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Processing and quality characteristics of apple slices processed under simultaneous infrared dry-blanching and dehydration with intermittent heating

Yi Zhu [a], Zhongli Pan [b,c,*], Tara H. McHugh [b], Diane M. Barrett [a]

[a] Department of Food Science and Technology, University of California, Davis, One Shields Avenue, CA 95616, USA
[b] Processed Foods Research Unit, USDA-ARS-WRRC, 800 Buchanan St., Albany, CA 94710, USA
[c] Department of Biological and Agricultural Engineering, University of California, Davis, One Shields Avenue, CA 95616, USA

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ABSTRACT

This study investigated the effects of three processing parameters, e.g. product surface temperature, slice thickness and processing time, on blanching and dehydration characteristics of apple slices exposed to simultaneous infrared dry-blanching and dehydration (SIRDBD) with intermittent heating. A three-factor factorial experiment design was conducted to determine the influence of processing parameters on product temperature, moisture reduction, drying rate, residual polyphenol oxidase (PPO) and peroxidase (POD) activities and surface color change. Slice thickness had a significant effect on product quality and processing characteristics, as faster inactivation of enzymes and quicker moisture reduction took place in thinner slices. A Page model performed well for describing drying behavior during the treatment, and first-order kinetics and a biphasic model fit well for PPO and POD inactivation, respectively. Surface color changes (ΔE) of apple slices during prolonged heating resulted from non-enzymatic browning with an increase in b value was observed. In order to achieve a 1 log reduction in POD activity, the process resulted in a reduction in moisture from 20% to 59% and in ΔE from 2.27 to 5.59. It is suggested that SIRDBD with intermittent heating could be used as an alternative to manufacture high quality blanched and partially dehydrated fruits and vegetables.

1. Introduction

Simultaneous infrared dry-blanching and dehydration (SIRDBD) is a new approach for blanching and partially dehydrating fruits and vegetables, resulting in high product quality (Pan and McHugh, 2004). The technology utilizes catalytic infrared (CIR) energy to inactivate enzymes in fruits and vegetables as well as to remove a certain amount of moisture at the same time. Conventionally, blanching and drying are normally executed in two separate steps by steam or hot water blanching and followed by hot air drying, both of which are related with several disadvantages, such as low energy and processing efficiency, poor finished product quality and environmental pollution (Bomben, 1977; Vanlaanen, 2003). On the other hand, the combined one-step process of SIRDBD leads to simpler process and higher energy and process efficiency than the conventional two-step process (Pan and McHugh, 2004). The mechanism of CIR has been illustrated in details in a recent publication (Zhu and Pan, 2009). Platinum catalyst inside the CIR emitter oxidizes natural or propane gas, resulting in medium- and far-infrared radiation with peak wavelengths between 3 to 6 μm which match reasonably well with the three infrared absorption peaks of water in the wavelength range. Therefore, rapid heating of high-moisture foods has led to the successful demonstrations of blanching and/or dehydration of many fruits and vegetables including pears, carrots, and sweet corn kernels (Pan and McHugh, 2004), onions (Gabel et al., 2006), bananas and strawberries (Pan et al., 2008; Shih et al., 2008), blueberries (Shi et al., 2008a,b), and apples (Zhu and Pan, 2009).

SIRDBD can be operated in two heating modes, continuous and intermittent heating. During continuous heating, the radiation intensity is maintained constant by retaining a continuous supply of natural gas to the CIR emitter. For quick come-up and moisture removal or enzyme inactivation, continuous heating is advantageous since it delivers a constant high energy to the surface of the product. Our lab has found that by using appropriate processing conditions of SIRDBD in continuous heating mode it was able to achieve 90% inactivation of POD in apple slices with thicknesses from 5 to 13 mm in 2–15 min. The resulting moisture reductions were in the range of 15–49% while surface color of the apple slices were preserved well (Zhu and Pan, 2009). However, it was also observed that when prolonged heating was required (e.g. to achieve

* Corresponding author. Address: Processed Foods Research Unit, USDA-ARS-WRRC, 800 Buchanan St., Albany, CA 94710, USA. Tel.: +1 510 559 5861; fax: +1 510 559 5851.
E-mail address: zpan@ars.usda.gov (Z. Pan).

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Nomenclature

A	residual enzyme activity (–)
A_0	initial enzyme activity (–)
a, b, c	constants of Eq. (3) (–)
D_{eff}	effective moisture diffusivity (m^2/s)
D_o	coefficient of Eq. (5) (–)
$D_{Ts,Tc,H}$	decimal reduction time (min)
E_a	activation energy (kJ/mol)
E_{R0}	initial concentration of heat-resistant isozyme of POD (–)
E_{L0}	initial concentration of heat-labile isozyme of POD (–)
ΔE	overall color change (–)
H	apple-slice thickness (cm)
K_R	reaction rate constants of heat-resistant isozyme of POD (–)
K_L	reaction rate constants of heat-labile isozyme of POD (–)
k, n	empirical coefficients of Page model (–)
$k_{Ts,Tc,H}$	overall rate constant of Eq. (7) (s^{-1})
k_R	inactivation rate constant of heat-resistant isozyme of POD (min^{-1})
k_L	inactivation rate constant of heat-labile isozyme of POD (min^{-1})
M	moisture content (g water/g dry solid)
M_0	initial moisture content (g water/g dry solid)
MR	moisture ratio (–)
MR_{pre}	model-predicted moisture ratio (–)
MR_{exp}	experimental value of moisture ratio (–)
R	universal gas constant (kJ/mol K)
r^2	coefficient of determination (–)
t	time (s)
T_c	actual center temperature (°C)
T_s	target surface temperature (°C)

more than 90% inactivation of POD in thick apple slices or to achieve a large percentage of moisture removal), continuous heating could cause severe surface discoloration (Zhu and Pan, 2009). Sandu (1986) has suggested applying intermittent heating, which has been shown to solve the problem of limited penetration of far infrared (FIR) and the application of FIR on thick materials. Intermittent heating is normally achieved by keeping product temperature constant through turning the natural gas supply on and off. The advantages of intermittent heating have been well recognized in terms of energy savings and improved product quality, since the desired processing temperature can be maintained (Chua and Chou, 2003).

The relationship between processing parameters and product quality during SIRDBD with continuous heating has been investigated (Zhu and Pan, 2009). The current study was designed to better understand the performance of SIRDBD in intermittent heating mode and to evaluate its effect on final product quality. The objectives of this study were to: (1) investigate the influence of processing parameters (apple slice surface temperature, apple-slice thickness, and processing time) of SIRDBD with intermittent heating on processing characteristics and product quality, (2) establish mathematical relationships between processing parameters and product quality by using empirical modeling methods, and (3) provide recommendations on appropriate processing parameters to achieve desirable product quality.

2. Materials and methods

2.1. Preparation of apple samples

Freshly harvested apples (*Malus domesticus* Borkh. Var. Golden Delicious) from a local orchard (Apple Hill, Camino, CA) were stored at 0 ± 1 °C with relative humidity of 90–95%. The quality of the raw material was relatively stable since all the experiments were completed in one month. The firmness and moisture content of the apple samples were recorded as 44.3 ± 4.6 N and 83.5 ± 1.0% (wet basis), respectively. The measurement methods for firmness and moisture content were described in details in Zhu and Pan (2009). Apple samples were then prepared in the same way reported in prior publication (Zhu and Pan, 2009) to achieve slices with the thicknesses of 5, 9, and 13 mm.

2.2. CIR blancher/dehydrator setup

The description of the setup of CIR blancher/dehydrator can be found in Zhu and Pan (2009). In each experiment only one piece of apple slice was placed in the center of the CIR blancher/dehydrator in order to apply well controlled and constant radiative heating from the emitter. A T-type thermocouple (model HYP-0, Omega, CT; response time 0.5 s) was inserted just beneath the surface of the apple slice to detect the surface temperature. The thermocouple was connected to a data acquisition system to control the on and off time for the gas supply to the emitter for achieving a constant surface temperature of the apple slice. The automatic data acquisition and control system were developed in our laboratory and used to control and record various operation parameters including emitter and product temperatures.

2.3. SIRDBD trials

This study investigated three processing parameters important to intermittent heating processing performance and product quality: apple slice surface temperature (70, 75, and 80 °C), slice thickness (5, 9, and 13 mm) and processing time (2, 5, 7, 10, 15, 20, 30, and 40 min). The selection of apple slice surface temperature was based on preliminary tests which showed that target surface temperature lower than 70 °C resulted in unacceptably long blanching time while a target surface temperature higher than 80 °C led to complete inactivation of PPO before apple slice surface temperature reached target temperature. A three-factor factorial experimental design was conducted to investigate the effects of processing parameters on apple slice characteristics, such as drying rate and drying kinetics, and on final product quality in terms of apple slice surface color, moisture reduction, and PPO and POD activities. Based on some preliminary results, the SIRDBD treatment was stopped for each combination of slice thickness and target surface temperature when approximately 90% of POD was inactivated. Peroxidase is usually chosen as enzymatic indicator for blanching in food industry since it is one of the most heat-resistant enzymes in fruits and vegetables (Williams et al., 1986; Halpin and Lee, 1987). However, very limited evidence has shown a direct link between peroxidase activity and quality deterioration during the storage of the fruits and vegetables (Lee et al., 1989). Heating for complete inactivation of peroxidase may be more than adequate for the inactivation of enzymes directly related with quality change and thus may lead to over-blanching (Burnette, 1977). It was suggested that a residual activity of peroxidase of about 3–10% after blanching was sufficient for freezing storage (Gunes and Bayindirli, 1993). Therefore for this study 90% inactivation of peroxidase was considered as the endpoint of blanching treatment and each experimental condition was replicated three times.

2.4. Quality and processing characteristics

Several dependent variables representing processing characteristics and product quality, such as surface and center temperatures, moisture reduction, surface color change, and residual PPO and POD activity, were all measured by using the same methods indicated in our prior publication (Zhu and Pan, 2009).

2.5. Modeling of drying kinetics

An empirical Page model was chosen to fit the drying curves in this study due to its simplicity and good performance of describing drying thin-layer fruits and vegetables in many reported works (Togrul, 2005, 2006; Gabel et al., 2006; Kumar et al., 2006; Sacilik and Elicin, 2006). The model was stated as:

$$\mathrm{MR} = \exp(-kt^n) \tag{1}$$

where MR is moisture ratio that can be calculated by Eq. (2) stated below, t is time, and k and n are empirical coefficients.

The moisture ratio (MR) could be simplified as:

$$\mathrm{MR} = \frac{M}{M_0} \tag{2}$$

where M is moisture content (g water/g dry solid) and M_0 is initial moisture content (g water/g dry solid). This simplification is justified because the moisture content of samples dried by using IR may close to zero (Togrul, 2005, 2006). Regression analyses of the model equation were done by using MATLAB Version R2006a (Natick, MA) "nlinfit" routine. The empirical coefficients (*coc*) of the Page model (k and n) were regressed with processing variables including slice thickness (H) and target surface temperature (T_s) by logarithmic type (Togrul, 2006) (Eq. (3)). The coefficient of determination (r^2) and root mean square error (RMSE) were calculated to determine the performance of the model.

$$\mathrm{coc} = a + b\ln(T_s) + c\ln(H) \tag{3}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right]^{1/2} \tag{4}$$

where $\mathrm{MR}_{\mathrm{pre}}$ is model-predicted moisture ratio and $\mathrm{MR}_{\mathrm{exp}}$ is experimental value of moisture ratio.

In the meantime, effective moisture diffusivity (D_{eff}, $\mathrm{m^2\ s^{-1}}$) was calculated by plotting the experimental moisture ratio against processing time on a semi-logarithmic diagram (Crank, 1975) since they have the relationship expressed as:

$$\ln(\mathrm{MR}) = \ln\left(\frac{M}{M_0}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left[\pi^2\frac{D_{\mathrm{eff}}t}{H^2}\right] \tag{5}$$

Then plotting effective diffusivity (D_{eff}) against the reverse of absolute surface temperature ($1/T_s$) achieved activation energy (E_a) by using the Arrhenius relationship:

$$D_{\mathrm{eff}} = D_0\exp\left(-\frac{E_a}{RT_s}\right) \tag{6}$$

where D_0 is coefficient, R represents the universal gas constant ($\mathrm{kJ\ mol^{-1}\ K^{-1}}$), and T_s is the absolute target surface temperature (K).

2.6. Modeling of enzyme inactivation

Since infrared radiation has limited penetration capability, there must be temperature difference between the top surface and the center of the apple slices. As described in the previous publication (Zhu and Pan, 2009), in order to apply common enzyme inactivation kinetic models for describing the blanching process of SIRDBD an overall rate constant ($k_{Ts,Tc,H}$) was reported as inactivation rate constant at certain surface and center temperatures for apple slice with certain thickness. The subscript T_s, T_c, and H denoted surface temperature, center temperature and slice thickness, respectively. The same constraints were also applied on the decimal reduction time ($D_{Ts,Tc,H}$). The center temperatures of the product were measured by thin T-type thermocouples with a response time of 0.5 s (Omega, CT) and were recorded by an Omega HH147 RS-232 data logger thermometer with an interval of 5 s. Five measurements were performed for each processing condition and the average value was reported.

A widely used first-order kinetics model was used to describe the inactivation of PPO in apple slices according to Eq. (7)

$$\log(A/A_0) = -(k_{Ts,Tc,H}/2.303)/t \tag{7}$$

where A_0 is initial enzyme activity and A is the residual enzyme activity at certain processing time t (Unal and Sener, 2006; Unal, 2007; Matsui et al., 2007). The decimal reduction time $D_{Ts,Tc,H}$ was then calculated as

$$k_{Ts,Tc,H} = 2.303/D_{Ts,Tc,H} \tag{8}$$

Fitting the data of inactivation of POD achieved success by using a biphasic model (Ling and Lund, 1978). To apply this mathematical model, it is assumed that there are only two types of isozymes where one is heat resistant (E_R) and the other is heat labile (E_L). In addition, each fraction of the enzyme is assumed to follow first-order kinetics and mathematically expressed as:

$$\frac{A}{A_0}(\%) = \left[\frac{K_R E_{R0} e^{-k_R t}}{K_R E_{R0} + K_L E_{L0}}\right] \times 100 \tag{9}$$

where E_{R0} and E_{L0} are the initial concentration of the heat-resistant and heat-labile isozyme fractions, respectively; K_R and K_L are the reaction rate constants for the respective isozyme fractions with the substrate; k_R and k_L ($\mathrm{min^{-1}}$) are the first-order rate constants for thermal inactivation of the respective isozyme fractions. The limiting condition of long heating time was applied to obtain the special rate constant of heat-resistant isozyme fraction by rearranging Eq. (9) to obtain Eq. (10):

$$\log\left[\frac{A}{A_0}(\%)\right] = \log\left[\frac{K_R E_{R0}}{K_R E_{R0} + K_L E_{L0}} \times 100\right] - \frac{k_R}{2.303}t \tag{10}$$

The portion of the shallow slope straight line of the curve had a slope equal to $-k_R/2.303$ and extrapolating the line to time zero, the intercept would be equal to $K_R E_{R0}/(K_L E_{L0} + K_R E_{R0})$. Knowing the proportion of heat-resistant isozyme fraction and plugging the value into Eq. (11) resulted in the determination of a rate constant for heat-labile isozyme fraction based on Eq. (12).

$$\begin{aligned} &\mathit{EnzymeActivity}\ (\%) - \left[\frac{K_R E_{R0}}{K_R E_{R0} + K_L E_{L0}}\right] \times 100 \\ &\quad = \left[\frac{K_L E_{L0} e^{-k_L t}}{K_R E_{R0} + K_L E_{L0}}\right] \times 100 \end{aligned} \tag{11}$$

$$\begin{aligned} &\log\left[\mathit{EnzymeActivity}\ (\%) - \frac{K_R E_{R0}}{K_R E_{R0} + K_L E_{L0}} \times 100\right] \\ &\quad = \log\left[\frac{K_L E_{L0}}{K_R E_{R0} + K_L E_{L0}} \times 100\right] - \frac{k_L}{2.303}t \end{aligned} \tag{12}$$

When the proportion of heat-resistant isozyme fraction was subtracted from the original activity values and the data was replotted on a logarithmic scale against heating time, the slope of the resulting straight line was $-k_L/2.303$. In this way, the overall rate constants for both heat-labile and heat-resistant isozymes

were estimated. These rate constants were also reported with the constraints of apple slice surface and center temperatures and apple-slice thickness.

2.7. Statistical analysis

The significance of the effects of surface temperature and slice thickness on surface color measurements at the same processing time were determined by conducting two-way analyses of variance (ANOVA). All the statistical tests were done at a significance level of 0.05 by using Minitab version 15 (Minitab Inc., State College, PA).

3. Results and discussion

3.1. Product temperature

Thin apple slices were heated up faster than thick slices during the come-up stage before the surface temperature reached a target

Table 1
Average center temperature, effective moisture diffusivities, and activation energies of apple slices processed under intermittent heating of IR.

Slice thickness (mm)	Target surface temperature (°C)	Average center temperature (°C)	Effective diffusivity (D_{eff}) × 10^{-9} m^2 s^{-1}	Activation energy (E_a) kJ/mol
5	70	67.4 ± 1.3	2.13	48.80
	75	70.1 ± 1.3	2.49	
	80	74.4 ± 1.7	3.02	
9	70	66.5 ± 0.8	2.99	39.22
	75	70.5 ± 1.3	3.43	
	80	76.3 ± 1.0	4.39	
13	70	65.0 ± 0.8	3.54	26.28
	75	67.9 ± 1.3	4.14	
	80	73.4 ± 0.8	4.50	

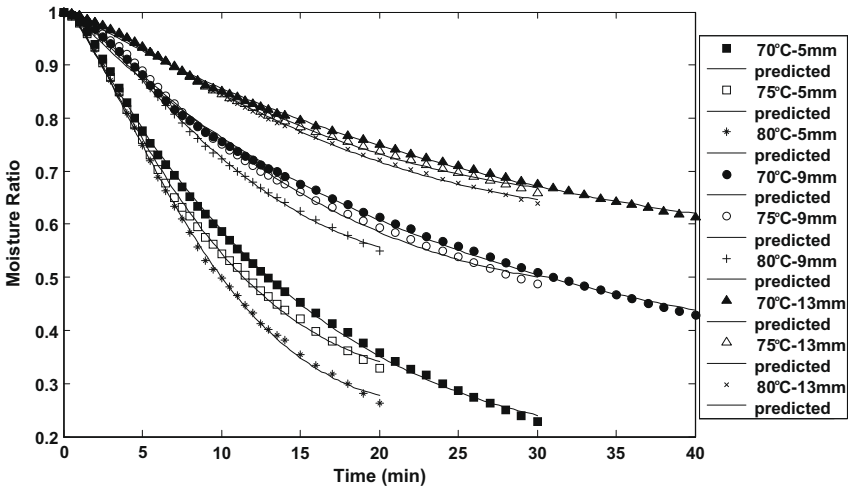

Fig. 1. Measured and Page model-predicted moisture ratios of apple slices at different heating times under various processing conditions.

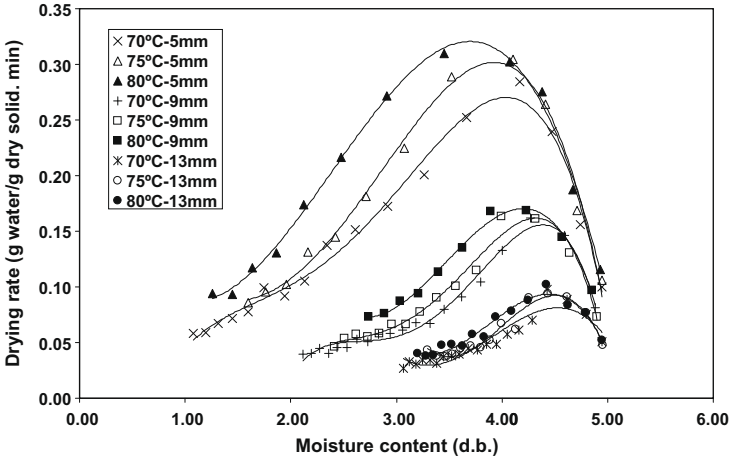

Fig. 2. Drying rates of apple slices at various processing conditions.

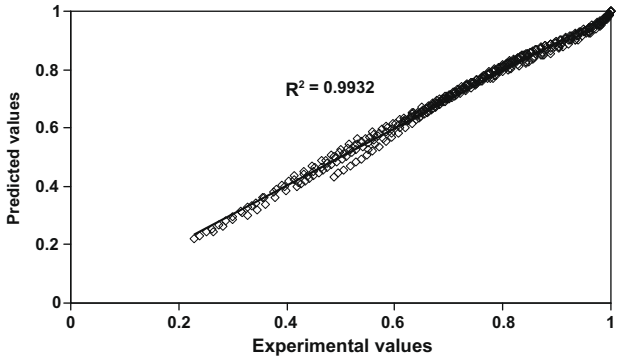

Fig. 3. Correlation between experimental moisture ratios and the Page model-predicted values with constants and coefficients derived from logarithmic type model (Eq. (13)).

temperature. For example, to heat up apple slices to achieve surface temperature of 70 °C, it took approximately 4, 6 and 8 min for slice thicknesses of 5, 9, and 13 mm, respectively. In addition, 5 and 9 mm thick slices had higher average center temperatures than the 13 mm thick slice, shown in Table 1. The average center temperatures were calculated from the average values of center temperatures of the slices after the slice surface temperature reached target temperature. The difference between the surface temperature and the center temperature was higher with thick slice (13 mm) than that with thin slice (5 mm). This is because when the surface layer required a certain amount of energy to reach the target temperature, the center of the thick slice was heated up to a lesser extent than the thin slice due to the large distance between surface and center.

3.2. Moisture reduction and drying kinetics

Thin slices lost moisture more rapidly than thick slices at the same target surface temperature. In addition, it showed that the influence of slice thickness was stronger than that of surface temperature (Fig. 1). The drying curves of apple slices with the same slice thickness were close to each other because the investigated surface temperatures were in a narrow range. The processing conditions tested resulted in moisture reductions between 35% and 79%, where the moisture reduction is defined as the ratio of evaporated moisture to the initial weight of moisture in the sample.

The change in drying rate versus moisture content in dry basis (d.b.) is shown in Fig. 2. For all the processing conditions, the drying rates increased in the early stage of the drying, reached a peak, and decreased in the middle and late stages. The dramatic drop in drying rate after reaching the peak was mainly because following moisture removal in the surface layer, the speed of further drying is limited to the rate of moisture diffusion from the interior of the slice to the surface layer. This did not show a constant drying rate period, which agreed with many other infrared drying studies such as the infrared drying of onions and strawberries (Gabel et al., 2006; Shih et al., 2008). In general, thin slices showed higher drying rates than thick slices. Though thin slices reached the target temperature sooner than the thick slices, internal moisture of the thin slices could be migrate to the surface for evaporation faster than that of thick slices. Slice thickness had a more significant effect on drying rate than surface temperature. The difference in drying rate due to the variation in surface temperature decreased as the slice thickness increased. For the thickest slices (13 mm), elevating the surface temperature did not enhance the drying rate apparently.

A simple Page model showed good performance in fitting all the drying curves (r^2 = 0.99, RMSE = 0.013). The constants and coefficients obtained from the Page models were regressed against surface temperature (T_s) and slice thickness (H) by using logarithmic

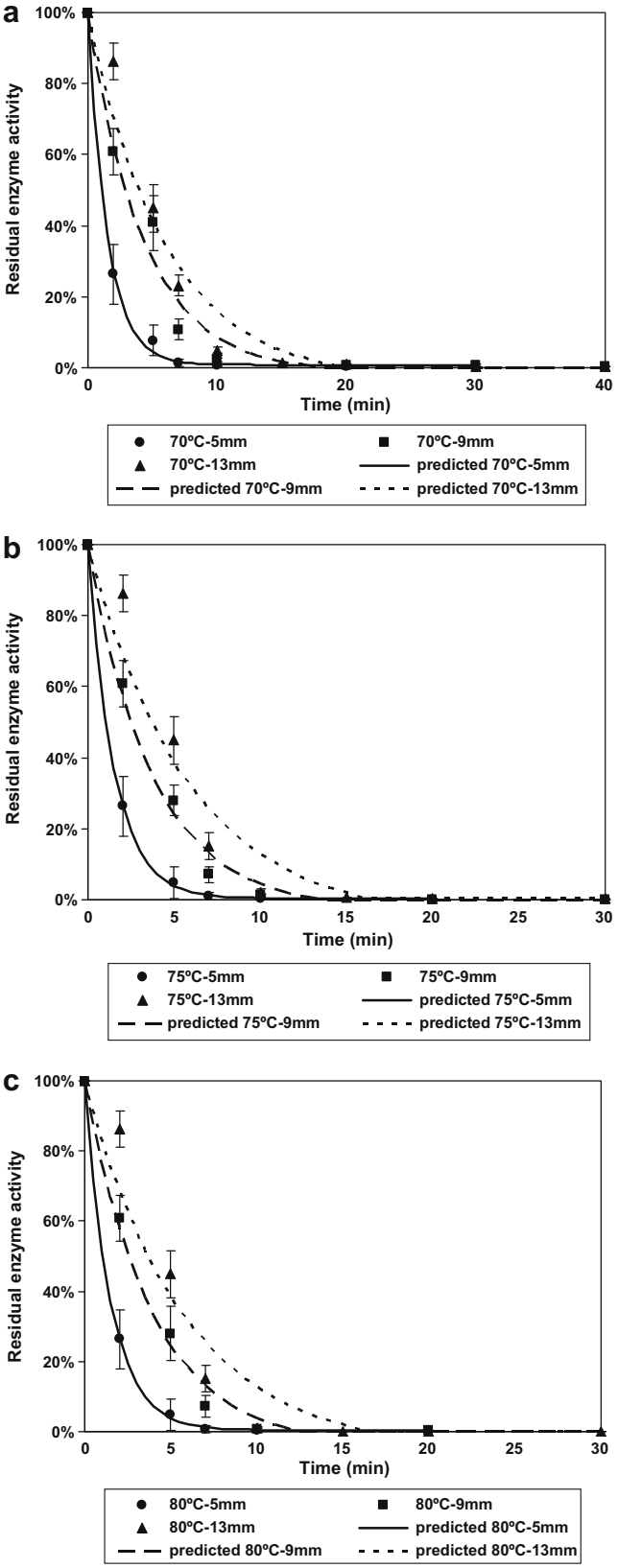

Fig. 4. Residual PPO activities (solid symbols) and predicted enzyme activities (lines) of apple slices at different heating times with various target surface temperatures.

Table 2
Summary of thermal inactivation parameters for PPO inactivation.

Slice thickness (mm)	Target surface temperature T_s (°C)	$k_{Ts,Tc,H}$ (s^{-1})	$D_{Ts,Tc,H}$ (min)	r^2
5	70	0.00921	4.17	0.97
	75	0.01036	3.70	0.99
	80	0.01152	3.33	0.98
9	70	0.0055	6.94	0.91
	75	0.0064	5.95	0.95
	80	0.0071	5.38	0.91
13	70	0.0046	8.33	0.94
	75	0.0055	6.94	0.93
	80	0.0067	5.75	0.90

type model. The empirical drying equation (Eq. (13)) achieved demonstrated good predictability with a strong correlation between predicted and experimental values (r^2 = 0.99, RMSE = 0.016) (Fig. 3).

$$MR = \exp\{[0.2982 - 0.0456 \times \ln(T_s) - 0.0320 \times \ln(H)] \times t^{[-3.6229+1.1457\times\ln(T_s)-0.1607\times\ln(H)]}\} \quad (13)$$

The effective diffusivities for various processing conditions were in the range of $2.12–4.50 \times 10^{-9}$ m^2 s^{-1} which is at the high end of the general range of $10^{-9}–10^{-11}$ m^2 s^{-1} for air drying of food materials (Table 1). These values were higher than the effective moisture diffusivity ($7.29 \times 10^{-11}–1.51 \times 10^{-10}$ m^2/s) obtained from FIR drying of 1–2 mm thick carrot slices at 50–80 °C reported by Togrul (2006). This may be because the device used in this study generates CIR energy which is absorbed by the samples more efficiently because of the difference in physical structure. The effective moisture diffusivities increased as the surface temperature increased or as slice thickness increased, which agrees with the study of FIR drying of potato slabs by Afzal and Abe (1998). The activation energy was calculated based on the average center temperature and the E_a values were 48.80, 39.22, and 26.28 kJ/mol for apple slices with thicknesses of 5, 9, and 13 mm, respectively. This indicates that as slice thickness increased, the activation energy decreased. This trend also agrees with that suggested by Afzal and Abe (1998). The values of activation energy obtained are slightly higher than the activation energy resulting from hot air drying of Red Delicious apples with thickness of 4 mm (19.96–22. 62 kJ/mol) (Kaya et al., 2007) and FIR drying of 1–2 mm carrot slices (22.43 kJ/mol) (Togrul, 2006) but still in a reasonable range. The difference may be due to variations in processing and operation conditions and the type of drying device used. The effective moisture diffusivity represents overall mass transport of moisture in the material including liquid diffusion, vapor diffusion, or any other possible mass transfer mechanism (Afzal and Abe, 1998). The higher surface temperature led to a higher center temperature of the slices which caused a higher rate of moisture diffusion. In addition, the higher effective diffusivity for thicker slices may be due to the decrease in activation energy when slice thickness increases. Afzal and Abe (1998) suggested that decreased activation energy with increased potato-slice thickness indicated the penetration of infrared radiation into biological materials causes the water molecule to vibrate. Therefore, the molecules require less energy to transfer from a porous material in the mobilized state.

3.3. Inactivation of PPO

The residual PPO activities after application of various processing conditions are presented in Fig. 4. Generally speaking, thin slices and/or high surface temperature resulted in faster inactivation of enzymes than thick slices and/or low surface temperature. However, the slice thickness had a stronger impact on PPO inactivation than surface temperature. This may be due to the relatively narrow range of temperatures tested. For example, at a surface temperature of 70 °C, 10 min blanching inactivated 99.4%, 97.8%, and 95.1% PPO for 5, 9, and 13 mm apple slices, respectively. On the other hand, for a 5 mm slice after 10 min of heating at 70, 75, and 80 °C the residual PPO activities were 0.56%, 0.23%, and 0.21%, respectively.

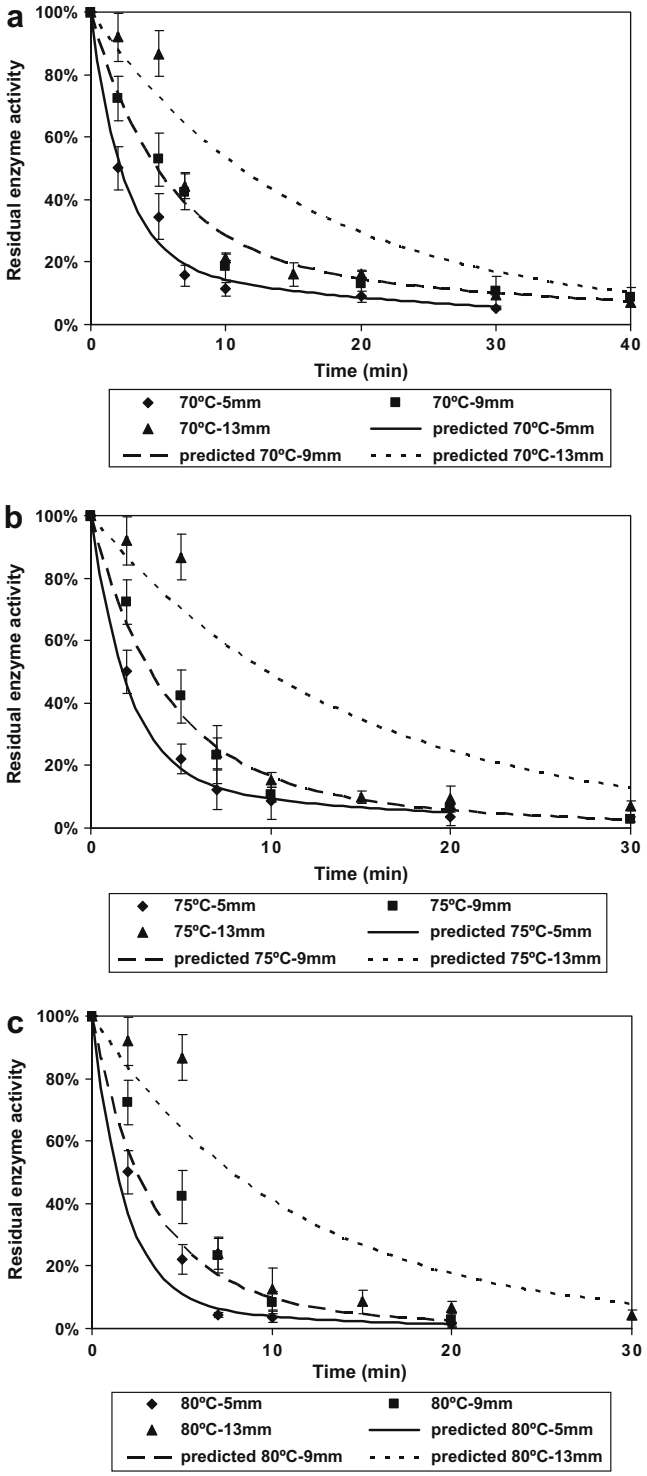

Fig. 5. Residual POD activities (solid symbols) and predicted enzyme activities (lines) of apple slices at different heating times with various target surface temperature.

A first-order kinetics model showed good fit to the inactivation curves (r^2 = 0.90–0.99). The rate constants and decimal reduction times were highly dependent on slice thickness and product temperatures (Table 2). When the slice thickness was increased, the rate constants were reduced while the decimal reduction times were elevated significantly. Though they were operated at the same surface temperature, thick slices usually had lower center temperatures. Thus, the enzyme inactivation rate was slower in thick slices and the required processing time to achieve 90% PPO inactivation was increased.

3.4. Inactivation of POD

POD inactivation showed a similar trend as that of PPO inactivation. Low surface temperature and/or thick slices required longer processing times to achieve 90% of POD inactivation than higher surface temperatures and/or thin slices (Fig. 5). Slice thickness played a more important role in influencing the inactivation rate than surface temperature. For example, to obtain a 90% inactivation of POD in 5 mm thick slices, it took 7, 10, and 20 min when the target surface temperatures were 80, 75, and 70 °C, respectively. When the slice thickness was increased to 13 mm, the required processing time was elevated dramatically to 15, 20, and 30 min at target surface temperatures of 80, 75, and 70 °C, respectively.

POD is more heat tolerant than PPO. Heating the 13 mm slice for 10 min at target surface temperatures of 70, 75, and 80 °C resulted in residual PPO activity of 4.9%, 2.2%, and 0.9%, respectively. On the other hand, after processing for these same times, the residual POD activities were 21.4%, 15.4%, and 12.5% at target surface temperatures of 70, 75, and 80 °C, respectively. This indicates that 10 min heating of the 13 mm slice at 70–80 °C may lead to a 1–2 log reduction of PPO but less than 90% inactivation of POD.

The logarithmic values of residual POD activities were not linear versus processing times (data not shown). Instead, there was a drastic reduction in enzyme activities during the first 5 min while for longer heating times there was a pronounced change in slope and another linear reduction in enzyme activity but less inactivation. This agrees favorably with the enzyme inactivation pattern described by the biphasic model, which is also known as the 2-fraction model (Saraiva et al., 1996; Rodrigo et al., 1997). Fitting enzyme inactivation curves into the biphasic model resulted in rate constants ($k_{Ts,Tc,H}$) and decimal reduction times ($D_{Ts,Tc,H}$) for two isozymes of POD with different heat tolerance, namely the heat-labile and heat-resistant isozymes (Table 3). The fraction of the heat-resistant isozyme of POD decreased as surface temperature increased while it increased when slice thickness increased. This agreed with the findings reported by Morales-Blancas et al. (2002). The authors showed that the fraction of heat-resistant POD varied greatly in different materials and in different parts of the same material. For example, when inactivation was conducted at 70 to 95 °C in broccoli florets the percentage of heat-resistant POD was in the range of 16–23% while the proportion was in the range of 19–43% in asparagus tip, 18–32% in asparagus stem, 9–25% in carrot cortex, and 26–29% in carrot core (Morales-Blancas et al., 2002). In this study, the proportion of heat-resistant POD in apple slices varied between 9.4% and 29.9%, which is in a reasonable and comparable range. This study also suggests that the relative proportions of heat-resistant POD fractions were dependent on material size and inactivation temperature.

The inactivation rate constants and decimal reduction times determined for both heat-labile and heat-resistant isozymes showed dependence on product temperature and slice thickness. The increase in product temperature or the decrease in slice thickness resulted in the elevation of rate constants and the reduction of decimal reduction time. The effect of slice thickness on the rate constants was more significant for heat-labile isozymes than for heat-resistant isozymes. Comparing these model parameters showed that the rate constants were much higher for heat-labile isozymes than for heat-resistant isozymes when the slice thickness was 5 or 9 mm. For thick slices (13 mm), the rate constants had similar values for heat-labile and heat-resistant isozymes. This may be due to the lower center temperatures of the 13 mm thick slices under the intermittent heating mode. The actual center temperature during intermittent heating may be 5–7 °C lower than the target surface temperature for the 13 mm thick slice. At these center temperatures, the inactivation of heat-labile isozymes of POD may not show much advantage over that of heat-resistant isozymes. In addition, the correlation coefficient showed lower values for the scenario of 13 mm than that of 5 or 9 mm. In general, for 13 mm thick slices, the experimental residual activities were higher than the model-predicted value during short heating time. This could be due to the long heating up for thick slices. Though the model parameters derived from this study may not be used without the constraints of product temperature and apple-slice thickness, they provided valuable information for the characterization of the blanching process of SIRDBD and recommendations for appropriate processing conditions.

3.5. Surface color change

The overall color change (ΔE) is presented against moisture content in wet basis (w.b.) for various processing conditions in Fig. 6. The trend of surface color change versus moisture content was clear and quite similar for each case. When the moisture contents of the apple slices decreased from their original values (about 83%) to approximately 80%, the ΔE values increased rapidly at first, and then decreased. When the moisture contents reached around 75%, the overall color change increased steadily again. A similar trend in overall color change was reported in combined convective and microwave drying of potatoes (Chua and Chou, 2005). The first increase of ΔE values corresponded to enzymatic browning due to

Table 3
Summary of thermal inactivation parameters for POD inactivation.

Slice thickness (mm)	Target surface temperature (°C)	Heat resistant isozyme fraction (%)	Heat–labile isozyme			Heat-resistant isozyme		
			$k_{Ts,Tc,H} \times 10^4$ (s^{-1})	$D_{Ts,Tc,H}$ (min)	r^2	$k_{Ts,Tc,H} \times 10^4$ (s^{-1})	$D_{Ts,Tc,H}$ (min)	r^2
5	70	19.82	69.09	5.56	0.96	6.91	55.56	0.95
	75	15.15	80.61	4.76	0.82	9.21	41.67	1.00
	80	9.40	94.42	4.07	0.99	16.12	23.81	0.91
9	70	22.77	32.24	11.90	0.98	4.61	83.33	1.00
	75	21.45	43.76	8.77	0.99	11.52	33.33	0.99
	80	22.16	57.58	6.67	0.88	18.42	20.83	0.96
13	70	29.89	5.90	65.10	0.98	5.99	64.10	0.96
	75	26.03	6.45	59.52	0.82	7.85	48.88	0.96
	80	19.56	6.86	55.93	0.98	8.57	44.80	0.96

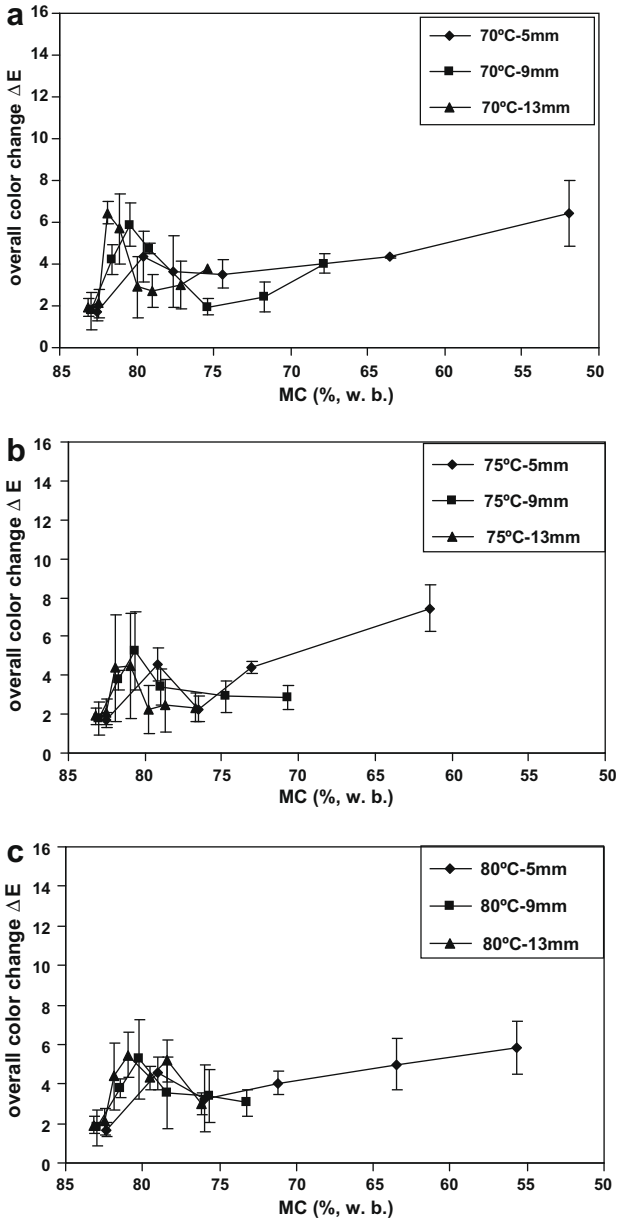

Fig. 6. Overall color change (ΔE) of the top surface of apple slices at various target surface temperatures.

the high residual PPO activity in apple slices, and resulted in a dramatic increase of a value. When intermittent heating proceeded, the reduced moisture content on the surface of the apple slices induced enhanced reflectivity of the samples and accordingly the increase in L values. Similar increases in L values were also observed during processing of apple slices by SIRDBD in a continuous heating mode (Zhu and Pan, 2009). Since the increase of a value became steady, while the L value increased again, the ΔE values dropped after they reached a peak. When surface moisture was further removed from the slices, the b value began to increase significantly, indicating yellowing, which contributed to the second increase of ΔE values. This agreed with many literature findings, which showed that prolonged drying usually resulted in the increase of a and b values of apple products (Krokida et al., 2000; Fernandez et al., 2005; Rababah et al., 2005). The increase in b value could be due to the concentration of certain yellowish phytochemicals (possibly phenolic compounds) when a large amount of moisture was removed after prolonged heating. Rababah et al. (2005) reported that total phenolics and anthocyanins increased 150% and 245%, respectively, due to concentration during drying of apple slices at 40 °C for 24 h. Non-enzymatic browning of the product may also contribute to the increase in the b value.

3.6. Recommendations on processing conditions

Determining the appropriate processing conditions is very important for achieving desirable product quality, in terms of reasonable residual enzyme activity and moisture reduction while best preserving color. Using a biphasic model it is possible to obtain the required processing times for a 1 log inactivation of POD. The processing time calculated agreed with experimental data very well. It was also shown that the moisture reductions of 5, 9, and 13 mm thick slices followed a second polynomial relationship (data now shown). Based upon these mathematical equations the moisture reductions at the processing time for 90% inactivation of POD were obtained as in the range of 19.8–59.5% (Table 4). At these processing times, the top surface color change (ΔE) was obtained from the closest processing time tested and also presented in Table 4. It can be deduced that for thin and thick slices (5 and 13 mm), the recommended surface temperature is 75 °C because this resulted in the least surface color change ($\Delta E = 2.27$ and 2.46) and a reasonable length of processing time (7.5 and 20.3 min). For 9 mm apple slices, high surface temperature (80 °C) resulted in more overall surface color change than low surface temperature (70 °C). However, considering the length of process, surface temperature of 75 °C may be suggested as an appropriate processing condition leading to a light surface color ($\Delta E = 3.38$) and a reasonable processing time (11 min). In summary, 75 °C is the suggested surface temperature for apple slices with various thicknesses in the range of 5–13 mm processed with SIRDBD with intermittent heating. The best processing parameters for the intermittent heating mode are a surface temperature of 75 °C, 5 mm slice, and 7.5 min processing time, which lead to final product with 10% residual POD, less than 1% residual PPO, 36% moisture reduction, and overall surface color change of 2.27.

Table 4
Required processing time, moisture reduction, and surface color change of apple slices at a 1 log reduction of POD with different surface temperatures.

Slice thickness (mm)	Surface temperature (°C)	Time for inactivation of 90% POD (min)	Moisture reduction (%) for 1 log reduction of POD	Top surface color change (ΔE)
5	70	16.5	59.5	4.34[a]
	75	7.5	36.0	2.27[a]
	80	6.4	34.2	3.27[a]
9	70	29.8	51.0	2.44[a]
	75	11.0	26.6	3.38[ab]
	80	7.7	21.5	5.88[b]
13	70	30.5	33.9	3.00[a]
	75	20.3	27.0	2.46[a]
	80	13.1	19.8	4.31[a]

Note: Values within the same column for the same slice thickness followed by different letters are significantly different at $p < 0.05$.

When a continuous heating mode was used, it was demonstrated that when more than 90% inactivation of POD is required, continuous heating under high radiation intensity resulted in severe surface discoloration (Zhu and Pan, 2009). On the other hand, intermittent heating is relatively slower process but it can avoid the possible problem of surface charring. For certain fruits and vegetables, moisture removal may not be desired during blanching. In this case, quick blanching and minimum moisture reduction are desired which means continuous heating is beneficial for such applications. On the other hand, for certain scenarios drying needs to be conducted after proper blanching (e.g. to produce dehydrofrozen products). In such a case, intermittent heating is recommended since it never causes severe surface darkening. In summary, both continuous and intermittent heating modes have their own advantages and disadvantages. An appropriate heating mode and appropriate processing conditions shall be chosen based on the purpose of processing and the property of food materials.

4. Conclusions

Apple-slice thickness, as one of the processing parameters of SIRDBD with intermittent heating, plays an important role in determining product quality and processing characteristics. Thinner slices lead to faster inactivation of enzymes and quicker moisture reduction. The surface temperature is a less important variable than slice thickness in the tested ranges. A higher surface temperature generally results in a higher center temperature, faster inactivation of enzymes, and less surface color change. POD is more heat resistant than PPO. The inactivation of PPO and POD follows first-order kinetics and biphasic models, respectively. The estimated kinetic parameters, inactivate rate constant and decimal reduction time, provide valuable information for characterization of the blanching process. A simple Page model performs well for describing the drying behavior of the process. Surface color change of the apple slices during the process is primarily due to increase of a and b values, corresponding to the enzymatic and non-enzymatic browning occurring during the process, respectively. The best processing parameters for the intermittent heating mode are a surface temperature of 75 °C, 5 mm slice, and 7.5 min processing time, which lead to final product with 10% residual POD, less than 1% residual PPO, 36% moisture reduction, and overall surface color change of 2.27. When targeting for achieving about 90% POD inactivation, compared to continuous heating the intermittent heating is generally a slower heating process which resulted in higher moisture reduction but a similar overall surface color change. The intermittent heating mode is more advantageous than the continuous heating mode when prolonged heating is necessary since no severe surface discoloration ever occurred.

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