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# Experimental And Simulatinon Study Of Water Immersion Cooling Of Canned Carrot Puree

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## Abstract

In the food industry, knowledge of thermal properties is of fundamental importance to analyze transport phenomena and to design food processing equipment, such as heat exchangers, chillers and evaporators. Cooling is usually accomplished by using traditional methods of slow air, air blast and water immersion cooling. In each case, the heat transfers to the surface is by conduction and from the surface by convection. Thermal properties of cooked carrot puree were estimated in this research, they included thermal conductivity, thermal diffusivity, density, enthalpy and specific heat from 0 to 80 °C. Enthalpy was calculated , temperature was measured used thermocouple, using a mathematical model the evaluated thermal properties agreed well with the Comsol Multiphysics simulation, mathematical models relating thermal properties and composition were used and compared with the Comsol Multiphysics results . The composition ranged from 85.11% moisture, 0.23% fat, and 1.87% protein (wet basis), the thermal conductivity ranged from 0.519 to 0.615 (W/m.°C) and from 3819.04 to 3867.86 kJ/(kg·K) for heat capacity. Both thermal conductivity and heat capacity increased with temperature (20 to 80°C). The thermal diffusivity ranged from 0.131 to 0.153 $m^2/s$ .The Chen's model [1] gives good results compared to the Comsol Multiphysics results.

**Key words:** cooling, canned carrot puree, thermal properties, simulation

## 1. Introduction

The rapidly growing demand for high quality cooked foods in the market has increasingly stimulated the food industry to develop new technologies to meet the guidelines of cook–chill systems [2]. Cooling is an important process in the cooked food industry, for safety and quality of cooked food, rapid cooling of product should be achieved immediately after cooking to minimize the growth of surviving organisms [3]. The main consideration in selecting a cooling method for cooked food should be the cooling rate achieved, the cooling rate of foods may be affected by the foods themselves, size, geometry and composition, and the cooling methods [4]. The geometry of the foods has the most pronounced effect on the cooling rate [5]. Exact solutions for the problems governed by Fourier's heat conduction equation are only possible for simple geometries with simple initial and boundary conditions [7] [6]. There is now a large literature that presents empirical data of thermal properties of food, as well as literature on composition-based approach to predict thermal properties of food. Examples of literature for thermal conductivity values and prediction of food are [20] [7]. Mathematical models by Long [21] [8], Lentz [22] [9], Kopelman [23] [10], Poppendick et al. [24] [11], and Rahman [20] [7] have discussed this property. The preliminary research comparing the thermal properties of several types of food products using the Choi and Okos models and the published experimental values showed that their models could predict well the thermal properties of liquid food, but their accuracy for solid foods were poor [16] [12]. The main thermo-physical characteristics are thermal conductivity, thermal diffusivity and apparent specific heat. The thermal conductivity of a material can be defined as the ability of a substance to conduct heat. It is a property of materials that expresses the heat flux, F (W/m2) that will flow through the material if a certain temperature gradient ΔT (K/m) exists over the material. Thermal conductivity of materials can be defined as the heat flow per unit area per unit time when the temperature decreases by one degree in unit distance .The most viable option is to predict the thermal properties of foods using mathematical models that account for the effects of chemical composition and temperature. In this paper, prediction methods for estimating these thermophysical properties are quantitatively evaluated by comparing their calculated results with a simulation, thermophysicals properties data from the Comsol Multiphysics. The aim of the current work is to investigate the effects on the water immersion cooling process of the carrot puree, based on the validated Comsol Multiphysics for water immersion cooling in porous media, to provide a better understanding of the mechanism to improve the process and to develop a simple method for the mathematical modeling (finite element analysis) of the heat transfer during water immersion cooling of cooked food, that describe the temperature evolution in the porous media, compared to the experimental approach which can provide valuable data on water cooling system performance . The main purpose of this paper is to use Comsol Multiphysics Software to follow the temperature of the carrot puree during and after chilling, thermophysical property models are quantitatively evaluated by comparison to a comprehensive experimental thermophysical property data set compiled from the literature.

## 2. Materials and Method

### 2.1. Mathematical model of heat transfer of cooked carrot puree during water immersion

The heat conduction transfer in cylindrical coordinates is modeled as a three-dimensional axi-symmetric (assuming that heat transfer in the circumferential direction is negligible) ,the governing equation are the following differential equation :

$$\rho Cp\,\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial \mathrm{r}}\left(r\lambda\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda\frac{\partial T}{\partial \theta}\right) \qquad (1)$$

where ρ is density (kg.m−3); Cp is specific heat ($kJ.kg^{-1}.K^{-1}$); T is temperature (°K); t is time (s); λ is thermal conductivity ($kW.m^{-1}.K^{-1}$); x, r and θ are the cylindrical coordinates.
The initial condition for this equation is : t=0, T=T0 (2)

and the boundary conditions are : x = 0, $\frac{\partial T}{\partial \mathrm{x}} = 0 \;;\; -\lambda\frac{\partial \mathrm{T}}{\partial \mathrm{x}} = 0$ (3)

θ = 0, $\frac{\partial T}{\partial \theta} = 0 \;;\; -\lambda\frac{\partial \mathrm{T}}{\partial \theta} = 0$ (4)

and on the surface : r = 0, $\frac{\partial T}{\partial \mathrm{r}} = 0 \;;\; -\lambda\frac{\partial \mathrm{T}}{\partial \mathrm{r}} = 0,$ $0 < r \leq R$ (5)

### 2.2. Cooling environment

The estimated heat fluxes were used to solve the direct heat conduction problem for the internal temperature distributions at any position and time including internal surface temperature. Beck et al., [38] [13] used the Taylor series expansion developed the following algorithm for calculating heat flux: $q_m = \frac{\sum_{i=0}^{n}(Y_{m+i-1} - T_{m+i-1})\Phi_i}{\sum_{i=0}^{n}\Phi_i^2}$ (6)

Where qm is the estimated heat flux, m is the index for discrete time, n is the number of time steps, Tm+i-1 is the estimated temperature and Y_(m+i-1) is the calculated temperature, the heat flux at 25°C is assumed to be known as 0 and Φ is the sensitivity coefficient defined as:

$$\Phi = \frac{\partial T}{\partial q} \quad (7)$$

Incorporating this equation in the governing equations yield the following equations for the sensitivity coefficients:

$$\rho \mathrm{Cp}\,\frac{\partial \Phi}{\partial \mathrm{t}} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \Phi}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial \mathrm{r}}\left(r\lambda \frac{\partial \Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda \frac{\partial \Phi}{\partial \theta}\right) \quad (8)$$

The initial and boundary conditions are given as follows:

at t =0 , Φ (0,r) = 0 (9)

at r = 0 , $-k = \frac{\partial \Phi}{\partial \mathrm{r}} = 0$ (10)

at r = R , $-k = \frac{\partial \Phi}{\partial \mathrm{r}} = 1$ (11)

Although the surface heat transfer coefficient is not a thermal property of a food or beverage, it is needed to design heat transfer equipment for processing foods and beverages where convection is involved. The surface heat transfer coefficient depends on the velocity of the surrounding fluid, product geometry, orientation, surface roughness, and packaging, as well as other factors. Therefore, for most applications it must be determined experimentally [11] [14].

From the work of [39] [15] , the following equation is used to estimate the effective heat transfer coefficient from the estimated heat flux and surface temperature at each time step:

$$h_m = \frac{q_\mathrm{m}}{[(T_{\mathrm{R,m}} + T_{\mathrm{R,m-1}})/2] - T_\infty} \quad (12)$$

### *2.3. Variable Thermophysical Properties*

The sample is composed of water, protein, glucids, ash and fat. The thermal conductivity, density and specific heat of the sample are expressed as functions of compositions given below. The main characteristics of this vegetable are summarized in Table 1.

**Table 1.** Input conditions for modeling studies

| **Properties** | **Value (unit)** | **Reference** |
|---|---|---|
| Initial moisture content, $M_w$ | 85.11 % | measured method |
| Total sugar | 11.22 % | measured method |
| Fibers | 2.14 % | measured method |
| Fat | 0.23 % | measured method |
| Ash | 0.85 % | measured method |
| Proteins | 1.87 % | measured method |
| Initial freezing point | -1.4°C | Literature [40] [16] |
| Enthalpy at initial freezing point, $H_f$ | 320 kj/kg | Literature [41] [17] |

Thermal conductivity of the carrot puree was determined based on Choi and Okos [16] [12] model given as follows for temperature between 20 and 100°C:

The thermal conductivity ($\lambda$) of a product is estimated as a sum of products between the conductivity of pure components ($\lambda_i$ ) and the volume fraction of each component ($x_{vi}$).The values of thermal conductivity ($k_i$) of each pure, constituent can be estimated as a linear function of temperature ,in which subscript w,p,f,c and a, are , respectively, water, protein, fat, carbohydrate and ash.

$$\lambda = \sum \lambda_i \,.\, x_{vi} \qquad W/(m.°C) \qquad (13)$$

$$\lambda_w = 0{,}57109 + 1{,}7625.10^{-3}.t - 6{,}7306.10^{-6}.\, t^2 \qquad (14)$$

$$\lambda_p = 0{,}1788 + 1{,}1958.10^{-3}.t - 2{,}7178.10^{-6}.\, t^2 \qquad (15)$$

$$\lambda_f = 0{,}1807 - 2{,}7604.10^{-3}.t - 1{,}7749.10^{-7}.\, t^2 \qquad (16)$$

$$\lambda_c = 0{,}2014 + 1{,}3874.10^{-3}.t - 4{,}3312.10^{-6}.\, t^2 \qquad (17)$$

$$\lambda_{fi} = 0{,}18331 + 1{,}2497.10^{-3}.t - 3{,}1683.10^{-6}.\, t^2 \qquad (18)$$

$$\lambda_a = 0{,}3296 + 1{,}401.10^{-3}.t - 2{,}9069.10^{-6}.\, t^2 \qquad (19)$$

The volume fraction ($x_{vi}$), of each component is determined from the mass fraction ($x_i$), the individual density ($\rho_I$), and the composite density ($\rho$), as follows:

$$x_{vi} = \frac{x_i \,.\, \rho}{\rho_i} \qquad (20)$$

$$\rho = \frac{1}{\Sigma(x_i|\rho_i)} \qquad (21)$$

The individual densities, in kg/m$^3$, for water $\rho_w$, protein $\rho_p$ , fat $\rho_f$, carbohydrate $\rho_c$ , fiber $\rho_{fi}$ and ash $\rho_a$ are :

$$\rho_w = 997{,}18 + 3{,}1439.10^{-3}.t - 3{,}7554.10^{-3}.t^2 \qquad (22)$$

$$\rho_p = 1329{,}9 - 0{,}51814.t \qquad (23)$$

$$\rho_f = 925{,}59 - 0{,}41757.t \qquad (24)$$

$$\rho_c = 1599{,}1 - 0{,}31046.t \qquad (25)$$

$$\rho_{fi} = 1311{,}5 - 0{,}36589.t \qquad (26)$$

$$\rho_a = 2423{,}\, 8 - 0{,}28063.t \qquad (27)$$

The values of thermal diffusivity ($\lambda_i$) in m$^2$/s of each pure consituent can be estimated as a linear function of temperature : $\lambda = \sum \lambda_i \,.\, X_i$ (28)

in which the subscript i refers to a particular component

$$\lambda_w = 1{,}3988.10^{-1} + 3{,}0429.10^{-4}.t \qquad (29)$$

$$\lambda_p = 8{,}7055.10^{-2} + 2{,}4021.10^{-4}.t \qquad (30)$$

$$\lambda_f = 1{,}0306.10^{-1} + 1{,}5507.10^{-4}.t \qquad (31)$$

$$\lambda_c = 9{,}0371.10^{-2} + 2{,}4548.10^{-4}.t \qquad (32)$$

$$\lambda_a = 8{,}3039.10^{-2} + 1{,}1764.10^{-3}.t \qquad (33)$$

Specific heat is a measure of the energy required to change the temperature of a food by one degree. Therefore, the specific heat of foods or beverages can be used to calculate the heat load imposed on the refrigeration equipment by the cooling or freezing of foods and beverages. In unfrozen foods, specific heat becomes slightly lower as the temperature rises from 0°C to 20°C. For frozen foods, there is a large decrease in specific heat as the temperature decreases. A more appropriate way to estimate the specific heat of solids and liquids are the correlations obtained by Choi and Okos [16] [12]. The specific heat, in J/(kg.K), as a function of t (in Celsius degrees) for various components of foods are expressed as follows, for :

Water above freezing point : $C_w = 4176,2 - 9,0862.10^{-5}.t + 5473,1.10^{-6}.\ t^2$ (34)

Proteins : $C_p = 2008,2 + 1208,9.10^{-3}.t - 1312,9.10^{-6}.\ t^2$ (35)

Fats : $C_f = 1984,2 + 1473,9.10^{-3}.t - 4800,9.8^{-6}.\ t^2$ (36)

Carbohydrates : $C_c = 1548,8 + 1962,5.10^{-3}.t - 5939,9.10^{-6}.\ t^2$ (37)

Fibers : $C_{fi} = 1845,9 + 1930,6.10^{-3}.t - 4650,9.10^{-6}.\ t^2$ (38)

Ash : $C_a = 1092,6 + 1889,6.10^{-3}.t - 3681,7.10^{-6}.\ t^2$ (39)

The specific heat ($C_{ave}$) of a product is estimated as a sum of products between the specific heat of pure components ($C_i$ ) and the volume fraction of each component ($x_{vi}$).

Than the specific heat of the mixture above the freezing point is :

$$C_{ave} = X_w.C_w + X_P.C_p + X_F.C_f + X_C.C_c + X_{FI}.C_{fi} + X_A.C_a \qquad (40)$$

Equation ($C_{ave}$) is valid for narrow temperature range above freezing because temperature term is not included.

A simpler model for the specific heat of an unfrozen food is presented by Chen [1]. If detailed composition data are not available, the following expression for specific heat of an unfrozen food can be used:

$$C_u = 4,19 - 2,30.\mathrm{x_s} - 0,628\,.\mathrm{x_s^3} \qquad (41)$$

where $c_u$ is the specific heat of the unfrozen food in kJ/(kg·K) and $x_s$ is the mass fraction of the solids in the food.

The change in a food’s enthalpy can be used to estimate the energy that must be added or removed to effect a temperature change. Above the freezing point, enthalpy consists of sensible energy; below the freezing point, enthalpy consists of both sensible and latent energy.

For foods at temperatures above their initial freezing point, enthalpy may be obtained by integrating the corresponding expression for specific heat above the freezing point. Thus, the enthalpy $H$ of an unfrozen food may be determined by integrating Equation of the total specific heat .

$$H = \sum H_i.X_i = \sum\int c_i.x_i\, dT \qquad (42)$$

where $Hi$ is the enthalpy of the individual food components and $xi$ is the mass fraction of the food components. In Chen’s [1] method, the enthalpy of an unfrozen food may be obtained by integrating Equation (41):

$$H = H_f + (t - t_f)(\,4,19 - 2,30.\mathrm{x_s} - 0,628\,.\mathrm{x_s^3}) \qquad (43)$$

*where*

$H$ = enthalpy of food, kJ/kg

$H_f$ = enthalpy of food at initial freezing temperature, kJ/kg

$t$ = temperature of food, °C

$t_f$ = initial freezing temperature of food, °C

$x_s$ = mass fraction of food solids

### 2.4. Experimental setup

Experiment was carried out in a laboratory water immersion cooler to validate the Comsol simulation results. The water immersion cooler used in this study has the dimension of 1000cm (L) /400cm (W) /200cm (H). The system consists of water refrigerator and water pump to provide the velocity water in the cooling cube, the cooling of the carrot puree is from 90 to 10°C. The cooked carrot puree sample used in the study was a cylindrical canne in a alumium package, with a diameter of 5 cm and a length of 10 cm. The hypodermic thermocouples T-type (diameter = 2 mm) were mounted on the can at the set position while the other end was connected to a data logger ,which is connected to a computer equipped with the Squirrel View software. The can was heated in an autoclave until the can center temperature was about 90°C, the sample is get off after 20 min, then the can was placed in the water cooler, and thermocouples were inserted into the carrot puree core at 5 cm depths so that the temperatures could be measured during the cooling process, then the cooling process began by an immersion in cube water with a pump for the remaining cooling period with a velocity of 0.15m/s, it's with integrated controllers that we can choose the default preset speed to keep a constant rate over time of the water temperature and the condition of the shutter (open or closed). (fig.1)

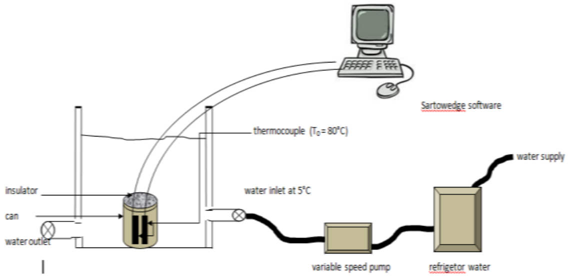
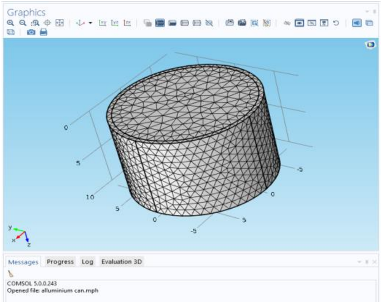


**Figure 1.** Water cooling experimental

### 2.5. Comsol Multiphysics Simulating

Simulating inside cans packed with carrot purees were used to study a heat transfer in porous medium as a function of time during the immersion cooling cycle of the thermal processing of canned foods. The Simulation methodology was performed by using Comsol Multyphysics, a finite element–based engineering simulation software. The simulation model is shown in Fig. 2.



COMSOL 5.0.0.243
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**Figure 2.** Cylindrical simulation model

## 3. Results

### 3.1. cooling process

From the simulation results at t=0mn,the carrot puree is at 90°C.Temperature is irregular ,this is typical in food engineering because of the low values of thermal conductivities in most foods compared to other materials, these observations are consistent with the experimental data available in the literature [46] [18]. Fig. 4 shows the temperature distribution of contact the temperature by the end of this step is 30°C at the core and near the water cooling temperature at the surface.

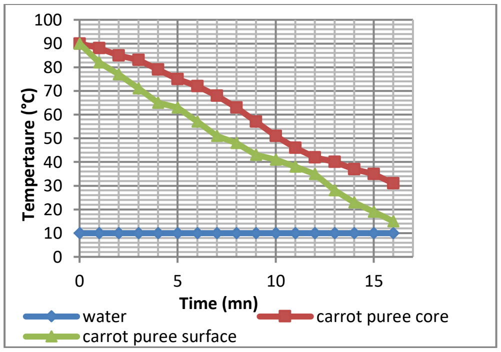
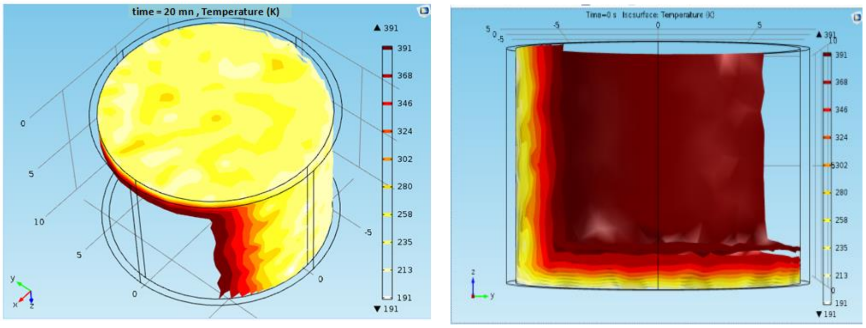


**Figure 4.** Mesured temperature profiles as function of chilling time

The temperature of the carrot puree after chilling is higher at the core and decreases from the core towards the surface, temperature in the product is not uniform (fig.5). Temperature rise decreased rapidly with time during initial stages of cooling , due to the rapid transfer of thermal energy through heat conduction from the outer most layers of the samples, adjacent to cooling water, to inner layers. The Experimental validation is supported by data obtained, a similar result was found by Golestani et al [47] [19].



(a) (b)

**Figure 5**. Typical simulation results in 3-D visualization for the predicted temperature distribution of the cylindrical can carrot puree at 20 mn chilling time *(a: carrot puree surface, b: carrot puree core)*

The surface temperature of the cylindrical carrot puree was cooled from 90 to 11.9°C in 20 min with the predicted temperature at 11.4°C in the same cooling period. This shows also the good agreement between simulation and experimental data. The temperature distribution in the food at any instance is important because spoilage can start from higher moisture content region, consequently, investigating the temperature and moisture distribution is critical in the case of food cooling, than the modeling and simulation study was helpful in this regard, because it was difficult to measure the moisture distribution experimentally. After 20 min of water cooling of 10°C and velocity of 0.15m/s, there still exists a difference between the core temperature and those at the surface, which could be due to case hardening and temperature hold up at the testa layer, therefore, it is not suitable to achieve a rapid cooling by decreasing the temperature of cooling medium to below 0°C. The time used to reduce the core temperature from 90 to 10°C is the total cooling time, than for with water velocity of 0.15m/s and water temperature of 10°C, the cooling time to 30°C is 20 min for the can puree carrot.

## 3.2. thermal properties

### 3.2.1. conductivity , diffusivity and density

Using equations (20)–(36) thermal conductivity, diffusivity and density for a carrot puree was calculated. The thermal properties were found to increase with increasing temperature. A similar behavior was observed by Hu & Mallikarjunan [48] [20] for oysters, by Telis-Romero et al [49] [21] for Brazilian orange juice and by Singh & Goswami [50] [22] for cumin seed. Sweat [51] [23] reported a thermal conductivity of 0.513 W/m.K for red apples at 28°C with 84.9% moisture and a thermal diffusivity of 1.37 $10^{-7}$ $m^2/s$ . For the total density of carrot puree , results shows the decrease tendency with the temperature increasing.Thermal conductivity and thermal diffusivity values obtained by Comsol Multiphysic simulation are on (Figs. 10 and 11), the results from the developed simulator were very similar to values obtained by the proposed model allowed by Choi and Okos [16] [12], method for the main part of products .

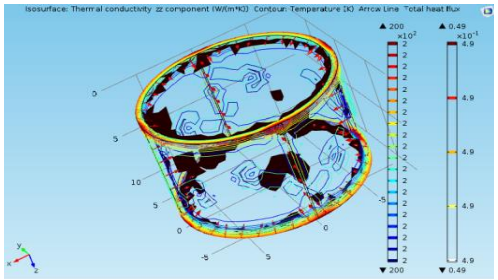


**Figure 10**. Carrot puree thermal conductivity simulation as a temperature function, (alpha = 1)

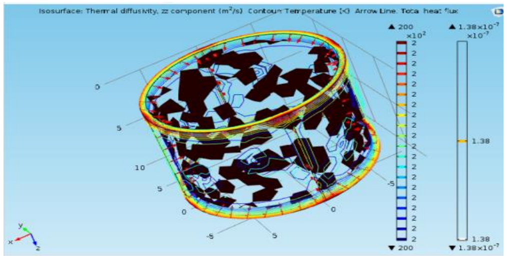


**Figure 11**. Carrot puree thermal diffusivity simulation as a temperature function, (alpha = 1)

Since most of the product is water, thermal conductivity of water would dominate the most [52] [24], in the measured range of 5 to 30 °C, temperature remains insignificant, this was also stated by Sweat [31] [25], who concluded from several models that temperature had effect on thermal conductivity. In the figure for thermal conductivity versus temperature, an increasing trend is noticed, which agreed well with the positive correlation reported in most of the literature for thermal conductivity and temperature [52] [24]. The enthalpy value (668,43 Kj/kg) agreed well with those reported by Singh and Heldman, [53] [26], various researchers reported that the major factors influencing thermal properties of materials are: temperature, water content, fat, state of pressure and density, it is obvious that enthalpy is a function of temperature, since enthalpy refers to the energy content of the food measured. Also, heat conductivity of solids increases with moisture content ([54] [27],[25] [28]).

### 3.2.2. heat flux and specific heat

The decreases of the values of heat flux surface as function of cooling time than the heat flux is maximum at the start of cooling so, once the heat flux was known and the surface temperature was calculated, an effective heat transfer coefficient was calculated.The high moisture content inside the puree carrot provides a better conductivity effect for heat transfer than the product temperature reached the cooling. The heat transfer coefficient profile for the carrot puree increases with time , a similar trend was reported by Varga and Oliveira [56] [29]. The reason for the higher rate of increase in the effective heat transfer coefficient at the early stage of cooling is because of the high temperature gradient close to the surface, resulting in higher heat flux coupled with higher rate of decrease in surface temperature, resulting in increase in the effective heat transfer coefficients [39] [15]**.** They also reported that the surface temperature decreases quickly at the beginning of the cooling, then becomes almost stable during the rest of the cooling period. Due to this fact, a time-averaged effective heat transfer coefficient may be more practical to represent the thermal resistance during the cooling cycle. During the cooling processes, the heat first transfers from the core to the surface by heat conduction and then releases to the cooling environments by heat convection. The cooling rate is controlled by the heat conduction due to the poor thermal conductivity of carrot puree.The increase water velocities could enhance the convective heat transfer, which means that the water immersion cooling could accelerate the temperature drop on the surface and thus accelerate the reduction in core temperature. However, this enhancement will reach its maximum when the surface temperature approaches to the temperature of cooling medium. For water immersion cooling, it takes a very short time to reduce the surface temperature to near the temperature of cooling medium as shown in fig6. The surface temperature could be dropped under 5°C within 10 min by water immersion cooling with the water velocity of 0.15m/s and temperature of 10°C. [57] [30].The effect of the velocity of cooling medium on the total cooling time is important, the bigger the velocity of cooling medium, the shorter the total cooling time. However, the effect of increasing cooling medium velocity, becomes smaller and smaller. During the cooling processes, the heat first transferred from the core to the surface by heat conduction and then released to the cooling environments by heat convection. The cooling rate is controlled by the heat conduction due to the poor thermal conductivity of cooked can. The increase water velocities could enhance the convective heat transfer , which means that the water immersion cooling could accelerate the temperature drop on the surface and thus accelerate the reduction in core temperature. However, this enhancement will reach its maximum when the surface temperature approaches to the temperature of cooling medium. For water immersion cooling, it takes a very short time to reduce the surface temperature to near the temperature of the cooling medium. This is the reason why a rapid cooling could not be achieved even though the velocity of cooling medium is increased to a very high value .[58] [31].Values for $C_p$ calculated using Choi and Okos [16] [12] correlations are generally higher than those calculated using Siebel's equations at high moisture contents ($M > 0{,}70$). Choi and Okos' correlations are more accurate at low moisture contents and for a wider range of product composition [60] [32]. The specific heat values increase with the increase in temperature [63] [33].

## Conclusions

The thermophysical properties of foods are required in order to calculate process times and to design equipment for the storage and preservation of food. There are a multitude of food items available, whose properties are strongly dependent upon chemical composition and temperature. Composition-based thermophysical property models provide a means of estimating properties of foods as functions of temperature. Numerous models have been developed and the designer of food processing equipment is faced with the challenge of selecting appropriate ones from those available. In this paper selected thermophysical property models are quantitatively evaluated by comparison to a comprehensive experimental thermophysical property data set compiled from the literature. For future studies, some improvements in the current model can be made by incorporating the diffusivity model as a function of moisture content or combined function of moisture content and temperature. This can be further improved by taking into account the diffusivity difference between the testa and cotyledon layers as the testa layer has a different cellular structure compares to the cotyledon. Such difference could result in different degree of drying as the testa layer usually dries faster compare to the cotyledon ([67] [34], [68] [35]).

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