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EXPERIMENTAL DETERMINATION OF CONVECTION HEAT TRANSFER COEFFICIENT FOR EGGPLANT, ZUCCHINI AND POTATO USING A SOLAR COOKER BOX-TYPE

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ABSTRACT

In this work, experimental results to determine the convection heat transfer coefficient in the cooking process of eggplant, zucchini and potato using a solar cooker box-type are presented. Experimental data of temperatures for the fluid (water), surface and central point of the vegetables were used.

To determine the convection coefficient, the vegetables were modeled as cylinders and a sphere according to their forms. The temperatures evolution was defined using thermocouples located at water, surface and central point in the vegetables.

In the experimental process a NI Compact Field Point was used as acquisition data system which allows measure temperatures in simultaneous form. Also, a solar simulator as source of energy for the solar cooker function was used.

Using heat transfer convection equations in transitory state and the temperatures measured, the Biot number and the convection coefficient were determined.

To define how the cooking process occurs, diffusivity, density and heat specific were considered.

Agree to results, the highest values to convection coefficient are obtained for eggplant while the minor values correspond to potato.

The experimental tests for the cooking process were done in similar conditions which allow comparing results and generating a discussion for the same ones.

INTRODUCTION

For many applications the convection heat transfer coefficient must be determined. Due to this, the variety of cases is big, such as next is exposing.

The external heat transfer coefficient in steam processing was determined experimentally in a pilot scale retort for this, the heat transfer equations were solved applying finite elements and using the actual retort temperature profile as boundary condition. The instantaneous values of the heat transfer coefficient were determined, to analyse its time-variability along a retort cycle [1].

It is common knowledge that an object with a higher thermal diffusivity will always heat faster in comparison to that with a lower thermal diffusivity. In a work was undertaken to demonstrate numerically and experimentally that this is not always true. To accomplish this, a finite difference model was developed, and temperature changes at the surface and geometric center of cubic particles of different thermophysical properties were obtained for different convective heat transfer coefficient values (50 and 1000 W/m^2 K) [2].

The design of food refrigeration equipment requires estimation of the cooling and freezing times of foods and beverages, as well as the corresponding refrigeration loads. The accuracy of these estimates, in tum, depends upon accurate estimates of the surface heat transfer coefficient for the cooling or freezing operation. For this purpose, a unique iterative algorithm, utilizing the concept of "equivalent heat transfer dimensionality," was developed to obtain heat transfer coefficients from cooling curves. Cooling curves were obtained from an industrial survey, and, utilizing the iterative algorithm, heat transfer coefficients were determined for various food items [3].

In a work, an attempt has been made to experimentally determine the heat transfer properties of potato in terms of convective heat transfer coefficient, specific energy consumption and specific heating rate. Drying experiments with potato cylinders were performed in an in-house fabricated laboratory scale natural convection indirect solar dryer with self tracking mechanism. The convective heat transfer coefficient of cylindrical potato samples was evaluated by considering the combined effects of heat capacities of food product as well as radiative heat transfer from drying chamber to the food product. This study revealed that the convective heat transfer coefficient for potato cylinders was varying from 11.73 to 16.23 W/m^2 °C with an experimental error of 7.86 % [4]

An optimization algorithm and a numerical solution were used to determine simultaneously the convective heat transfer coefficient, h_H, and the thermal diffusivity, α, for an individual solid with cylindrical shape, using experimental data obtained during its cooling. To this end, the one-dimensional diffusion equation in cylindrical coordinates is discretized and numerically solved through the finite volume method, with a fully implicit formulation. This solution is coupled to an optimizer based on the inverse method, in which the chi-square referring to the fit of the numerical simulation to the experimental data is used as objective function. The optimizer coupled to the numerical solution was applied to experimental data relative to the cooling of a cucumber. The obtained results for α and h_H were coherent with the values available in the literature. With the results obtained in the optimization process, the cooling kinetics of cucumbers was described in details [5].

In a work was developed an appropriate and simple methodology to determine the spatial distribution of h values inside tunnels. A dedicated device, consisting of a rectangular metal tank filled with an alcoholic solution, with a temperature sensor inserted in its interior, was used as a model system. The transient temperatures of the system (tank solution) were used to calculate h values at different positions inside the tunnels. The main result of this study was the experimental method itself, which is a reproducible and reliable procedure for determining heat transfer coefficients inside industrial tunnels [6].

In a study has been employed an optimization process among experimental temperatures and those obtained by finite elements analysis (FEA) for the determination of the convective heat transfer coefficient (h) during a stand-up retortable pouch process in a steam-air retort. The results obtained were validated experimentally by meat product sterilization, presenting good correlation between experimental values and those obtained by the model. The values obtained contribute to the studies of heat transfer and thermal processes; besides, its values for pouches processes are scarce in the literature [7].

Thermal processing is the most important and utilized method for food preservation, being those carried out with the food inside the package the most appropriated for safety consumption guarantee. During processing, the packaged food was surrounded by a heat transfer medium, in general a fluid as water, steam, air or its mixtures. To pointed out this, in a work is described an appropriated method to determining the convective heat transfer coefficient (h) in thermal process of foods [8].

In an article, the behavior of heat and mass transfer relation during khoa making was investigated. Various indoor experiments were performed for simulation of developed thermal model for maximum evaporation during heating of milk. It was observed that the convective and evaporative heat transfer coefficients decrease with the increase in rate of heating (varying voltage). It was also observed that convective and evaporative heat transfer coefficients increase with the increase in operating temperature. The rate of increment of evaporative heat transfer coefficient was higher than the convective heat transfer coefficient [9].

The convective heat transfer coefficient is a useful parameter in characterizing heat flow across a fluid/solid interface when the fluid flow field is complex and solution of the coupled transport equations impractical. While convective heat transfer coefficient values for many unit operations have been tabulated, the boiling phase of immersion frying has not been quantified. In a study, was developed a laboratory method for the measurement of the convective heat transfer coefficient during immersion frying. The method that was developed was applied to the immersion frying of potato cylinders at an oil temperature of 180 °C. The convective heat transfer coefficient was initially 300 W/m² K, it increased sharply to 11 00 W/m² K, and gradually decreased to 300 W/m² K over the duration of the process. The method allows study the effects of oil temperature, oil quality, product shape/size, and product quality on heat transfer coefficients [10].

In this work experimental results for the convection heat transfer coefficient are presented. Three vegetables were considered in the cooking process: eggplant, zucchini and potato.

Agree to results, the highest values to convection coefficient are obtained for eggplant while the minor values correspond to potato.

NOMENCLATURE

T	[°C]	Temperature
θ	[dimensionless]	Difference of temperatures
F_O	[dimensionless]	Fourier number
α	[m²/s]	Diffusivity
D	[m]	Diameter
t	[seg]	Time
A_1, λ_1	[dimensionless]	Constants
S, R	[dimensionless]	Constants
Bi	[dimensionless]	Biot number
k	[W/mK]	Thermal conductivity

Special characters

∞	Medium, water
α	Difusitity

Subscripts

s	Surface of the vegetables
c,o	Center of the vegetables
i	Initial reference

EXPERIMENTATION

For the experimental work, a solar cooker with eggplant, zucchini and potato was used. Each product was evaluated in individual tests.

The solar cooker is integrated by the following elements: 1. a cover with two flat glasses with a clearance between them. 2. Internal reflectors made in commercial aluminium paper placed to different tilt angles, 3. Thermal insulator placed in the lateral part of the same one, and 4. Recipient contains the product to cook. The solar cooker is locked air tightly; this allows reaching considerable temperatures in the test fluid. In figure 1 the solar cooker is shown.

Figure 1 Solar cocker box-type

Thermocouples k-type at surface, central points of the vegetables and water were placed. The temperature measuring was realized each 10 minutes. The time cooking process considered was 4 hours (240 minutes).

In the test was sought that the masses of the vegetables were as similar as possible. The average value was 250 g. The average value for the water was 250 ml.

The geometrical characteristics and the thermocouples colocation at eggplant, zucchini and potato are shown in figures 2, 3 and 4.

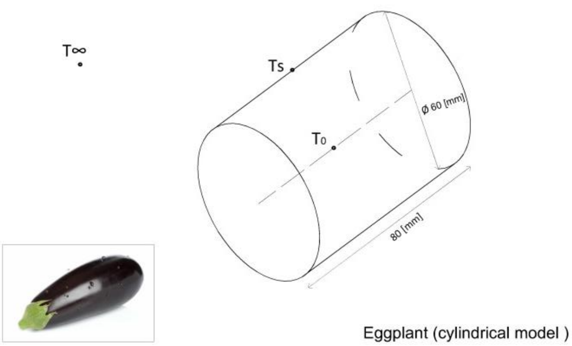

Figure 2 Thermocouples position and geometry for eggplant

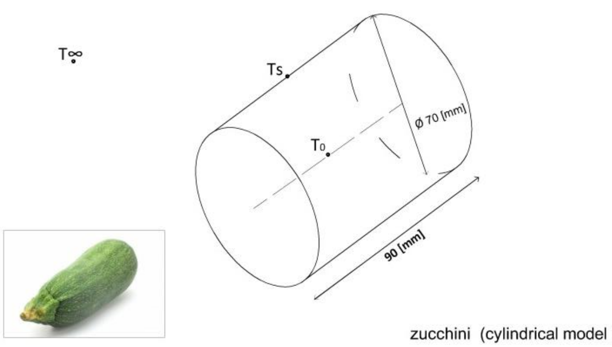

Figure 3 Thermocouples position and geometry for zucchini

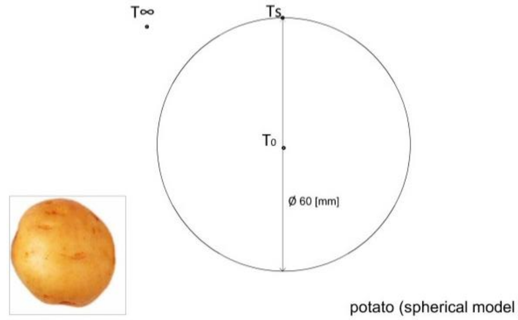

Figure 4 Thermocouples position and geometry for potato

In the temperature measures, an NI Compact Field Point was used. This device allows measure many temperatures at the same time. By means of data acquisition, the temperature values were obtained. This device is shown in figure 5.

Figure 5 NI Compact Field Point device

A solar simulator generates the energy source impacting on the solar cooker. This simulator is built with an arrangement of infrared lamps.

In figure 6 an arrangement for the experimentation is shown.

Figure 6 Experimental arrangement: Solar simulator, solar cooker and acquisition device

In figures 7, 8 and 9, temperature data for eggplant, zucchini and potato after to the experimental procedure are shown.

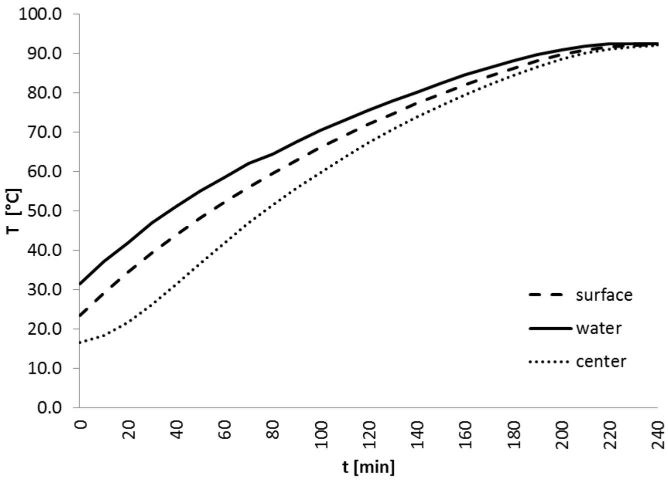

Figure 7 **Experimental temperatures: Eggplant**

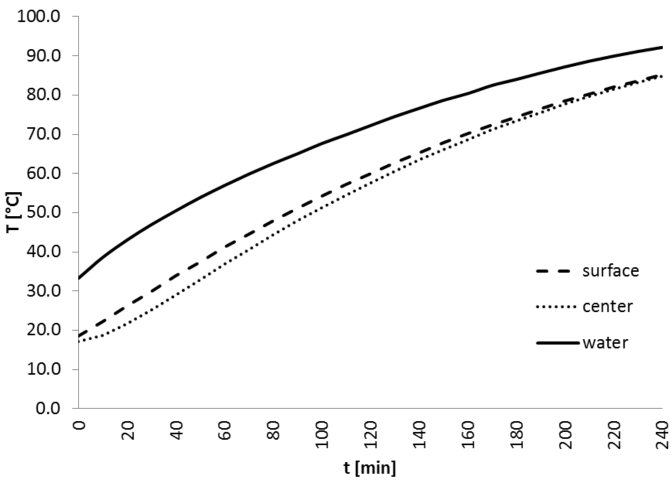

Figure 8 **Experimental temperatures: Zucchini**

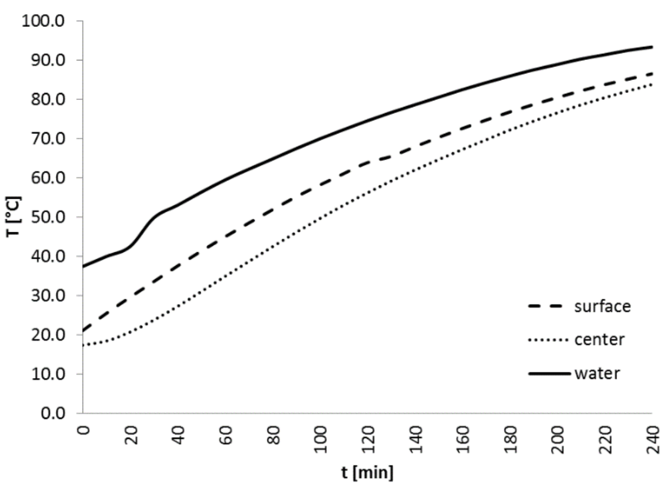

Figure 9 **Experimental temperatures: Potato**

CONVECTION COEFFICIENTS RESULTS

Once temperature data is obtained, heat transfer equations are used to determine the convection heat transfer coefficient. Some considerations were done for this purpose: 1. Thermal conductivity constant. 2. One-dimensional flow. 3. Without heat generation. 4. Cylindrical and spherical coordinates.

The properties for the vegetables were determined using correlations in function of temperature. These one can see in Appendix [11].

Agree to data measured, is possible to determine the temperatures difference ratio in function of water, surface and center by using [12]

$$\theta = \frac{T_0 - T_\infty}{T_i - T_\infty} \tag{1}$$

This equation is related with correlations. Two references to determine the convection heat transfer coefficient were considered.

First of them is [12]

$$\theta = A_1 e^{-\lambda_1^2 F_0} \tag{2}$$

Where A_1 and λ_1 must be determined by tables using Bi number and the Fourier number defined as

$$F_0 = \frac{\alpha t}{D^2} \tag{3}$$

The second equation is [13]

$$\theta = R e^{-S F_0} \tag{4}$$

Where

$$R = 0.411 \tan^{-1}\left(\frac{Bi}{2}\right) + 0.007242 \tan^{-1}(11Bi) - 0.1021Bi(Bi+11)+0.9984 \tag{5}$$

$$S = 0.411 \frac{Bi}{Bi+2} + 1.2365 \tan^{-1}\left(\frac{Bi}{3}\right) - 0.1641(2Bi) - 0.0077624 \tag{6}$$

Due to Biot number is

$$Bi = \frac{hD}{k} \tag{7}$$

The convection heat transfer coefficient can be determined when equation 7 is solved for *h*.

However, the Biot number is unknown, for this reason an iterative method is used to determine A_1, λ_1, *R* and *S*.

So, starting with equation 1, equations 2 and 4 are solved for *Bi*. After this, h can be determined by using equation 7. This procedure is applied for along the time in the cooking process.

In figures 10, 11 and 12, results for the Biot number corresponding to eggplant, zucchini and potato are shown. The convection heat transfer coefficient values for eggplant, zucchini and potato are shown in figures 13, 14 and 15.

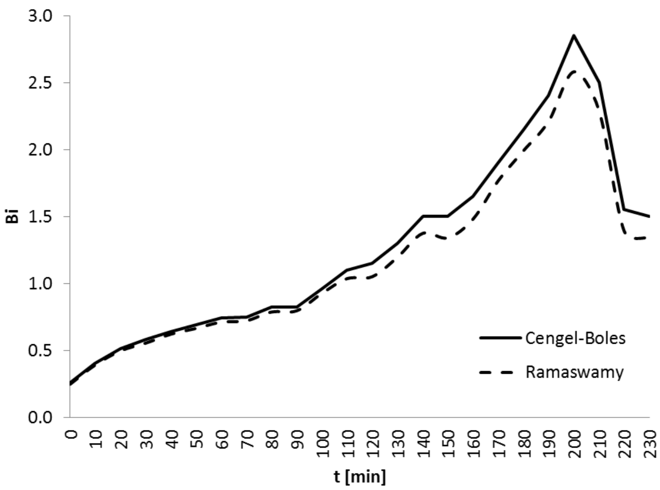

Figure 10 Biot number for eggplant

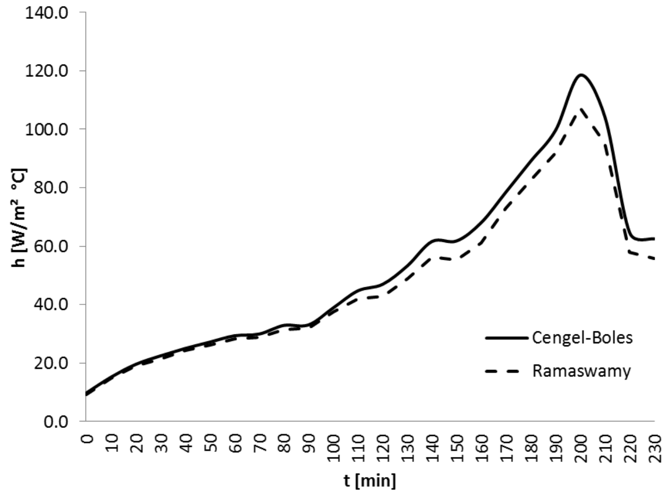

Figure 13 Convection coefficients for eggplant

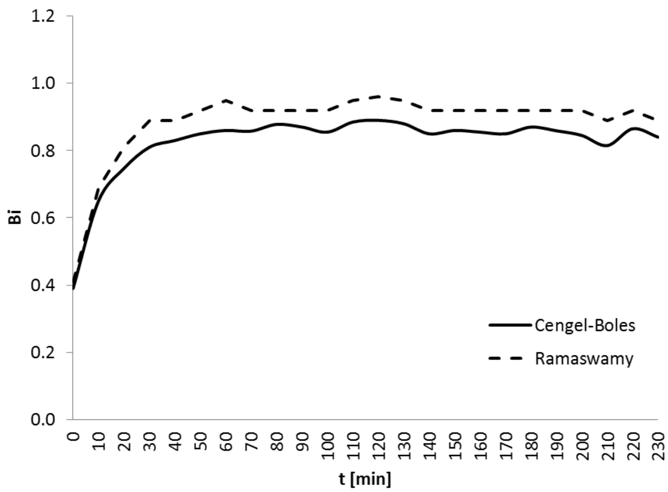

Figure 11 Biot number for zucchini

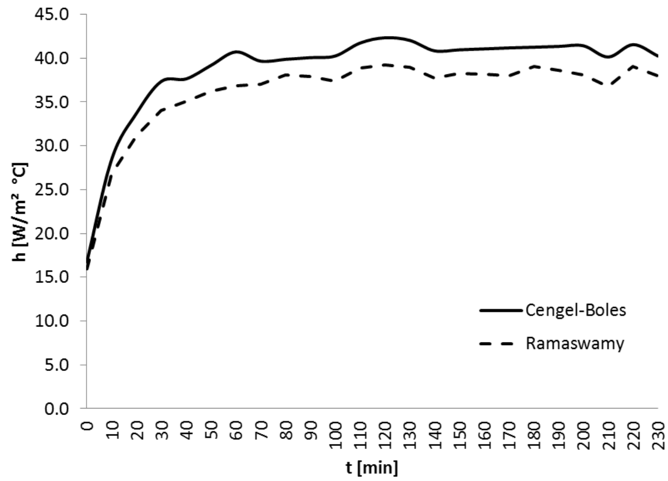

Figure 14 Convection coefficients for zucchini

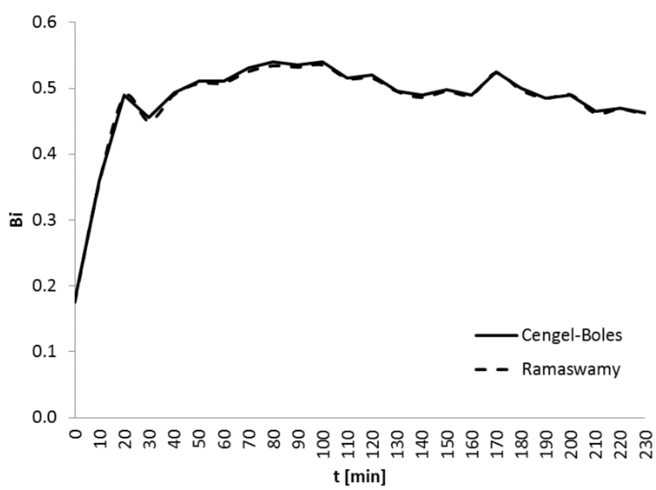

Figure 12 Biot number for potato

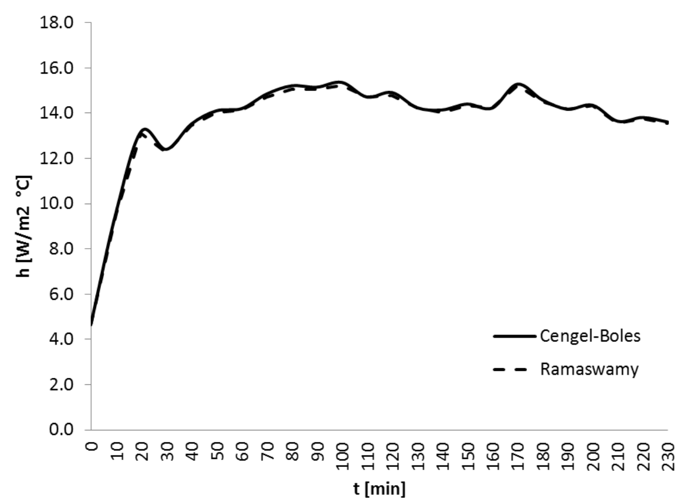

Figure 15 Convection coefficients for potato

DISCUSSION

Agree to results, temperatures follow next behavior $T_f > T_s > T_f$ for all cases. This is consistent for the heating process.

The difference temperatures between surface and center for the vegetables were 0.06, 0.36 and 2.72 °C, it correspond to eggplant, zucchini and potato respectively.

The center temperature in the vegetables was 92.12 °C (eggplant), 84.86 °C (zucchini) and 83.84 °C (potato). This temperature is enough to reach a complete cooking in the same ones.

The maximum Biot values were 2.85 (Cengel-Boles) for eggplant, 0.96 (Ramaswamy) for zucchini and 0.54 (Cengel-Boles and Ramaswamy) for potato.

These results indicate that the conduction resistance is greater than the convection resistance for the eggplant while the convection resistance is greater than the conduction resistance in the potato.

The convection heat transfer coefficient values were 120 W/m² °C, 40 W/m² °C and 15 W/m² °C approximate, that correspond to eggplant, zucchini and potato.

Two references have been used in figures 10 to 15, in all cases for the vegetables; the maximum difference did not exceed 1%.

CONCLUSION

An experimental procedure to determine the convection heat transfer coefficient was exposed.

The results show how the convection happens in the heating process for eggplant, zucchini and potato.

The resistance values are useful, because it allow identify the most important resistance in the heating process for eggplant, zucchini and potato.

The convection coefficient can be used in numerical simulation, particularly, in solar energy applications due to this information is unknown and there is not works about it.

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APENDIX

Correlations to determine properties in vegetables [11]

Density

$$\rho = \frac{1}{\frac{x_i}{\rho_{H_2O}}+\frac{x_i}{\rho_{protein}}+\frac{x_i}{\rho_{fat}}+\frac{x_i}{\rho_{carbohidrates}}+\frac{x_i}{\rho_{fiber}}} \quad (A.1)$$

$$x_i = \text{ Mass component fraction for each product} \quad (A.2)$$
$$\rho_{H_2O} = 997.18 + 0.00031429T + 0.0054731T^2 \quad (A.3)$$
$$\rho_{protein} = 1329.9 - 0.5185T \quad (A.4)$$
$$\rho_{fat} = 925.59 - 0.41757T \quad (A.5)$$
$$\rho_{carbohidrates} = 1329.9 - 0.5185T \quad (A.6)$$
$$\rho_{fiber} = 1311.5 - 0.36589T \quad (A.7)$$

Thermal conductivity

$$k = k_{H_2O}x_i + k_{protein}x_i + k_{fat}x_i + k_{carbohidrates}x_i + k_{fiber}x_i \quad (A.8)$$
$$x_i = \text{ Mass component fraction for each product} \quad (A.9)$$
$$k_{H_2O} = 0.57109 + 0.0017625T - 0.0000067036T^2 \quad (A.10)$$
$$k_{protein} = 0.17881 + 0.0011958T - 0.0000027178T^2 \quad (A.11)$$
$$k_{fat} = 0.18071 - 0.0027604T - 0.00000017749T^2 \quad (A.12)$$
$$k_{carbohidrates} = 20141 + 0.0013874T - 0.0000043312T^2 \quad (A.13)$$
$$k_{fiber} = 0.18331 + 0.0012497T - 0.0000031683T^2 \quad (A.14)$$

Heat specific

$$C = C_{H_2O}x_i + C_{protein}x_i + C_{fat}x_i + C_{carbohidrates}x_i + C_{fiber}x_i \quad (A.15)$$
$$x_i = \mathit{Mass\ component\ fraction\ for\ each\ product} \quad (A.16)$$
$$C_{H_2O} = 4176.2 - 0.090864T - 0.0054731T^2 \quad (A.17)$$
$$C_{protein} = 2008.2 + 1.2089T - 0.0013129T^2 \quad (A.18)$$
$$C_{fat} = 1984.2 - 1.4733T - 0.0048008T^2 \quad (A.19)$$
$$C_{carbohidrates} = 1548.8 + 1.9625T - 0.0059399T^2 \quad (A.20)$$
$$C_{fiber} = 1845.9 + 1.8306T - 0.0046509T^2 \quad (A.21)$$

Difusivity [12]

$$\alpha = \frac{k}{\rho C} \quad (A.22)$$