THE COOLING AND FREEZING OF PARALLELEPIPED FOOD PRODUCT: INFLUENCE OF THE SIZE AND INICIAL MOISTURE CONTENT

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Abstract. *The freezing is a physical treatment widely used in operations such as drying, conservation and lyophilization of foods products. In the processing and improvement industry potatoes, parameters like dimensions and initial moisture content of the product has strong influence in the cooling, freezing and tempering kinetics. In the sense, this work presents a transient three-dimensional mathematical modeling including phase-change to describe the heat transfer during the process, of cooling and freezing of parallelepiped food product. The governing equation was solved numerically using the finite-volume technique and a full implicit formulation. As application this methodology was used to describe freezing of potato (french-fry). Results of the temperature distribution inside the solid and cooling, freezing and tempering kinetics are showed and analyzed. It was verified that, as smaller the dimensions and the initial moisture content of the product, more fast occurs the solidification of water inside the solid. The largest temperature gradients were identified in the surface, close to the regions of the vertexes of the solid.*

Keywords*: french-fry, finite-volume, heat diffusion, simulation*

1. Introduction

Freezing is a well known preservation method widely used in the food industry aiming at to maintain the sensorial attributes and nutritious properties of these products. In these cases, the effect of the temperature in the time of useful life of the product is quite significant. Thus, the products should be quickly cooling and/or freezing, reducing its respiratory rate and, consequently, increasing its useful life. The freezing process combines the favorable effect of low temperatures with the conversion of water into ice. At temperatures lower than –10ºC few microorganisms can develop, chemical reactions are also delayed (Delgado & Sun, 2001). In this sense, several cooling and/or freezing methods, such as, cooling/freezing with water, air, air-water and vacuum are used (Dincer and Genceli, 1994; Teruel Mederos, 2000).

Specifically, during the freezing (water transformation into ice) of a food product, its thermophysical properties constantly change. This is due to the fact of the continuous variation of the solid fraction and, consequently, of the liquid fraction inside the material, until that the same solidifies completely. In this situation, the use of numerical techniques is recommended for obtaining of the solution of the governing equation in every domain of time: cooling, freezing and post-freezing (tempering). The correct mathematical formulation of the physical phenomenon in study is of very important in the reliability of the results obtained. The numerical solution of the heat transfer equation, in a domain three-dimensional domain, in agreement to the experimental data of freezing kinetics of biological materials, it makes possible to investigate with larger precision that happens, with the temperature, inside the material along the process (through the analysis of the temperature distribution). Then the influence of parameters such as size and initial moisture content can be verified in the cooling and/or freezing kinetics of the product. The knowledge of such influences is indispensable, because it allows to optimize cooling/freezing systems in industrial scale. The main variation parameters demanded by the customers are related to the product size and to its initial moisture content. These parameters influence directly so much in the process time and in the final quality of the product (Montague *et al*., 2003).

In this sence, the aim of this study is to model and simulate the three-dimensional heat transfer during the freezing and tempering of solids with parallelepiped shape. As application, the model was used to verify the influence of the dimensions and moisture content of the product, in the temperature distribution inside french-fry (potatoes peaces).

2. Materials and methods

2.1. Mathematical modeling

The general conservation equation can be written in the following way (Maliska, 1995; Nascimento, 2002):

$$\frac{\partial}{\partial t}(\lambda\varphi) = \nabla \cdot \left(\Gamma^{\varphi}\nabla\varphi\right) + S^{\varphi} \tag{1}$$

where Γ^{φ}, λ are transport properties; φ is the dependent variable; S^{φ} is the source term (energy generation) and $\nabla = \frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k}$ is Nabla operator.

To heat transfer: $\lambda = \rho c_P$; $\varphi = T$; $\Gamma^{\varphi} = k$ and $S^{\varphi} = q'''$, so the Eq. (1) can be rewritten as follows:

$$\frac{\partial}{\partial t}(\rho c_P T) = \nabla \cdot (k\nabla T) + q''' \tag{2}$$

where ρ is the density; T is the temperature; c_P is the specific heat; k is the thermal conductivity and q''' it is energy generation term associated to the phase change.

During the freezing, occurs transformation of water in the liquid phase to ice with consequent energy generation simultaneously. The energy generation term in the Eq. (2) represents the heat liberated during the phase-change given by (Limeira, 2003):

$$q''' = \rho L_S \frac{\partial f_S}{\partial t} \tag{3}$$

In this case, the heat transfer equation (including generation of internal energy) applied to a solid with parallelepiped shape (Fig. 1) can be written as follows:

$$\frac{\partial}{\partial t}(\rho c_P T) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \rho L_S \frac{\partial f_S}{\partial t} \tag{4}$$

where L_s is the latent heat of solidification, $f_s = (T_L - T)/(T_L - T_S)$ represents the solid fraction (ice) formed during the freezing phase, T_L is the initial freezing temperature, T_S is the final freezing temperature and t is the time.

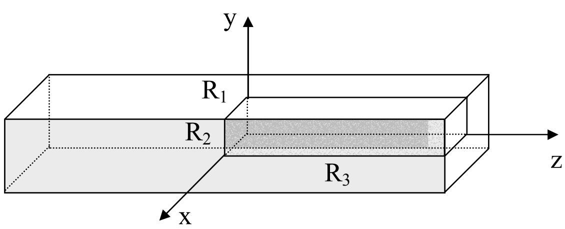

Figure 1. Geometrical configuration of a solid parallelepiped

Due to the symmetry in the solid, is just considered 1/8 of the solid volume. The following: initial, symmetry and boundary conditions are used:

a) Initial condition: uniform distribution of temperature.

$$T(x,y,z,t=0) = T_o \tag{5a}$$

b) Symmetry condition: no heat flow in the symmetry regions.

$$\frac{\partial T(x=0,y,z,t)}{\partial x} = 0$$
$$\frac{\partial T(x,y=0,z,t)}{\partial y} = 0 \tag{5b-c-d}$$
$$\frac{\partial T(x,y,z=0,t)}{\partial z} = 0$$

c) Boundary condition at the surface: convection heat transfer at the surface of the solid.

$$-k\frac{\partial T(x,y,z,t)}{\partial x} = h_c\,[T(x,y,z,t) - T_{eq}]\;,\; x = R_1;$$
$$-k\frac{\partial T(x,y,z,t)}{\partial y} = h_c\,[T(x,y,z,t) - T_{eq}]\;,\; y = R_2; \qquad (5e\text{-}f\text{-}g)$$
$$-k\frac{\partial T(x,y,z,t)}{\partial z} = h_c\,[T(x,y,z,t) - T_{eq}]\;,\; z = R_3;$$

In the Eqs. (5e-f-g) h_c and T_{eq} represent the convective heat transfer coefficient and air temperature, respectively.

2.2. Numerical procedure

Various numerical methods can be used to solve the Eq. (4) such as finite-difference, finite-element, boundary element and finite-volume methods (Patankar, 1980; Maliska, 2004; Fortuna, 2000; Versteeg & Malalasekera, 1995). In this work, the governing equation was solved numerically using the finite-volume technique and a full implicit formulation. Figure 2 shows the control-volume used in this study.

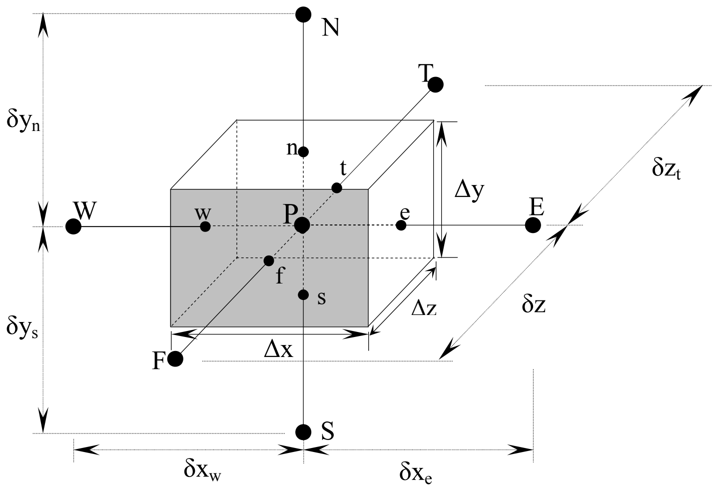

Figure 2. Control-volume of the physical domain

Applying to integral on both sides of the Eq. (4), in the space and time, we have:

$$\int_V\int_t \frac{\partial\left[\rho\left(c+\frac{L_S}{T_L - T_S}\right)T\right]}{\partial t}dtdV = \int_V\int_t \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dtdV + \int_V\int_t \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)dtdV + \int_V\int_t \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)dtdV \qquad (6)$$

In the discretized form we can written the Eq. (6) as follows:

$$A_P T_P = A_E T_E + A_W T_W + A_N T_N + A_S T_S + A_F T_F + A_T T_T + A_P^o T_P^o + BT_{eq} \qquad (7)$$

where:

$$A_P = A_E + A_W + A_N + A_S + A_F + A_T + \rho_P\left(c_P + \frac{L_S}{T_L - T_S}\right)\frac{\Delta x\Delta y\Delta z}{\Delta t} + B$$

$$A_E = \frac{k_e}{\delta x_e}\Delta y\Delta z \qquad A_W = \frac{k_w}{\delta x_w}\Delta y\Delta z \qquad A_N = \frac{k_n}{\delta y_n}\Delta x\Delta z \qquad A_S = \frac{k_s}{\delta y_s}\Delta x\Delta z$$

$$A_F = \frac{k_f}{\delta x_f}\Delta x\Delta y \qquad A_T = \frac{k_t}{\delta x_t}\Delta x\Delta y \qquad A_P^o = \rho_P^o\left(c_P^o + \frac{L_S}{T_L - T_S}\right)\frac{\Delta x\Delta y\Delta z}{\Delta t} \qquad B = 0$$

This formulation is valid for all the internal points to the domain. The mathematical formulation for the boundary points is obtained through an energy balance for each control-volume, considering the boundary conditions used. The coefficients of the Eq. (7) for the boundary points are given by:

$$A_E = 0 \qquad A_F = 0 \qquad A_N = 0$$

$$B = \frac{\Delta y\Delta z}{\left(\frac{1}{h_c} + \frac{\delta x_e}{k_e}\right)} \qquad B = \frac{\Delta x\Delta z}{\left(\frac{1}{h_c} + \frac{\delta y_n}{k_n}\right)} \qquad B = \frac{\Delta x\Delta y}{\left(\frac{1}{h_c} + \frac{\delta z_f}{k_f}\right)}$$

The set of algebraic equations was solved using Gauss-Siedel's interactive method with convergence criterion of $|T^{n+1} - T^n| \leq 10^{-8}$. For obtaining of the numerical results, a computational code using the software Mathematica® was developed. In all simulations was used a uniform grid of 20 x 20 x 20 nodes and Δt=0,5s. Details about the validation and grid and time refine (without phase-change) may be found in Nascimento (2002).

2.3. Applications

Details about physical validation of the mathematical model can be found in Silva *et al.* (2004). In this work, the methodology was used to predict the influence of the size and moisture content in the cooling, freezing and tempering kinetics of french-fry.

The following experimental data were used: $\rho_{(pc)}$=1012 kg.m^{-3}; $\rho_{(ac)}$=1069 kg.m^{-3}; $c_{p(pc)}$=1870 J.(kg.ºC)$^{-1}$; $c_{p(ac)}$=3420 J.(kg.ºC)$^{-1}$; L_S=246888.30 J.kg^{-1}; T_o=31.1ºC; T_{eq}=–29.1ºC; U_o=0.7372 wet basis. (LeBlanc *et al.*, 1900); k_{pc}=0.980 W.(m.ºC)$^{-1}$; k_{ac}=0.470 W.(m.ºC)$^{-1}$ (Silva *et al.*, 2004). To verify the effect of the size of the solid in the heat transfer the following dimension were used: 10x10x20, 10x10x30 and 10x10x60 mm.

During the freezing phase the following equations were proposed for the thermal conductivity, specific heat and density, respectively, in each point inside the product:

$$k_{dc} = f_s k_{ac} + (1 - f_s)k_{pc}$$
$$c_{P_{dc}} = f_s c_{P_{ac}} + (1 - f_s)c_{P_{pc}} \qquad (7a\text{-}b\text{-}c)$$
$$\rho_{dc} = f_s \rho_{ac} + (1 - f_s)\rho_{pc}$$

where the indexes *ac*, *dc* e *pc* represent before, during and after of the freezing, respectively.

To verify the effect the moisture content of the moisture content in the heat transfer the following moisture contents were used: 20, 30, 40 e 50% wet basis. The experimental data in this study are presented in the Tab. 1. The values of the frozen product thermophysical properties were estimated, considering proportion between the properties, of liquid and solid water.

Table 1. Potato experimental conditions used in this work

U_o % wet basis		c_P [a], J.(kg.ºC)$^{-1}$	ρ [b], Kg.m^{-3}	k [c], W.(mº.C)$^{-1}$	L_S*, J.kg^{-1}	α**=$k/(\rho c_P)$ (x10^{-8}, m^2.s^{-1})
20,0	frozen product	1173.28 [d]	1300.60 [e]	0.1280 [f]	66980.0	8.3881
	unfrozen product	2148.87	1373.97	0.0615		2.0829
30,0	frozen product	1249.20 [d]	1289.85 [e]	0.2870 [f]	100470.0	17.8110
	unfrozen product	2287.92	1362.62	0.1380		4.4265
40,0	frozen product	1344.78 [d]	1268.11 [e]	0.4187 [f]	133960.0	24.5520
	unfrozen product	2462.98	1339.65	0.2012		6.0978
50,0	frozen product	1467.76 [d]	1227.51 [e]	0.5390 [f]	167450.0	29.9160
	unfrozen product	2688.22	1296.76	0.2590		7.4297

[a] Wang and Brennan (1993); [b] Wang and Brennan (1995); [c] Wang and Brennan (1992) ** Thermal diffusivity;
[d] 0.546 of the unfrozen product; [e] 0.9466 of the unfrozen product; [f] 2.0813 of the unfrozen product;
* $L_S=L_oU_o$, onde L_o=334900.0 J/kg is the latent heat of solidification of the pure water (LeBlanc *et al.*, 1990);

3. Results and discussion

The water-ice transition maintains the tissue structure and separates the water fraction in the form of ice crystals this way the water is not available either as solvent or reactive component. Consequently, the diffusion of other solutes in the tissue is very slow and together with the temperatures reduction helps to diminish the reaction rate. Factors as the size and, mainly, the initial moisture content of the product, present large influence in the freezing kinetics. For this reason, a numerical study should be used.

3.1. Influence of the product size

Typical temperatures histories obtained during a cooling, freezing and post-freezing are presented in Fig. 3, for the three sizes of french-fry. In the beginning of the solidification, the heat transfer rate (ºC/s) falls quickly, tending to a minimum value, identifying the nucleation phenomenon begins. Starting from this point, the rate stays approximately constant until the complete solidification of the existent free water in the material. The end of the process of phase-change is characterized by an abrupt increase in the numerical value of the heat transfer rate. These results are in concordance with the experimental results obtained by Rahman *et al*. (2002).

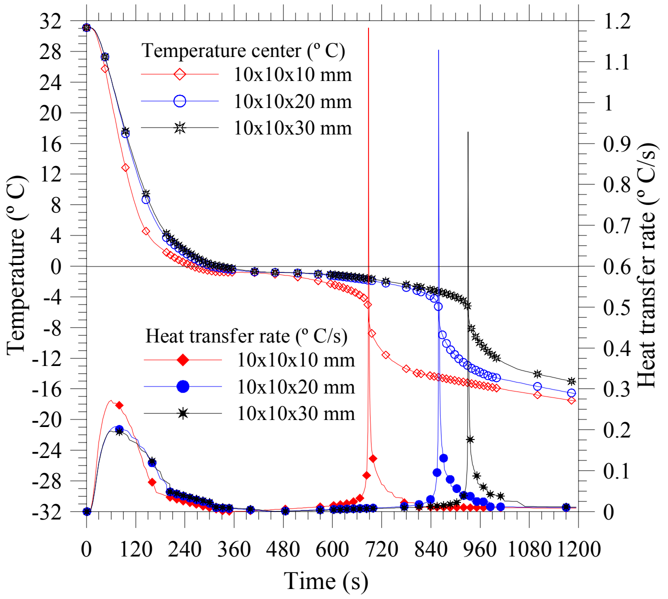

Figure 2. Predicted temperature and heat transfer rate to various sizes of the french-fry (calculated in the center of the solid)

Therefore, through the numerical value of the heat transfer rate during the process, it is possible to obtain the times and temperatures at the beginning and end of phase-change. Still in relation to the Fig. 3, it is observed that as smaller the size of the solid, lowest is the solidification time of the water inside the potato. Physically, this behavior can be explained by the numerical value of the relationship (area/volume). As larger it is this relationship, more quickly the heat transfer occurs during the process.

Figure 4 illustrates the temperature distribution in two planes (xz and xy) in the solid center. It is possible to verify the behavior of the water inside the food. This figure shows regions of the frozen water (dotted lines) and the water-ice transition (hatched lines). It is noted that the freezing front advances from the vertex in direction to the center of the potato, in concordance with the results reported by LeBlanc *et al.* (1990). Therefore, through the application of the mathematical model presented in this work, it is possible to determine accurately, the total times of the phase-change process, as well as to predict the front advance of solidification inside the food in direction to center. This manner it is possible to optimize the freezing process in the processing industry and to produce improvement in the potatoes (Montague *et al*., 2003).

3.2. Influence of the initial moisture content

In the particular case of the french-fry, the quality, referent to the texture of the product after frozen, it is strongly linked to its moisture content in the beginning of the process (Montague *et al*., 2003). Figure 4 shows the numerical results of cooling, freezing and post-freezing kinetics, as well as, heat transfer rate (ºC/s) for the following initial moisture content of 20, 30, 40 and 50% wet basis. It is verified, as expected, that as smaller the initial moisture content, lowest is the solidification time of the water inside the product. It is observed that for the smallest moisture content

(20% wet basis), largest it is the beginning the freezing time, this behavior is linked to the value of the thermo-physical properties for this moisture content, particularly thermal conductivity, that decreases along the process. In this sense, it is important to note the effect of the thermal diffusivity in each period of the freezing kinetics. For all the moisture contents, the thermal diffusivity of frozen material it is largest than the unfrozen product (see Table 1). Is is explains the fast temperature decline soon after the solidification of the water in all the studied cases.

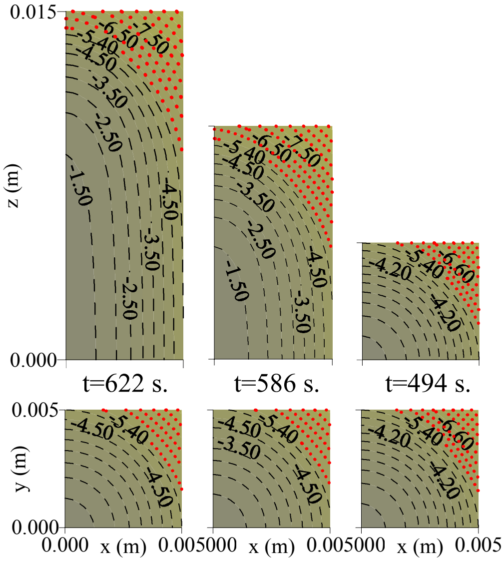

Figure 4. Predicted temperature distributions in the central plane of the french-fry (U_o=73,72% wet basis)

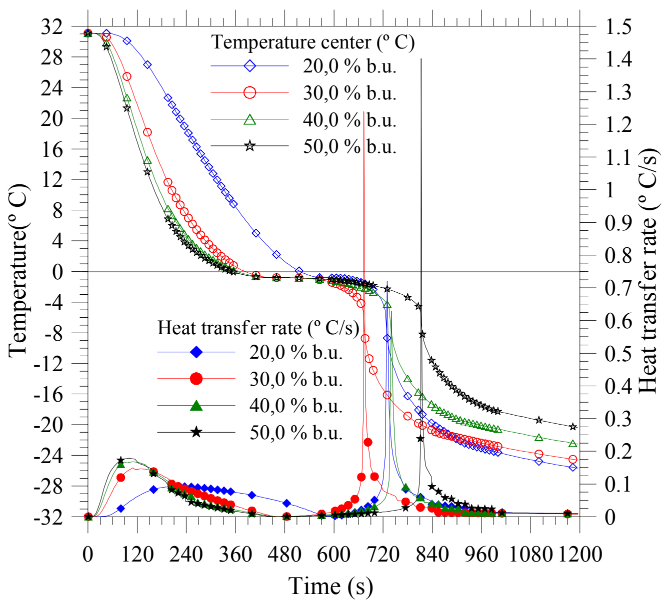

Figure 4. Predicted temperature and heat transfer rate to many initial moisture contents of the french-fry (calculated in the center of the solid)

By observing the temperature distribution for the moisture contents of 20, 30 and 40% wet basis, in the time of 230 s. (Fig. 5), it is possible to verify the existence of three different regions, a region where the product is completely unfrozen (continuous lines, $T > -0{,}8^o$ C); a region where ice and water coexist (hatched lines,$-0{,}8^o C < T < -5{,}4^o$ C) and still a considerable region of frozen water (dotted lines, $T < -5{,}4^o$ C). The behavior of the water inside the potato, like shows in Fig. 4, is not desirable, because the solid will be submitted to mechanical tensions due to large temperature difference of the phases of the water inside the product, with consequent quality losses. The condition more critics occur when the initial moisture content is of 20% wet basis, reducing its effect as the moisture content increases.

As a final comment, through the mathematical modeling presented in this work, it is possible to determine with good precision, the times of the period of the phase-change process, as well as to predict the solidification front, for many process conditions. Montague *et al*. (2003) report the importance of the capacity of adaptation of the processing unit to attend its customers' needs.

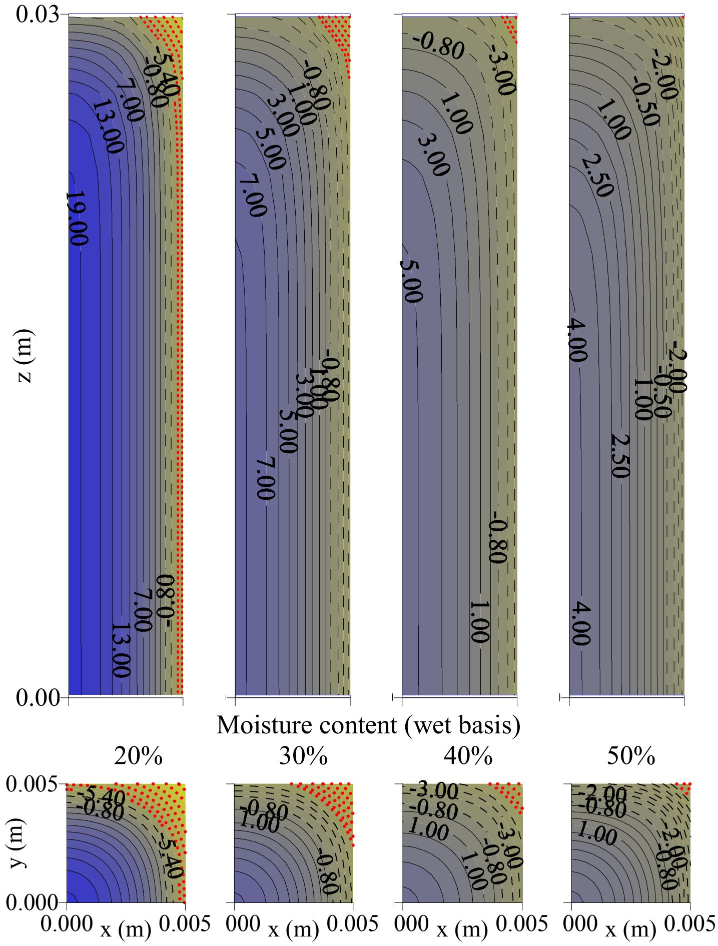

Figure 5. Predicted temperature distribution in the central plane of the french-fry (t=230 s.) to many initial moisture contents

4. Conclusions

From the results we concluded than: (a) The model and the technique used has great potential and it is accurate and efficient to simulate many practical problems of diffusion such as heating, cooling, freezing, wetting and drying in parallelepiped solids; (b) in the two situations studied, the largest temperature gradients were identified at the surface, close to the regions of the vertexes of the solid. In this region begins the freezing of the water advancing to the solid center; (c) the size of the body influence in the freezing kinetics, as larger the relationship (area/volume) smaller it is the time of transformation of the water in ice, for the same conditions of the process; (d) as smaller the initial moisture content, smaller it will be the time of freezing (phase-change) of the french-fry, for the same process conditions.

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