EXPERIMENTAL AND NUMERICAL EVALUATION OF THE KINETIC OF FREEZING BRAZILIAN CODLING (*Urophycis brasiliensis*) MUSCLE

JARBAS LUIZ LIMA DE SOUZA[1], DANIELE COLEMBERGUE DA CUNHA VANZIN[2], LUIZ ANTÔNIO DE ALMEIDA PINTO[3], CEZAR AUGUSTO DA ROSA[4], CARLOS PRENTICE[5].

ABSTRACT

This work carried out an experimental and numerical study of the kinetics of freezing of the Brazilian codling (*Urophycis brasiliensis*) muscle in air blast freezer, with air temperature set at 253.15 K and the average convective heat transfer coefficient at 25.4 W m^{-2} K^{-1}. The initial temperature of the fish muscle was 277.15 K and the final temperature 255.15 K. The objective of this work was to verify the best agreement between the experimental temperature profile and the numerical temperature profile to Brazilian codling muscle, using the CFD (Computational Fluid Dynamics) as numerical tool. In relation to the obtained results, it was verified that a good agreement between the experimental and numerical temperature profiles for the Brazilian codling muscle. The experimental freezing time found was 6618 s, and the freezing time through the numerical simulation was 6246 s. The error percentage found was 5.6%.

KEYWORDS: FREEZING KINETICS, FISH MUSCLE, ENTHALPY-POROSITY.

AVALIAÇÃO EXPERIMENTAL E NUMÉRICA DA CINÉTICA DO CONGELAMENTO DO MÚSCULO DE ABRÓTEA (*Urophycis brasiliensis*)

RESUMO

Este trabalho realizou um estudo experimental e numérico da cinética de congelamento do músculo de abrótea (*Urophycis brasiliensis*) em uma câmara fria de convecção a ar forçado, com a temperatura do ar fixada em 253,15 K e o coeficiente convectivo médio de transferência de calor de 25,4 W m^{-2} K^{-1}. A temperatura inicial do músculo do pescado foi de 277,15 K e a temperatura final de 255,15 K. O objetivo deste trabalho foi verificar a

---

[1] School of Chemistry and Food, Federal University of Rio Grande – FURG. Phd Student in Food Science Engineering. Email: jarbas.souza@riogrande.ifrs.edu.br

[2] Federal Institute of Education, Science and Technology of Rio Grande do Sul – IFRS. PhD in Food Science Engineering. Email: daniele.cunha@riogrande.ifrs.edu.br

[3] School of Chemistry and Food, Federal University of Rio Grande – FURG. Phd in Chemical Engineering. Email: dqmpinto@furg.br

[4] School of Chemistry and Food, Federal University of Rio Grande – FURG. Phd in Chemical Engineering. Email: darosacezar@gmail.com

[5] School of Chemistry and Food, Federal University of Rio Grande – FURG. PhD in Food Engineering. Email: dqmprent@furg.br

melhor concordância entre o perfil de temperatura experimental e o perfil de temperatura numérico para o músculo de abrótea, utilizando o CFD (*Computational Fluid Dynamics*) como ferramenta numérica. Em relação aos resultados obtidos, verificou-se uma boa concordância entre os perfis experimentais e numéricos de temperatura para o músculo de abrótea. O tempo de congelamento experimental encontrado foi de 6618 s, e o tempo de congelamento pela simulação numérica foi de 6246 s. O percentual de erro encontrado foi de 5,6%.

PALAVRAS-CHAVE: CINÉTICA DE CONGELAMENTO; MÚSCULO DE PESCADO; ENTALPIA-POROSIDADE.

1. INTRODUCTION

The main method of conservation of the fish is through freezing, being widely used by the cold stores. However, despite of being a very old and widely used method, it still presents many challenges for food engineering. Foods do not present thermophysical properties and freezing kinetic as observed in pure substances or common mixtures [14]. In addition, each food, even of the same type, presents many variations within its classification, which interferes in its characteristics and behavior in the freezing process.

The rate of freezing also affects the quality of the food; a fast freezing rate is desirable because it has the effect of decreasing the size of the ice crystals, thereby improving nutritional characteristics, texture, flavor and chemical composition [9].

According to RAHMAN et al. [16], to design and simulate a cooling and/or freezing equipment, there are several aspects to be considered by food professionals, such as: the amount of energy to be removed (sensitive and latent), composition (height, length, radius, thickness and width), physical properties (density, freezing point, latent heat, specific heat and thermal conductivity), and the initial freezing temperature.

Authors such as SCHEERLINCK et al. [18] and TAN and FOK [19] investigated the freezing process of different types of fish, however, considering the thermophysical properties of the product above the initial freezing temperature for the numerical simulation, in which they are practically constant with the temperature variation. In this sense, the use of UDFs (User Defined Functions) to customize the variable thermophysical properties during the freezing process, represent an alternative for the numerical simulation of food freezing through the enthalpy-porosity method.

In this sense, the objective of the work was to evaluate, experimentally and numerically, through the enthalpy-porosity method with the variable thermophysical properties, the freezing kinetics of the Brazilian codling muscle, one of the main species caught on the south coast of Brazil (according to ANDRADE, DUARTE-PEREIRA and ABREU-SILVA [2]) and one typical product of great importance, both economic and cultural, for that region.

2. NUMERICAL MODEL DEVELOPMENT

In the enthalpy-porosity method, the liquid-solid interface (mushy zone) is modeled as a pseudo-porous medium, with the porosity being defined as a function of a quantity called liquid fraction. This method is implemented through the addition of source terms in the momentum conservation equations based on Darcy's law and the Carman-Kozeny equation for flows in porous media whose advantage is to function adequately both in case of phase change isothermal (involving pure materials) and for the case of phase change occurring within a temperature range (involving mixtures or alloys), in which solidified parts coexist along with the liquid phase [5, 19, 10].

According to ODONE [10], the mathematical model, representative of process, by enthalpy-porosity method, examines the mass conservation equations, momentum and energy, shown in Equations (1) to (4).

$$\nabla.\vec{\mathrm{V}} = 0 \tag{1}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{u}) + \nabla.\left(\rho\vec{\mathrm{V}}\mathrm{u}\right) - \nabla.(\mu\nabla \mathrm{u}) = -\frac{\partial \mathrm{P}}{\partial \mathrm{x}} - \mathrm{A_m}\frac{(1-\gamma)^2}{(\gamma^3+\varepsilon)}\mathrm{u} \tag{2}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{v}) + \nabla.\left(\rho\vec{\mathrm{V}}\mathrm{v}\right) - \nabla.(\mu\nabla \mathrm{v}) = -\frac{\partial \mathrm{P}}{\partial \mathrm{y}} - \mathrm{A_m}\frac{(1-\gamma)^2}{(\gamma^3+\varepsilon)}\mathrm{v} + \rho g \beta(\mathrm{h} - \mathrm{h_{ref}})/\mathrm{c} \tag{3}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{h}) + \nabla.\left(\rho\vec{\mathrm{V}}\mathrm{h}\right) - \nabla.(\alpha\nabla \mathrm{h}) = -\frac{\partial}{\partial \mathrm{t}}(\rho\Delta \mathrm{H}) - \nabla.\left(\rho\vec{\mathrm{V}}\Delta \mathrm{H}\right) \tag{4}$$

where u and v are the velocities of flow in the x and y directions, respectively, P is the pressure, $\vec{V}$ is the fluid velocity, A_m is the mushy zone constant, γ is the liquid fraction, μ is the dynamic viscosity of fluid, h is the sensitive enthalpy, $\triangle H$ is the variation of latent heat, α is thermal diffusivity, ρ is density, g is the acceleration of gravity, β is the coefficient of volumetric expansion, h_{ref} is the reference enthalpy, and c is the specific heat at constant pressure.

The mathematical equations used to solve the solidification and fusion models of Fluent software (v. 18.2.0 – ANSYS Academic, Inc. - USA) depend on the enthalpy-porosity and finite-volume method (Equations (5) to (10)).

$$\frac{\partial}{\partial t}(\rho H)+\nabla.\left(\rho\vec{V}H\right) = \nabla.(k\nabla T) + S \tag{5}$$

$$H = h + \Delta H \tag{6}$$

$$\Delta H = \gamma L \tag{7}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} c dt \tag{8}$$

where k is the thermal conductivity, T is the temperature, T_{ref} is the reference temperature and L is the latent heat of solidification.

The liquid fraction (γ) is defined as:

$$\begin{aligned} &\gamma = 0 \ \text{ if } T < T_{sol} \\ &\gamma = 1 \ \text{ if } T > T_{liq} \\ &\gamma = \frac{T - T_s}{T_{liq} - T_{sol}} \ \text{ if } T_{sol} < T < T_{liq} \end{aligned} \tag{9}$$

where T_{sol} and T_{liq} are temperature in the solid phase and liquid, respectively.

In the first, the fusion interface is not explicitly controlled. An amount called the liquid fraction, which indicates the fraction of the volume of the cells in liquid form, is associated with each of the cells in the domain. The net fraction is calculated at each iteration based on the enthalpy balance. The interface zone is a region in which the liquid fraction lies between 0 and 1, being modeled as a pseudo-porous medium, in which the porosity decreases from 1 to 0, when the material solidifies. When the material is completely solid in the cell, the porosity becomes zero, resulting in the velocity drop to zero [1].

The source term (S) is defined in Equation (10).

$$S = \frac{(1-\gamma)^2}{(\gamma^3+\varepsilon)} A_m \vec{V} \tag{10}$$

This term S was included in the momentum because the phase change effect on the convection. The term ε is a small-defined value to prevent the division by zero, which was adopted as 0.001. However, the constant of the zone mushy (A_m), describes the kinetics of the process in the zone of liquid-solid interface normally between 10^4 and 10^7 [1].

According to FLUENT [8], the solution for temperature is essentially an iteration between the energy equation Equation (5) and the net fraction equation Equation (9). The direct use of Equation (9) to update the net fraction usually results in low convergence of the energy equation. The method suggested by VOLLER and SWAMINATHAN [20] is used to update the liquid fraction.

The thermophysical properties used in the numerical simulation were determined using the C programming language (UDFs) to customize the density, thermal conductivity and specific heat through mathematical correlations and equations, relating the properties of its components with the temperature and the respective mass fractions of composition, according to CHOI and OKOS [7] and ASHRAE [4]. The chemical composition of the Brazilian codling muscle: moisture, proteins, lipids and ashes, was determined by the AOAC [3] methods (Table 1).

TABLE 1: Chemical composition of the Brazilian codling muscle

Moisture (g 100 g $^{-1}$)	82.33±0.67
Protein (g 100 g $^{-1}$)	15.42±0.34
Fat (g 100 g $^{-1}$)	1.25±0.07
Ash (g 100 g $^{-1}$)	0.85±0.07

* Average of three replications ± standard deviation

The initial freezing temperature (T_f) was determined by the experimental freezing curve as the point where the slope (dT/dt) of the curve equals zero (Equation (11)), according to RAHMAN et al. [15].

$$\frac{dT}{dt} \cong \frac{T(t+\Delta t)-T(t)}{\Delta t} \tag{11}$$

To determine thermal properties of food below the initial freezing temperature, the mass fraction of ice (X_{ice}) is necessary to be determined, by Equation (12) according to ASHRAE [4].

$$X_{ice} = \frac{1.105 X_{wo}}{1+\frac{0.7138}{Ln(T_f - T + 1)}} \tag{12}$$

where X_{wo} is the mass fraction of water in the unfrozen food and T_f is the initial freezing point of food.

The specific heat due to the discontinuity of the function near the initial freezing temperature, the lever rule for the approximate determination of this property was used.

The thermal conductivity was determined through the mean between models parallel and perpendicular to the fibers of the food, according to ASHRAE [4].

Due to the enthalpy-porosity method, the latent heat is only released in the second part of the freezing curve, instead of considering this energy release in the second and third portions, as in the freezing of food, the latent heat of solidification used in the numerical simulation, was determined through Equation (13), thus, the latent heat ($\Delta\mathrm{H}$) involved in the process was adequate to only the second region of the freezing curve. The mass fraction of ice (X_{ice}) was determined at the temperature of 268.15 K (end of critical zone).

$$\Delta\mathrm{H} = \mathrm{X_{ice}L_a} \tag{13}$$

where L_a is latent heat of water solidification (333600 J/kg)

The average convection heat transfer coefficient (h_c), used in the numerical simulations was estimated through of the energy balance between quantity of heat removed of product (Equations (14) to (17)), according to ASHRAE [4], and Newton's cooling law Equation (18). The mean mass of the Brazilian codling muscle used in the freezing assays was 0.121 kg.

$$\mathrm{Q_1 = mc_1(T_1 - T_f)} \tag{14}$$

$$\mathrm{Q_2 = m\Delta H_f} \tag{15}$$

$$\mathrm{Q_3 = mc_2(T_f - T_2)} \tag{16}$$

$$\mathrm{Q_T = \frac{Q_1+Q_2+Q_3}{3600n}} \tag{17}$$

$$\mathrm{q = h_cA(T_s - T_\alpha)} \tag{18}$$

where Q_1, Q_2, Q_3 are the heat removed of product, m is the mass of product, $\triangle H_{al}$ is the latent heat of solidification of food, c_1 is the specific heat of product above freezing, T_1 is the initial temperature of product above freezing, T_f is the initial freezing temperature of product, c_2 is the specific heat of product below freezing, T_2 is the final temperature of product below freezing, n is the freezing time, q is the heat transfer by convection, Ts is the food's surface temperature, T_α is the surrounding fluid temperature and A is the food's surface area.

On the surface of the fish muscle, we have: $q = Q_T$, therefore:

$$h_c = \frac{Q_T}{A(T_s - T_\alpha)} \tag{19}$$

3. MATERIAL AND METHODS

The materials used in this work were the fresh Brazilian codling muscles from the local fish warehouse, Rio Grande municipality, from the 2016/2017 harvest. The products were transported refrigerated to the laboratories for the accomplishment of the analyzes and experiments.

3.1 Experimental procedure

The samples had their dimensions standardized for the freezing tests, through the use of a 0.07 m x 0.14 m x 0.015 m glass shape. Excess muscle was cut with stainless steel knife. The samples were then packed in polyvinyl chloride (PVC) film in order to avoid dehydration during the freezing process.

Preceding the freezing tests, the samples remained in air blast freezer for 24 h, in order to reach the thermal equilibrium, standardizing the temperature of all samples at 277.15 K. The freezing tests of the Brazilian codling muscles were performed in air blast freezer at 253.15 K. The air temperature was measurement and recording by the electronic controller TC-900 Ri clock and Sitrad software, respectively, both instruments of the Company Full Gauge.

This equipment is formed by expanded polystyrene isopals, having an internal volume of 0.73 m^3. The refrigeration system used is composed of a condensing unit of the Company Elgin, Model TUM - 2053-E, evaporator of the Company Mipal, Model MMI015AHI and thermostatic expansion valve of the Company Danfoss, Model TX2-0.3. The refrigerant used by the refrigeration system was R-22 (chlorodifluoromethane).

The experiment consisted of three freezing tests (temperature x time) for the determination of the temperature profile of the Brazilian codling muscle (one sample at a time, repeated three times with different samples, within the harvest period of the fish). Type K thermocouple sensor (diameter 1.48×10^{-3} m and range 73.15 K to 1533.15 K) provided with data logger (Fieldlogger) of the Company Novus, was used for the measurement and recording of products time temperature evolutions during of process freezing. This instrument was programmed to collect and record temperatures in time intervals of 300 s.

To perform the measurements, sensor was inserted in the geometric center of the sample, on which it was placed on a tray, with the following dimensions: 0.29 m (width), 0.29 m (length) and 0.8 x 10^{-3} m (height), and the registered temperature data were loaded into a computer through a dedicated interface with the data logger software. The experiment was performed in triplicate (one sample at a time, repeated three times with different samples, within the harvest period of the fish) and were stopped when the geometric center of the fish muscle reached a temperature of 253.15 K.

3.2 Numerical resolution method

In order to solve the problem of heat transfer in the fish muscle during freezing in air blast freezer (Figure 1), through the enthalpy-porosity method, some considerations and simplifications were defined for the resolution of the physical-mathematical model:

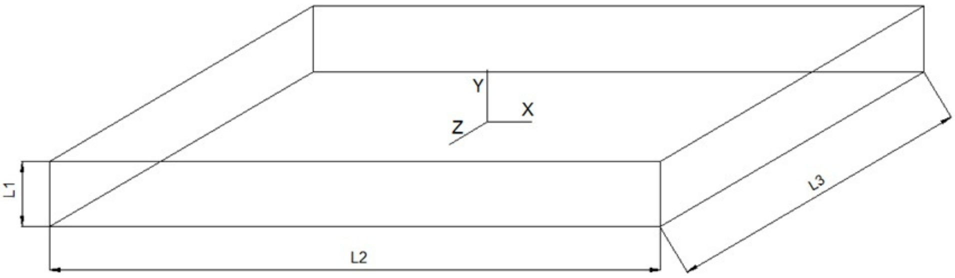


FIGURE 1: Geometry of the Brazilian codling muscle.

- Cartesian geometry;
- Unsteady-state heat transfer;
- Negligible volume variation during freezing;
- Negligible thermal resistance of the tray (8 x 10^{-4} m thickness);
- Convective terms and null source in the computational domain;
- Thermal properties (k, ρ and c) variables defined by the UDFs, being used in the computational domain and in the boundary conditions (walls);
- Methods of numerical solution:
  - Scheme: SIMPLE;

- Spatial discretization (gradient): least squares cell based;
- Spatial discretization (energy equation): upwind second order;
- Transient formulation: implicit second order;
- Convergence criterion adopted: < 10^{-6};

- T_{liq}= 271.65 K e T_{sol}= 268.15 K (critical zone);
- Initial condition: T(t=0) =To(y), 0<y<L1:
  - To(y) = 277.35 K;
- Convective boundary conditions at surfaces zx (t>0):
  - $h_{zx}T_y = k_y \frac{\partial}{\partial y}(T_y)$, y=$L_1$;
- Boundary conditions at surfaces yx e yz (t>0):
  - Walls adiabatic.
- Boundary conditions at the centre (t>0):
  - $k_y \frac{\partial}{\partial y}(T_y) = 0$, y=0.

In this sense, adopting the defined considerations and simplifications, the Equation (5) has become Equation (20).

$$\frac{\partial}{\partial t}(\rho H) = \nabla.(k\nabla T) \tag{20}$$

The domain of Figure 1 was covered by a mesh with hexahedral elements using a mesh generation package (Gambit v. 2.3.16 - ANSYS, Inc. - USA). The mesh was exported to the solver package (Fluent v. 6.3.26 - ANSYS, Inc. - USA), where the mathematical model, described by Equations (5) to (9) was solved numerically.

The appropriate mesh size was determined testing different refinements, with 5832, 6859 and 9261 hexahedral elements. The grid with 6859 presents a good fitting between experimental values and numerical results. Grid independence was achieved using time step of 0.1 s.

3.3 Percent error

The percent error between the numerical and experimental temperature was estimated by Equation (21).

$$\text{Err} = \frac{(\text{T numerical} - \text{Texperimental})}{\text{Texperimental}} \times 100 \tag{21}$$

4. RESULTS AND DISCUSSION

Figure 2 shows the freezing curve of the Brazilian codling muscle, in which it presents the typical general shape of the literature, being composed basically of three regions. (1) cooling, which removes sensible heat, reducing the temperature of the product to the freezing point; (2) removal of the product's latent heat of solidification, changing the water to ice crystals; and (3) continued cooling below the freezing point, which removes more sensible heat, reducing the temperature of the product to the desired or frozen storage optimum temperature. The longest part of the freezing process is removing the latent heat of solidification as water turns to ice. Many food products are sensitive to freezing rate, which affects yield (dehydration), quality, nutritional value, and sensory properties [4].

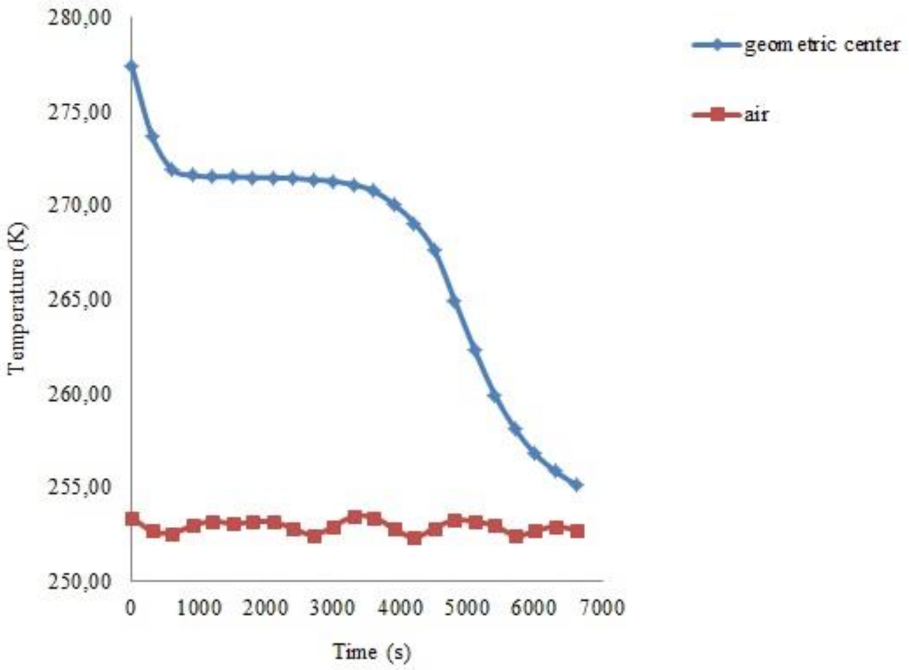


FIGURE 2: Experimental freezing curve of the Brazilian codlin muscle.

Table 2 shows the synthesis of the results obtained during the freezing of the Brazilian codling muscle.

TABLE 2: Experimental results of the freezing process of the Brazilian codling muscle

Freezing time (s)	6618± 249.6
Initial muscle temperature (K)	277.37± 0.27
Final muscle temperature (K)	255.11±0.12
Initial freezing temperature (K)	271.58±0.09
Average air temperature (K)	252.98±0.05

* Average of three replications ± standard deviation

Analyzing the Table 2, it is observed that the experimental freezing time and the initial freezing temperature of the Brazilian codling muscle were 6618 s and 271.58 K, respectively.

According to RAHMAN et al. [15], in fish with moisture content between 50% and 81%, the initial freezing temperature varies between 272.55 K to 269.55 K. In this sense, the author relates the initial freezing point with the mass fraction of water present in the different fish species.

The freezing speed of the Brazilian codling muscle during the process was 0.20 K min^{-1} (0.0033 K s^{-1}). According to the speed, the freezing process can be classified as slow or fast. In slow freezing, the products are frozen at 0.05 K min^{-1} (0.00083 K s^{-1}), while in the fast freezing, the applied rate is 0.5 K min^{-1} (0.0083 K s^{-1}) according to OLIVEIRA et al. [11].

Figure 3 show experimental versus numerical freezing temperature of the Brazilian codling muscle.

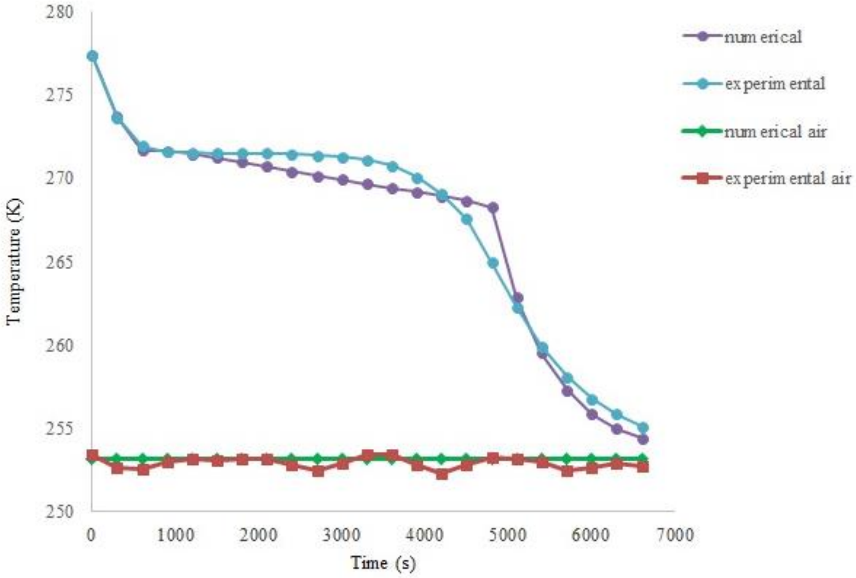


FIGURE 3: Comparison of measured and simulated temperature of the Brazilian codling muscle.

Figure 3 shows a good concordance between the experimental and numerical temperature values, where the numerical curve presented the three characteristics of an experimental freezing curve. However, there is a small difference between the second and third sections of the curves. This is due to the fact that the enthalpy-porosity method considers only sensible heat exchange in the third section, ie, temperatures lower than or equal to the temperature of the solid adopted in the numerical simulations (T_{sol} = 268.15 K) only sensitive.

However, as SINGH and HELDMAN [17] point out, in the final freezing temperature of the food, the frozen food may still have a little water in the liquid state, in fact up to 10% of the water percentage may be in the liquid state for food frozen to 255.18 K, thus, with a small latent heat exchange in the third part of the freezing curve.

In addition, in relation to the second section, the difference is due to the enthalpy-porosity method, consider a linear relationship between the liquid fraction and the temperature (Equation (9)), but in the freezing of foods the reduction of the water fraction is exponential (Equation (12)). Due to this difference, the second stretch of the numerical curve of the Brazilian codling muscle is larger than the second stretch of the experimental curve, despite the reduction of the latent heat adopted for the model's suitability.

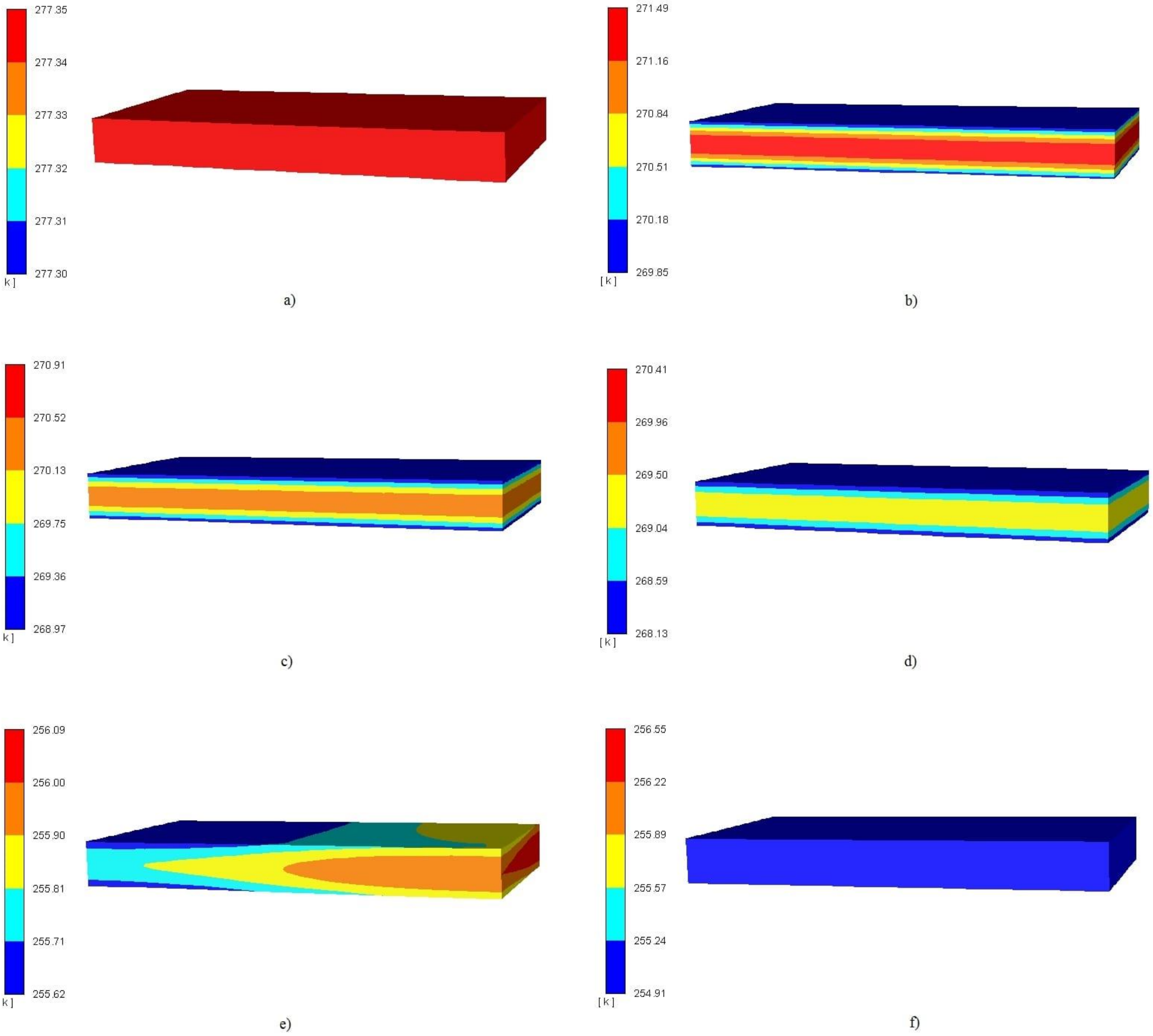
The numerical freezing time found was 6246 s while the experimental freezing time was 6618 s. In this sense, the percentage of error found between the predicted model and the experimental procedure was 5.6%. Therefore, it can be stated that the numerical solution of the enthalpy-porosity method using the UDFs and the suitability of the latent heat of solidification to the model, showed a good agreement with the experimental freezing time of the Brazilian codling muscle.

PHAM [13] determined the following properties for foods from their chemical composition: enthalpy, freezing temperature, specific heat before and after freezing, and the percentage of non-freezing water. The use of these calculated properties generated good results in the prediction of freezing times, with acceptable errors (approximately 10%) for meats, fish, fruits and cheeses. Ice cream and fats have made big mistakes in the times.

TAN and FOK [19] performed the numerical simulation of the freezing of tilapia fillets in different geometries using the enthalpy-porosity method with Fluent 6.2 software, without the use of UDFs and thermophysical properties (density, specific heat and conductivity thermal) constants. Afterwards, they compared the freezing time predicted by the numerical simulation with those obtained by the analytical models of PHAM [12] and CAMPANONE at al [6]. For tilapia fillets with 0.25 m long, 0.140 m wide and 16 x 10^{-3} m high, the authors found a freezing time of 5688 s to reach the temperature of

253.15 K in the thermal center, while PHAM [12] and CAMPANONE et al [6] found 6084 s and 6192 s, respectively. The percentage of error between the times predicted by the simulation and the analytical models were 6.5% and 8.1%, respectively.

Since the proposed model presented a good fit, we can predict, with the Fluent program, the temperature contours along the freezing process of the Brazilian codling muscle, as shown in Figure 4.



a) b) c) d) e) f)

FIGURE 4: Contours of temperatures of the computational domain (Brazilian codling muscle); a) t= 0 s; b) 1200 s; c) 2400 s; d) 3600 s; e) 6000 s; f) 6240 s.

Figure 4 shows the heat flow from the center of the computational domain (thermal center of the Brazilian codling muscle) to the upper and lower extremities, characterizing the transient unidirectional heat flow due to the simplified hypothesis adopted on the front, back, left and right as adiabatic, since they have a reduced thermal exchange area.

5. CONCLUSION

The experimental freezing temperature profile of the Brazilian codling muscle described a typical literature freeze curve, presenting the three characteristic regions. The time and freeze velocity found were 6618 s and 0.20 K min^{-1} (0.0033 K s^{-1}), respectively. The initial freezing temperature found was 271.58 K, being in agreement with the values of literature.

The enthalpy-porosity method proved to be valid to predict the final freezing time, presenting a percentage of error between the experimental test and the numerical simulation of 5.6%. Comparing the experimental and numerical temperature profiles, the enthalpy-porosity method described the freezing kinetics of the product, showing a small distance between the second and third portions of the freezing curve.

It is believed by the numerical simulation results, through the enthalpy-porosity method plus the user-defined functions in C language for the thermal conductivity, density and specific heat, and adjusting the latent heat of solidification of the food to the second region of the curve that the method can contribute to predict the freezing time of foods with high water content with low percentage of error, because, in this way, the method would be closer to its original characteristic, that is, to simulate the freezing of substances pure or a mixture of two liquids.

REFERENCES

[1] AL-ABIDI, A. A.; MAT., S.B.; SOPIAN, K.; SULAIMAN, M. Y.; MOHAMMED, A. TH. CFD applications for latente heat termal energy storage: a review. **Renewable and Sustainable Energy Reviews,** v. 20, p. 353–363, 2013.

[2] ANDRADE, H.A.; DUARTE-PEREIRA, M.; ABREU-SILVA, J. L. Idade e crescimento da abrótea (*Urophycis brasiliensis*) capturada no sul do Brasil. **NOTAS TÉC. FACIMAR**, v. 8, p. 107-117, 2004.

[3] AOAC. **Association of official analytical chemistrys**. Official Methods of Analysis. 20 Ed. AOAC International, Gaithersburgs, 2016.

[4] ASHRAE. **ASHRAE Handbook of Refrigeration.** American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 2014.

[5] BRENT, A. D.; VOLLER, V. R.; REID, K. J. Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of pure metal. **Numerical Heat Transfer**, v.13, p. 297-318, 1988.

[6] CAMPANONE, L. A.; SALVADORI, V.O.; MASCHERONI, R. H. Food freezing with simultaneous surface dehydration: an approximate prediction of freezing time. **International Journal of Heat and Mass Transfer**, v. 48, p. 1205-1213, 2005.

[7] CHOI, Y.; OKOS, M. R. Effects of Temperature and Composition on the Thermal Properties of Foods.**Food Engineering and Process Applications**, v. 1, p. 93-101, 1986.

[8] FLUENT, 2016. Ansys Fluent Tutorial Guide. Ansys Inc. Disponível em: <https://pt.scribd.com/doc/316554319/ANSYS-Fluent-Tutorial-Guide-r170>. Acesso em: 10 mar. 2018.

[9] MORAGA, N. O.; JAURIAT, A.; LEMUS-MONDACA, R.A. Heat and mass transfer in conjugate food freezing/air natural convection. **Int. J. Refrigeration**, v. 35, p. 880-889, 2012.

[10] ODONE, M.W. N. **Estudos numéricos na solução de problemas de mudança de fase**. 132p. Dissertação (Mestrado em modelagem computacional), Universidade Federal de Juiz de Fora, Juiz de Fora, 2014.

[11] OLIVEIRA, M.R.; GUBERT, G.I.; ROMAN, S.S.; KEMPKA, A.P.; PRESTES, R.C. Meat quality of chicken breast subjected to different thawing methods. **Brazilian Journal of Poultry Science**, v.17, p. 165-172, 2015.

[12] PHAM, Q. T. Simplified equation for predicting the freezing time of foodstuffs. **Journal of Food Technology**, v.21, p. 209-219, 1986.

[13] PHAM, Q.T. Prediction of Calorimetric Properties and Freezing Time of Foods from Composition Data. **Journal of Food Engineering**, v. 30, p. 95-107,1996.

[14] PHAM, Q.T. Modeling heat and mass transfer in frozen foods: a review. **Int. J. Refrigeration**, v. 29, p. 876-888, 2006.

[15] RAHMAN, M. S.; GUIZANI, N.; AL-KHASEIBI, M.; AL-HINAI, S.A.; AL-MASKRI, S.S.; AL-HAMHAMI, K. Analysis of cooling curve to determine the end point of freezing. **Food Hydrocolloids**, v.16, p. 653-659, 2002.

[16] RAHMAN, M. S.; MACHADO-VELASCO, K. M.; SOSA-MORALES, M. E.; VELEZ-RUIZ, J.F. Freezing Point: Measurement, Data and Prediction, in: RAHMAN, M. S. Food properties handbook. 2 Ed. Boca Raton: CRC Press, 2009. Chapter 5, p. 54-192.

[17] SINGH, R. P.; HELDMAN, D.R. **Introduction to Food Engineering**, 5. Ed. Amsterdam, Elsevier Inc., 2014.

[18] SCHEERLINCK, N.; VERBOVEN, P.; FIKIIN, K. A.; BAERDEMAEKER, J.; NICOLAI, B.M. Finite element computation of unsteady phase change heat transfer during freezing or thawing of food using a combined enthalpy and Kirchhoff transform method. **American Society of Agricultural Engineers**, v. 44, p. 429-438, 2001.

[19] TAN, F.; FOK, S-CH. Freezing of tilapia fillets in an air blast freezer. **International Journal of Food Science and Technology**, v. 44, p. 1619–1625, 2009.

[20] VOLLER, V. R.; BRENT, A. D.; PRAKASH, C. The modeling of heat, mass and solute transport in solidification systems. **International Journal of Heat and Mass Transfer**, v.32, p.1719-1731, 1989.

[21] VOLLER, V. R.; SWAMINATHAN, C. R. Generalized Source-Based Method for Solidification Phase Change. **Numer. Heat Transfer B** , v. 19, p. 175-189, 1991.

ACKNOWLEDGMENTS

The authors acknowledgment the Full Gauge Company for the donation of the electronic controller TC-900 Ri clock used in the freezing tests. The authors also acknowledgment all the various professionals involved in the development of this research.