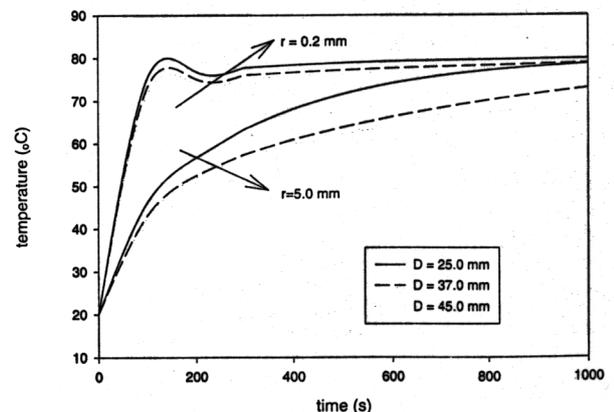


Fig. 5. Simulated temperatures at distances  $r=0.2$  and 5.0 mm from the surfaces of three sizes of cucumbers blanching at 80°C.  $D$  is the cucumber diameter.

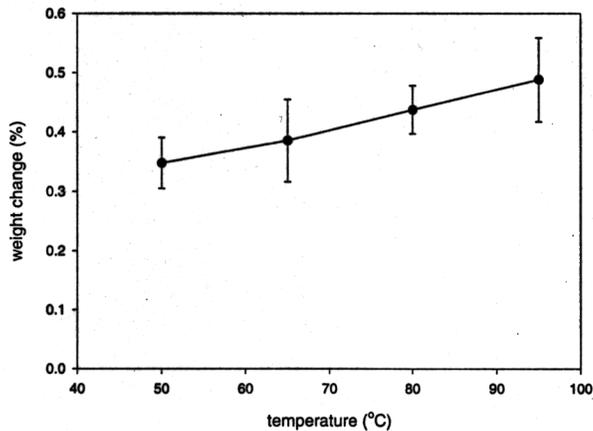


Fig. 6. Percent change in weight of cucumbers during blanching. Each experimental point is the average for five samples.

procedure (SAS, 1996) showed that the increase in weight was not significant ( $P < 0.05$ ). Mass transfer is, therefore, negligible during the blanching of cucumbers. The average moisture content of the cucumbers were measured to be  $95.23 \pm 0.14\%$ . Moisture content determination was carried out by adapting the standard for moisture content measurement of cabbage (ASAE, 1996).

One of the reasons for modeling a physical system is to be able to investigate the response of the system to changes in process/material factors. We envisaged that the water movement during blanching of cucumbers at the commercial level will be different from the water bath condition used in this study. In heat transfer, these changes are manifested in the  $h$ , which was measured to be between 1500 and 2500  $W/m^2 K$  for the conditions used in this study. In forced convection involving water, the heat transfer coefficient can vary from 50 to 10,000  $W/m^2 K$  (Singh & Heldman, 1993). Fig. 7 shows that heat transfer coefficient (between 500 and 6000  $W/m^2 K$ )

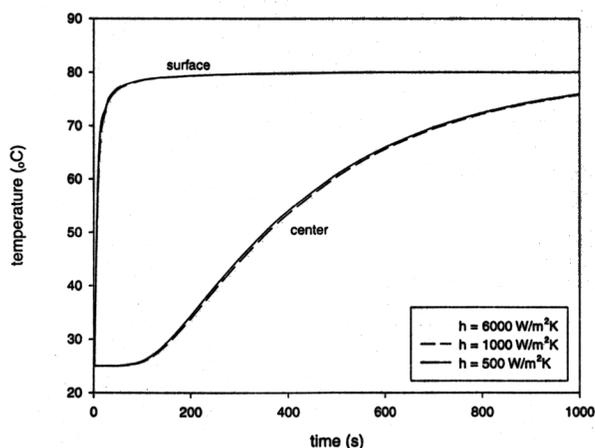


Fig. 7. Influence of the heat transfer coefficient on the surface and center temperatures of 37 mm diameter cucumbers blanched at 80°C.

had no effect on predicted surface and center temperatures of 37 mm diameter cucumbers blanched in 80°C water for 1000 s.

#### 4. Conclusions

The following conclusions can be drawn from this study:

- Within the temperature range of 20°C and 95°C, the thermal properties (specific heat and thermal conductivity) of cucumbers were independent of temperature.
- A 2-D diffusion equation, in cylindrical coordinates, can be used to model the blanching of cucumbers. The standard error of predicted center and surface temperatures from experimental values was less 4.5°C.
- Mass transfer was negligible when cucumbers were blanched in water for 25 min within the temperature range of 50–95°C.
- The average temperatures of cucumbers were not affected by the heat transfer coefficient within the limits of 500 and 6000  $W/m^2 K$ .

#### Acknowledgements

This investigation was supported in part by a research grant from Pickle Packers International, Inc., St. Charles, IL.

#### References

- Anderson, E. E., Ruder, L. F., Esselen, jr., W. B., Nebesky, E. A., & Labbee, M. (1951). Pasteurized fresh whole pickles. II. Thermal resistance of microorganisms and peroxidase. *Food Technology*, *V*, 364–368.
- Anonymous (1987). *Federal Register* 52, 37654–37656.
- ASAE. (1996). *ASAE standard: standards, engineering practices and data*. American Society of Agricultural Engineers, St. Joseph, MI.
- Breidt, F., & Fleming, H. P. (1998). Modeling of the competitive growth of *Listeria monocytogenes* and *Lactococcus lactis* in vegetable broth. *Applied Environmental Microbiology*, *64*, 3159–3165.
- Draper, N.R., & Smith, H. (1981). *Applied Regression Analysis*. New York: John Wiley & Sons.
- Esselen, W. B., & Anderson, E. E. (1957). The pasteurization of pickles. *The Glass Packer*, *36*, 46–50.
- Esselen, W. B., Anderson, E. E., Fagerson, I. S., & Labbee, M. (1952a). Pasteurized fresh whole pickles. V. Factors influencing pasteurization requirements. *The Glass Packer* *31*, 326–327, 346–347.
- Esselen, jr., W. B., Anderson, E. E., Ruder, jr., L. F., & Pflug, I. J. (1951). Pasteurized fresh whole pickles. I. Pasteurization studies. *Food Technology*, *V*, 279–284.
- Esselen, W. B., Fagerson, I. S., Pflug, I. J., & Anderson, E. E. (1952b). Pasteurized fresh whole pickles III. Heat penetration in fresh pack pickles. *The Glass Packer* *31*, 175–178, 201.

- Etchells, J. L., Bell, T. A., Costilow, R. N., Hood, C. E., & Anderson, T. E. (1973). Influence of temperature and humidity on microbial, enzymatic, and physical changes of stored, pickling cucumbers. *Applied Microbiology*, 26, 943–950.
- Etchells, J. L., Bell, T. A., & Jones, I. D. (1955). Studies on the origin of pectinolytic and cellulolytic enzymes in commercial cucumber fermentation. *Food Technology* 9, 14, 16.
- Etchells, J. L., Costilow, R. N., Anderson, T. E., & Bell, T. A. (1964). Pure culture fermentation of brined cucumbers. *Applied Microbiology*, 12, 523–535.
- Etchells, J. L., & Jones, I. D. (1942). Pasteurization of pickle products. *Fruit Products Journal*, 21, 330–332.
- Etchells, J. L., & Jones, I. D. (1944). Procedure for pasteurizing pickle products. *The Glass Packer* 23, 519–523, 546.
- Fasina, O. O., & Sokhansanj, S. (1995). Modeling the bulk cooling of alfalfa pellets. *Drying Technology*, 13(8&9), 1881–1904.
- Fleming, H. P. (1982). Fermented vegetables. In A.H. Rose (Ed.), *Economic microbiology. Fermented food* (Vol. 7, pp. 227–258). New York: Academic Press.
- Fleming, H. P., Kyung, K. H., & Breidt, F. (1995). Vegetable fermentations. In H. J. Rehm, & G. Reed (Eds.), *Biotechnology* (Vol. 9, pp. 631–661). New York: VCH.
- Fleming, H. P., & Moore, W. R., Jr. (1983). Pickling. In I.A. Wolff (Ed.), *Processing of horticultural crops in the United States. CRC handbook of processing and utilization in agriculture* (Vol. II, pp. 397–463). Boca Raton, FL: CRC Press.
- Humphries, E. G., & Fleming, H. P. (1989). Anaerobic tanks for cucumber fermentation and storage. *Journal of Agricultural Engineering Research*, 44, 133–140.
- Incropera, F. P., & DeWitt, D. P. (1996). *Fundamentals of heat and mass transfer* ((4th ed.)). New York: Wiley.
- Holman, J. P. (1996). *Heat transfer* ((8th ed.)). New York: McGraw-Hill.
- Labbee, M., Esselen, W. B., & Anderson, E. E. (1952). Pasteurized fresh whole pickles. IV. Enzymes and off-flavor in fresh pack pickles. *The Glass Packer* 31, 252–253, 282.
- Meneley, J. C., & Stanghellini, M. E. (1974). Detection of enteric bacteria within locular tissue of healthy cucumbers. *Journal of Food Science*, 39, 1267–1268.
- Mohsenin, N. N. (1986). *Physical properties of plant and animal materials: Structure, physical characteristics and mechanical properties* ((2nd ed.)). New York: Gordon and Breach.
- Monroe, R. J., Etchells, J. L., Pacilio, J. C., Borg, A. F., Wallace, D. H., Rogers, M. P., Turney, L. J., & Schoene, E. S. (1969). Influence of various acidities and pasteurizing temperatures on the keeping quality of fresh-pack dill pickles. *Food Technology*, 23, 71–77.
- Myers, G. E. (1971). *Analytical methods in conduction heat transfer*. New York: McGraw-Hill.
- Nicholas, R. C., & Pflug, I. J. (1962). Over- and under-pasteurization of fresh cucumber pickles. *Food Technology*, 16, 104–108.
- Nicholas, R. C., Pflug, I. J., & Costilow, R. N. (1957). Effects of jar size, liquor, and product-to-liquor ratio on heating characteristics of fresh-packed pickle products. *Food Technology*, XI, 488–490.
- Ozisk, M. N. (1985). *Heat transfer – a basic approach*. New York: McGraw-Hill.
- Rodrigo, M., & Alvarruiz, A. (1988). The influence of fermentation and pasteurization on the texture of cucumber pickles. *Journal of Food Engineering*, 7, 113–125.
- Samish, Z., Etinger-Tulczynka, R., & Bick, M. (1963). The microflora within the tissue of fruits and vegetables. *Journal of Food Science*, 28, 259–266.
- SAS. (1996). *SAS Users' Guide*. Statistical Analysis Systems Inc., Cary, NC.
- Singh, R. P., & Heldman, D. R. (1993). *Introduction to food engineering* ((2nd ed.)). New York: Academic Press.
- Sweat, V. E. (1986). Thermal properties of foods. In M.A. Rao, & S.S.H. Rizvi (Eds.), *Engineering properties of foods* (pp. 49–87). New York: Marcel Dekker.