THE THERMAL PROPERTIES OF POTATOES AND CARROTS AS AFFECTED BY THERMAL PROCESSING[1]

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ABSTRACT

The effects of processing on the thermal properties of white potatoes and carrots were studied. The test samples were blanched, boiled, cooked and canned. Whole potato tubers were baked to study the effects of starch gelatinization. The thermal conductivity (k) and density (ρ) were measured and the specific heat (c_p) and thermal diffusivity (α) were calculated. Results showed that in general, α initially decreased and then increased during processing. Test samples were found to have a gain in α when their moisture content increased by more than 9%. The α of potatoes decreased after canning and increased after boiling. In carrots, a similar trend was also observed but to a lesser degree. The k of potatoes was unaffected after blanching or cooking. In all the processing treatments of carrots, the k and the c_p increased and the ρ was unaffected. The baking study showed that gelatinization significantly decreased the k of potatoes.

INTRODUCTION

When establishing a thermal process, conservative procedures are used to ensure food safety. In thermal processing of low-acid canned foods, this is satisfied by calculating lethality based on the 'cold spot' temperature. The 'cold spot' is the location in food materials which has the slowest heating rate during the heat treatment. For conduction-heated food products, the 'cold spot' is usually at the center of a particle located near the center of the can and its temperature is measured with a thermocouple. In aseptic processing, where food materials continuously move in a system of pipes, the particulate temperature cannot be measured. An alternative is to predict temperature by using mathemat-

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ical models, which require knowledge of the thermal properties. For mathematical models to be conservative, the thermal properties must be measured at an appropriate stage of processing, e.g., raw, blanched, or fully processed, such that the model calculates the process parameters corresponding to the slowest heat transfer. For conduction in particulates, this is the state when the thermal diffusivity (α) of the product is lowest. It should be noted that heat transfer in aseptic systems includes conduction and convection and the heating rate in particulates is dependent on their thermal properties and the velocity profiles around them, which are also affected by their density (ρ). This study considers only the internal heat transfer in food particulates.

In aseptic processing, particulate foods are immersed either in water or in water-based solutions like soup or saline solution. The thermal properties of foods can change by absorbing/desorbing water and solutes and thermally degrading some food components. Raw carrots and potatoes are predominantly made up of water and their dry matter consists mostly of carbohydrates. Because water has higher thermal conductivity (k) than carbohydrates (0.602 vs 0.25 W/m-°K) (Choi 1985), an increase in water content increases the k of potatoes and carrots. Changes in the concentration of salt in food materials also affects thermal properties. M.W. Kellogg Co. (1955) reported that an increase in salt concentration lowered the k and increased the ρ of saline solution. Murakami (1994) reported that shrimp and scallops blanched in saline solution had lower thermal conductivities than those blanched in water.

Thermal processing can also alter the thermal properties of carrots and potatoes by the thermal degradation of some of their components, such as starch and protein. Lumbago and Hallstrom (1986) reported that potato starch started to gelatinize at 55C and ceased at 75C, with the maximum gelatinization occurring at 66C. Choi (1985) estimated that starch gelatinization decreased the k of carbohydrate solutions by 13%.

Several studies have shown the relative effects of changes and measurement errors in thermal properties on various process parameters. In a simulation of several critical parameters in aseptic processing of particles, Larkin (1990) showed that lethality (F_0) was sensitive to errors in the thermal properties. He calculated that lethality will be underestimated by 10% if ρ is overestimated by 2.5%, if specific heat (c_p) is overestimated by 1.6%, or if k is underestimated by 2.6%. Process time is directly proportional to holding tube length in continuous aseptic processing systems. Simulations by Chandarana *et al.* (1989), Chandarana and Gavin (1989), and Sastry (1986) suggested that a 50% increase in α of particulate food requires a corresponding 29% reduction in holding tube length (Larkin 1990). An error analysis by Lee *et al.* (1990) indicated that a 1.0% overestimation in the α would result in a 0.5% reduction in the calculated process time. Depending on the application, this can be significant since the reported level of accuracy in α measurements varies widely, from ±1% (Knibbe and Raal 1987) to ±11% (Parson and Mulligan 1978). The accuracy of α measurements is usually lower than k measurements (Nieto de Castro *et al.* 1988).

The thermal properties of potatoes and carrots have been previously studied. Rao *et al.* (1975) reported that the thermal conductivities, densities and thermal diffusivities of five varieties of raw potatoes were 0.533-0.571 W/m-°K, 1.04-1.05 g/cc and $0.165\text{-}0.184 \times 10^{-6}$ m^2/s, respectively. The freshly harvested test samples had a moisture content (X_{wb}) range of 81.2-83.6%wb. Thermal conductivity and thermal diffusivity were measured simultaneously by using the line-heat source technique. Studies have shown that the k of potatoes is not affected by temperature up to 70C (Wang and Brennan 1992) but does increase at 130C (Gratzek and Toledo 1993). For fresh carrots ($X_{wb}=90\%$), Sweat (1974) reported that their k was 0.605 W/m-°K and their ρ was 1.04 g/cc. The objective of this study was to determine the effect of thermal processing on the thermal properties of potatoes and carrots.

MATERIALS AND METHODS

Preparation of Carrots and Potatoes

The carrots and the potatoes (White Russet) were bought fresh from a local grocery store and stored in a refrigerator. For comparison, commercially-canned potatoes were included in the study. Commercially-canned carrots were not included because their diameters were too small for the k probe apparatus. The potatoes and carrots were peeled and shaped into cylinders ($D=22.2$ mm, $L \geq 50$ mm) with a cork borer to provide uniform thermal treatment during blanching, cooking and canning. For k measurements of raw and baked potatoes, the ellipsoid tubers were cut in half along the minor axis. The peel was left intact and the exposed areas were covered with a sheet of plastic wrap (low density polyethylene) to minimize moisture loss. The k probe was pierced through the plastic wrap and transferred to several locations in the half tuber for replications. The number of measurements for each half tuber was between 3-5, which was equal to the number of cylindrical test samples that could have been made with a 22.2-mm cork borer. For the baking and canning tests, the k data for raw potatoes were measured from at least four half tubers. For cooking and blanching processes, each potato tuber was cut in half and one-half was used as raw sample and the other half was processed. At least two potato tubers were used in those tests, giving a total of at least 6 replicates for both raw and processed potatoes. For raw carrots, the k determination was conducted with test samples that were at least 22.2 mm in diameter. There were at least five replicates for raw and processed carrots.

The processing operations used simulated the thermal processing of particulate foods. The carrots were blanched and canned and the potatoes were blanched, cooked, canned and baked. Although baking is not one of the unit operations in thermal processing, potatoes were baked in a convection oven to determine the effect of gelatinization without a change in X_{wb} on k. The canned carrots were preblanched in steam kettles (Groen Kettle Co., Elkgrove, IL) before they were placed in tin cans (300 × 404) and sealed using a manual Dixie can sealer (Dixie Canner Equipment Co., Athens, GA). The carrots were retorted in steam using a Dixie vertical still retort. The canned potatoes were prepared using the same procedure except that they were not blanched (Table 1).

TABLE 1.
THE CANNING PROCEDURE AND THE PROCESS DATA FOR CARROTS AND POTATOES

Samples	Blanching	Retorting
1. Potatoes	None	a. Filled with 2% brine b. Retorted to F_o=3.7, 23.5 min i. time = 16.5, 35.0 min ii. j_h = 1.27 iii. f_h = 8.90
2. Carrots	Boiled in water for 2 min	a. Filled with 2% brine b. Retorted to F_o=3.7, 27.9 min i. time = 13.6, 35 min ii. j_h = 0.80 iii. f_h = 7.89

Note:
T_r = 121.1 C (250 F), T_i = 37.8 C (100 F),
Can size = 300 x 404, Come up time = 2 min.

The carrots were blanched in boiling 2% saline solution for 4 min and the potatoes in boiling water for 10 min and 2.5 h in a covered aluminum pot. The extended blanching or boiling was used to evaluate the properties of potatoes that had equilibrated during processing. The potatoes were cooked in boiling cream of potato soup (CPS) for 60 min in the same cooking pot to simulate aseptic processing. The CPS was prepared by mixing equal amounts of whole milk and commercially-available condensed CPS. In another treatment, test samples were preblanched for 10 min in boiling water and then cooked in CPS for 50 min.

The carrots and potatoes were canned following the procedure of Lopez (1987) and the process parameters were determined from heat penetration tests (Table 1). The carrots were pretreated by blanching them in boiling water for 2 min. Tin cans with 2% brine were filled with four pieces of carrots and potatoes. There were 10 cans of each carrots and potatoes. Both carrots and potatoes were given a thermal treatment equivalent to an $F_0=3.7$ min. The process parameters were previously determined by running a heat penetration test for 35 min, as described by Murakami (1994). The carrots used in the heat penetration tests had an $F_0=27.9$ min and the potatoes had $F_0=23.5$ min.

Three whole potato tubers were baked at 205C for 0.5, 1.0, 1.5 and 2.0 h in a convection oven. Each tuber was wrapped in two layers of aluminum foil to avoid moisture loss. Prior to the measurement of thermal properties, the baked potatoes were allowed to cool overnight at room temperature before they were unwrapped.

The paired t-test was used to determine the statistical significance of the various treatments relative to the raw test samples and drift of the k probe. The prepared samples for each thermal treatment were divided into reference and test lots. The reference materials were kept raw and the test materials were processed. Except for the test samples that were canned and baked, comparison between raw and processed samples were based on data that were measured on the same day. For the cooked and blanched potatoes, the raw and processed samples were made from the same tuber and at least two tubers were used in each test. The data presented for raw potatoes and carrots were calculated by combining the measurements from the various processes. Although this approach required repetitive measurements of raw test samples and cannot be used for statistical comparison between the thermal treatments, it has several advantages. It eliminated the errors due to sample-to-sample diversity, storage effects, day-to-day variation of operator efficiency and equipment wear and tear. Moreover, the paired t-test approach also allowed the completion of the various tests over a long period of time. All statistical analysis were performed by using a 2-tailed t-test with a 95% confidence interval. The statistical significance of changes in the values of c_p and α were not evaluated. Because their values were calculated from mathematical models, the corresponding standard deviations and significance of changes in properties could not be determined.

Thermal Properties

The thermal properties studied were thermal conductivity (k), density (ρ), specific heat (c_p) and in some cases, the volumetric expansion (ν) after processing. Thermal diffusivity (α) was calculated from $k/\rho c_p$. Prior to measurement the processed test samples, except those that were canned, were cooled to room temperature (~25C) for about 2 h in the liquid in which they were processed. The canned test samples were retorted in cream of potato soup (arbitrarily chosen), stored at ambient conditions and analyzed 3 days after processing. All processed test samples were assumed to have sufficient time for temperature and X_{wb} equilibration.

Measurement of Thermal Conductivity and Density

The k was determined by using a PC-based k probe apparatus (Murakami 1994). The k measurement was conducted for 10 s and the power input was fixed at 11.4 W/m. Before the tests were started in a given day, the k apparatus was calibrated with 0.6% water-agar gel. At the end of the day, the system was recalibrated to determine drift. Drift was evaluated by comparing the calibration results using the t-Test (2 tailed, $\alpha' = 0.05$) and it was found that the drift of the system was not significant.

To avoid moisture loss during k measurements, the raw and baked test samples were wrapped in plastic sheets, and the processed test samples were submerged in the liquid in which they were processed. The processed test samples were shaped into cylinders; and to avoid errors with edge effects, their size was maintained at $D = 22.2$ mm and $L \geq 50$ mm. (Murakami 1994; Murakami *et al.* 1996). During the k measurements, it was difficult to place the k probe at the exact geometric center of the cylinders, which caused a potential problem with edge effects. Therefore, a test was devised to evaluate the effects of off-center probe locations. Measurements were made with the k probe positioned at the center ($r=0$), r/3, r/2 and 2r/3. To eliminate the effect of sample-to-sample variations, all four probe locations were evaluated in each cylinder and four different test samples were used. Results showed that the readings from all the off-center probe positions were not different from those taken at the center. It was possible that there were edge effects, especially at 2r/3, but they were negligibly small since the test samples and the surrounding medium had similar thermal conductivities.

Density and volumetric expansion were measured gravimetrically (Mohsenin 1970) by using a 25-mL pycnometer bottle. The details of the procedure were reported by Murakami (1994). The X_{wb} of all test samples was determined using a vacuum oven set at 96.7C and 13.5 Kpa. and the drying time was at least 20 h, when the test sample weight became constant. The test samples were shredded to small pieces and there were five replicates.

Calculations of Specific Heat, Thermal Diffusivity and Error or Uncertainty

Specific heat was evaluated by taking the sum of the heat contents of the various food components (i.e., water, protein, fat, carbohydrate, fiber and ash). It was calculated from:

$$c_p = \sum_i X_i^w c_{pi} \tag{1}$$

where:

c_{pi} = specific heat of each food component
X^w_i = weight fraction of each food component

The c_p values of the various food components were determined at $T=25C$ using the equations developed by Choi (1985). The errors of Choi's (1985) equations were between 2-6%. The composition of carrots and potatoes were calculated from the handbook by Adams (1975). The composition of raw test samples were based on raw and unpeeled materials and the processed test samples on those that had been boiled and pared. The composition was adjusted for the appropriate X_{wb} of the test samples.

The α was determined from the following:

$$\alpha = \frac{k}{\rho c_p} \tag{2}$$

The uncertainties of the measured properties were equal to the standard deviation of the replicates. The uncertainty of the c_p equation was estimated from the standard error of the equation for the carbohydrate which was reported by Choi (1985) to be approximately equal to 6%. For calculated values, Kline and McClintock (1953) (Huggins 1975) suggested that the uncertainty can be derived from the partial differential of the working equation with respect to the various variables. For α, the expression for uncertainty (E_α) was derived from Eq. 2 and the resulting equation is:

$$E_a = \left[\left(\frac{1}{\rho c_p} E_k\right)^2 + \left(\frac{k}{\rho^2 c_p} E_p\right)^2 + \left(\frac{k}{\rho c_p^2} E_{C_p}\right)^2\right]^{1/2} \tag{3}$$

The variables E_k, E_ρ, E_{cp} are the uncertainties of the k, ρ and c_p, respectively.

RESULTS AND DISCUSSION

The k, X_{wb} and ρ of fresh carrots were found to be 0.569 W/m-°K, 87.6 % wb (wet basis) and 1.029 g/cc, respectively (Table 2). The X_{wb} value compares favorably to the data (88.2%wb) published by Adams (1975). Results show that all the thermal treatments significantly changed the k and X_{wb} of carrots but did not affect the ρ (Table 3). Blanching the carrots in saline solution caused them to absorb a significant amount of water (1.7%), which consequently, increased the k by 1.4%. However, the change in X_{wb} was not high enough to influence the ρ. Compared with the thermal properties of water, the k of raw carrots was 5.5% lower and ρ was 2.9% higher. Thus, during thermal processing when the potential for changes in X_{wb} is high, the k is more sensitive than ρ. This was

TABLE 2.
THERMAL PROPERTIES OF RAW POTATOES AND CARROTS

	Raw Potatoes[a]		Raw Carrots[a]	
	$\bar{x} \pm E^b$	N	$\bar{x} \pm E^b$	N
X_{wb} (%, wb)	77.8±2.3	35	87.6±0.1	5
ρ (g/cc)	1.089±0.022	23	1.029±0.003	10
k (W/m-°K)	0.563±0.007	44	0.569±0.010	17
c_p^c (kJ/kg-°C)	3.603±0.216		3.849±0.231	
α^c (m^2/s, $x10^{-6}$)	0.144±0.009		0.144±0.009	

[a] Evaluated from raw data from all processing operations and were not used to calculate change in the values of properties.

[b] E= uncertainty, for ρ and k =standard deviation, for c_p = 6% of c_p, for α= calculated from eqn. 3

[c] Calculated.

TABLE 3.
THERMAL PROPERTIES AND VOLUMETRIC EXPANSION OF BLANCHED AND CANNED CARROTS

	Blanched (2% saline solution, 4 min.)				Canned (F_o=27.9)				Canned (F_o = 3.7)			
	$\bar{x} \pm E^a$	N	Δ, %[b]	*t*-test[c]	$\bar{x} \pm E^a$	N	Δ, %[b]	*t*-test[c]	$\bar{x} \pm E^a$	N	Δ, %[b]	*t*-test[c]
X_{wb} (%, wb)	89.1±0.4	10	1.7	s	93.7±0.1	5	7.0	s	93.5±0.4	5	6.7	s
ρ (g/cc)	1.036±0.016	5	0.4	ns	1.029±0.002	5	-0.2	ns	1.031±0.002	10	-0.1	ns
k (W/m-°K)	0.577±0.005	19	1.4	s	0.591±0.006	8	3.8	s	0.589±0.003	22	3.5	s
v (%)	2.3±1.7	4										
C_p^d (kJ/kg-°C)	3.985±0.234		1.2		4.015±0.241		4.2		4.009±0.241		4.3	
α^d (m^2/s, $x10^{-6}$)	0.143±0.009		-0.2		0.143±0.009		-0.2		0.143±0.009		-0.7	

[a] E= uncertainty, calculations of E for X_{wb}, ρ and k =standard deviation, for c_p = 6 % of c_p, and for α= calculated from eqn. 3

[b] Change in values of processed with respect to raw products

[c] Based on 2-tailed *t*-test at α =0.05 of raw vs processed products.

[d] Calculated

evident in the canned carrots. Although their X_{wb} increased by about 7%, the change in ρ was negligible while in k it was significant. The c_p of carrots increased in all processes, especially after canning when the moisture absorption was high. The α of carrots decreased slightly in all processes.

The average thermal properties of raw white potatoes were calculated by using the values from all unprocessed samples (Table 2). After the standard deviation was taken into account, it was found that the average k, ρ, and α values in this study compared favorably to the values reported by Rao *et al.* (1975). Relative to the thermal properties of water, the k of raw potatoes is 7.3% lower and their ρ is 8.9% higher. This means that when potatoes absorb water, their k and ρ values are more likely to change than carrots. However, in thermal processing of starchy materials the change in k can be counteracted by starch gelatinization, which decreases k.

Blanching the potatoes for 10 min increased their X_{wb} by 5.9% and resulted in a 1.7% decrease in ρ, while the k was unaffected (Table 4). The negligible effect of the increase in moisture on the k of blanched potatoes may have been neutralized by starch gelatinization. The c_p of potatoes after blanching increased and their α decreased. Boiling the potatoes for an extended duration increased their moisture by 9.8% and k by 4.2% and the ρ decreased by 2.3%. The large change in the X_{wb} indicated that the potatoes did not reach equilibrium X_{wb} during the shorter blanching process. Due to the large amount of water absorbed, the c_p of the boiled samples increased. However, due to the decrease in ρ and increase in k, the α increased by 1.1%.

The X_{wb} of potatoes canned to an $F_0=3.7$ min increased by 7.7% (Table 5). The change was high enough to significantly change the ρ but not the k. The longer F_0 treatment caused the test samples to absorb enough moisture to change both the ρ and k. The commercially-canned potatoes had higher X_{wb} than those canned to an $F_0=23.5$ min. The X_{wb} of the commercial potatoes was so high that their k was not significantly different from that of the liquid that it was canned with ($k=0.589\pm0.004$ W/m-°K). Results also showed that the k of the liquid from the cans was significantly lower than the plain water. Due to large amounts of moisture absorption, the c_p of all canned test samples increased by more than 4%. This resulted in decreases in α for the samples canned in the study. However, the commercially canned samples gained moisture by more than 13%, causing the k to increase by more than 5% and consequently increase the α.

Statistically, the two cooking treatments had similar effects on the thermal properties of potatoes (Table 6). Both treatments increased the X_{wb} but the k and ρ were not significantly affected. Although the change in k of the unblanched potatoes was higher than the standard deviation, it was not significant because it was lower than the standard deviation of the unprocessed test samples. Moreover, both cooking processes resulted in increases in c_p and decreases in α. Potatoes cooked in CPS did not absorb as much moisture as those boiled in

TABLE 4.
THERMAL PROPERTIES AND VOLUMETRIC CHANGE OF BLANCHED AND BOILED POTATOES

	Blanched (10 min.)				Boiled (2.5 h)			
	$\bar{X} \pm E^a$	N	Δ, %^{b}	t-Test^c	$\bar{X} \pm E^a$	N	Δ, %^{b}	t-Test^c
X_{wb} (%, wb)	80.2±1.0	10	5.9	s	85.1±0.3	5	9.8	s
ρ (g/cc)	1.088±0.019	9	-1.7	s	1.064±0.001	5	-2.3	s
k (W/m-°K)	0.551±0.007	22	-0.7	ns	0.567±0.006	3	4.2	s
v (%)	11.0 ± 2.8	4						
c_p^d (kJ/kg-°C)	3.666 ± 0.220		3.3		3.793 ± 0.228		5.5	
α^d ($m^2/s, \times 10^{-6}$)	0.138 ± 0.009		-2.2		0.140 ± 0.009		1.1	

[a] E= uncertainty, calculations of E for X_{wb}, ρ and k =standard deviation, for c_p = 6 % of c_p, and for α= calculated from eqn. 3
[b] Change in values of processed with respect to raw products
[c] Based on 2-tailed *t*-test at α'=0.05 of raw vs processed products.
[d] Calculated

water. This may be due to the lower amount of available moisture in CPS. The test samples that were preblanched prior to cooking had lower moisture intake than those that were immediately cooked. The preblanching may have caused the test sample surface to initially harden so as to decrease moisture diffusivity. However, this effect seemed temporary since as previously discussed when potatoes were boiled for an extended period, they absorbed more moisture (Table 4).

The result of the baking tests showed that k decreased significantly for potatoes that were baked for 1.5 h and longer and remained unchanged for those baked for 1 h or less (Table 7 and 8). Although the average k of potatoes baked for 1 h decreased by 1.6%, it was found to be statistically insignificant since the standard deviation was relatively high. The standard deviations of the k values

TABLE 5.
THERMAL PROPERTIES OF CANNED POTATOES

	F_o = 3.7 min.				F_o = 23.5 min.				COMMERCIAL			
	$\overline{X} \pm E^a$	N	Δ, %[b]	t-Test[c]	$\overline{X} \pm E^a$	N	Δ, %[b]	t-Test[c]	$\overline{X} \pm E^a$	N	Δ, %[b]	t-Test[c]
X_{wb} (%, wb)	85.3±0.4	5	7.7	s	85.6±0.6	5	8.1	s	87.3±0.7	10	13.2	s
ρ (g/cc)	1.061±0.002	10	-1.6	s	1.065±0.002	5	-1.2	s	1.054±0.004	11	-3.2	s
k (W/m-°K)	0.569±.007	23	0.5	ns	0.576±0.007	12	1.6	s	0.583±0.007	14	5.1	s
c_p^d (kg/kJ-°C)	3.798±0.228		4.3		3.806±0.228		4.6		3.850±0.231		7.4	
α^d (m^2/s, $x10^{-6}$)	0.141±0.009		-2.1		0.142±0.009		-1.7		0.144±0.009		1.1	

[a] E= uncertainty, calculations of E for X_{wb}, ρ and k =standard deviation, for c_p = 6 % of c_p, and for α= calculated from eqn. 3

[b] Change in values of processed with respect to raw products

[c] Based on 2-tailed *t*-test at α =0.05 of raw vs processed products

[d] Calculated

TABLE 6.
THE THERMAL PROPERTIES OF COOKED POTATOES

	Blanched + Cooked[a]				Cooked[b]			
	$\bar{X} \pm E^c$	N	Δ, %[d]	t-Test[e]	$\bar{X} \pm E^c$	N	Δ, %[d]	t-Test[e]
X_{wb} (%, wb)	81.4±0.3	5	5.5	s	82.2±0.4	5	6.6	s
ρ (g/cc)	1.086±0.012	5	-0.3	ns	1.089±0.011	5	-0.1	ns
k (W/m-°K)	0.557±0.010	6	-0.2	ns	0.568±0.009	5	1.8	ns
c_p^f (kg/kJ-°C)	3.697±0.222		3.1		3.718±0.223		3.6	
α^f (m^2/s, $\times 10^{-6}$)	0.139±0.009		-2.9		0.140±0.009		-1.7	

[a] Blanched for 10 min. in boiling water and cooked in boiling cream of potato soup (CPS) for 50 min.

[b] Cooked in boiling CPS for 60 min.

[c] E= uncertainty, calculations of E for X_{wb}, ρ and k =standard deviation, for c_p = 6 % of c_p, and for α= calculated from eqn. 3

[d] Change in values of processed with respect to raw products.

[e] Based on 2-tailed *t*-test at α'=0.05 of raw vs processed products

[f] Calculated

of the test samples baked for 0.5 and 1 h were higher than those baked longer; indicating that those baked longer had more uniform composition and were cooked completely. Visually, the potatoes baked for 0.5 h had uncooked centers while the others had a uniform cooked color. The baking test had no significant effect on the X_{wb} of the potatoes. This indicated that the change in the k values may be the result of starch gelatinization.

Because gelatinization can lower the k of potatoes by more than 2%, it can counteract the effect of increasing X_{wb}, e.g., potatoes that were canned to F_0=3.7 (Table 5) and cooked in CPS (Table 6). The X_{wb} in those cases increased by >5% but the k increased by only 2%. Thermal conductivity is more sensitive to moisture increases in materials with low starch content. For example, carrots canned to an F_0=3.7 increased in X_{wb} by 6.7% and k by 3.5% (Table 3). In comparison, similarly processed potatoes increased in X_{wb} by 7.7%

and k by only 0.5% (Table 5). The baking results showed that gelatinization is an important factor in the k of thermally processed starchy materials. It should be included in mathematical models that are used to calculate them. It is especially important in potatoes which have k values much lower than water.

TABLE 7.
THE THERMAL CONDUCTIVITY POTATOES BAKED FOR 0.5 AND 1.0h

	0.5 h				1.0 h			
	$\bar{X} \pm E^a$	N	Δ, %[a]	t-Test[b]	$\bar{X} \pm E^a$	N	Δ, %[a]	t-Test[b]
X_{wb} (%, wb)	82.5±4.8	5	0.8	ns	81.9±0.6	5	0.1	ns
k (W/m-°K)	0.567±0.015	16	-0.4	ns	0.560±0.014	12	-1.6	ns

[a] Change in values of baked with respect to fresh potatoes.
[b] Based on 2-tailed *t*-test at $\alpha' = 0.05$ of raw vs processed products.

TABLE 8.
THE THERMAL CONDUCTIVITY OF POTATOES BAKED FOR 1.5 AND 2.0 h

	1.5 h				2.0 h			
	$\bar{X} \pm E$	N	Δ , %[a]	t-Test[b]	$\bar{X} \pm E$	N	Δ , %[a]	t-Test[b]
X_{wb} (%, wb)	81.1 ± 1.0	5	-0.9	ns	81.8 ± 0.8	5	-0.1	ns
k (W/m-°K)	0.554 ± 0.010	12	-2.6	s	0.556 ± 0.009	12	-2.2	s

[a] Change in values of processed with respect to the fresh potatoes in Table 7.
[b] Based on 2-tailed *t*-test at $\alpha' = 0.05$ of raw vs processed products.

The results of this study show that the values of thermal properties that provide the most conservative estimate of F_0 are those measured after potatoes have been blanched and cooked and carrots have been canned to an $F_0=3.7$ min. Conversely, the least conservative values of thermal properties are those measured for raw carrots or for potatoes boiled for a long time or canned and stored for a long time. To illustrate the significance of this study and using the analysis of Lee *et al.* (1990), if a product whose lethality is based on potato, and if the thermal properties of potatoes that had been canned and stored are used in the calculation, the process time would be underestimated by 2%. If the lethality of a product is based on carrots and if the thermal properties of raw carrots are used in the analysis, the process time would be underestimated by less than 0.5%. It should be noted that this analysis is valid only for the processes evaluated in this study.

SUMMARY AND CONCLUSIONS

The results of the study are summarized below:

(1) Processed potatoes expand more than 10%, 4 times as much as carrots. In the development of heat and mass models for processing of potatoes, it may be necessary to include volumetric expansion as one of the variables. The determination of product loading, which is volumetric fraction of particulates in a food product, for potatoes may be based on processed materials and for carrots on raw materials.

(2) Materials with high starch content such as potatoes, have a lower tendency to change their k values during processing. Thermal processing increases the X_{wb} of food materials and causes their k values to increase. However, it also causes starch gelatinization which decreases the k values. The combined effect of increases in X_{wb} and starch gelatinization has a stabilizing influence on k values.

(3) Potatoes absorb less moisture in soup than in plain water. This is important in product development where product texture is one of the quality parameters.

(4) Generally, α decreased after thermal processing since the c_p increased more than k. However, in processes where the X_{wb} increased by more than 9%, α increased due to larger increases in k than in c_p.

(5) The results from this study show that the thermal properties of blanched and cooked potatoes and carrots canned to an $F_0=3.7$ min provide the most conservative estimate of F_0. Conversely, the least conservative estimates are derived from potatoes that had been either boiled for a long time or canned and then stored for a long time and from raw carrots.

(6) This study has shown that α changes with process time. In aseptic processing, this implies that α changes as the product moves along the holding tube. Depending on the state of the various materials in a product as they enter the holding tube, α could either initially decrease and then increase or just increase. In either case, a lethality calculation should be based on the properties of the material when its α is lowest.

NOMENCLATURE

CPS	Cream of potato soup
c_p, c_{pi}	Specific heat and specific heat of food component, kJ/kg-°C
D	Diameter
E_α, E_k, E_ρ, E_{cp}	Uncertainties or errors of the various thermal properties
f_h	f-value in thermal processing, min
F_o	Lethality or sterilizing value, min
j_h	Lag factor
k	Thermal conductivity, W/m-°K
L	Length
s, ns	Statistically significant and insignificant, respectively
N	Number of replicates
r_s	Sample radius, mm
t	Test time, s
T, T_r, T_i	Temperature, retort and initial temperature, respectively, °C
V_p, V_r	Volume of processed and raw samples, respectively, cc
X_{wb}	Moisture content, % wb (wet basis)
X^w_i	Weight fraction of food component
$\bar{x}$	Mean
α	Thermal diffusivity, m^2/s
α'	Coefficient of region outside the confidence interval
ρ	Density, g/cc
Δ	Change in a thermal property, %
ν	Volumetric expansion, %

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