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Modeling fruit internal heating rates for hot air and hot water treatments

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Abstract

Hot air and hot water heating methods have been extensively studied as thermal treatments to control insect pests in fruits to replace chemical fumigation. An inherent difficulty in using these methods is that slow heating rates may result in long treatment times and possible damage to fruit quality. Many factors influence heating time. A systematic analysis of those influences is desirable to help in designing effective treatment protocols. A simulation model based on heat transfer theory was developed to study the effect of fruit thermal property, fruit size, heating medium and heating medium speed on heat transfer rates within spherical fruits. The simulation demonstrated that the small variation in thermal diffusivity among fruits had little effect on heating time. Fruit internal heat transfer rate was significantly influenced by fruit size and by heating medium. Water was a more efficient medium than air and increasing air speed increased heating rates. Water circulation speeds had little influence on heat transfer rate. The Biot number showed that internal energy transfer by conduction was a heating rate limiting factor. Combining low frequency electromagnetic energy with hot air or hot water eliminated conduction as a major rate-limiting factor because the energy was directly delivered to the fruit interior. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Thermal medium heating; Fruit disinfestation; Simulation model; Heat transfer

1. Introduction

Thermal treatment methods using hot water, vapor or hot air have been investigated extensively as alternatives to methyl bromide fumigation for fruit disinfestation (Sharp et al., 1991; Yokoyama et al., 1991; Moffitt et al., 1992; Neven, 1994; Neven and Rehfield, 1995; Neven et al., 1996; Lurie, 1998; Mangan et al., 1998). Varying degrees of efficacy have been reported using different thermal treatments alone or in combination with cold or controlled atmosphere (CA) storage conditions (Toba and Moffitt, 1991; Neven and Mitcham, 1996; Soderstrom et al., 1996; Shellie et al., 1997). Since insects may stay in the center of the fruit, the thermal energy needs to be delivered to that location. Conventional heating consists of convective heat transfer from

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the heating medium to the fruit surface and then conductive heat transfer from the surface to the fruit center. A common difficulty with hot air or water heating methods is the slow rate of heat transfer resulting in hours of treatment time (Hansen, 1992). Reported heating times for fruit center to reach the desired maximum temperatures range from 23 min for cherries to 6 h for apples (Table 1). Thermal energy delivered to the interior of the fruits was significantly influenced by fruit size, heating medium temperature and heating methods. Slow conductive heat transfer often led to heating times in excess of 60 min. In general, external and internal damage caused by heat over long exposure times included peel browning, pitting, poor color development and abnormal softening (Lurie, 1998). Visible heat damage was reported in grapefruits exposed to forced vapor at 46°C for 3.75 h (Hallman et al., 1990) and in mangos exposed to CA at more than 45°C for 160 min (Ortega-Zaleta and Yahia, 2000). Flavor and appearance of air-heated grapefruits at 46°C for 3 h with CA were inferior to those of non-heated fruits (Shellie et al., 1997). Surface browning of avocados was observed when heated with hot air at 43°C for 3.5 h (Kerbel et al., 1987). Skin browning and internal breakdown were observed in apples exposed to hot water treatment at 46°C for 45 min (Smith and Lay-Yee, 2000). There is a need to fully understand the influence of various factors on heat transfer in fruits to minimize adverse effects on fruit quality.

Heat transfer theory has been well-established (Campbell, 1977; Incropera and DeWitt, 1996; Dincer, 1997; Holdsworth, 1997). However, little has been reported in the horticultural literature on the application of heat transfer theory to study heating rates for fruit disinfestation. Past research efforts on thermal quarantine treatments were mostly empirical and were pest and commodity specific. These tests are very labor intensive and costly, and the results are only useful for the fruits tested under the specific conditions investigated. Investigations of the influence of physical parameters on heat transfer rate can be based on fundamental heat transfer theory via computer simulation models. A major advantage of the computer simulation model is its ability to assess the effect of various physical parameters on heating profiles in fruits. Hayes and Young (1989) developed a thermal diffusion model to predict temperature variation at different depths in papaya when it was heated in hot water, but they did not investigate the influence of different heating methods and fruit physical parameters on fruit temperature profiles. Hansen (1992) developed empirical models to correlate fruit center temperature to heating time. However, the parameters in those empirical models were limited to fruits tested in that study.

The objectives of this study were to develop from theory a heat transfer simulation model for fruits, and to use this model to determine the relative importance of fruit thermal diffusivity, fruit size or heating method on the rate of heat transfer to the fruit center. Evaluation of the influence of various factors provided insight into the limitations of hot air and hot water heating methods and provided a means of optimizing these treatments. The potential of using low frequency electromagnetic energy to deliver the thermal energy directly into the fruit center was considered.

2. Materials and methods

2.1. Heat transfer model

The geometry of most fruits, such as cherries, apples and oranges, can be characterized as a spherical shape. Temperature distribution in those fruits is thus a function of radial position and treatment time. In conventional heating, hot air and/or water is the source of thermal energy. Thermal energy is transferred from the heating medium to the fruit surface ($r = r_o$) by convection as described by the following boundary heat flux equation (Dincer, 1997):

$$\underbrace{-k\frac{\partial T}{\partial r}}_{\text{Heat flow into fruit}}\Bigg|_{r=r_o} = \underbrace{h[T(r_o,t) - T_e]}_{\substack{\text{Heat flow from heating medium}\\ \text{(Convection to heat fruit surface)}}} \quad (1)$$

where k is the thermal conductivity of the fruit (W m^{-1}°C^{-1}), h is the surface heat transfer coeffi-

Table 1
Heating characteristics of fruits during thermal treatments reported in the literature

Medium temp. (°C)	Heating methods	Fruit	Heating medium speed (m s^{-1})	Max. center temp. (°C)	Heating time (min)	Sources
40	Hot air	Apple	1	40	360	Whiting et al. (1999)
44	Hot air	Apple	2	42	97	Neven et al. (1996)
45	Hot air	Tangerine	2	45	115	Shellie et al. (1993)
45	Hot air	Cherry	2	44	23	Neven & Mitcham (1996)
46	Hot air	Orange	2	46	145	Mangan et al. (1998)
48	Hot water	Small Potato	2	48	140	Hansen (1992)
48	Hot water	Large Potato	2	48	220	Hansen (1992)
48	Hot water	Grapefruit	2	48	300	Shellie & Mangan (1996)
50	Hot air	Mango	2	48	150	Mangan & Ingle (1992)
52	Hot air	Mango	2.5	39	75	Sharp et al. (1991)

cient (W m^{-2}°C^{-1}), r is the radial coordinate originate from the fruit center, r_o is the fruit radius (m), t is the treatment time (s), T is fruit temperature (°C), and T_e is the heating medium temperature (°C). According to Eq. (1), heat flux from the heating medium to the fruit surface is proportional to the surface heat transfer coefficient, h, and the temperature difference between the heating medium and the fruit surface [$T(r_0,t)$-T_e]. With forced convection and turbulent flow, the convective heat transfer coefficient can be estimated based on boundary layer similarity for a sphere (Campbell, 1977; Dincer, 1997):

$$h = \frac{k_f \mathrm{Nu}}{d} = 0.34\frac{k_f}{d}\left(\frac{ud}{v_f}\right)^{0.6} \tag{2}$$

where d is the sphere diameter (m), k_f is the thermal conductivity of the medium (W m^{-1}°C^{-1}), Nu is the dimensionless Nusselt number, u is the heating medium speed (m s^{-1}) and v_f is the kinematic viscosity of the medium (m^2 s^{-1}). Thermal resistance at the fruit surface can be considered as $1/h$. Increasing air or water speed increases the value of h, and reduces thermal resistance at the fruit surface.

Once the thermal energy is transferred to the fruit surface, it moves into the fruit interior by conduction. Fruit temperature as a function of time at any locations within spherical fruit is governed by a general energy balance equation (Holdsworth, 1997):

$$\underset{\textit{Heating rate}}{\rho C_p \frac{\partial T}{\partial t}} = \underset{\textit{Heat conduction within fruit}}{k\left(\frac{\partial^2 T}{\partial^2 r} + \frac{2}{r}\frac{\partial T}{\partial r}\right)} \underset{\textit{Heat generation}}{+ Q} \tag{3}$$

where C_p is the specific heat of the fruit (J kg^{-1}°C^{-1}), Q is the heat generation within the fruit (Wm^{-3}), and ρ is the fruit density (kg m^{-3}). Relative to externally applied energy, the heat of respiration is small over the period of quarantine heating. Thus, $Q = 0$. Dividing by ρC_p and substituting α for $k/\rho C_p$, Eq. (3) becomes:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial^2 r} + \frac{2}{\mathrm{r}}\frac{\partial T}{\partial r}\right) \tag{4}$$

where α is the thermal diffusivity (m^2 s^{-1}). Conductive heat transfer within fruit, as represented by the right hand side of Eq. (4), is slow due to the relatively small value of thermal diffusivity for fruits ($\alpha \approx 1.6 \times 10^{-7}$ m^2 s^{-1}, as compared to 1.5–17×10^{-5} m^2 s^{-1} for metals). As a result, the heating rate at the fruit center can be very slow, especially for large fruits such as apples. The internal thermal resistance can be represented by a value of r_0/k. The influence of surface and internal thermal resistances on the heating rate can be described by the non-dimensional Biot number (Bi) defined as (Incropera and DeWitt, 1996):

$$\mathrm{Bi} = \frac{\text{Internal resistance}}{\text{Surface resistance}} = \frac{hr_0}{k} \tag{5}$$

When Bi is less than 0.1, the surface thermal resistance dominates the rate of heat transfer and the internal temperature gradients are small. When the Bi number is large (e.g., 10), internal thermal resistance plays the most important role and the internal temperature gradients are significant.

When provided with initial fruit temperature, heating medium temperature and speed, fruit diameter and thermal properties, Eq. (4) in combination with Eq. (1) can be solved numerically. In developing the simulation model in this study, Eqs. (1) and (4) were replaced by finite difference equations at different depths and then were reduced to a group of algebraic equations. Fruit temperature as a function of time and depth was obtained using an iterative procedure with a simulation time step of 1 s.

2.2. Validation of the simulation model

A simulation model must be validated before it can be used with confidence. In this study, the simulation model was validated both by analytical solutions and by experiments.

2.2.1. Model validation by analytical solutions

Analytical solutions to transient heat conduction problems have been presented in general temperature-time charts (Heisler, 1947). These charts provide information in dimensionless temperature based on Biot and Fourier numbers and have been extensively used in engineering calculations (Incropera and DeWitt, 1996; Dincer, 1997). The comparison between simulation results and analytical solutions was conducted for a fruit of $d = 9$ cm and $\alpha \approx 1.7 \times 10^{-7}$ m^2 s^{-1} at an initial temperature of 21°C. When subjected to forced hot air ($h = 13$ W m^{-2}°C^{-1}) at a constant temperature of 52°C, temperatures at the fruit surface and the center as a function of the heating time were obtained by the simulation model. Temperatures at the fruit surface and the center at selected heating times (0, 50, 100 and 200 min) were also estimated from the analytical solutions.

2.2.2. Model validation by experimental methods

Heating tests with forced air were conducted in a tray drier (UOP8, Armfield Limited, UK) (Fig. 1). Ambient air was moved by a fan through a square duct (28 × 28 cm^2) and heated by a group of electric heaters. The air speed and the final air temperature were regulated by fan speed and electric heater power settings. The test samples were put in the middle section of the drier. Air speed, temperature and sample temperatures were measured by a hot-wire anemometer and type-T thermocouples, respectively. All data were recorded by a data logger (Strawberry Tree Inc., Sunnyvale, California, USA).

Heating tests with forced hot water were performed using a water bath (model ZD, Grant, Cambridge, UK) in which a constant temperature was maintained and the water was circulated at a speed of about 1 m s^{-1}. The samples were immersed completely in the water.

'Red Delicious' apples or 'Bing' cherries were used in the tests. The average fruit diameters for apples and cherries were 7.2 and 2.4 cm, respectively. All tests were conducted in triplicate.

To validate the computer model, predictions were compared with experimental data. The goodness of fit was evaluated by mean temperature difference (MTD, °C) defined as:

$$\mathrm{MTD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[T_{\mathrm{sim}}(i) - T_{\mathrm{mea}}(i)]^2} \tag{6}$$

where T_{sim} is the simulated temperature (°C) and T_{mea} is the measured temperature (°C) at selected locations in the fruit, and N stands for the number of data points collected over a selected period of time.

2.3. Radio frequency electromagnetic heating

In convection heating with air and water, heating rate decreases with treatment time, especially when the center temperature is close to the medium temperature, due to the significant decrease of the convective and conductive heat fluxes as expressed in Eqs. (1) and (3). This is a general limitation of conventional heating. If additional heat energy Q, in Eq. (3), is added by radio frequency (RF) heating, the heating rate will not be limited to the temperature gradients between the fruit surface and the heating medium.

A unique feature of RF treatments is that RF energy is directly coupled to a dielectric (lossy) material to generate heat, Q (W m^{-3}) in Eq. (3). This can significantly increase the heating rates and reduce heating time. The magnitude of the heat generation is proportional to the loss factor ε'', at a given frequency f (Hz) and electric field E (V m^{-1}) (Nelson, 1996):

$$Q = 5.563 \times 10^{-11} f\varepsilon'' E^2 \tag{7}$$

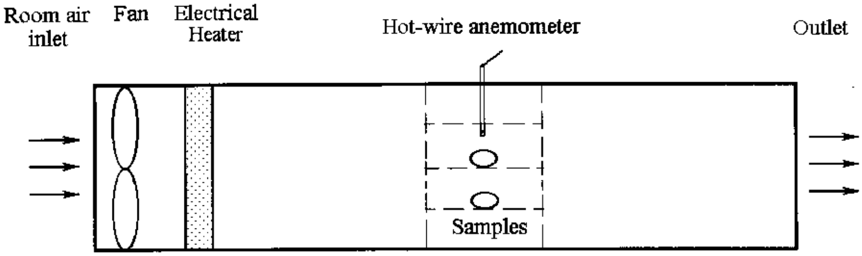

Fig. 1. Schematic view of the forced hot air test apparatus.

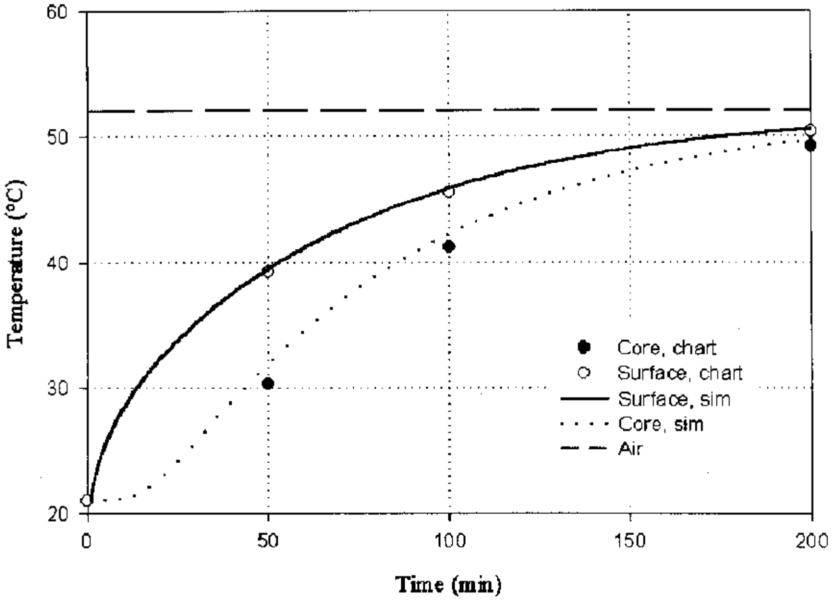

Fig. 2. Temperatures at the fruit (9 cm diameter) surface and center obtained by simulation (sim) and analytical charts (Dincer, 1997) using $h = 13$ W $\mathrm{m^{-2}{}^{\circ}C^{-1}}$.

For a fast heating process in which heat conduction is relatively small, Eq. (3) reduces to:

$$\partial T = \frac{Q}{\rho C_\mathrm{p}} \partial t. \tag{8}$$

That is, the temperature increases linearly with treatment time. Adjusting RF power may control the temperature-increasing rate. This is a major advantage of RF heating over conventional heating methods.

A 6 kW, 27 MHz pilot scale RF system (Combi6-s, Strayfield International Limited, Workingham, UK) with plate electrodes was used to heat six apples. A detailed description of the RF system is given in Wang et al. (2000). Individual 'Red Delicious' apples with a diameter of 7.2 cm were heated between the electrode plates. The gap of the electrodes in the RF system was adjusted to provide 0.5 kW of power. The apple center temperature was measured by a FISO fiber-optic sensor system (UMI, FISO Technologies Inc., Saint-Foy, Canada). The experimental apple center temperature in the RF system was compared to the heating rate in hot air with an air speed of 4 m $\mathrm{s^{-1}}$.

3. Results and discussion

3.1. Model precision

As shown in Fig. 2, the simulation results agreed well with the analytical solutions, both for fruit surface and center temperatures. The MTD values between simulated and analytical solutions were 1.10 and 0.30°C for the center and surface temperatures, respectively. However, the general analytical charts consist of curves for dimensionless temperatures, Biot and Fourier numbers over a large range of values. For fruits undergoing conventional heating, those charts were difficult to estimate a temperature profile at the beginning of the heating period, because the curves are clustered (Heisler, 1947). The computer simulation was used to predict conventional heating performance after further validation using experiments.

Fig. 3 shows the simulated and measured apple center and surface temperatures when exposed to forced hot air with air speeds of 1 and 4 m $\mathrm{s^{-1}}$. At the beginning of heating, the apple center temperature increased very slowly due to a significant thermal lag from the surface to the center. Similarly, the increase in fruit center temperature slowed when this temperature approached the heating medium temperature. When the air speed increased from 1 to 4 m s^{-1}, the heating time to reach a specific temperature was reduced. The MTD differences between the measured and predicted temperatures at the apple center and the surface were calculated by Eq. (6), and the results are shown in Table 2. MTD values were 1.05 and 0.72°C for apple center and surface temperatures when subjected to hot air heating at an air speed of 1 m s^{-1}. Those values were reduced to 0.68 and 0.65°C when the hot air speed increased to 4 m s^{-1}. Large discrepancies between simulation and measurement were found at the beginning of heating. The error was probably caused by the actual non-spherical shape.

Fig. 4 shows the simulated and measured apple center and surface temperatures during hot water

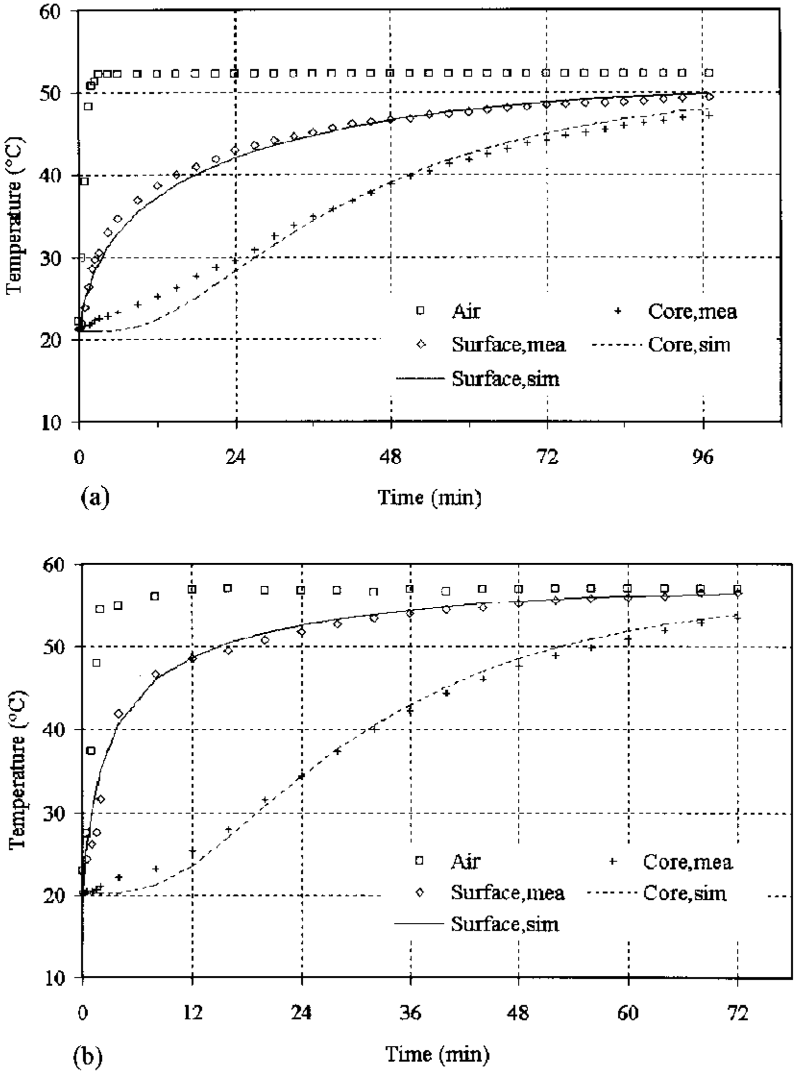

Fig. 3. Comparison of the surface and center temperatures of apples (7.2 cm diameter) between measurement (mea) and simulation (sim) for hot air heating at a speed of 1 m s^{-1} (a) and 4 m s^{-1} (b).

Table 2
Mean temperature difference (MTD, °C) between measured and predicted temperatures using the computer simulation model

Fruits, heating methods	MTD at the center (°C)	MTD at the fruit surface (°C)
Apple, air heating at air speed 1 m s^{-1}	1.05	0.72
Apple, air heating at air speed 4 m s^{-1}	0.68	0.65
Apple, water heating at water speed 1 m s^{-1}	0.11	0.04
Cherry, water heating at water speed 1 m s^{-1}	0.05	N/A

heating. The heating rate was greater than during hot air heating. The MTD values for apple center and surface temperatures during hot water heating were 0.11 and 0.04°C (Table 2), respectively. But for cherries during hot water heating (Fig. 5), the MTD value for the center temperature was 0.05°C. The close agreement between simulation and experiment demonstrated that the simulation model was able to predict fruit temperatures under these conditions.

3.2. *Influence of fruit physical parameters on heating rates at the fruit center*

The validated heating model was used to study the influence of different physical parameters on heat transfer in fruits.

3.2.1. *Influence of fruit thermal diffusivity*

Thermal conductivity, specific heat and density are primary thermal properties of fruits that influence heating rates. Since the fruit temperature used in thermal treatments is normally between 20 and 55°C, the variation in fruit thermal properties was small (Holdsworth, 1997). Typical values reported in the literature are listed in Table 3 (Mohsenin, 1980; Hayes and Young, 1989; Rahman, 1995). It is important to note from Eq. (4) that the combined parameter, the thermal diffusivity α, is the only internal fruit thermal property that governs the temperature variation within fruits. Although large variations may exist in density (ρ), specific heat (C_p) and thermal conductivity (k) for different fruits and varieties (Table 3), the values of thermal diffusivity for fruits fall between 1.4×10^{-7} and 1.7×10^{-7} $m^2\,s^{-1}$. The simulation model was used to study the influence of three thermal diffusivities

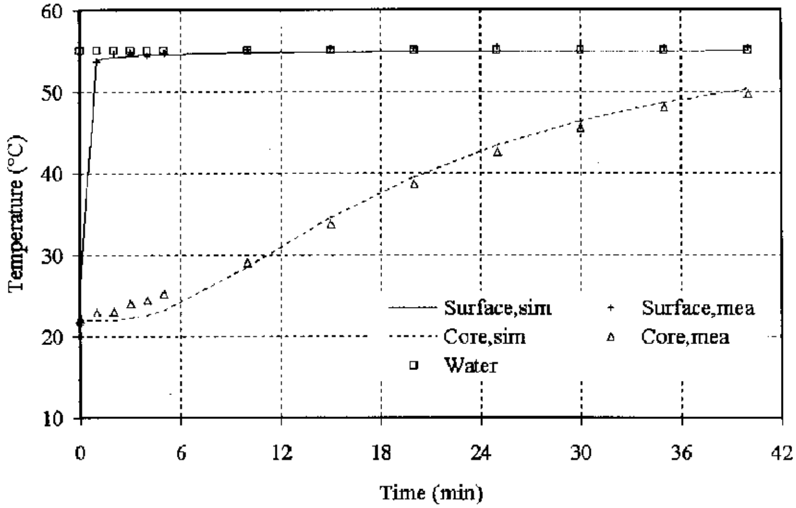

Fig. 4. Comparison of the surface and center temperatures between measurement (mea) and simulation (sim) for apples (7.2 cm diameter) in a water bath (55°C, 1 m s^{-1}).

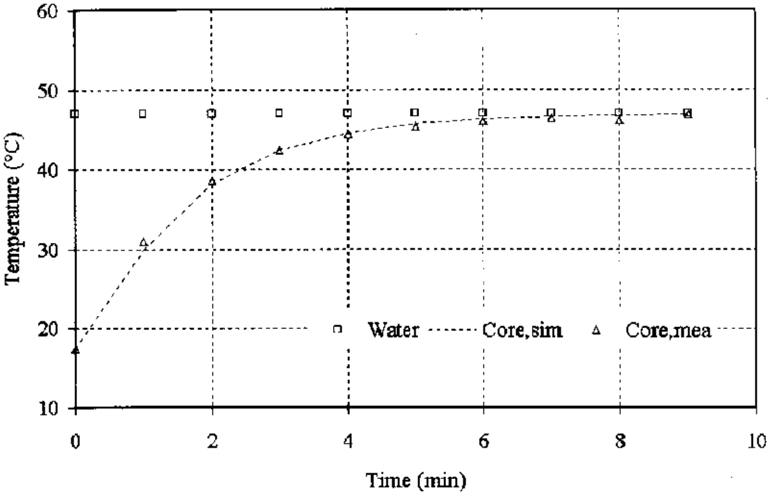

Fig. 5. Comparison of the center temperature between measurement (mea) and simulation (sim) for cherries (2.4 cm diameter) in a water bath (47°C, 1 m s^{-1}).

(1.4×10^{-7}, 1.6×10^{-7} and 1.8×10^{-7} m^2 s^{-1}) on heating rates of a 6 cm diameter fruit.

Fig. 6 shows the effect of thermal diffusivities on the heating rate at the fruit center when subjected to hot air at a speed of 1 m s^{-1}. The higher the thermal diffusivity, the faster the heating rate. The heating periods were 84, 81 and 79 min to reach 50°C for thermal diffusivities of 1.4, 1.6 and 1.8 × 10^{-7} m^2 s^{-1}, respectively. That is, regardless of the fruit variety or type, the heating rates are close for a given size fruit when heated with hot air. Similarly simulation results were obtained for the diffusivity effect on the heating rate when subjected to hot water circulating at 1 m s^{-1} (Fig. 7). It took about 26, 23 and 21 min for the fruit of 6 cm diameter with above three diffusivities to reach 50°C.

The difference of thermal diffusivity from its middle value (1.6×10^{-7} m^2 s^{-1}) resulted in about 4 and 13% difference in heating time for hot air and water treatments, respectively. Different effects of thermal diffusivity during hot air or water heating have been the result of the relative magnitude between the internal and surface heat resistance. The Bi number (Eq. (5)) for hot air heating for fruit of 6 cm diameter was between 1 and 3, and for hot water was between 82 and 130 (Table 4). This suggests that the internal heat resistance in fruit during water heating was a more dominant factor in controlling the heat transfer rates than in hot air. As a result, variation in the thermal diffusivity caused a relatively large variation in heating time during hot water heating as compared with hot air heating. However, this difference in heating times was small when compared to the effect of fruit size or heating methods. In general, the variations in thermal diffusivity among fruit varieties and types may not influence heating time to cause any practical concern in real treatment systems. It is, therefore, possible to use a substitute fruit of desired size for heating tests when the fruit is out of season and not available. In the following studies, a model fruit having a thermal diffusivity of 1.6×10^{-7} m^2 s^{-1} was used to analyse influence or other parameters.

3.2.2. Influence of fruit size

The effect of fruit sizes (3, 6 and 9 cm diameter) on heat transfer to the fruit center was assessed using the simulation model. Fig. 8 shows the fruit center temperature as influenced by different fruit diameters when subjected to forced hot air (air temperature, 55°C; air speed, 1 m s^{-1}). The center temperatures of the fruit took about 28, 81, and 153 min to reach 50°C for diameters of 3, 6 and 9 cm, respectively. The heating process for small fruits was much faster than for large fruits. It is clear that the effect of fruit size was very important as compared to variations in thermal diffusivity among fruit varieties.

Table 3
Thermal properties of selected fruits

Fruits	Density ρ (kg m^{-3})	Specific heat C_p (J kg^{-1}°C^{-1})	Thermal conductivity k (W m^{-1}°C^{-1})	Thermal diffusivity α ($\times 10^{-7}$ m^2 s^{-1})	Sources
Apple (green)	790	3700	0.422	1.44	Rahman (1995)
Apple (red)	840	3600	0.513	1.70	Rahman (1995)
Cherry	1010	3643	0.511	1.39	Mohsenin (1980)
Cherry tomato	1010	3300	0.527	1.58	Rahman (1995)
Orange	1030	3661	0.580	1.54	Rahman (1995)
Papaya	N/A	3433	N/A	1.52	Hayes & Young (1989)
Pear	1000	3700	0.595	1.61	Rahman (1995)
Potato	1100	3515	0.560	1.45	Rahman (1995)

When fruits of different sizes were subjected to hot water treatments (55°C, 1 m s^{-1}), it took about 6, 23 and 52 min to reach 50°C for the fruit diameter of 3, 6 and 9 cm, respectively (Fig. 9). The heating time in water immersion was much shorter than with the hot air heating. A 1-cm diameter difference (17%) among medium size fruits would result in a 27 and 35% difference in time for fruits to reach 50°C for hot air and hot water treatments, respectively. Heat conduction in fruits depends largely on fruit size. Little can be done to increase internal heat conduction. Therefore, sorting is very important to help achieve uniform heating among fruits when using hot air or hot water treatments.

3.2.3. *Influence of heating medium speeds*

Computer simulation results are presented in Fig. 10 for a fruit of 6 cm diameter in hot air under different air circulating speeds. When heated in circulating air at 0.5 m s^{-1} and 55°C, the center temperatures of the fruit increased very slowly to approach the heating medium temperature. For example, it took about 113 min for the center temperature to increase from 20 to 50°C (Fig. 10). By increasing circulating air speed to 1, 2 and 4 m s^{-1}, the time for the same center temperature rise was reduced to about 81, 61 and 47 min, respectively. The value of the Bi number for air heating was a little larger than 1 (Table 4), so that the thermal resistance at the surface boundary layer was comparable to that within the fruits. The effect of increasing air speeds on the heat transfer was the result of the increased heat transfer coefficient and increased Bi number as shown in Eqs. (2) and (5). Attention should be paid to uniform air distribution to ensure uniform heating among fruit in bins and chambers. For example, if air speeds at the center and corner of a chamber varied from 0.5 to 2 m s^{-1}, the heating time of the fruits at those positions will vary by about 46%.

When heated in a circulating water bath at 55°C, the heating rate at the fruit center was significantly increased as compared to hot air heating. Yet, it still took about 23 min for the center temperature to rise to 50°C. Water circulating speeds had little effect on heating time. This was because in all cases the Bi number was greater

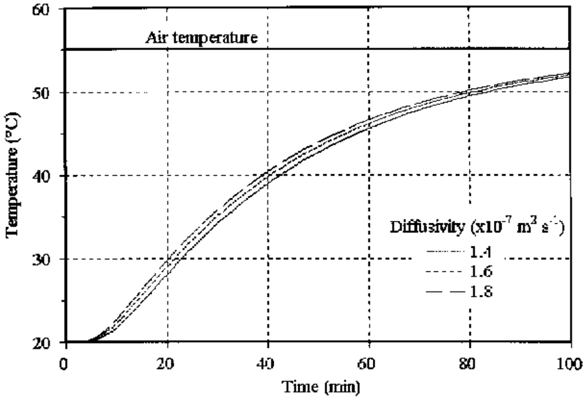

Fig. 6. Simulated center temperatures of a fruit (6 cm diameter) influenced by thermal diffusivity when subjected to hot air (55°C, 1 m s^{-1}).

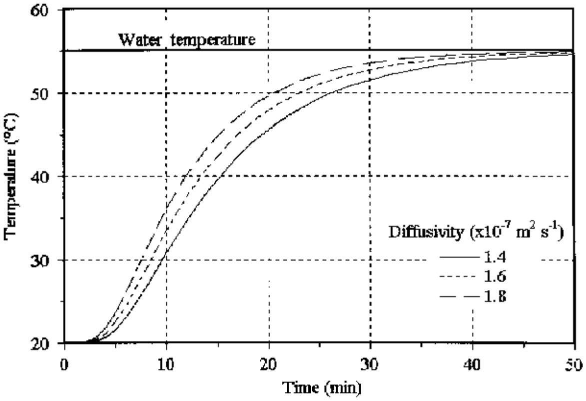

Fig. 7. Simulated center temperatures of a fruit (6 cm diameter) influenced by thermal diffusivity when subjected to hot water (55°C, 1 m s^{-1}).

than 50 (Table 4), indicating that the surface thermal resistance was very small compared to the internal thermal resistance. When using water as the heating medium, further reduction in the surface thermal resistance by increasing water circulation speed will not practically increase the heating rate. In this case the only benefit of water circulation is to ensure temperature uniformity among the individual fruit. Circulating water as a heating medium for fruits represented a practical best-case scenario in terms of heat transfer to deliver thermal energy to the fruit surface with conventional heating methods. In practice, only a small circulating water speed is needed to provide uniform water temperature in a conveying flume.

3.3. Radio frequency heating

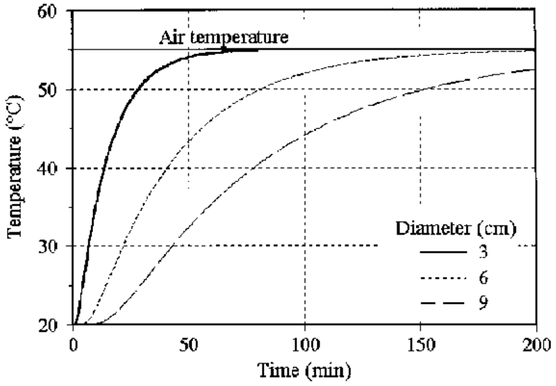

Fig. 8. Simulated center temperatures of a fruit with a thermal diffusivity of 1.6 × 10^{-7} m^2 s^{-1} influenced by diameter when subjected to hot air (air speed, 1 m s^{-1}).

Fig. 11 shows experimental time–temperature profiles for an apple (7.2 cm diameter) center when subjected to hot air treatment (55°C at 4 m s^{-1} air speed) and a RF treatment. With hot air treatment, the heating rates were very small at the beginning and decreased as the apple temperature approached the heating medium temperature. It took about 56 min for the apple center to reach 50°C. With RF treatment, the apple center temperature increased linearly with process time, as predicted by Eq. (8). The heating rate can be further increased by RF power input. After only a 4.9 min treatment, the center temperature reached 54°C in air. RF treatments have particular advantages over conventional hot air heating in treating large fruits. Similar results were obtained for wal-

Table 4
Simulated Biot (Bi) number of a fruit with a diameter of 6 cm and a thermal diffusivity of 1.6×10^{-7} m^2 s^{-1}

Cases	Bi
Air heating at air speed 1 m s^{-1}	1.1
Air heating at air speed 4 m s^{-1}	2.5
Water heating at water speed 0.5 m s^{-1}	82.7
Water heating at water speed 1 m s^{-1}	125.4

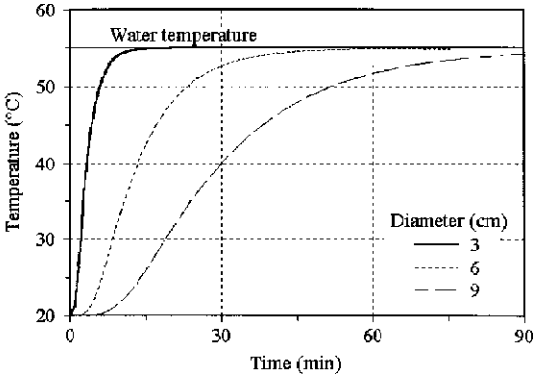

Fig. 9. Simulated center temperatures of a fruit with a thermal diffusivity of 1.6 × 10^{-7} m^2 s^{-1} influenced by diameter when subjected to hot water (55°C, 1 m s^{-1}).

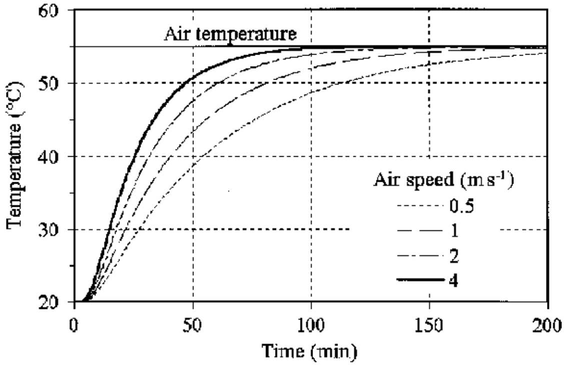

Fig. 10. Simulated center temperatures of a fruit (6 cm diameter) with a thermal diffusivity of 1.6×10^{-7} m^2 s^{-1} influenced by air speed when heated by hot air (55°C).

nuts when subjected to RF and hot air treatments (Wang et al., 2000). Walnut kernel temperature took 3 min to reach 53°C in RF system but took more than 40 min to reach 48°C in hot air at 53°C with air speed of 1 m s^{-1}. This is a potential way to control insect pests in fruits without causing significant damage to fruit quality.

In RF treatment, however, it is crucial to provide uniform heating so that insects in fruits are subjected to similar thermal energy. In general, when treating fruit in air during RF treatments, the center temperature tends to increase faster than that at the surface. This problem can be solved by combining the RF treatment and hot air or water heating. Another practical solution is to immerse the fruit in saline water during RF treatment. The heating rate at the fruit center and the water surface can be equalized by adjusting the salt concentration of the water (Ikediala et al., 2001).

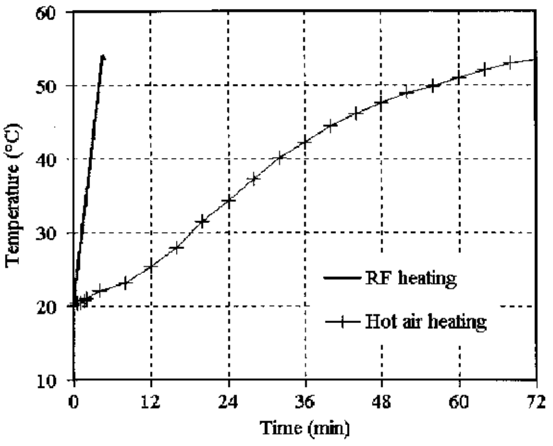

Fig. 11. Experimental heating curves for the apple (7.2 cm diameter) center when subjected to forced hot air (air temperature, 55°C; air speed, 4 m s^{-1}) and radio frequency (RF: 27.12 MHz) treatments.

3.4. Practical application of the model

The simulation model was reduced from a set of differential equations that govern heat transfer in fruits into a group of algebra equations. The model was executed in this study using a BASIC programming language, but it can be easily adapted to an EXCEL file. The inputs of this program were fruit properties (diameter and diffusivity), boundary conditions (heating medium speed and temperature, and initial fruit temperature) and heating methods (air or water). The outputs were the temperature history at selected locations in fruits. The temperature–time profile can be readily used with other information, such as insect mortality kinetics or quality degradation kinetics to evaluate thermal treatments based on hot air or water heating methods (Tang et al., 2000).

Precaution needs to be taken when using the model for analyzing large-scale systems in which a large amount of fruit is treated. In a realistic system in which bulk fruit are treated, each fruit may be exposed to different conditions depending upon the flow pattern of the heating medium and the design of the system. However, studying heating of individual fruit serves as a basis for understanding the influence of the flow pattern in a large-scale system.

4. Conclusions

With the simulation model validated by analytical solutions and experimental results, the influence of various parameters on heating rates when using forced hot air and water treatments was systematically studied. The effect of fruit diffusivity on the heat transfer was not significant. The most important parameters in the model were the fruit size, the heating medium and the heating medium speed. Water was a more efficient heating medium than air and increasing air speed raised the heating rate in fruits. Water circulation speeds had little influence on heating rates.

This study demonstrated that the computer simulation model could be used to evaluate the influence of various treatment conditions on the temperature–time history in fruits. Furthermore, when combined with insect mortality and quality kinetic information, it could predict the efficacy of a particular treatment and guide appropriate selection of treatment conditions.

A fast heating method using RF energy was considered. With this method, the electric energy was directly delivered to the fruit center and the fruit temperature increased linearly with the heating time. This represents a major advantage over conventional heating methods.

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