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COEFFICIENT ESTIMATION FOR HEAT TRANSFER ON VEGETABLE MACROPOROUS MEDIA

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Abstract. *This paper presents two methods to identify heat transfer coefficients for stored bulk frozen vegetables. Product and air into a pallet are modeled as a macroporous media, submitted to natural air flow. Thermal conductivity and convective coefficients are obtained by a combination of experimental measurements and numerical simulation for two frozen products: slices of carrots and extra thin green beans. Values are compared to literature sources and among them. The calculated equivalent thermal conductivities are 0.14 $Wm^{-1}K^{-1}$ for carrot slices and 0.10 $Wm^{-1}K^{-1}$ for green beans, which differs less than 10% to the correspondent literature values of 0.13 $Wm^{-1}K^{-1}$ and 0.09 $Wm^{-1}K^{-1}$, obtained with the Kupriczca's correlation for a macroporous media compound by spheres. Convective coefficient for carrot slices and green beans are estimated as 2.4 $Wm^{-2}K^{-1}$ and 2.3 $Wm^{-2}K^{-1}$, respectively, within the expected values calculated with different correlations from literature. The proposed methods are a simple and good tool to obtain an order of magnitude for these coefficients. Coefficients are similar for both porous media, even though they display different geometries. The equivalent conductivity for carrots was 28.5% bigger than for green beans, since its porosity (0.55) was smaller than for green beans (0.65). The convective coefficients were very close for both products, but a slightly higher for carrots (7%).*

Key words: *vegetable freezing, macroporous media, thermal conductivity, porous media natural convection.*

1. INTRODUCTION

In frozen food industry, products, and in the particular case of vegetables, are stored at low temperature in cold rooms, packed in box pallets covered with a plastic bag. Storage duration can range from few months up to one year, before being transfer to small packages, in order to be commercialized. During long term storage into cold rooms, frozen products are exposed to air temperature fluctuations that impact product quality, like ice recrystallization, dehydration, frost formation, among them. Therefore, losses can be expected due to the quality of temperature management.

In order to understand the behavior of bulk storage of frozen vegetables, and to avoid quality losses, it is necessary to analyze multiphysical phenomena involved inside a pallet box, such as heat transfer, airflow, and frost formation.

Frozen vegetables and the air trapped inside are modeled as a macroporous domain, submitted to external air temperature fluctuations, caused by the operation of the storage facility refrigerating system. Heat transfer, airflow by natural convection, and mass transport lead to product dehydration and frost formation inside the pallet.

Determination of equivalent thermal conductivity and convective heat transfer coefficient are needed as a first step to study heat transfer phenomena in an enclosure vegetable macroporous media, which is the aim of the present work.

1.1 Porous media modeling

Porous medium consists on a fixed solid matrix with interconnected void spaces, called pores, whose interconnection allows fluid flow through the material. Porous media are characterized by geometric parameters as porosity ε (void fraction), specific surface A_{spec} $[m^{-1}]$ (rate of interior solid matrix surface to total volume) and permeability K $[m^2]$ (hydraulic resistance) and thermodynamic properties such as density ρ $[kgm^{-3}]$ and specific heat c_{p_p} $[kJkg^{-1}K^{-1}]$. Equivalent thermal conductivity k_{eq} $[Wm^{-1}K^{-1}]$ and interior convective heat transfer coefficient h $[Wm^{-2}K^{-1}]$ depends on thermodynamic properties of solid and fluid phases, and geometric characteristics of the porous medium.

An enclosure macroporous media is characterized by a ratio of container characteristic length to particle characteristic length smaller than 10.

The porosity is a geometric characteristic of a porous media, and it is defined as the fraction of void volume over total volume of the media. In natural porous media such as soils, sediments, rocks, etc., the porosity is in general smaller than 0.6. In common porous media it can vary close to limit values, 0 and 1. In the case of a bed of uniform spheres, porosity ranges from 0.2595 to 0.4764 (Neild and Bejan, 2006).

The equivalent thermal conductivity of a porous medium is the capacity of heat diffusion, assuming the arrange of solid and fluid phases as a solid with uniform properties. Equivalent thermal conductivity depends on the thermal conductivity of each phase, the structure of the solid matrix and the contact resistance between particles. In the literature, different correlations are presented to estimate this value. **Table 1** summarizes some different correlations to predict the equivalent conductivity. The limit values of equivalent conductivity were obtained from the composite layer models (Ingham and Pop, 1998), solid and fluid layers in parallel arrangement gives the maximum value, and in series arrangement gives the minimum value. So, all porous media have an equivalent conductivity between these values. A rough and ready estimation could be made from the weighted geometric mean (Neild and Bejan, 2006). Others correlations were reviewed by Kaviany, 1998, like the Krupicza's correlation for the isotropic equivalent conductivity, obtained experimentally for a packed bed of particles. However, in the literature it was not found a correlation for others geometries more similar to our products, so the ones presented in Table 1 will be used as reference values to be compared to determined values.

Table 1 - Summary of correlations for the equivalent conductivity $\boldsymbol{k_{eq}}$ of a porous media.

Model	Correlation	Remarks
Parallel	$k_{eq} = k_f\varepsilon + k_s(1-\varepsilon)$	Maximum value
Series	$\frac{1}{k_{eq}} = \frac{\varepsilon}{k_f} + \frac{(1-\varepsilon)}{k_s}$	Minimum value
Geometric	$k_{eq} = {k_f}^{\varepsilon}.{k_s}^{(1-\varepsilon)}$	k_f and k_s same order of magnitude
Krupiczka	$\frac{k_{eq}}{k_f} = \left(\frac{k_s}{k_f}\right)^{0.280-0.757log\varepsilon-0.057\log\left(\frac{k_s}{k_f}\right)}$	$0.2 \leq \varepsilon \leq 0.6$

In respect to the convective heat transfer coefficient into a porous media, Wakao and Kaguei, 1982 carried out a critically review of experimental values obtained for steady-state and unsteady-sate measurements. They re-evaluated the heat transfer coefficients, considering only the data they found reliable, and proposed a Nusselt correlation as a function of the Reynolds number. Alvarez, 1992 and Ben Amara et al., 2004 measured experimentally the convective heat transfer coefficient into a macroporous media, in steady state regime, by neglecting conduction and radiation between solid particles. They placed a sphere of high conductivity material into a packed bed of spheres of very small conductivity. An electrical resistance heated the sphere and temperature was measured by a thermocouple, assuming uniform temperature. Alvarez, 1992 established a Nusselt correlation for turbulent flow. Ben Amara et al., 2004 studied the influence of the operational parameters on the convective coefficient, and proposed a correlation for Reynolds in the range from 74 to 495 (low velocities), similar to the one proposed for Wakao and Kaguei, 1982.

There were several researches working with porous media, in general with spherical particles. However, few researches had been carried out the characterization and identification of macroporous media heat transfer coefficients, even less for confined porous media at very low air velocity.

In this work, the porous media consists on frozen product and air. Equivalent thermal conductivity and convective coefficient of two porous media were determined using experimental measurements and complemented with numerical techniques.

2. MATERIALS AND METHODS

2.1 Products

Sliced carrots and extra thin green beans were chosen to be studied as they are the most susceptible to damage during frozen storage.

Frozen slices of carrots were prepared from fresh carrots, peeled, cut, and frozen at $-30\,℃$. Standard dimensions in the industry are diameter between 15 mm and 30 mm, and thickness between 6 mm and 7 mm. A sample of 100 carrot slices was taken to measure their average diameter and thickness, with the correspondent uncertainties: $24.3 \pm 5.4\ mm$ and $7.0 \pm 1.7\ mm$ respectively.

Fresh extra thin green beans were prepared by removing the beans tips and then frozen at $-20\,℃$. Standard dimensions in the industry are diameter between 6.5 mm and 8 mm, and length between 80 mm and 120mm. A sample of 50 green beans was taken to measure their average diameter and length, with the correspondent uncertainties: $6.6 \pm 1.0\ mm$ and $92.7 \pm 12.5\ mm$ respectively.

2.2 Experimental and Computational Procedures

2.2.1 Equivalent thermal conductivity

Equivalent thermal conductivity was calculated by a combined experimental and numerical approach. Frozen food samples were kept in a 15.5cm x 10.7cm x 9.5cm (length, width and height) box insulated by a 7.0cm wall and a 4.0cm bottom of polyurethane (Figure 1). A thin steel plate was placed in the top of the box.

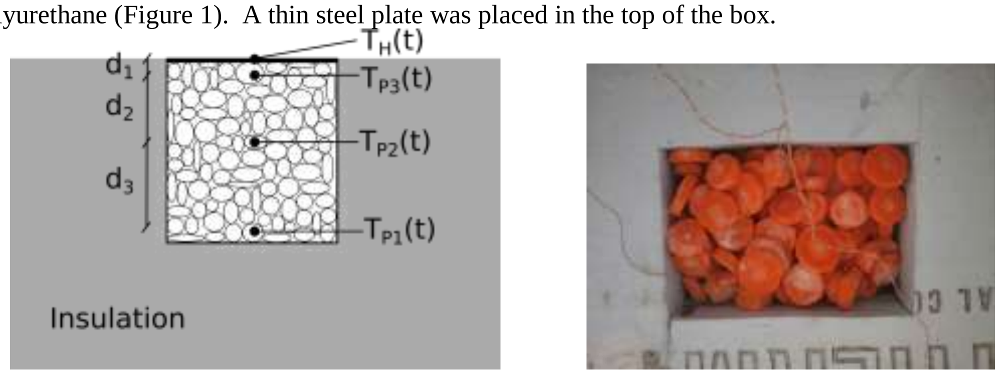

Figure 1 - a) Scheme of experimental device used for conductivity measurement; b) Experimental device, top view.

Type T thermocouples were placed at known positions along the box center axis (T_{P1}, T_{P2} and T_{P3}), into three pieces of product (slices of carrot or green beans), in order to acquire temperature. Frozen product at -20 ºC filled the box, and top surface was closed with a phase chance material operating at -10ºC, measured by T_H. The complete setup was placed in a -20°C freezer to start a two hours long measurement repeated twice.

The top layer surface acted as a heating element to avoid natural convection flow. Heat transfer was modeled in COMSOL as unidirectional unsteady state diffusion and the equivalent thermal conductivity k_{eq} was calculated with Eq.(1).

$$(1-\varepsilon)\rho_P c_{P_P}\frac{\partial T_P}{\partial t} = k_{eq}\frac{\partial^2 T_P}{\partial x^2} \quad (1)$$

where ε is the porosity, and ρ_P, c_{P_P} and T_P are the density, specific heat and temperature of the product, respectively. Imposed temperature at the top (measured experimentally T_H) and no heat flux at the bottom of the box, were taken as boundary conditions. The equivalent conductivity of the porous medium was obtained by comparing the temperature evolution in time from the model to the measured one. The least square method was used to fit the best conductivity value.

2.2.2 Convective heat transfer coefficient into the porous media

The air-product natural convective heat transfer coefficient h was estimated after a transient experiment performed in a container, presented in Figure 2.

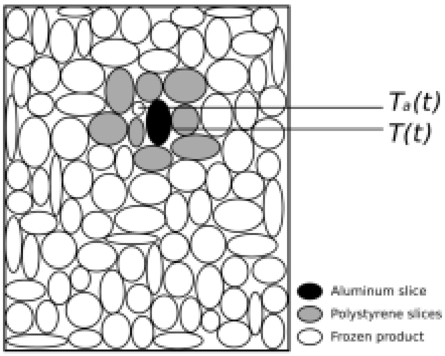

Figure 2 - Scheme of experimental device used for convective coefficient estimation.

The method was similar to the one reported by Alvarez, 1992 and Ben Amara et al., 2004, for macroporous media. A 17.9 cm x 15.6 cm (diameter x height) cylindrical plastic container, insulated by a 8 cm polystyrene plate at the top and at the bottom (Figure 2), was filled with frozen product. An aluminum probe with dimensions close to the ones of the product (20.0 mm diameter and 6.4 mm thickness for carrots; 6.0 mm diameter and 10.0 mm thickness for green beans), with an embeded type T thermocouple. The probe was surrounded by isolated matter with similar geometry, such as polystyrene slices for carrots and hollow plastic tubes for green beans, chosen to avoid thermal contact between the probe and frozen product (Figure 3

Figure 3). Under these conditions, it was assumed that natural convection was the unique heat transfer phenomenon affecting the aluminum slice.

Figure 3 - Experimental device used for convective coefficient estimation, for each vegetable.

Temperature was recorded under unsteady state conditions from the aluminum probe and the surrounding air along the experiment.

A uniform temperature profile was assumed for the aluminum probe, after a prior verification of the Biot number, smaller than 0.1 (aluminum conductivity = 273 $Wm^{-1}K^{-1}$; convective heat coefficient= 2.4 $Wm^{-2}K^{-1}$; characteristic length as half of the thickness = 3.0 mm). Therefore, the transient diffusion equation could be applied assuming a constant air temperature, given by Eq. (2):

$$T = T_a + (T_o - T_a)e^{-(t/\tau)} \quad \text{with } \tau = \frac{mc_P}{hA} \qquad (2)$$

where A, m and c_P are heat transfer surface, mass and specific heat of the aluminum probe, respectively; T_a is the air temperature; T_o is the probe initial temperature and T is the probe temperature varying with time. The convective heat transfer coefficient could be calculated by adjusting the parameters of an exponential curve (solution of Eq. (2)) to fit the experimental points.

3. RESULTS

3.1 Equivalent thermal conductivity

The thermal experiment described in section 2.2.1 was performed twice for each vegetable in order to identify the equivalent thermal conductivity of carrots and green beans.

A unidirectional conduction model was implemented in COMSOL software, with data from product density, apparent specific heat and porosity. These parameters were obtained from Urquiola et al., 2017, by measurements or from the literature, whose values are presented in

Table **2**.

Table 2 - Parameters values used for the model.

Parameters	Symbol	Carrot slices	Green beans
Product density	ρ_P	$997\ kgm^{-3}$	$976\ kgm^{-3}$
Apparent specific heat	C_{p_P}	Temperature functions	
Porosity	ε	0.55	0.65

Correlations presented in Table 1 for limit values were used in order to estimate the range of porous media equivalent conductivity k_{eq}. Main property values were: air conductivity $k_f = 0.026Wm^{-1}K^{-1}$, frozen carrot conductivity $k_{s_c} = 2.0Wm^{-1}K^{-1}$ (Heldman and Singh, 1981), frozen green bean conductivity $k_{s_{gb}} = 1.3Wm^{-1}K^{-1}$ (ASHRAE Handbook, 2006, Chapter 9).

Equivalent thermal conductivity for carrot slices ranged from $0.05Wm^{-1}K^{-1} < k_{eq_c} < 0.91Wm^{-1}K^{-1}$, and for green beans $0.04Wm^{-1}K^{-1} < k_{eq_{gb}} < 0.72Wm^{-1}K^{-1}$.

Simulations were carried out by sweeping the equivalent conductivity within these ranges. Figure 4 shows the comparison between experimental measures and simulation results for carrot slices, for an equivalent conductivity of $k_{eq_c} = 0.12Wm^{-1}K^{-1}$. As it can be seen, the general shape of temperature evolution for different positions was similar in simulations and experimental measurements. However, it was not possible to fit all temperatures by adopting the same value of equivalent conductivity, probably due to the porosity deviation near the wall, which was not taken into account by the uniform porosity assumption. For this reason, only product temperature in the center of the box (T_{P2}) was used for the comparison.

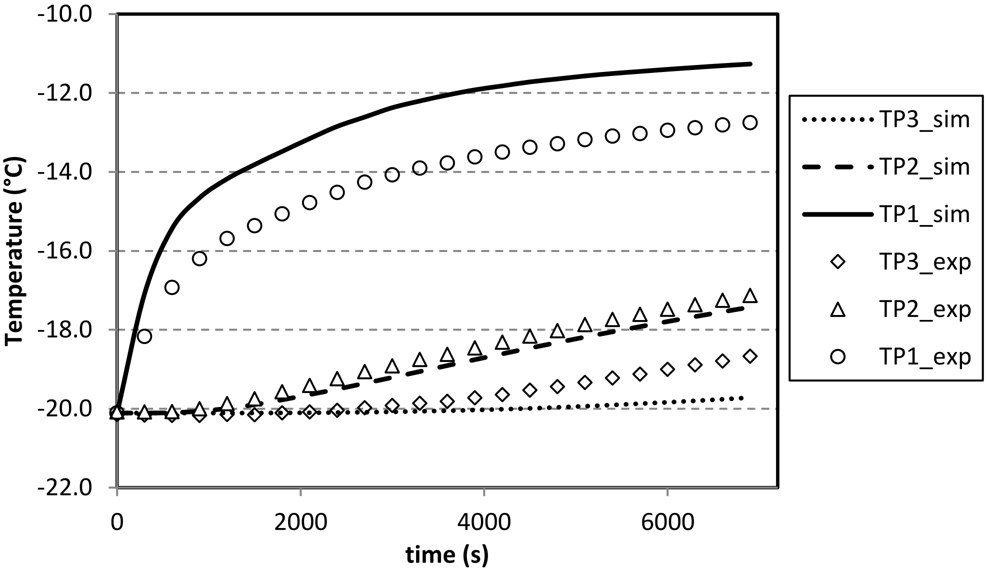

Figure 4 - Experimental and simulated temperatures versus time, for carrot slices (k_{eqC} = 0.12 $Wm^{-1}K^{-1}$)

The minimum square method was used to obtain the better adjustment of equivalent conductivity. The error, e_j, was calculated for each temperature value as in Eq. (3), then the mean quadratic error, e_{cm}, was calculated for each equivalent conductivity (Eq. (4)).

$$e_j = \left|T_{exp} - T_{sim}\right| \tag{3}$$

$$e_{cm} = \sqrt{\frac{\sum_{j=1}^{n} {e_j}^2}{n}} \tag{4}$$

The minimum error was obtained for $k_{eq_c} = 0.14\, Wm^{-1}K^{-1}$ for carrots and $k_{eq_{gb}} = 0.10\, Wm^{-1}K^{-1}$ for green beans, with a maximum error lesser than $0.12°C$. Figure 5 shows the comparison between measured and simulated temperatures in the center of the box (T_{P2}) for carrots (left) and green beans (right), with these calculated conductivities.

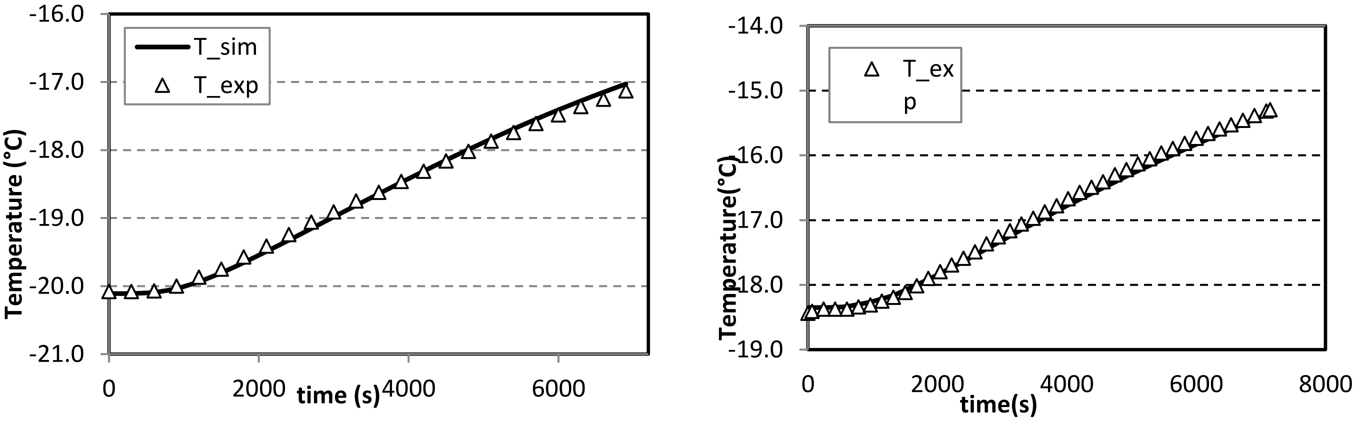

Figure 5 - Experimental and simulated temperatures in the center of the box (T_{P2}) versus time, for (left) carrot slices, (k_{eqC} = 0.14 $Wm^{-1}K^{-1}$) and (right) green beans ($\boldsymbol{k_{eq_{gb}} = 0.10\, Wm^{-1}K^{-1}}$)

The equivalent conductivities can be validated by comparison to the ones calculated with different models, as shown in Table 3.

Table 3 - Equivalent conductivities obtained with different correlations, for carrot slices and green beans.

Model	Correlation	$k_{eq_c}(Wm^{-1}K^{-1})$	$k_{eq_{gb}}(Wm^{-1}K^{-1})$

Present work	Experimental value	0.14	0.10
Parallel	$k_{eq} = k_f \varepsilon + k_s(1-\varepsilon)$	0.91	0.47
Series	$\frac{1}{k_{eq}} = \frac{\varepsilon}{k_f} + \frac{(1-\varepsilon)}{k_s}$	0.05	0.04
Geometric	$k_{eq} = {k_f}^{\varepsilon}.{k_s}^{(1-\varepsilon)}$	0.18	0.10
Krupiczka	$\frac{k_{eq}}{k_f} = \left(\frac{k_s}{k_f}\right)^{0.280-0.757log\varepsilon-0.057log\left(\frac{k_s}{k_f}\right)}$	0.13	0.09

The difference in products conductivities and porosities explains that the equivalent conductivity was bigger for carrots bed than for green beans bed. The geometric model gave a good approximation, as a reference value, but it gives better results for fluid and solid conductivities similar conductivities (Neild and Bejan, 2006). Krupiczka correlation predicted very similar results if compared to experiments, and deviation was 7.1% for carrots and 10% for green beans, according to Eq. (5).

$$e_k = \frac{k_{identified} - k_{Table\,3}}{k_{identified}} 100 \qquad (5)$$

The method appeared to be adequate as the identified values were within the expected range. The equivalent conductivities found for both products are of the same order of magnitude; however, it is 28.5% bigger for carrots, since its porosity (0.55) was smaller than for green beans (0.65), which it involves less air volume fraction and more solid volume fraction into the porous medium.

3.2 Convective heat transfer coefficient

In order to estimate the convective heat transfer coefficient into the porous media, the experimental procedure described in section 2.2.2 was done for each vegetable.

The experiment was repeated twice for each vegetable, and it was checked that measures were repeatable. Air and product temperatures were measured during 50 minutes, but only temperature differences in the range of $2°C < T - T_a < 5°C$ were taken, similar to real product storage condition into the container.

The dimensionless temperature difference was calculated and plotted versus time in Figure 6. The adjustment of an exponential trend curve to experimental points is also presented in Figure 6, with a good correlation coefficient. The value of time constant was $\tau = 5.0 \times 10^{-4}$, and convective coefficient was $h_c = 2.4\ Wm^{-2}K^{-1}$.

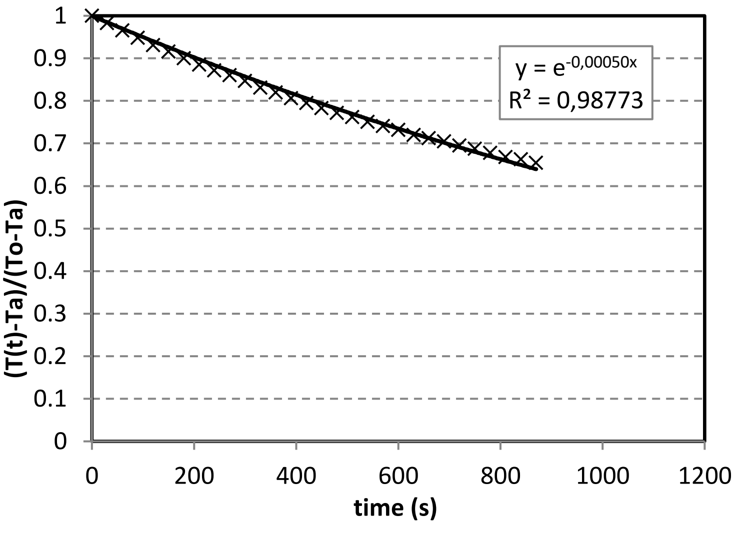

Figure 6 - Aluminum probe dimensionless temperature versus time and its fitting curve, for carrot slices.

In order to evaluate the experimental convective coefficient obtained for carrot slices, it was compared to the convective coefficient for a sphere, since it was not found in the literature correlations for a geometry more similar to carrot slices. Assuming the unique phenomena was conduction in the air around the sphere (convection was neglected in respect to conduction), the Nusselt number for a single sphere was $Nu = 2$, and using the slice diameter as characteristic length, $(D = 0.0243\ m)$ and the air conductivity $(k_{air} = 0.026\ Wm^{-1}K^{-1})$, the convective coefficient was $h = 2.1\ Wm^{-2}K^{-1}$.

Considering the local natural convection, the correlation proposed by Yuge (Holman, 1972) for heat transfer between a single sphere and air could be used to obtain an order of magnitude.

$$Nu = 2 + 0{,}392 Gr^{0{,}25} \qquad (1 < Gr < 10^5) \qquad (6)$$

Using the temperature difference obtained from the simulation of the order of $1°C$, diameter as the characteristic length $(D = 0.0243\ m)$, and air properties at -15°C $(\nu = 1.2 \times 10^{-5} m^2 s^{-1}$, $k_{air} = 0.026\ Wm^{-1}K^{-1}$ and $\beta = 3.87 \times 10^{-3} K^{-1})$ the Grashoff was $Gr = 3779$. Finally the Nusselt number was 5,1 and the convective heat transfer coefficient obtained was $h = 5.4\ Wm^{-2}K^{-1}$.

For a bed of spheres, Wakao and Kaguei, 1982 proposed the following correlation for forced convection.

$$Nu = 2 + 1{,}10\ Pr^{1/3} Re^{0{,}6} \qquad (7)$$

In the present experiment, the Reynolds number was of the order of 2, calculated from a simulated velocity $(v \cong 1\ mm.s^{-1})$, the diameter as a characteristic length $(D = 0.0243\ m)$ and air kinematic viscosity $(\nu = 1.2 \times 10^{-5} m^2 s^{-1})$. The convective heat transfer coefficient using Eq. (7) is 3.7 $Wm^{-2}K^{-1}$.

Ben Amara, 2004 proposed a correlation obtained for a macroporous media compose by spheres in cubic arrange, as follows.

$$Nu = 2 + 1{,}09\ Pr^{1/3} Re^{0{,}53} \qquad (8)$$

This correlation was obtained from an experimental measurement, similar to proposed here, and also similar to Wakao and Kaguei (Eq. (7)).The convective heat transfer coefficient using Eq. (8) is 3.6 $Wm^{-2}K^{-1}$.

Table 4 summaries the different estimations for the convective coefficient in the carrots bed, submitted to an airflow. Despite these correlations were for spheres and in some cases for a single one, the values obtained were of the same order of magnitude than the experimental one. The correlations that better adjust to the experimental value are the pure air conduction over a sphere and the forced convection in a bed of spheres, obtained experimentally by Ben Amara.

Table 4 – Convective coefficients estimated by different correlations, for carrot slices.

Model	$h_c\ (Wm^{-2}K^{-1})$
Present work (experimental)	2.4
Air conduction over a sphere	2.1
Natural convection in a single sphere	5.4
Forced convection in a bed of spheres, Wakao and Kaguei	3.7
Forced convection in a bed of spheres, Ben Amara	3.6

The same procedure was repeated with green beans (Figure 7) and the time constant was $\tau = 5.5 \times 10^{-4}$and convective coefficient was $h_{gb} = 2.3\ Wm^{-2}K^{-1}$.

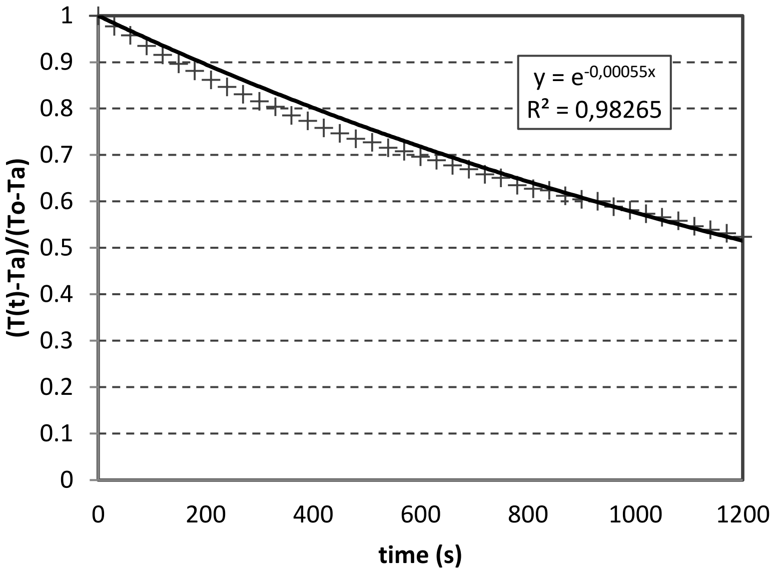

Figure 7 - Aluminum probe dimensionless temperature versus time and its fitting curve, for green beans.

Similar to carrots, this coefficient was compared to different correlations. Assuming a unique green bean in conditions of natural convection, the convective coefficient can be estimate as a horizontal and vertical cylinder. For horizontal cylinder, the Rayleigh number was 41, calculated from air properties at -15°C ($\nu = 1.2 \times 10^{-5} m^2 s^{-1}$, $k_{air} = 0.026 W m^{-1} K^{-1}$, $\beta = 3.87 \times 10^{-3} K^{-1}$ and $Pr = 0.72$), diameter as the characteristic length ($D = 0.006\, m$) and a temperature difference of 1ºC. Making use of the correlation present in Eq. (9) from Incropera and De Witt, 1999 for an infinite horizontal cylinder, the Nusselt number was 1.43 and the convective coefficient was 6.2 $W m^{-2} K^{-1}$.

$$Nu = \left[0.6 + \frac{0.387 Ra^{1/6}}{\left[1+\left(\frac{0.559}{Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \qquad (Ra < 10^{12}) \qquad (9)$$

For an infinite vertical cylinder the convective coefficient was calculated using the same parameters, except the characteristic length which was the green bean length ($L = 0.092\, m$). The Rayleigh number was 14.77×10^4 ($Pr = Pr_w$) and Nusselt obtained from Eq. (10) from Mijeev and Mijeeva, 1979 was 14.9. Finally the convective coefficient for a vertical cylinder was 4.2 $W m^{-2} K^{-1}$.

$$Nu = 0.76 Ra^{0.25} \left(\frac{Pr}{Pr_w}\right)^{0.25} \qquad (10^3 < Ra < 10^9) \qquad (10)$$

Considering the condition of force convection of a cylinder with cross airflow, Nusselt can be calculated from Eq. (11). The values of constant C and m depends on the Reynolds number, which was 0.5, calculated from a velocity obtained from the simulation ($v \cong 1\, mm.s^{-1}$), diameter as a characteristic length ($D = 0.006\, m$) and air kinematic viscosity ($\nu = 1.2 \times 10^{-5} m^2 s^{-1}$). For the range of $0.4 < Re < 4$, $C = 0.989$ and $m = 0.33$. Nusselt was 0.69 and the convective coefficient was 3.0 $W m^{-2} K^{-1}$.

$$Nu = C' Re^m Pr^{1/3} \qquad (11)$$

Another way to estimate the convective coefficient was by assuming arranges as an aligned or staggered tube bank, subjected to airflow. Zhukauskas (Incropera and De Witt, 1999) proposed the correlation present in Eq. (12) for tube bank.

$$Nu = C' Re^m Pr^{0.36} \left(\frac{Pr}{Pr_w}\right)^{0.25} \qquad (12)$$

Constant C and m varies depending on the Reynoldsnumber ($Re = 0.5$) and the arrangement (aligned or staggered).Even when the correlation could be applied for Reynolds bigger than 10, a rough approximation was done. For aligned tube bank and $10 < Re < 100$ ($C = 0.8$ and $m = 0.4$) Nusselt is 0.54 and the convective heat transfer coefficient is $2.3\ Wm^{-2}K^{-1}$. For staggered tube bank and $10 < Re < 100$ ($C = 0.9$ and $m = 0.4$) Nusselt is 0.61 and the convective heat transfer coefficient was $2.6\ Wm^{-2}K^{-1}$.

Table 5 summaries the different estimations for the convective coefficient in the green beans bed, submitted to natural airflow. As it can be seen, the experimental value obtained in the present work is of the same order of magnitude than the values estimated by different correlations for a single cylinder and for arranges of cylinders. The correlations that better adjust to the experimental value are the forced convection in arranges of tube bank (aligned and staggered), in which differs less than 12%.

Table 5 - Convective coefficients estimated by different correlations, for green beans.

Model	$h_{gb}(Wm^{-2}K^{-1})$
Present work (experimental)	2.3
Natural convection in horizontal cylinder	6.2
Natural convection in vertical cylinder	4.2
Forced convection in cylinder with cross airflow	3.0
Forced convection in an arranges as an aligned tube bank	2.3
Forced convection in an arranges as an staggered tube bank	2.6

Convective coefficients for carrot slices was *2.4* $Wm^{-2}K^{-1}$ and for green beans *2.3* $Wm^{-2}K^{-1}$. The values found are very close, probably due to their similar water content: 88% carrots and 90% green beans (ASHRAE Handbook, 2006, Chapter 9). That behavior allowed to conclude that product thermal properties have a bigger influence in convective coefficient than geometry.

4. CONCLUSION

Two simple and low cost methods to evaluate the order of magnitude of equivalent conductivity and convective coefficient into a macroporous media were proposed and implemented. The methods combined experimental and numerical approach. Coefficients were evaluated for two porous media: carrot slices - air and green beans – air, and the values were compared to literature sources and among them. The calculated equivalent thermal conductivities were *0.14* $Wm^{-1}K^{-1}$ for carrot slices and *0.10* $Wm^{-1}K^{-1}$ for green beans, which differs less than 10% to the literature values of *0.13* $Wm^{-1}K^{-1}$ and *0.09* $Wm^{-1}K^{-1}$, obtained with the Kupriczca's correlation for a macroporous media compound by spheres. Convective coefficient for carrot slices and green beans were estimated as *2.4* $Wm^{-2}K^{-1}$ and *2.3* $Wm^{-2}K^{-1}$, respectively, within the expected values calculated with different correlations from literature, which varies between *2.1* $Wm^{-2}K^{-1}$ and *5.4* $Wm^{-2}K^{-1}$ for carrot slices, and between *2.3* $Wm^{-2}K^{-1}$ and *6.2* $Wm^{-2}K^{-1}$ for green beans.

It can be conclude that the proposed methods are a simple and good tool to obtain an order of magnitude for these coefficients. Measured coefficients were in accordance to reference ones from literature, and they displayed the same order of magnitude for both tested products, even though they display different geometries. The equivalent conductivity was 28.5% bigger for carrots, since its porosity (0.55) was smaller than for green beans (0.65). The convective coefficients were very close for both products, but a slightly higher for carrots (7%).

Multivariate optimization tools

For future works is could be employed in future work to take into account parameters like density, porosity and specific heat.

5. ACKNOWLEDGEMENTS

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