



# Thermal transition and thermo-physical properties of potato (*Solanum tuberosum* L.) var. Russet brown

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## Abstract

Potatoes are an important food in many regions of the world and are commonly used in a variety of food products. Thermal transition and thermo-physical properties of potatoes are important in order to design efficient food processes and select appropriate storage conditions. In this study, we determined the thermal transitions and thermophysical properties of raw and blanched/par-fried potato for a temperature range of  $-32$  to  $21.1$  °C. Using differential scanning calorimetry, we found an initial freezing point ( $T_f$ ) at  $-1.8 \pm 0.1$  °C, an onset of melting ( $T_m'$ ) at  $-9.9 \pm 0.2$  °C and an unfreezable water content ( $X_w'$ ) for maximally freeze-concentrated raw potato at 0.21 kg water/kg potato. Corresponding values for blanched/par-fried potatoes were  $-0.9 \pm 0.1$  °C,  $-11.0 \pm 0.2$  °C and 0.18 kg water/kg potato. Results show that an increase in solids content decreased  $T_f$  of both raw and blanched potatoes. We modelled the relationship between them using the Chen model. The apparent specific heat ( $C_{app}$ ) increased around  $T_f$  to  $31.7 \pm 1.13$  kJ/kg K for raw potato and  $26.7 \pm 0.62$  kJ/kg K for blanched/par-fried potato. For frozen raw potato at  $-32$  °C, thermal diffusivity ( $\alpha$ ) was  $0.89 \pm 0.01 \times 10^{-6}$  m<sup>2</sup>/s and thermal conductivity ( $k$ ),  $1.82 \pm 0.14$  W/m K, respectively. These values were higher for frozen raw potato than for the unfrozen raw potato ( $0.15 \pm 0.01 \times 10^{-6}$  m<sup>2</sup>/s and  $0.56 \pm 0.08$  W/m K, respectively at  $21.1$  °C). The apparent density ( $\rho$ ) of frozen raw potato ( $992 \pm 4.00$  kg/m<sup>3</sup> at  $-32$  °C) was less than that for unfrozen raw potato ( $1053 \pm 4.00$  kg/m<sup>3</sup> at  $21.1$  °C), and a similar trend was obtained for blanched/par-fried potato ( $993 \pm 2.00$  kg/m<sup>3</sup> at  $-32$  °C and  $1188 \pm 7.00$  kg/m<sup>3</sup> at  $21.1$  °C, respectively). This study established a correlation between thermo-physical properties and temperature. Findings may be used to inform the design and optimization of freezing processes and frozen storage for potato products.

**Keywords** Potato · Apparent density · Diffusivity · Conductivity · Apparent specific heat · Thermal transition

## Introduction

To ensure effective process design, optimization, storage and handling conditions of foods, it is important to determine their thermo-physical properties. Data on apparent density, specific heat, thermal conductivity, and thermal diffusivity is

needed to determine the rate of heat transfer during thermal processes such as freezing, drying, frying and baking [1–3]. Such properties also help to estimate the energy requirements during food processes that involve heat transfer. These properties are affected by the cultivar, temperature, water content and state/phase of water in a food. For example, the ice fraction in a frozen food determines the property values, since ice has different thermal and physical properties than water [4–6].

Thermal transition parameters, namely initial freezing point ( $T_f$ ), onset of ice melting ( $T_m'$ ), and unfreezable water content ( $X_w'$ ) are necessary in order to design freezing processes and to optimize frozen storage and transport conditions. During cooling, the temperature at which the first ice nucleus forms in the food is denoted as equilibrium freezing point  $T_f$ . The end point of freezing, generally determined using differential scanning calorimetry as onset of ice crystal

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melting, is denoted as  $T_m'$ . Freezing of water in food results in a concentrated solution, and the fraction of water in the food remains unfrozen ( $X_w'$ ) due to the extremely high viscosity of the water fraction, which hinders crystallization. At temperatures below  $T_m'$ , the concentrated solution may also pass through glass transition at temperature  $T_g'$ . Ice formation ceases below  $T_g'$  with restricted molecular motion, causing vitrification of solutes with unfreezable water [7–10]. This unfrozen water in frozen foods creates several chemical and biochemical reactions [11, 12], including oxidation of lipids and vitamins and enzyme activity.

A significant portion of potato produced today is consumed in the form of processed products, including French fries, shredded potatoes, potato nuggets, wedges, cubes and slices, which are distributed in the frozen state. The food service sector purchases most potatoes as a ready-to-cook frozen food that is later deep-fried, baked or microwaved at restaurants. In the U.S., French fries are very popular, with 34% of the potato crop converted into frozen fries (2012, USDA/US Department of Commerce Report). Different cultivars of potatoes are used to produce French fries: Russet brown, Atlantic and Shepody in the U.S. [13], Agria in New Zealand [14], Maris Piper, Pentland Dell, King Edward, Daisy, and Markies in the U. K [15]. Among all cultivars, Russet brown potatoes are the most popular due to the high solids content, creating a distinct quality of French Fries. For low starch and high-water content potatoes, water evaporation is higher during frying, resulting in a more porous product. Both consumers and the potato industry prefer dense French fries. The color of French fries is the result of Maillard reaction, which is dependent on reducing sugars, frying temperature and frying period [16]. The texture of French fries is influenced by blanching method [17], solids content, starch granule size [18] and specific gravity [19]. Russet brown potatoes are also used in commercial baking and frying, since the end product has an outer crispy surface and an inner fluffy surface. Since they produce long pieces, they increase final product yield during production. Therefore, Russet brown potatoes are the preferred variety for producing French fries.

Although a large fraction of potatoes is processed into different products, few studies have investigated the most basic thermo-physical and thermal transition parameters of potatoes. This study determined thermal parameters for Russet brown potatoes to inform development of new products. Most processed potato products are stored and marketed in the frozen state, including French fries, shredded potatoes, potato nuggets, wedges, cubes and slices. Frozen products often go through state and phase transitions due to temperature fluctuations during storage and transport. This temperature fluctuation is unavoidable during cold storage and transport of frozen products. Efficient handling, package design, cold storage and transport management strategies for

frozen potato products requires understanding of thermal transition parameters. In industrial practice, French fries and other products are prepared by blanching raw potatoes and then partially frying them (also known as par-frying), followed by freezing at  $-18$  °C. Hence, data on the thermal and physical properties of blanched/par-fried potatoes is also useful to the industry.

The objectives of this study were to determine the thermal transition parameters ( $T_f$ ,  $T_m''$  and  $X_w'$ ) and thermo-physical properties ( $\rho$ ,  $C_{app}$ ,  $k$  and  $\alpha$ ) of raw and blanched/par-fried potato in the temperature range  $-32$  to  $21.1$  °C. Findings can be used in the development of new potato products, process optimization and storage stability.

## Materials and methods

### Materials and potato preparation

Russet brown variety of potatoes (*Solanum tuberosum*) (Potatoes Goodness Unearthed®, United States Potato Board Inc., Denver, CO) were procured from a local market (Walmart Supercenter, Pullman, WA). The raw potato was cleaned, peeled and cut into cylinders (radius  $1.5 \times 10^{-2}$  m, and height  $2.7 \times 10^{-2}$  m) and held in cold storage (Food Science Pilot Plant, WSU). The potato pieces were wrapped with a flexible plastic film (Glad® Cling Wrap, The Glad Products Company, Oakland, CA), allowing for volume expansion and preventing surface moisture loss. The thermo-physical properties of the raw potato were measured at the temperatures shown in Table 1. A low temperature bath (VWR Scientific, Arlington Heights, IL) circulating an aqueous solution of 50% ethylene glycol was used to maintain the temperature of potato. The core temperature of the raw potato was measured with an external  $K$  type thermocouple (Omega Engineering Inc., Norwalk, CT) to ensure that it reached the target temperature. The water content of the raw potatoes was determined using an oven-dry method [20] in a hot air oven at  $105$  °C for 24 h. The average initial water content was  $0.75 \pm 0.02$  kg water/kg potato ( $N = 9$ ).

**Table 1** Time required for raw and blanched/par-fried potato to reach target temperature

Temperature (°C)	Time (h)
-32	28
-19.4	21
-12	17
-10	14.5
-6	12.5
-4	10
0	9.5
1.7	8

To prepare the blanched/par-fried potato, raw potatoes were peeled and cut into a standard size for a commercial medium French fry. The square cross section was  $3/8''$  ( $9.5 \times 10^{-3}$  m) or and length  $\geq 2''$  ( $5.0 \times 10^{-2}$  m), following the manual Keen Kut Shoe Stringer (Shaver Specialty Co., Los Angeles, CA). A batch of about 150 g of raw potato pieces was then blanched in hot water at  $82^\circ\text{C}$  for 20 min. The potatoes were then left to dry in an open atmosphere for 20 min to remove surface moisture. This method of surface drying was selected according to a laboratory scale study. The potatoes were then par-fried in pre-heated commercial vegetable oil at  $196^\circ\text{C}$  for 30 s using a commercial fryer (Model RF114, Robot Coupe USA, Jackson, MS). The thermal transition and thermo-physical properties of the blanched/par-fried potato were also determined. An outer crust layer averaging 2 mm thick formed on the blanched/par-fried potatoes at a distance of 2.75 mm from the center ( $N=9$ ), measured using a standard ruler. The same temperature regimes were used in the experiments with blanched/par-fried potatoes, and the time required to attain the target temperature was similar. The blanched/par-fried potato had an average initial water content of  $0.81 \pm 0.02$  kg water/kg potato ( $N=9$ ).

## Methods

### Thermal transitions ( $T_f$ , $T_m'$ , and $X_w'$ )

To determine the thermal transition properties, approximately,  $15 \pm 2$  mg of raw potato was equilibrated at  $25^\circ\text{C}$  for 1 min, cooled to  $-25^\circ\text{C}$  at a rate of  $5^\circ\text{C}/\text{min}$ , held isothermally for 5 min and then heated to  $25^\circ\text{C}$  at a rate of  $5^\circ\text{C}/\text{min}$ . A low ramp rate was used to ensure detection of sharp transition points in the thermogram. The obtained differential scanning calorimetry (DSC) thermograms were analysed for  $T_m'$ ,  $T_f$  and  $X_w'$ . ( $N=9$ ). A similar procedure was used to determine the thermal transition parameters of the blanched/par-fried potato. Par-frying results in a very thin (2 mm) crust on the potato, which is rich in oil and contains less water. Since the sample size used for DSC was very small, the sample was selected from the core to represent the bulk potato.

The  $X_w'$  of the raw and the blanched/par-fried potato was determined from the enthalpy of the ice fraction in the frozen potato. The enthalpy of fusion was obtained by integrating the melting peak from the DSC thermogram with  $X_w'$  and calculated as follows [21, 22]:

$$X_w' = X_{ow} - \frac{(\Delta H_m)_{\text{frozen food}}}{(\Delta H_m)_{\text{water}}} \quad (1)$$

where  $X_w'$  is unfreezable water in potato, kg water/kg potato;  $X_{ow}$  = Water content of the frozen potato, kg water/kg potato;  $(\Delta H_m)_{\text{frozen food}}$  = Change in enthalpy during the melting of

ice in the frozen food, kJ/kg; and  $(\Delta H_m)_{\text{water}}$  = Latent heat of ice melting, 334 kJ/kg.  $X_w'$  was also obtained using the intercept method [23, 24]. Potato samples of varying moisture contents (0.75, 0.80, 0.85, 0.90 and 0.95 kg water/kg reconstituted potato flakes) were prepared by mixing commercial dry potato flakes (Oregon Potato Co., Boardman, OR) with the pre-calculated amount of water. The final moisture content of the prepared mashed potato was then determined. This ensured that the target moisture content was attained. The prepared mashed potato was then subjected to DSC, and  $(\Delta H_m)_{\text{frozen food}}$  was obtained for each moisture level. The  $X_w'$  was then estimated as the water content corresponding to the  $(\Delta H_m)_{\text{frozen food}} = 0$  from the linear plot between moisture content and  $(\Delta H_m)_{\text{frozen food}}$ .

To determine  $T_f$  as a function of moisture content, the aforementioned approach of reconstituting potato flakes with a pre-calculated amount of water was repeated. This produced potato samples of varying moisture contents of 0.75, 0.7, 0.65, 0.60 and 0.55 kg water/kg reconstituted potato flakes [23, 24]. To obtain a similar set of samples for the blanched potato flakes, raw potatoes were blanched, as per the method described in the previous section. They were then frozen to  $-35^\circ\text{C}$  in cold storage (Food Science Pilot Plant, WSU), followed by freeze-drying (Virtis freeze mobile 24 with Unitop 600 L, VirTis SP Industries Co., New York) at a shelf temperature of  $-25^\circ\text{C}$ , a condenser temperature of  $-60^\circ\text{C}$ , a drying temperature of  $5^\circ\text{C}$ , a pressure of 20 Pa, and a drying time of 72 h.

### Thermo-physical properties

#### Apparent density ( $\rho$ )

The  $\rho$  value of raw potato at the aforementioned temperatures was measured using the volume by geometry method [25]. The raw potato was cut into the desired size using a sharp-edged metallic cylinder of radius  $1.7 \times 10^{-2}$  m and height  $2.9 \times 10^{-2}$  m (open at both ends) and was left in the cylinder to reach a specific temperature. During the freezing process, the cylindrical raw potato piece underwent a volume change due to expansion through the open ends. Once the raw potato reached the desired temperature, the volume of material that protruded from the ends of the open cylinder (overrun) was removed using a sharp knife, and the weight of raw potato and cylinder was immediately recorded. The mass of the raw potato (after removing the overrun) and the known volume of the steel cylinder were used to calculate the  $\rho$  of the frozen raw potato. To avoid surface dehydration/case hardening due to moisture loss on the surface of the raw potato (the cylinder was open at both ends to facilitate expansion), the ends were wrapped with a flexible plastic film (Glad® Cling Wrap, The Glad Products Company, Oakland, CA), allowing for volume expansion and preventing

surface moisture loss. The apparatus was loosely sealed with electrical duct tape. The study was replicated (N=9). To measure the same parameters for the blanched/par-fried potato, the raw potato was cut into the same dimensions as above, and then blanched for 34 min at 82 °C, followed by the par-frying steps previously noted. The blanched/par-fried potato was then inserted back into the steel cylinder and tightly packed. This study was repeated using the same procedure as for raw potato (N=9).

### Apparent specific heat ( $C_{app}$ )

For the raw and blanched/par-fried potato, the  $C_{app}$  value was measured using DSC of Q2000 V24.10 (TA Instruments, New Castle, DE) [26, 27]. Approximately,  $15 \pm 2$  mg of raw potato was hermetically sealed and loaded into the DSC cell. The raw potato was equilibrated at 25 °C for 1 min and cooled to  $-35$  °C at a rate of 10 °C/min. The raw potato was held isothermally for 5 min, followed by heating to 25 °C at a rate of 10 °C/min. The  $C_{app}$  values at specific temperatures were determined from the DSC thermogram (N=9).

### Thermal conductivity (k) and diffusivity ( $\alpha$ )

The  $k$  and  $\alpha$  of the raw and blanched/par-fried potato were measured with a handheld conductivity meter using the dual probe method (KD2 Pro®, Meter Group Inc., Pullman, WA, USA) for temperatures from  $-32$  to 21.1 °C [28–30]. The thermal conductivity meter consists of dual needles at a finite distance from each other. One needle applies heat for a specific time, while the other measures temperature during heating and cooling periods. The sensor was calibrated using a verification standard and then equilibrated to 20 °C. The sensor was inserted into the potato (cut to the dimensions previously discussed) and the potato material was brought to the desired testing temperature ( $-32$  to 21.1 °C). The  $k$  and  $\alpha$  values were recorded after an equilibration time of ten minutes (N=9).

### Predictive equations and statistical analysis

The Chen model [21], an extension of the ideal Clausius–Clapeyron equation (which is applicable only to dilute aqueous solutions), was used to model  $T_f$  values for changes in the moisture content of potato:

$$\delta = -\frac{\beta}{\lambda_w} \ln \left( \frac{1 - X_s - BX_s}{1 - X_s - BX_s + EX_s} \right) \quad (2)$$

where  $\delta$  is the freezing point depression ( $T_w - T_f$ ) relative to an increasing total solid content,  $T_f$  = the freezing point of the food material (°C),  $T_w$  = the freezing point of water (°C),

$\beta$  = the molar freezing point constant of water (1860 kg K/kg mol),  $\lambda_w$  = the molecular mass of water,  $X_s$  = the solids mass fraction,  $E$  = the molecular mass ratio of water to solids ( $\lambda_w/\lambda_s$ ), and  $B$  = the ratio of unfreezable water to the total solids content.  $E$  and  $B$  are determined by non-linear optimization analysis using the Solver function in Microsoft Excel®.

Statistical models for the experimental thermal property data as a function of temperature were developed using Minitab® 17 Statistical Software (Minitab, State College, PA). Regression analysis was performed using the Fitted Line Plot approach. The output from the quadratic model was chosen as the best fit, based on the  $R^2$  and Standard Error values. The equations obtained were used to determine the predicted values of the respective properties as a function of temperature. Trends in the properties of raw and blanched/par-fried potato were observed. A completely randomized design with one-way ANOVA by Fisher's Least Square Difference (LSD) method was used for the experimental design, where a value of  $p < 0.05$  was selected.

## Results and discussion

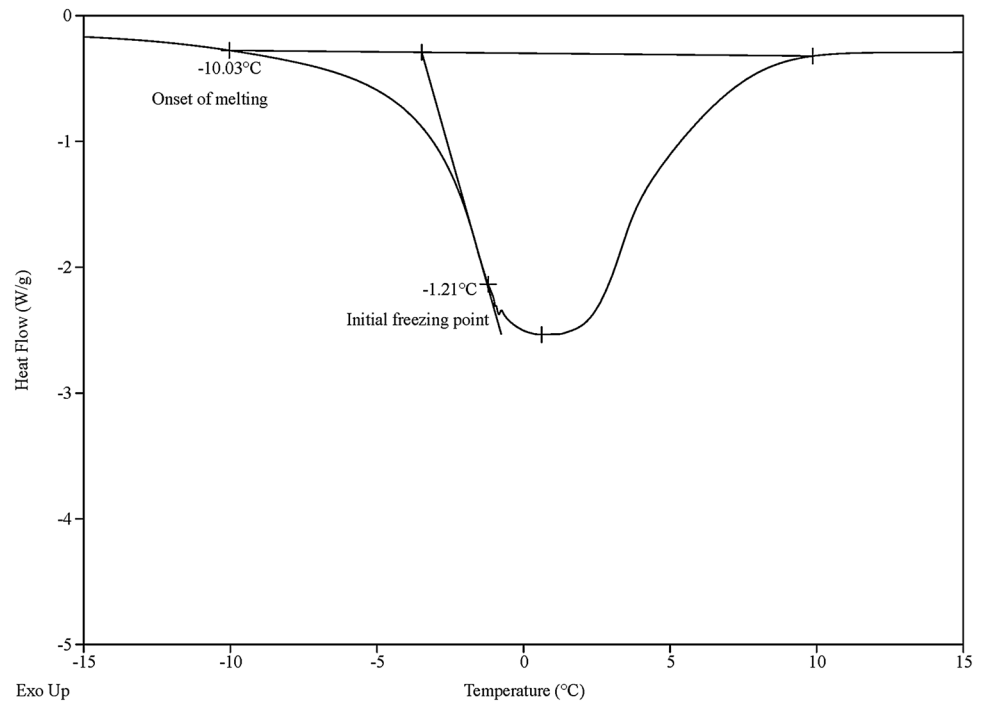
### Thermal transitions ( $T_m'$ , $T_f$ and $X_w'$ )

The average values of  $T_f$  and  $T_m'$  of the raw potato were  $-1.8 \pm 0.1$  °C and  $-9.9 \pm 0.2$  °C, respectively (Table 2; Fig. 1). For the blanched/par-fried potato,  $T_f$  was  $-0.9 \pm 0.1$  °C and  $-11.0 \pm 0.2$  °C (Table 2; Fig. 2). The difference in  $T_f$  between blanched/par-fried and raw potato was statistically significant ( $p < 0.05$ ). A lower  $T_f$  was found for the raw potato than for the blanched/par-fried potato. This may be due to the loss of dissolved solutes during blanching, which results in a higher water content. The water content of blanched/par-fried potato ( $0.81 \pm 0.02$  kg water/kg potato) was higher than that of

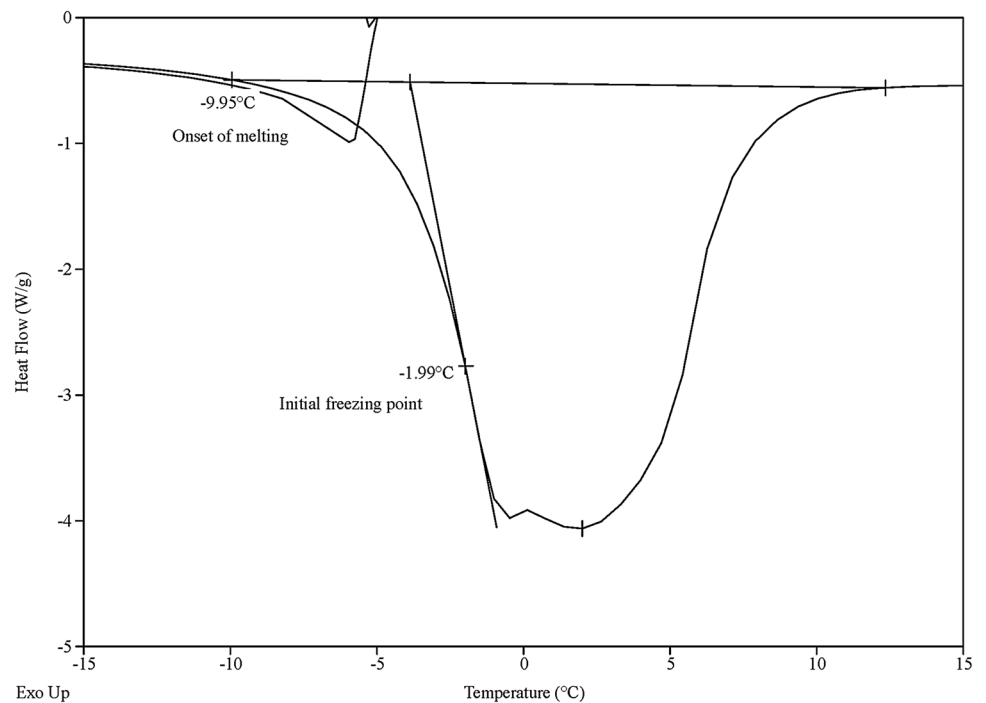
**Table 2** Thermal transition of raw and blanched/par-fried potato (N=9)

Property	Raw potato	Blanched/par-fried potato
Freezing point, $T_f$ (°C)	$-1.8 \pm 0.1$	$-0.9 \pm 0.1$
Onset of melting, $T_m'$ (°C)	$-9.9 \pm 0.2$	$-11.0 \pm 0.2$
Enthalpy change, $\Delta H$ (J/g)	181	213
Unfrozen water content, from the enthalpy of ice (kg water/kg potato)	0.21	0.18
Unfrozen water content, from the intercept method (kg water/kg potato)	0.23	–

**Fig. 1** DSC thermogram of raw potato: Initial freezing point ( $T_f$ ) and onset of melting ( $T_m'$ )



**Fig. 2** DSC thermogram of blanched/par-fried potato, core region: Initial freezing point ( $T_f$ ) and onset of melting ( $T_m'$ )



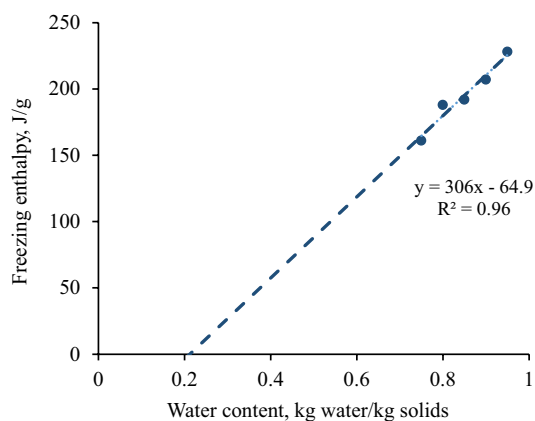
raw potato ( $0.75 \pm 0.02$  kg water/kg potato). Blanching leads to softening of tissues and a homogenous distribution of solutes, as well as enzyme denaturation. Potato starch in the raw potato primarily took the form of intact starch granules with the starch in an insolubilized state. Since potato starch gelatinizes at  $61.1^{\circ}\text{C}$  [31], the starch in the blanched/par-fried potato was gelatinized. This leads to

significant changes in thermal transition properties. When starch is heated above the gelatinization temperature, there is irreversible increase of water absorption capacity [32]. Upon gelatinization, the number of crystalline regions in a starch granule decreases, amylose chains disassociate, and water molecules disperse through amorphous regions. This may decrease the values of  $T_f$ . The first ice crystals form

more easily in blanched potato than in raw potato, where starch molecules are more crystalline and rigid.

With an increase in solids content, there was a depression of  $T_f$  for both raw and blanched potato, since the freezing point is a colligative property that is dependent on the number of solute molecules (data not shown). In addition, the blanched potato had higher  $T_f$  value than the raw potato at each moisture content compared. This behaviour could be attributed to the gelatinization, as explained above. The Chen model was able to describe the depression of  $T_f$  with increasing solids content. The predicted values for  $T_f$  were well within the range of experimental data for  $T_f$  over the moisture content range studied. Chen model constants previously obtained for raspberry were 0.141 and 0.064 for  $B$  and  $E$  values, respectively [21]. For the raw and blanched/par-fried potatoes in this study,  $B$  values were 0.135 and 0.137;  $E$  values were 0.028 and 0.020, respectively.

In this study,  $T_m'$  was lower ( $-11.0 \pm 0.2$  °C) for the blanched/par-fried potato than for raw potato ( $-9.9 \pm 0.2$  °C). This depression in  $T_m'$  may be due to an increase in moisture content upon blanching. Solutes may be leached out during blanching [33], with an increase in water content and reduction in the solid content of the potato. Gelatinization of starch during blanching results in an amorphous mass of hydrated starch, while water acts as a plasticizer and can depress thermal transitions [34]. The  $X_w'$  in raw potato obtained using the enthalpy of ice approach was 0.21 kg water/kg raw potato (Table 2), close to that of the intercept method (0.23 kg water/kg raw potato) (Fig. 3). The blanched/par-fried potato had  $X_w'$  of 0.18 kg water/kg, lower than that of raw potato. The  $X_w'$  in foods depends on the interaction between water and solutes. Unfreezable water is known to take part in a chemical reaction in frozen food, and thus compromises the quality of frozen food. Solute loss also occurs during hot water blanching of potatoes, making more water available for conversion to ice. In blanched/



**Fig. 3** Unfrozen water content determination of potato from the experimental freezing enthalpy values at different moisture contents

par-fried potatoes, less solutes were available to interact with water molecules, leading to an increased ice fraction. This can also be seen as an increase in the enthalpy of melting ( $\Delta H$ ) of blanched/par-fried potato (213 J/g) compared to that of the raw potato (181 J/g), resulting in lower  $X_w'$  upon blanching (Table 2). It is interesting to note that the DSC thermograms of raw and blanched/par-fried potato did not show  $T_g'$ . It has been reported that  $T_g'$  and  $T_m'$  values can coincide for products rich in starch [35]. The chain mobility may be suppressed in starch systems [35]. It is also possible that the DSC method was not sensitive enough to pick up the low temperature transition for starch rich potato.

## Thermo-physical properties

### Apparent density ( $\rho$ )

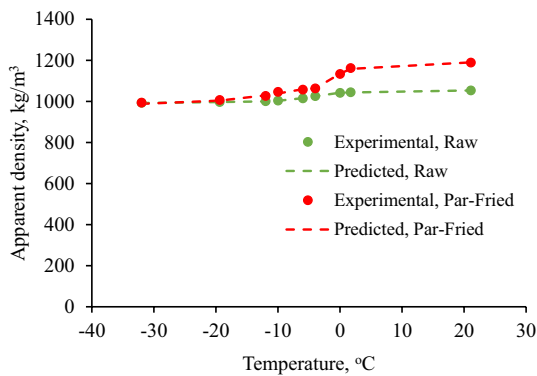
The  $\rho$  value of raw potato ranged from  $992 \pm 4.00$  to  $1025 \pm 3.00$  kg/m<sup>3</sup> in the frozen range (from  $-32$  to  $-4$  °C). In the unfrozen range ( $0$ – $21.1$  °C), values ranged from  $1041 \pm 9.00$  to  $1053 \pm 4.00$  kg/m<sup>3</sup>. (Table 3). Similarly, for the blanched/par-fried potato, the  $\rho$  value ranged from  $993 \pm 2.00$  to  $1063 \pm 2.00$  kg/m<sup>3</sup> in the frozen range ( $-32$  to  $-4$  °C) and ranged from  $1133 \pm 2.00$  to  $1188 \pm 7.00$  kg/m<sup>3</sup> for  $0$  to  $21.1$  °C (Table 3). The  $\rho$  for unfrozen raw potato was within the range of reported value for frozen, starch-rich foods, from  $1040$  to  $1070$  kg/m<sup>3</sup> [36]. The  $\rho$  value of frozen raw sweet potato, which has higher sugar and a slightly lower moisture content than white potato, has been reported as  $1150$  kg/m<sup>3</sup> at  $-18$  °C, while that of unfrozen raw sweet potato has been found to be  $1235$  kg/m<sup>3</sup> at  $33$  °C [37]. For frozen strawberries, the  $\rho$  value has not varied beyond 5% from that of unfrozen strawberries [38]. Potatoes and sweet potatoes, both in the raw form, show a reduction in  $\rho$  value by 5–7% between frozen and unfrozen states.

Since ice has a lower density than water ( $917$  vs.  $1000$  kg/m<sup>3</sup> at  $0$  °C), frozen food has lower  $\rho$  than unfrozen food. Below  $T_f$  ( $-1.8$  °C), more ice formation occurs, decreasing the  $\rho$  value of frozen food [38]. The most ice forms at  $T_m'$ , and therefore the change in potato apparent density at temperatures below  $-9.9$  °C is minimal. A similar trend was observed for blanched/par-fried potatoes, but  $\rho$  values are significantly higher than for raw potatoes ( $p < 0.05$ ). In this study, there was an increase in  $\rho$  value of about 13% with blanching and par-frying. At temperatures below the initial freezing point, the  $\rho$  values for raw and blanched/par-fried potatoes were comparable. However, the  $\rho$  of blanched/par-fried potatoes was higher ( $p < 0.05$ ) than for raw potato at temperatures above the initial freezing point (Fig. 4). The predicted values for  $\rho$  were within the range of experimental values ( $p < 0.05$ ) (as shown in Table 4). Cellular breakdown occurs during blanching, with a loss of intercellular and intracellular

**Table 3** Apparent density ( $\rho$ ), apparent specific heat ( $C_{app}$ ), thermal conductivity ( $k$ ), and thermal diffusivity ( $\alpha$ ) of raw and blanched/par-fried potato at selected temperatures (N=9)

Temperature (°C)	$\rho$ (kg/m <sup>3</sup> )		$C_{app}$ (kJ/kg K)		$k$ (W/m K)		$\alpha$ ( $\times 10^{-6}$ m <sup>2</sup> /s)	
	Raw	Blanched/par-fried	Raw	Blanched/par-fried	Raw	Blanched/par-fried	Raw	Blanched/par-fried
-32	992 ± 4.00 <sup>a</sup>	993 ± 2.00 <sup>a</sup>	2.55 ± 0.30 <sup>a</sup>	1.48 ± 0.08 <sup>a</sup>	1.82 ± 0.14 <sup>a</sup>	1.65 ± 0.12 <sup>a</sup>	0.89 ± 0.01 <sup>a</sup>	1.11 ± 0.03 <sup>a</sup>
-19.4	996 ± 3.00 <sup>a</sup>	1006 ± 5.00 <sup>b</sup>	2.96 ± 0.41 <sup>ab</sup>	1.65 ± 0.14 <sup>a</sup>	1.75 ± 0.00 <sup>a</sup>	1.51 ± 0.03 <sup>a</sup>	0.65 ± 0.11 <sup>b</sup>	0.9 ± 0.05 <sup>b</sup>
-12	1000 ± 2.00 <sup>a</sup>	1026 ± 5.00 <sup>c</sup>	2.99 ± 0.22 <sup>abc</sup>	2.24 ± 0.2 <sup>a</sup>	1.79 ± 0.00 <sup>a</sup>	1.56 ± 0.12 <sup>a</sup>	0.65 ± 0.10 <sup>b</sup>	0.88 ± 0.08 <sup>bc</sup>
-10	1003 ± 4.00 <sup>ab</sup>	1046 ± 5.00 <sup>d</sup>	3.55 ± 0.10 <sup>abc</sup>	2.74 ± 0.2 <sup>bc</sup>	1.83 ± 0.00 <sup>a</sup>	1.75 ± 0.16 <sup>a</sup>	0.54 ± 0.00 <sup>b</sup>	0.76 ± 0.07 <sup>c</sup>
-6	1014 ± 2.00 <sup>bc</sup>	1057 ± 6.00 <sup>de</sup>	4.18 ± 0.43 <sup>bc</sup>	4.26 ± 0.31 <sup>d</sup>	0.59 ± 0.00 <sup>b</sup>	0.55 ± 0.05 <sup>b</sup>	0.17 ± 0.04 <sup>c</sup>	0.29 ± 0.02 <sup>d</sup>
-4	1025 ± 3.00 <sup>c</sup>	1063 ± 2.00 <sup>e</sup>	31.7 ± 1.13 <sup>d</sup>	26.7 ± 0.62 <sup>e</sup>	0.59 ± 0.00 <sup>b</sup>	0.52 ± 0.04 <sup>b</sup>	0.19 ± 0.03 <sup>c</sup>	0.28 ± 0.02 <sup>d</sup>
0	1041 ± 9.00 <sup>d</sup>	1133 ± 2.00 <sup>f</sup>	6.98 ± 0.14 <sup>e</sup>	6.60 ± 0.50 <sup>f</sup>	0.54 ± 0.09 <sup>b</sup>	0.55 ± 0.05 <sup>b</sup>	0.14 ± 0.02 <sup>c</sup>	0.25 ± 0.02 <sup>d</sup>
1.7	1044 ± 4.00 <sup>d</sup>	1162 ± 1.00 <sup>g</sup>	4.21 ± 0.74 <sup>bc</sup>	5.4 ± 0.45 <sup>g</sup>	0.56 ± 0.08 <sup>b</sup>	0.56 ± 0.05 <sup>b</sup>	0.15 ± 0.01 <sup>c</sup>	0.21 ± 0.01 <sup>d</sup>
21.1	1053 ± 4.00 <sup>d</sup>	1188 ± 7.00 <sup>h</sup>	4.41 ± 0.42 <sup>c</sup>	3.51 ± 0.32 <sup>cd</sup>	0.56 ± 0.08 <sup>b</sup>	0.55 ± 0.04 <sup>b</sup>	0.15 ± 0.01 <sup>c</sup>	0.20 ± 0.01 <sup>d</sup>

Different superscripts in rows represent statistical significant differences between respective thermo-physical property values of potato ( $p < 0.05$ )



**Fig. 4** Experimental and predicted values of apparent density,  $\rho$  of raw and blanched/par-fried potato as a function of temperature (N=9)

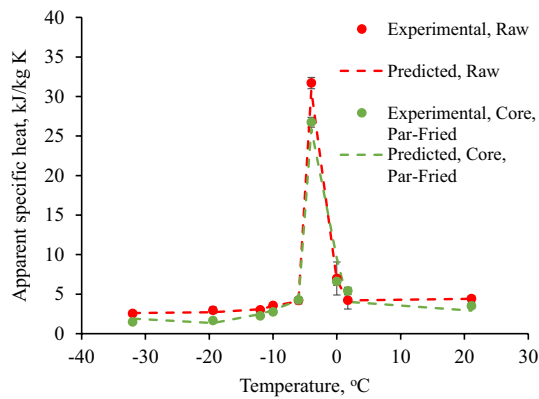
air pockets. There is also a loss of a small amount of low molecular weight solutes. With blanching and subsequent par-frying, a volume reduction occurs, leading to an increase in the  $\rho$  value of potato [39].

### Apparent specific heat ( $C_{app}$ )

The  $C_{app}$  value of frozen raw potato was between  $2.55 \pm 0.30$  kJ/kg K at  $-32$  °C and  $31.7 \pm 1.13$  kJ/kg K at  $-4$  °C, with different values for unfrozen potato at  $6.98 \pm 0.14$  kJ/kg K at  $0$  °C and  $4.41 \pm 0.42$  kJ/kg K at  $21.1$  °C (Table 3). The  $C_{app}$  profile shows the temperature range in which the phase change for the water in raw potatoes occurs. The  $C_{app}$  value of ice ( $2.03$  kJ/kg K) is less than that of water ( $4.19$  kJ/kg K) at  $0$  °C by approximately two times. As the temperature approaches  $T_f$  (about  $-1.8 \pm 0.1$  °C), there is an increase in  $C_{app}$  value to  $31.7 \pm 1.13$  kJ/kg K, at  $-4$  °C. This is associated with melting of ice, as shown in Fig. 5. During the phase change, the mobility of the water changes, affecting its ability to store internal energy; hence the difference in  $C_{app}$  value. In high-moisture foods during freezing, the  $C_{app}$  value increases with temperature, with the maximum value attained around  $T_f$  [38]. There is also a decrease in the  $C_{app}$  value in the unfrozen phase, since the food loses the latent heat of fusion immediately thereafter. Table 4 displays the corresponding prediction equation, within the range of experimental values ( $p < 0.05$ ).

**Table 4** Prediction equations for thermo-physical properties of raw and blanched/par-fried potato with respect to temperature (N=9)

Temperature range (°C)	Property	Raw potato	Blanched/par-fried potato
-30 to -6	Density	$1051 + 8.05T + 0.39T^2$	$1097 + 6.93T + 0.11T^2$
	Apparent specific heat	$5.03 + 0.19T$	$6.79 + 0.47T + 0.01T^2$
	Thermal conductivity	$1.92 + 0.02T$	$1.02 - 0.02T$
	Thermal diffusivity	$0.53 - 0.01T$	$0.71 - 0.01T$
-4 to 21.1	Density	$1042 + 0.53T$	$1134 + 15.3T - 0.6T^2$
	Apparent specific heat	$9.26 - 4.03T + 0.18T^2$	$9.57 - 3.48T + 0.15T^2$
	Thermal conductivity	$0.57 - 0.01T$	$0.57 - 0.01T$
	Thermal diffusivity	$0.16 - 0.01T$	$0.24 - 0.01T$

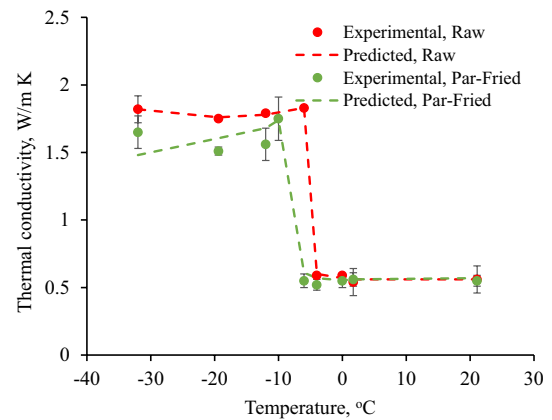


**Fig. 5** Experimental and predicted values of apparent specific heat,  $C_{app}$  of raw and blanched/par-fried potato as a function of temperature (N=9)

The  $C_{app}$  value of frozen blanched/par-fried potatoes was lower than for raw potato, between  $1.48 \pm 0.08$  kJ/kg K at  $-32$  °C and  $26.7 \pm 0.62$  kJ/kg K at  $-4$  °C. In addition, the  $C_{app}$  value varied between  $6.60 \pm 0.50$  kJ/kg K at  $0$  °C and  $3.51 \pm 0.32$  kJ/kg K at  $21.1$  °C (Table 3; Fig. 5). The  $C_{app}$  values for blanched/par-fried potato are significantly lower than that of raw potato ( $p < 0.05$ ). This is due to oil that may have penetrated into the blanched/par-fried potato. Generally, in fried foods, there is a decrease in specific heat due to an increase in oil content [40]. The temperature trends of  $C_{app}$  in both frozen and unfrozen states are similar in blanched/par-fried and raw potato [38]. Table 4 provides the corresponding prediction equations ( $p < 0.05$ ).

### Thermal conductivity (k) and diffusivity ( $\alpha$ )

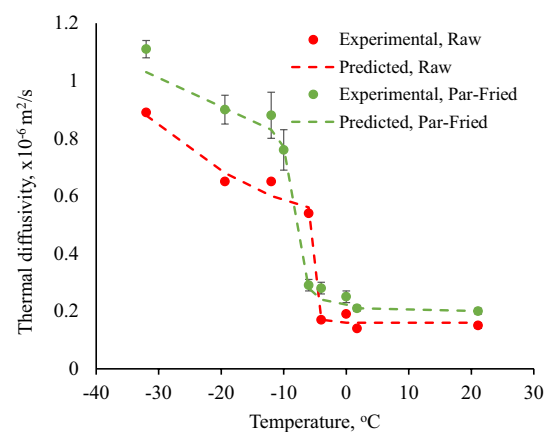
In this study, the  $k$  value of raw potatoes was between  $1.82 \pm 0.14$  W/m K at  $-32$  °C and  $0.59 \pm 0.00$  W/m K at  $-4$  °C, and between  $0.54 \pm 0.09$  W/m K at  $0$  °C and  $0.56 \pm 0.08$  W/m K at  $21.1$  °C (Table 3). Figure 6 presents the relationship between  $k$  and temperature. The  $k$  value in frozen food is higher than that of unfrozen food, since the  $k$  value of ice ( $2.22$  W/m K at  $0$  °C) is higher than that of water ( $0.6$  W/m K at  $0$  °C) by approximately four times. The  $k$  value increases at  $10$  °C below  $T_f$  for the product, and then remains constant [41]. Wang and Weller [38] predicted that the  $k$  value of a frozen food will decrease at  $T_f$  due to the melting of ice. The  $k$  values for unfrozen foods may vary between  $0.02$  W/m K (for air) to  $0.62$  W/m K (for water), while values for the frozen foods usually range from  $1.5$  W/m K at  $-40$  °C to  $0.5$  W/m K at  $T_f$ , depending up on the ice fraction in food [38]. The  $k$  value of raw sweet potatoes exhibits a 20% change between frozen and unfrozen states [37]. However, in this study, raw potatoes exhibited a 30% change, which was in the range of temperatures studied here. Table 4 displays the prediction



**Fig. 6** Experimental and predicted values of thermal conductivity,  $k$  of raw and blanched/par-fried potato as a function of temperature (N=9)

equation, which correlates well with experimental values ( $p < 0.05$ ). The  $k$  value of blanched/par-fried potatoes was between  $1.65 \pm 0.12$  W/m K at  $-32$  °C and  $0.52 \pm 0.04$  W/m K at  $-4$  °C, and between  $0.55 \pm 0.04$  W/m K at  $0$  °C and  $0.56 \pm 0.04$  W/m K at  $21.1$  °C, determined experimentally (Table 3; Fig. 6). Mittal [40] noted similar behavior of  $k$  and  $C_{app}$  of foods upon frying, to the trends obtained with blanched/par-fried potatoes in this study. Our predictions (Table 4) correlate well with experimental values ( $p < 0.05$ ).

The  $\alpha$  value of the raw potato ranged from  $0.89 \pm 0.01 \times 10^{-6}$  m<sup>2</sup>/s at  $-32$  °C to  $0.19 \pm 0.03 \times 10^{-6}$  m<sup>2</sup>/s at  $-4$  °C, and between  $0.14 \pm 0.02 \times 10^{-6}$  m<sup>2</sup>/s at  $0$  °C and  $0.15 \pm 0.01 \times 10^{-6}$  m<sup>2</sup>/s at  $21.1$  °C (Table 3; Fig. 7). The  $k$  and  $\alpha$  values followed similar trends, with larger  $\alpha$  values for frozen raw potato than for unfrozen raw potato. The  $\alpha$  is a measure of how fast heat can transfer through solid material. Water has a value of  $0.14 \times 10^{-6}$  m<sup>2</sup>/s, and ice has a value of  $1.09 \times 10^{-6}$  m<sup>2</sup>/s, at  $0$  °C (8 times higher). In an unfrozen



**Fig. 7** Experimental and predicted values of thermal diffusivity,  $\alpha$  of raw and blanched/par-fried potato as a function of temperature (N=9)



food, the  $\alpha$  value shows little or no change with temperature, since the determining factors ( $\rho$ ,  $k$  and  $C_{app}$ ) compensate for one another. As the  $C_{app}$  of the frozen food increases, the  $\alpha$  value of the food decreases. The phase change results in a 20–30% change in the  $\alpha$  value of both raw potato and raw sweet potato [37]. Again, our predictive models shown in Table 4 provided good correlations with experimental values ( $p < 0.05$ ). The  $\alpha$  value of the blanched/par-fried potato was from  $1.11 \pm 0.03 \times 10^{-6} \text{ m}^2/\text{s}$  at  $-32 \text{ }^\circ\text{C}$  to  $0.28 \pm 0.02 \times 10^{-6} \text{ m}^2/\text{s}$  at  $-4 \text{ }^\circ\text{C}$  and between  $0.25 \pm 0.02 \times 10^{-6} \text{ m}^2/\text{s}$  at  $0 \text{ }^\circ\text{C}$  and  $0.2 \pm 0.01 \times 10^{-6} \text{ m}^2/\text{s}$  at  $21.1 \text{ }^\circ\text{C}$  (Table 3; Fig. 7). The loss of the crystalline structure of starch led to an increase in diffusivity values upon blanching and par-frying and higher values compared to raw potato.

## Conclusions

In this study, we determined the thermal transition and thermo-physical properties of raw and blanched/par-fried potatoes. Results follow trends observed for other frozen foods. Blanching/par-frying led to an increase in  $T_f$  and  $\rho$  values and a decrease in  $T_m'$ ,  $X_w'$ ,  $C_{app}$  and  $k$  values. The  $T_f$  values decreased with increase in solids content, for both raw and blanched/par-frying potatoes. The  $\rho$  values decreased upon freezing, while  $k$  and  $\alpha$  values of both raw and blanched/par-fried potatoes increased. The polynomial equations developed may be used to predict these physical properties over the temperature range of  $-32$  to  $21 \text{ }^\circ\text{C}$ . Heat transfer models for the design and optimization of thermal processes for potato products can easily incorporate the temperature-dependent thermal and physical properties data obtained in this study.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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