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Effect of tuber skin on the thermal properties of whole tubers of potato and sweet potato

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Abstract. Temperature-dependent thermal coefficients of mathematical models of the postharvest storage process play an important role in determining the models accuracy. Thermal properties of tubers under storage available in literature are generally of those in semi processed form (skinless) such as those having undergone peeling, dicing and cutting actions. This study investigates the effect of tuber skin on the thermal properties of whole tubers of potato and sweet potato. A direct approach was used to measure the tubers' density and thermal conductivity and thermal diffusivity by the transient heat transfer method. Indirect approach was used to measure the tubers' specific heat. Experimental data were used to develop empirical models of the thermal coefficients as a function of temperature. Results of the study should find great use in the modeling of potato and sweet potato storage process.

Keywords: thermal properties, whole tubers, potato, sweet potato, tuber skin.

1. Introduction

Design of food processing systems, such as postharvest storage and food drying systems involves the proper specification of heating and cooling components of the equipment. Mathematical models are often employed to have a better understanding of the heat and mass transfer processes. One prominent drawback in the model approach is the use of appropriate thermal coefficients. Search through literature shows some works carried out by [1] and [2]. They both provided predictive equations for thermal conductivity of food stuffs. Due to substantial differences in the chemical and physical constituents of the food item, there is a need for each material to have its own predictive equation [3]. The limitation is that Literature search also revealed that thermal coefficients of food stuff are often associated with foods in semi processed form. An example is the abundant data on thermal properties of cuts or sliced pieces of peeled yams, potatoes and sweet potatoes which find use in the design of cooking, frying, or microwaving equipment. However, the postharvest storage process is associated with whole (unpeeled) tubers of food items. Experimental determination of appropriate thermo-physical properties of whole tubers of foods for the storage process will definitely yield better models. Good models will lead to better understanding of the storage process, thus control algorithms for the storage process can be developed. Ultimately, shelf life of stored products will be improved and in turn result in availability of the products outside its season and ensure its price stability.

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Attempt was made by [4] to model a potato storage process where due to lack of data on thermal properties of whole tubers of potato, that on mashed potatoes was managed. In determining some selected engineering properties of sweet potato as a function of temperature, [5] employed slab and cylindrical cuts of sweet potato. Investigations on the effects of variation in temperature and geometry on the thermal properties of pieces of yam in slab and cylindrical shapes were carried out by [6] . Experiments to determine the thermal properties of sweet potato and provide models as a function of temperature and moisture content were carried out by [7]. The tubers were peeled and then cut into cylindrical pieces. Measurements of thermal diffusivity of potato, malt bread and wheat flour were carried out by [8]. Potatoes were cooked, mashed and mixed to obtain homogenous products.

This study takes a look at the effect of the tuber skin on the thermal properties of whole tubers under storage with emphasis on potato and sweet potato. This study considered product temperature ranging from 8 to roughly 35^{O}C.

2. Materials and methods

Potato (solanum tuberosum) and sweet potato (Ipomea batatas) were purchased from the Chow kit market, in Kuala Lumpur, Malaysia. Cleaning, involved a simple process of brushing off the soil content from the sample bodies using a soft brush. No form of washing whatsoever was done to any of the tubers. The tubers were left in the whole form as bought from the market.

2.2. *Experimental Procedure*

2.2.1. Density [ρ] of the Tubers. The density of each sample was computed using equation 1. An electronic weighing scale of make and model METTLER Toledo B204-S was employed to determine the mass of the samples in grams. The values were then converted to kilograms. The scale has an accuracy of +_0.0001g. Through the principles of flotation [9], a 1000 ml measuring cylinder initially containing 300 ml of water was used to determine the volume of the samples. The final volumes were noted, the differences calculated and converted to SI units (m^3). The mass (kg) and volume (m^3) data were then plugged into (1).

$$\rho = \frac{mass\ of\ sample(kg)}{volume\ of\ sample\ (m^3)} \qquad (1)$$

2.2.2. Thermal Conductivity and Diffusivity [k, α] of the Yam Tuber. The thermal conductivity and diffusivity were measured using a KD2 thermal property analyzer (Decagon devices Inc., Pullman, USA). The device employs the transient method of thermal properties determination. Equation (2) illustrates the working principle of the KD2.

$$T - T_0 = \frac{q\left[\ln(t) - \gamma - \ln\left(\frac{r^2}{4\alpha}\right)\right]}{4\pi k} \qquad (2)$$

Where T is final temperature (^{O}C); T_0 is initial temperature before heating (^{O}C); q is heat produced per unit length per unit tie (Wm^{-1}); k is the thermal conductivity of the medium (Wm^{-1O}C^{-1}); t is time (s); γ is Euler's constant (0.5772); r is radial distance from the probe to the point where temperature is being measured (m); and α is thermal diffusivity (m^{2}s^{-1}).

The probe from the KD2 was inserted to the depth of the axis of the sample, then placed inside a temperature/humidity chamber and allowed to equilibrate with the surrounding atmospheric (temperature and humidity) conditions. The temperature/humidity chamber was then preset to the required environmental temperature. After about 30 minutes (after which the sample must have equilibrated with the environment) the KD2 was switched on and after about 25 seconds displays the product temperature and the computed thermal conductivity and diffusivity of the sample. Prior to the commencement of the experiment the KD2 was calibrated with an agar solution.

2.2.3. Specific Heat [c_p] of the Tubers. The indirect method (calculation) was used to determine the specific heat capacity -c_p- of the materials. Equation (3) represents the relation used to determine the specific heat capacity after rearranging to make c_p the subject of the formula.

$$c_\mathrm{p} = \frac{k}{\rho\alpha} \tag{3}$$

where k is the thermal conductivity ($Wm^{-1}K^{-1}$) of the material.
ρ is density (kg/m^3) of the material.
α is the thermal diffusivity (mm^2/s) of the material.

3. Results and discussion

On inspection of the samples it was discovered there was little variation in terms of skin color and texture and they were free of any skin abrasion. On the basis of these observations one could primarily conclude that the tubers were most likely of the same harvest. Since the sources of both tubers were a fresh vegetables market, estimates of moisture content were made for each material. A moisture content of about 75% was assumed for the potato tubers given the fact that fresh off the farm potato tubers usually have a moisture content of about 80% as stated by [4]. The reason here is that about 5% of the moisture content of the potatoes is assumed to have been lost during transit and initial storage. For the sweet potatoes, a moisture content of about 72% (wet basis) was made by [5].

3.1 Density (ρ)

The density of the materials was determined as earlier described and the results are presented in tables 1and 2. On the average the density of potato was found to be 1072 kg/m^3 with a standard deviation value of ±14.255 kg/m^3, while that of sweet potato was found to be 978 kg/m^3 with a standard deviation of ± 10.840. The results here are in agreement with those of literature [5] and [7].

3.2 Thermal conductivity (k)

The thermal properties for both potato and sweet potato were measured through temperature ranges as shown in tables 3 and 4 respectively. Specifically, that of potato spanned 11.7 to 34.6^OC as shown in table 2. Figure 1 shows that the thermal conductivity of whole tubers of potato ranged between values of 0.42 to 0.61W/m^OC within the range of study. Between 11.7^OC and 29.8^OC the thermal conductivity dips from a value of 0.45 W/m^OC (11.7^OC) to 0.52 W/m^OC (25.5^OC) then rises to 0.61W/m^OC (30^OC). The thermal conductivity drops to a value of 0.42 W/m^OC at 34.6^OC. Though the trend shown here is relatively similar to that observed by both [5] and [6] in their study of thermal properties of cuts of sweet potato and yam respectively, the values in this experiment are about twice theirs'. Equation (4) represents an empirical model of thermal conductivity of potato as a function of temperature.

Table 1. Experimental values of the density of potato.

Sample	Mass (g)	Volume (ml)	Density (kg/m^3)
A	75.1200	70.00	1073
B	121.1462	115.00	1054
C	104.0830	98.00	1062
D	99.3450	92.00	1080
E	79.5485	73.00	1090
Avg			1072 ± 14.255

Table 2. Experimental values of the density of sweet potato

Sample	Mass (g)	Volume (ml)	Density (kg/m^3)
A	135.0563	139.00	972
B	166.8247	170.00	981
C	154.3932	160.00	965
D	99.7649	102.00	978
E	91.4687	92.00	994
Avg			978 ± 10.840

Table 3. Thermal properties of potato as determined by the KD2 Thermal Analyzer and calculated.

	Experimental values					Calculated
S/N	Chamber Temperature (^{O}C)	Chamber Relative Humidity (%)	Tuber Temperature (^{O}C)	Thermal Conductivity (W/m^{O}C)	Thermal Diffusivity (x10^{-8}m^2/s)	Specific Heat Capacity (kJ/kg.K)
1	11.4	60.2	11.7	0.45	11.0	3.817
2	18.8	60.0	19.2	0.43	10.0	4.013
3	25.0	60.0	25.5	0.52	12.0	4.044
4	30.2	60.0	29.8	0.61	16.0	3.558
5	35.0	60.0	34.6	0.42	10.0	3.919

Table 4. Thermal properties of sweet potato determined by KD2 Thermal analyzer and calculated.

	Experimental values					Calculated
S/N	Chamber Temperature (^{O}C)	Chamber Relative Humidity (%)	Tuber Temperature (^{O}C)	Thermal Conductivity (W/m^{O}C)	Thermal Diffusivity (x10^{-8}m^2/s)	Specific Heat Capacity (kJ/kg.K)
1	7.7	80.0	8.0	0.46	11.0	4.280
2	9.8	80.0	10.2	0.44	10.0	4.504
3	13.8	80.0	14.4	0.50	12.0	4.265
4	18.0	80.0	18.7	0.42	10.0	4.299
5	30.0	80.0	29.7	0.42	10.0	4.299

Figure 2 shows that the thermal conductivity values for sweet potato in this experiment proved also higher than those of [5]. The value remained relatively constant at about 0.44 W/m^{O}C between 8 and 30^{o}C only for a jump to 0.50 W/m^{O}C at about 14.4^{O}C.

Based on the experimental values of k, (4) and (5) represent the empirical models describing thermal conductivity as a function of temperature for the potato and sweet potato tubers respectively.

$$k_{\mathrm{p}} = 0.010T^2 - 0.0225T + 1.854 \qquad (R^2 = 0.938) \qquad (4)$$
$$k_{\mathrm{sp}} = 8e - 05T^3 + 0.004T^2 + 0.075T + 0.089 \qquad (R^2 = 0.515) \qquad (5)$$

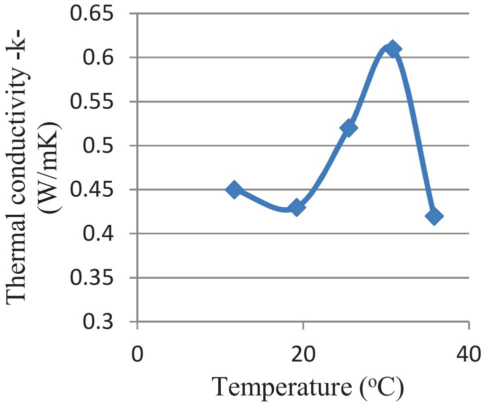

Figure 1. Plot of potato thermal conductivity (k) as a function of temperature.

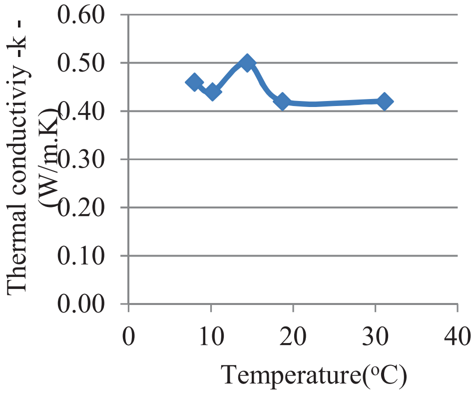

Figure 2. Plot of sweet potato thermal conductivity (k) as a function of temperature.

3.3 Thermal diffusivity (α)

Figure 3 shows that the thermal diffusivity value for potato remains relatively constant at a value of $12.0 \mathrm{x} 10^{-8}$ through the temperatures of 11.7 to 34.6^{O}C. These values are slightly higher compared to those of [5] and [6] who both recorded on average, values of about $7.0 \mathrm{x} 10^{-8} \mathrm{m}^2/\mathrm{s}$ for cuts of both sweet potato and yam.

The thermal diffusivities for sweet potato throughout the considered temperature range remained largely at $10.5 \mathrm{x} 10^{-8}\ \mathrm{m}^2/\mathrm{s}$. This is illustrated in figure 4. In line with that reported for potato, the results are higher than those reported by [5].

Equations (6) and (7) are empirical models describing the thermal diffusivity as a function of temperature for potato and sweet potato respectively.

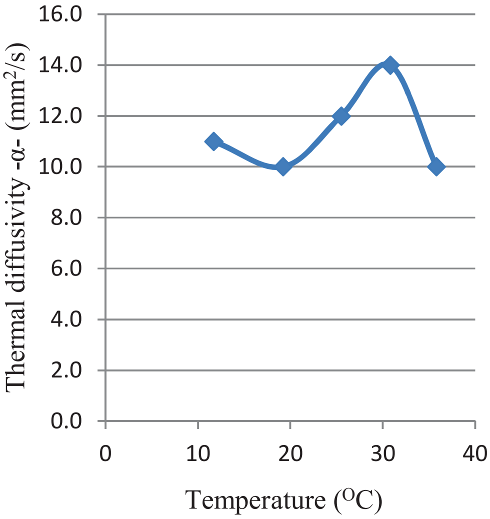

Figure 3. Plot of potato thermal diffusivity (α) as a function of temperature.

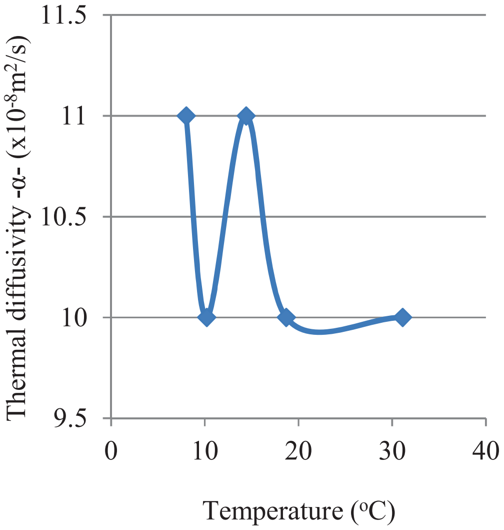

Figure 4. Plot of sweet potato thermal diffusivity (α) as a function of temperature.

$$\alpha_{\mathrm{p}} = -0.003T^3 + 0.251T^2 - 5.291T + 44.37 \quad (R^2 = 0.942) \tag{6}$$
$$\alpha_{\mathrm{sp}} = -0.003T^3 + 1.374T^2 - 13.80T + 59.13 \quad (R^2 = 1.0) \tag{7}$$

3.4 Specific heat (c_p)

The specific heat was determined for both materials using the indirect method. The specific heat for both materials was calculated using (3). Figure 5 indicates that the specific heat of potato rises from a value of 3.817 kJ/kg.K at 11.7^{O}C to 4.044 kJ/kg.K at 25.5^{O}C before dropping to a value of 3.919 kJ/kg.K at 34.6^{O}C. The results are not in agreement with those of [5] and [6] which show a steady and gradual drop in the specific heat for both sweet potato and yam from values of 2.5 kJ/kg.K to about 2.0 kJ/kg.K over the temperature range.

The sweet potato also shows a similar trend to that of the potato with the specific heat peaking at a value of 4.504 kJ/kg.K at a temperature of 10.2^{O}C. This is illustrated in figure 6.

The specific heats in our case also proved to be higher than those of [5] and [6] as was the cases of thermal conductivity and diffusivity.

The empirical models of specific heat as a function of temperature for both materials are represented by (8) and (9).

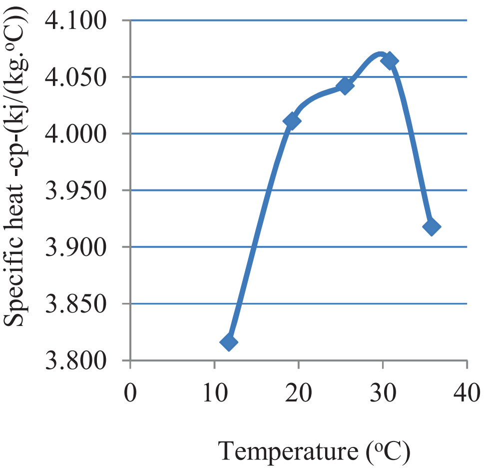

Figure 5. Plot of potato specific heat (c_p) as a function of temperature.

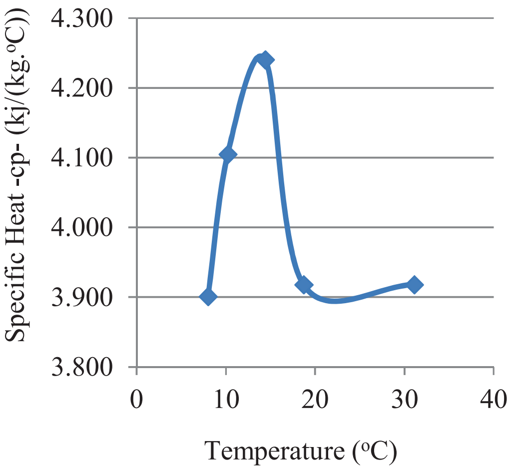

Figure 6. Plot of sweet potato specific heat (c_p) as a function of temperature.

$$c_{\mathrm{pp}} = -3e^{-05}T^3 + 0.025T + 3.487 \quad (R^2 = 0.966) \tag{8}$$
$$c_{\mathrm{psp}} = -0.036T^3 + 0.627T + 0.883 \quad (R^2 = 0.966) \tag{9}$$

4. Conclusion

The effect of the tuber skin on thermal properties of potato and sweet potato over a range of temperatures was studied. Temperature was varied over a range of 8^{O}C to 34.6^{O}C. Two of the thermo-physical properties were measured directly while a third was measured indirectly.

The values of all three thermal properties namely thermal conductivity, diffusivity and specific heat were observed to be higher than those found in literature. The density of the materials, a physical property was found to be in agreement with those of literature.

The high values of the experimental results prove that the tuber skins have an increased effect on the thermal properties. It would seem that the tuber skin create a sort of thermal drag on the food components in whole form. In comparison to tubers in full or semi processed forms, whole tubers will require more energy for processing especially as demanded by a storage (cooling) processes. Variation of the thermal properties was best described using empirical models in the form of polynomial equations of the third order.

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