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PARAMETRIC ANALYSIS OF THE SOLIDIFICATION PROCESS WITH NANOPARTICLES IN AN ENERGY STORAGE UNIT WITH A PARALLEL PLATE CONFIGURATION

Antonio Bruno de Vasconcelos Leitão, antoniobruno@ufpi.edu.br[1]
James Gomes Pereira, james1397@ufpi.edu.br[1]
Fátima Aparecida de Morais Lino, fatimalino@fem.unicamp.br[2]
Kamal Abdel Radi Ismail, kamal@fem.unicamp.br[2]

[1]Federal University of Piauí, University Campus Ministro Petrônio Portella, Technology Center, Mechanical Engineering Department, Teresina, PI, CEP 64.049-550, Brazil.
[2]Energy Department, Faculty of Mechanical Engineering, State University of Campinas, University City Zeferino Vaz, Mendeleiev street, 200, Barão Geraldo, Campinas, SP, CEP 13.083-860, Brazil.

Abstract: *The energy storage in the phase change material is a well-accepted technology and is expanding in several engineering and building applications. In this study, a thermal model based on pure conduction to describe the solidification process in a parallel plate storage system is developed. For the solution of this model, the governing equations for the solid and liquid phases and the interface moving are discretized using the finite difference approximation and totally implicit approach with variable time step. The computational code representing the thermal model for the phase change process around the parallel plates was tested and validated against available numerical and experimental results, showing good agreement. As the temperature on the surface of the plate decreases, there is a reduction in the time to complete phase change and a higher solidification rate. However, increasing the distance between the plates contributes to a longer time for complete solidification. A promising method for improving these thermal storage units is the addition of nanoparticles in phase change materials. The inclusion of these nanoparticles increased the effective thermal conductivity of the mixture, contributing to the increase in the solidification rate. However, the effect of reducing latent heat due to the increase in mixture concentration values is too little to unbalance the enhanced thermal performance, such as reducing the time for the complete phase. The energy stored, interface position, interface velocity and the time for fully solidification are presented and discussed in terms of the temperature of the cold plate and the volumetric concentration of the nanoparticles in the phase change materials. The contribution of this study through the adopted model and solution method aims at a provisional way of obtaining an evaluation of this type of storage configuration and expanding its use in commercial applications and scientific research, in addition to predicting its thermal performance parameters quickly and accurately.*
Keywords: *solidification, parallel plates, nano phase change material*

1. INTRODUCTION

In recent years, the global electric energy consumption tremendously increased due to the increase of population, rate of industrialization and the increase of living standards in most of the countries. These issues enhanced the production and massive utilization of conventional energy sources, which led to increasing global warming and accelerated depletion of conventional energy sources. This dramatic scenario accelerated the search for renewable energy sources, implementation of policies for energy conservation and efficient use of existing energy systems. Renewable energy sources have the problem of intermittency as in solar and wind energy, which require energy storage to remedy this problem. Recuperation of waste energy and general losses also require storage systems to be able to store and retrieve this energy when needed.

The knowledge of phenomena related to phase change, such as the solidification process, represents a factor for the design and development of various equipment in a wide field of applications, both in the industrial sector and in the academic and scientific sectors. Mathematical modeling and solution techniques for such phenomena have been studied over the years for different geometries and different Phase Change Materials (PCM), resulting in exact solutions for the easier problems, semi-analytical and numerical solutions for the most complex cases. The ice banks are a type of Latent Heat Thermal Energy Storage (LHTES) that uses water as a phase change material, which can operate in charge and discharge cycles. They are one of the promissory cold storage systems because water is an inexpensive PCM with a high

calorific capacity (Asgharian and Baniasadi, 2019). The main objective of the construction of this system is to alleviate the peaks in electricity consumption, that is, periods in which this demand is very high. The LHTES that combine a high energy density, with the advantage of the isothermal nature of the accumulation process, integrate several industrial applications, such as concentrated solar thermal plants and air conditioning units, cold and refrigeration production (Barz *et al.*, 2018). They are too designed to accumulate the lowest temperature compared to the environment temperature because the energy can be charged, stored, and discharged daily, weekly, monthly, or seasonal cycles (Mosaffa *et al.*, 2014).

Phase change materials are widely used in thermal energy storage systems, due to their high capacity for heat accumulation in latent form. The heat involved during the solidification process is high, and its thermal conductivity is low, which leaves charging and discharging times longer (Yilbas *et al.*, 2015). Al-Maghalseh and Mahkamov (2018) presented a comprehensive review of significant studies on thermal energy storage technologies using phase change materials. Many studies have been conducted on phase change materials for thermal storage in the form of cold, focusing mainly on the application in building structures, solar energy systems, air conditioning, refrigeration equipment, and others (Berdja *et al.*, 2019).

Many experimental and numerical studies involving LHTES have been accomplished in recent years.An experimental installation to study PCM with a melting temperature around 20°C to 25°C were designed, built, tested, and performed. This study analyzed the applicability of the free cooling installation to store cold outdoors at night and release it indoors during the day (Zalba *et al.*, 2004). Ismail and Lino (2011) performed an experimental investigation of the effects of radial fins and turbulence promoters in improving heat transfer by phase change external to a horizontal tube submerged in the PCM with a working fluid flowing through it. The experiments were realized on tubes without fins, finned tubes, and finned tubes with the turbulence promoter to obtain the results of interface position, interface velocity, fraction of the solidified mass, and the time for complete solidification as a function of the temperature of the working fluid, fluid mass and tube arrangement.

Finned geometries in the presence of the phase change materials are one of the most efficient methods to improve the energy transfer between the PCM and the heat transfer fluid. Thus, an appropriate arrangement of these extended surfaces performs a significant role in the project of a thermal energy storage unit in the form of latent heat (Deng *et al.*, 2019). A model based on a predictive control algorithm to find an appropriate combination of chillers and ice banks to provide the necessary cooling in a building at minimum cost within an electricity profile has been proposed. The system produced ice during the solidification or charging process when the cost of electricity was lower (Candanedo *et al.*, 2013).

The numerical and analytical analyzes of the processes involving solidification are complex. The analytical solutions are limited due to the high mathematical level observed in the phenomenon, while most numerical solutions require high computational costs. Teggar and Mezaache (2013) presented a conduction model that described the internal solidification of a phase change material, in this case, water, inside a flat plate type cold storage unit. In this study, an enthalpy method with a finite control volume approach was used and validated the model by comparison with experimental results available in the literature. The results of a numerical and experimental study of parallel flat plate ice banks to identify the relative importance of geometric and operational parameters, as well as the thermal performance of the system, have been presented (Ismail *et al.*, 1999). The stored energy, the interface position, and the time for complete solidification were discussed through the independent parameters such as the initial temperature of the PCM, the temperature on the cold plate surface, and the distance between them.The results were satisfactory to the experimental data previously reported.

Bechiri and Mansouri (2015) developed an analytical solution to study the volumetric effects of heat generation during the solidification process of a phase change material encapsulated in a horizontal cylindrical thermal energy storage container. For the solution of the energy equations representing the solid and liquid phases and in the transient regime, the variable separation method and the exponential integral function were used.

Nanofluids are obtained from the suspension of particles in conventional heat transfer fluids, whose sizes are in the nanometric scale (1 to 100 nm). Nanoparticles have characteristics that improve these processes when they are added to them. Due to these nanomaterials having superior thermal conductivity, the increment of small volumetric fractions of these elements to fluids can increase the thermal conductivity in relation to the base fluid (Das *et al.*, 2007). The main mechanisms used to justify the increase in the thermal conductivity of nanofluids are the Brownian motion of the nanoparticles, and the liquid layer of the base fluid that surrounds these same nanomaterials, the nanolayers. However, among all these mechanisms, there is no evidence to say, which is the main responsible for the increase in thermal conductivity attributed to this new class of fluid elements. The Brownian motion comes from the random collisions between the nanoparticles that move in a fluid. Therefore, when two particles collide, the heat transfer mode between them can increase the overall conductivity of the system. The effect of this movement is a diffusive and temperature-dependent process (Chandrasekar and Suresh, 2009).

The present investigation is focused on the development and formulation of a thermal model based on one-dimensional heat conduction for the solidification of nano PCM between two vertical flat parallel plates by obtaining relevant parameters such as the interface position, interface velocity, stored energy, and time for the phase change complete during the phase change. Adequate boundary and initial and final conditions are defined. The equations are discretized using the finite difference method and totally implicit approach with Modified Variable Time Step (MVTS). The computational code was tested, optimized and validated with available results. The nano PCM used is water mixed with Al_2O_3 nanoparticles. The developed model and solution method adopted aims at a provisional way of obtaining an evaluation of this type of storage configuration and expanding its use in commercial applications and scientific research.

2. MODEL DESCRIPTION

2.1 Physical Model

The parallel plate type heat storage unit consists of a set of interconnected cooling plates through which the cold fluid circulates, as shown in the Fig. 1. The storage tank consists of a set of parallel plates through which a heat transfer fluid flows with a temperature below 0°C. These cold plates are heat exchangers made with aluminum or copper material so maintain a constant and uniform temperature on their surface. The liquid PCM starts to solidify, moving in the normal direction of the plate surface to the right and the left, as shown in the dashed lines during the loading process. At the end of the process, the solidification front does not advance and, thus, the storage tank is fully charged. In this situation, the two fronts between two successive plates will meet in the middle of the distance between them, called the symmetry line or adiabatic line, since the temperature gradient in that location is zero. The phase change material used is liquid water mixed with Al_2O_3 nanoparticles.

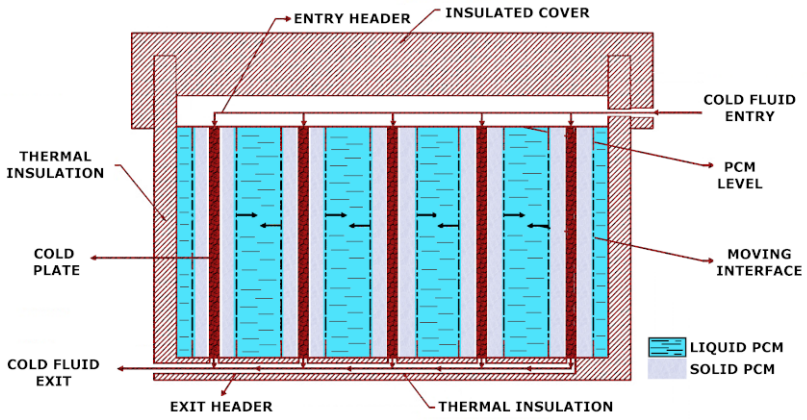


Figure 1: **Representation of the flat plate type latent heat storage unit.**

At the initial time t = 0, the liquid water confined to the space between the plates is at a temperature higher than the phase change temperature, T_m. The charging process begins when the surface of the flat plate is cooled to a constant temperature below 0°C by the cold fluid that circulates through it and, the solid-liquid interface begins to move to the symmetry region. It is assumed that there is no fluid movement and the transfer of heat from the liquid to the solid occurs exclusively by conduction, disregarding the convective effects (Ismail *et al.*, 2021).

2.2 Governing Equations

Before describing the mathematical model through its governing equations, the simplifying hypotheses assumed that were considered relevant for the development of this model are described below. The proposed model is of the one-dimensional transient type in the direction of the interface movement and perpendicular to the plate surface. Halfway through the distance between two successive plates, the phase change process or symmetry condition ends, and the temperature at the surface of the plate is kept constant. The mathematical formulation of the phase change problem, where the temperatures $T_s(x,t)$ and $T_l(x,t)$ for the solid and liquid phases, respectively, is described by Eq. (1) and Eq. (2) as follows:

$$\frac{\partial^2 T_s\left(x,t\right)}{\partial x^2} = \frac{1}{\alpha_s}\frac{\partial T_s\left(x,t\right)}{\partial t};\ 0 < x < s\left(t\right) \quad (\textbf{solid phase}) \tag{1}$$

$$\frac{\partial^2 T_l\left(x,t\right)}{\partial x^2} = \frac{1}{\alpha_l}\frac{\partial T_l\left(x,t\right)}{\partial t};\ s\left(t\right) < x < B \quad (\textbf{liquid phase}) \tag{2}$$

The additional equation, Eq. (3), is determined by considering an energy balance at the interface at $x = s\left(t\right)$, declared as:

$$k_l\frac{\partial T_l}{\partial x} + \rho Q_L\frac{\mathrm{d}s\left(t\right)}{\mathrm{d}x} = k_s\frac{\partial T_s}{\partial x};\ x = s\left(t\right) \qquad (\textbf{interface}) \tag{3}$$

where Q_L, α, ρ, k, B, and $s\left(t\right)$, are the latent heat of solidification per unit mass associated with the phase change, thermal diffusivity, density, thermal conductivity, the half the distance between the plates, and interface position, respectively. Figure 2 shows the coordinates of the one-dimensional solidification process.

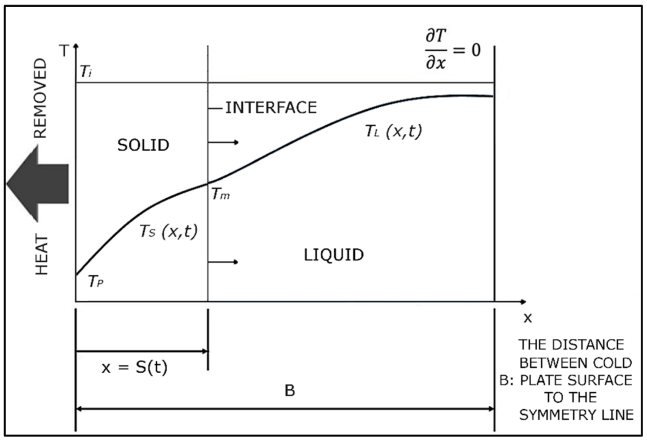


Figure 2: **Representation for one-dimensional solidification process.**

2.3 Determination of the thermal and physical properties

The thermal and physical properties of PCM are obtained from Cho and Sunderland (1974), Fukusako and Yamada (1993) while the properties of the mixtures of PCM and the Al_2O_3 nanoparticles are calculated based on Auriemma and Iazzetta (2016). The density and the latent heat of the nano PCM mixtures are given by Eq. (4) and Eq. (5).

$$\rho_{npcm} = \varphi\rho_{np} + (1-\varphi)\,\rho_{pcm} \tag{4}$$

$$Q_{L,npcm} = \frac{(1-\varphi)\,\rho_{pcm}Q_{L,pcm}}{\rho_{npcm}} \tag{5}$$

where φ is the volumetric fraction of the nanoparticles in the mixture. The specific heat and the thermal conductivity of the nano PCM is obtained using the Eq. (6) and Eq. (7) given by Vajjha *et al.* (2010) in which he assumes thermal equilibrium between the fluid base, PCM and the nanoparticles,

$$c_{p,npcm} = \frac{\varphi\rho_{np}c_{p,np} + (1-\varphi)\,\rho_{pcm}c_{p,pcm}}{\rho_{npcm}} \tag{6}$$

$$k_{npcm} = \frac{k_{np} + 2k_{pcm} - 2\,(k_{pcm} - k_{np})\,\varphi}{k_{np} + 2k_{pcm} + (k_{pcm} - k_{np})\,\varphi}k_{pcm} + 5\times10^4\beta\varphi\rho_{pcm}c_{p,pcm}\sqrt{\frac{B'T}{\rho_{np}d_{np}}}f\,(T,\varphi) \tag{7}$$

where B' is Boltzmann constant, 1.381×10^{-23} J/K, and the equation for β for the nanofluid with Al_2O_3 particles is given by Vajjha and Das (2009) as follow:

$\beta = 8.4407(100\varphi)^{-1.07304}$ valid for volume fraction $0.01 \leq \varphi \leq 0.1$ and the temperature in the range $273\text{K} \leq \varphi \leq 363\text{K}$.

The correlation $f\,(T,\varphi)$ is obtained using the Eq. (8) given by Vajjha *et al.* (2010), where T_{ref} is the reference temperature.

$$f\,(T,\varphi) = \left(2.8217\times10^{-2}\varphi + 3.917\times10^{-3}\right)\frac{T}{T_{ref}} + \left(-3.0669\times10^{-2}\varphi - 3.91123\times10^{-3}\right) \tag{8}$$

The above equations were used to calculate the properties of the nano PCM fluid with the nanoparticles volumetric fractions of Al_2O_3 of 0%, 1% and 3% adopted in the simulations. The thermal and physical properties of PCM and the Al_2O_3 nanoparticles are presented in the Tab. 1. The parameter dnp is the nanoparticle diameter.

3. NUMERICAL TREATMENT

The governing equations were discretized by the finite difference method with variable time interval proposed by Gupta and Kumar (1981) and described by Özişik *et al.* (2017) using the Modified Variable Time Step (MVTS). The numerical code was developed in *GNU OCTAVE software* according to the block diagram shown in Fig. 3.

It is important to note that the discretization method used in time works with properties in a totally implicit way, that is, in the advanced time step. By the numerical approach, MVTS, to solve the problem of solidification process in analysis with finite differences, the "$x-t$" domain is subdivided into small Δx intervals constant in the spatial domain and variable intervals in time Δt. The approach of the variable time step requires that, at each time level t_n, the time step

Table 1: **Thermophysical properties of nano PCM.**

PROPERTIES OF THE PCM AND NANOPARTICLE
Water in liquid phase
$\rho\,(T) = 3.419 \times 10^{-5}\,T^3 - 0.00741\,T^2 + 0.0476\,T + 999.961$ (kg/m^3)
$c_p\,(T) = -4.329 \times 10^{-5}\,T^5 + 0.00189\,T^4 - 0.0505\,T^3 + 0.872\,T^2 - 9.343\,T + 4229.507$ (J/kgºC)
$k\,(T) = 9.09091 \times 10^{-10}\,T^4 - 1.39068 \times 10^{-7}\,T^3 - 2.68907 \times 10^{-6}\,T^2 + 0.00203\,T + 0.54757$ (W/mºC)
$Q_L = 334.920$ (kJ/kg)
Water in solid phase
$\rho\,(T) = 917\left(1 - 1.17 \times 10^{-4}\,T\right)$ (kg/m^3)
$c_p\,(T) = \left(0.19 + \left(0.69 \times 10^{-2}\,T\right) \times 1000\right)$ (J/kgºC)
$k\,(T) = 1.16\left(1.91 - \left(8.66 \times 10^{-3}\,T\right) + \left(2.97 \times 10^{-5}\,T^2\right)\right)$ (W/mºC)
Aluminum Oxide (Al_2O_3)
$\rho = 3600$ (kg/m^3) $\quad c_p = 765$ (J/kgºC) $\quad k = 36$ (W/mºC) $\quad dnp = 59 \times 10^{-9}$ (m)

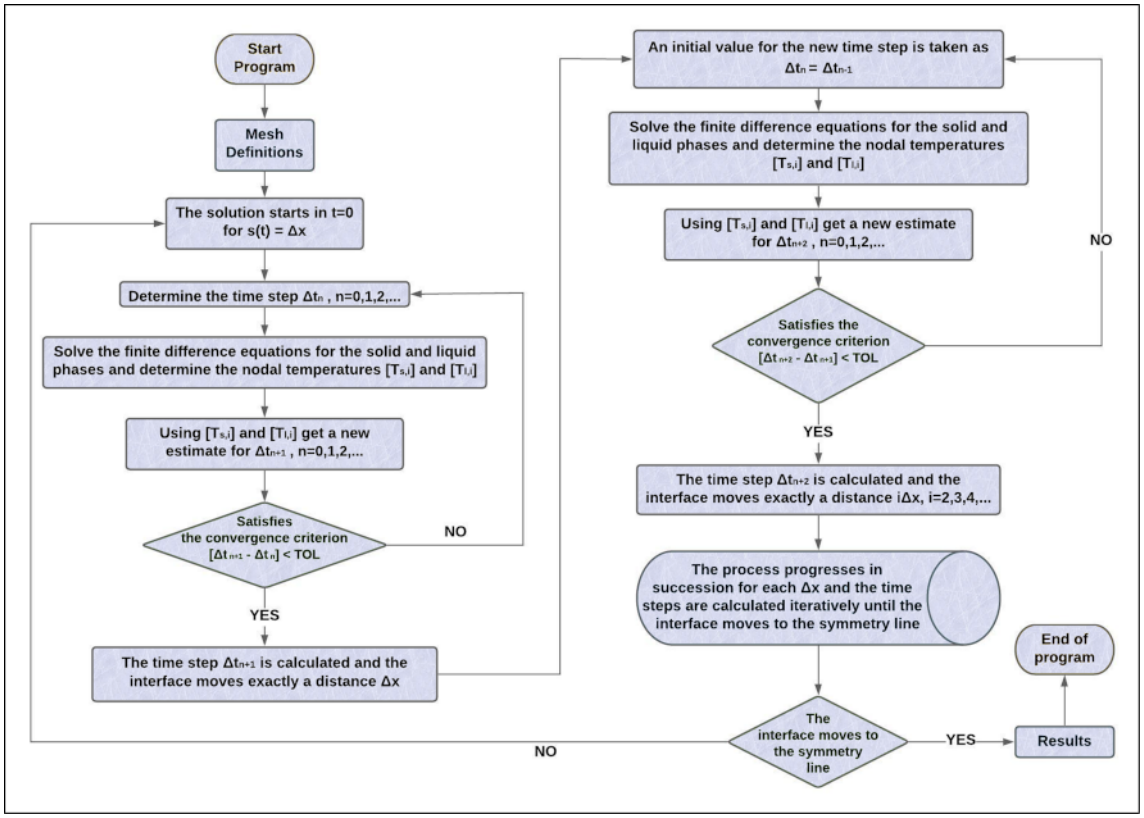


Figure 3: **Block diagram of the computational algorithm.**

Δt_n is chosen so that the interface moves just at a distance Δx in the same interval. Thus, the concern is to determine this time step. The energy balance at the interface represented by Eq. (3), when being discretized through the finite difference method, results in the Eq. (9) that describes the time step with the spatial domain as follows:

$$[\Delta t_n]^{(p+1)} = \frac{\rho_s L}{k_s}\left[\frac{(\Delta x)^2}{\left(T_m - T_{s,n}^{n+1}\right) - \frac{k_l}{k_s}\left(T_{l,n+2}^{n+1} - T_m\right)}\right]^{(p)} \tag{9}$$

An important numerical parameter defined for the computational cost is the convergence criterion specified as the difference between two consecutive time steps, in successive iterations, presented in the numerical method of the modified

variable time step (MVTS). In the simulation, the specified convergence criterion is 10^{-5}. The choice of this convergence criterion was determined by the error value between two successive iterations in each time step, despite the totally implicit approach of the method of finite differences in temporal properties being unconditionally stable. Once the convergence criterion is defined, it determines the best computational mesh to be adopted in the problem. To choose the most appropriate mesh, some simulations were performed, using different combinations of Δx, represented by the step in the space domain along the positive direction of x. The purpose of the tests is to evaluate the refinements of the meshes to reach a condition in which the quality of the results is not compromised and represents a shorter simulation time, and consequently, a lower computational cost. The computational mesh with 100 points along the spatial domain showed better results, whereas changing parameters such as T_P and B did not result in additional computational costs.

4. MODEL VALIDATION

Figure 4 shows the variation of the interface position with time predicted by the present method, by the heat balance integral method according to Cho and Sunderland (1969), and the experimental and numerical results from Ismail *et al.* (1999). It is instructive to divide the time scale into two intervals: one up to 250 min and the other more than 250 min. In the first time interval, one can observe the good agreement between the predictions of the present model and the heat balance integral solution, both are different numerical methods and both are distant from the experimental results. The experimental results are in good agreement with the numerical predictions for the case of variable plate surface temperature. The maximum difference between the present predictions and the experimental results is about 18.7%. Within the second time interval, the predictions from the numerical solution with variable plate surface temperature are in good agreement with the experimental results, while the present predictions seem to underestimate the interface position with a maximum difference with reference to experimental results of about 9.1%.

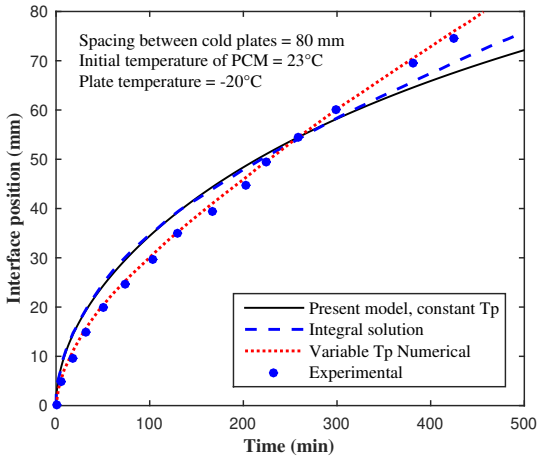


Figure 4: **Comparison of the present predictions with the experimental results from Ismail *et al.* (1999).**

5. RESULTS AND DISCUSSION

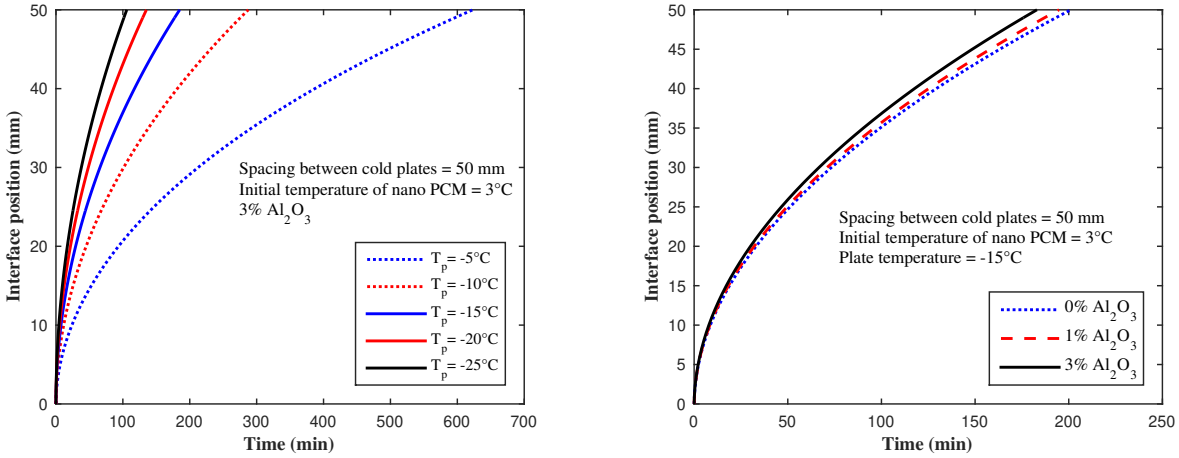
In the solidification process in a storage unit with parallel plate configuration, it was considered that the phase change material, liquid water with nanoparticles Al_2O_3, has its initial temperature above the solidification temperature. The interface position, interface velocity, stored energy, and the time for complete solidification were simulated for the conditions described in Table 2.

Table 2: **Parameters used in the simulations of nano PCM in the LHTES.**

Parameters	Cold Plate Temperature: -5°C, -10°C, -15°C, -20°C, -25°C and -30°C
Distance between cold plates (2B): 5 mm to 50 mm	Initial Temperature of the nano PCM: 2°C, 3°C or 4°C
	Nano Fraction Al_2O_3 in water: 1% to 7%
	Interface Position (mm)
	Interface Velocity (mm/min)
	Full Solidification Time (min)
	Stored Energy (kJ)

Figure 5 shows the variation of the interface position with the time for the distance between cold plates of the 50 mm. As can be seen in the Fig. 5(a), the decrease in plate temperature increases the temperature gradient between the temperature of its surface and the temperature of nano PCM. With the value of higher temperature gradient, the rate of heat

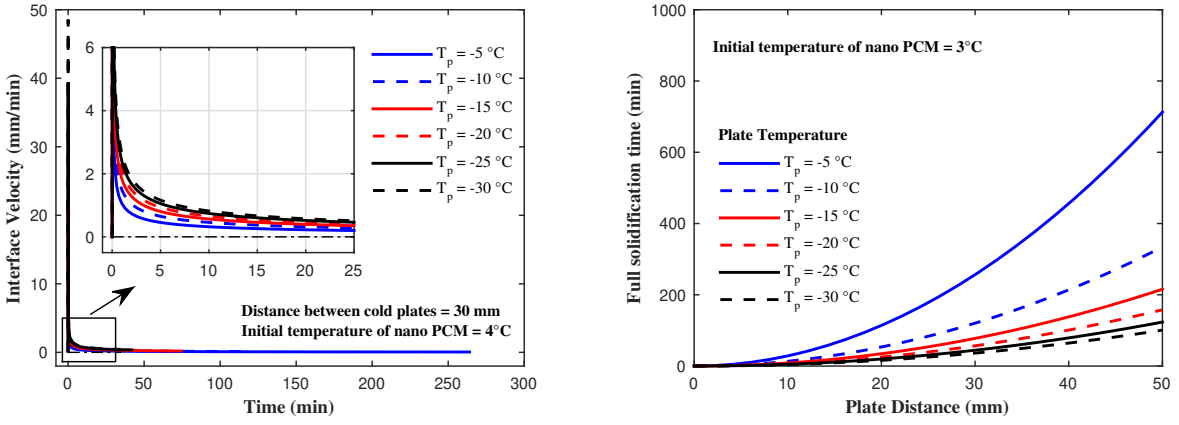
transfer increases. This increase leads to a decrease in the total solidification time from 610 min at the plate temperature of -5°C to 100 min for the case of the surface temperature of -25°C or a reduction of about 83%, which shows the influence of the temperature on the cold surface of the flat plate in the phase change process. In the Fig. 5(b), increasing the volumetric concentration of the nanoparticles in the mixture increases the effective thermal conductivity. This enhances the heat transfer between the plate surface and nano PCM increasing the solidification rate.



(a) Effect of plate surface temperature. (b) Effect of Al_2O_3 nanoparticles.

Figure 5: **Variation of the interface position with time.**

Figure 6(a) shows the variation of the interface velocity with the time for distance between cold plates of the 30 mm and six temperature values on its surface. As can be seen, initially, the interface velocity is high due to the small thermal resistance between the nano PCM and the plate surface. As the process progresses, the solidified mass layer increases and this resistance increases, causing the interface velocity to decrease. As the thickness of this layer increases, the resistance increases so much that the velocity becomes extremely small with practically no advance of the interface position. In the Fig. 6(b), the greater distance between plates increases the thermal resistance between its cold surface and the moving interface, which also reduces the heat transfer rate, resulting in a long time for the complete phase change.

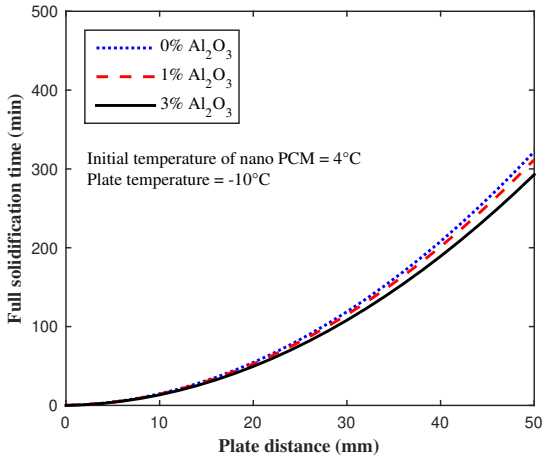


(a) Effect of plate surface temperature on the interface velocity. (b) Variation of the full solidification time with the plate distance.

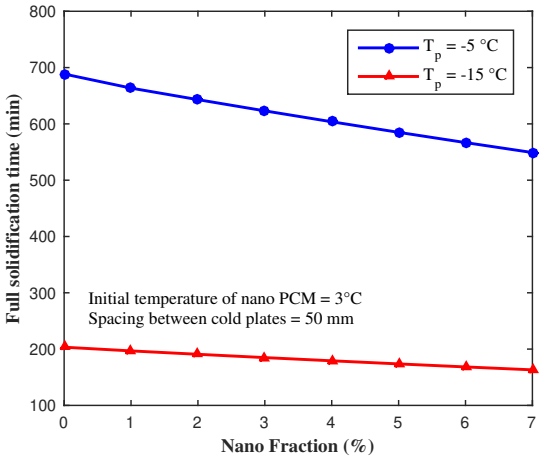
Figure 6: **Variation of the interface velocity and the full solidification time in process.**

In the Figure 7, increasing the nano fraction in PCM increases the effective thermal conductivity. Therefore, there is an increase in the solidification rate, in the interface velocity and reduces the complete phase change time. The Fig. 7(a) shows the effect of plate spacing on the solidification time and the Fig. 7(b) shows the influence of Al_2O_3 nanoparticles on the full solidification time.

Figure 8(a) shows the variation of stored energy with time for plate surface temperature of -15°C and plate spacing of 50 mm. As can be seen, the sensible heat stored is extremely low and the major part is latent heat. Fig. 8(b) shows the sensible and latent heat contributions to the total heat stored. As one can observe the contribution of the nanoparticles to the increase of sensible heat is relatively small for the fractions considered here. In addition, its reducing effect of the latent heat is also too small to unbalance the enhancing effect due the increased thermal conductivity of the nano PCM.

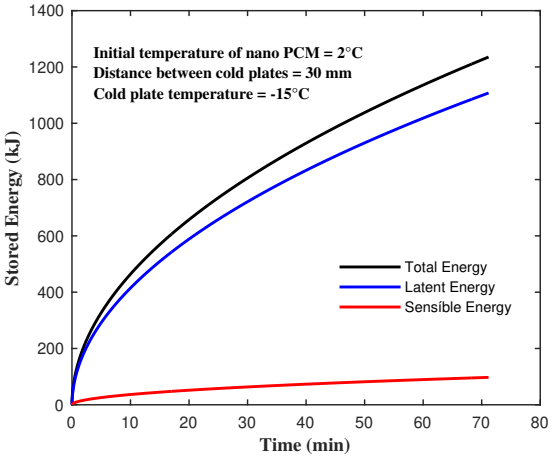


(a) Effect of plate spacing on the solidification time.

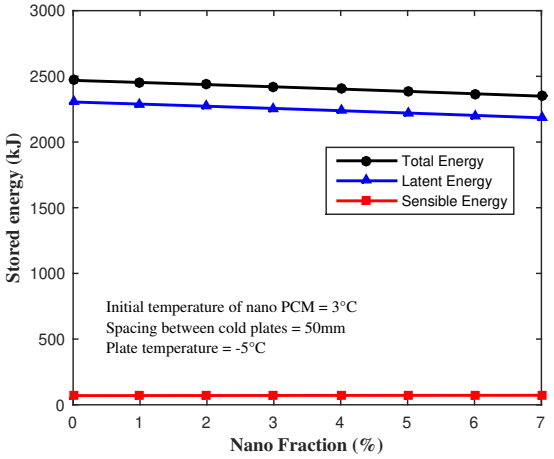


(b) Influence of Al_2O_3 nanoparticles on the full solidification time.

Figure 7: **Variation of the full solidification time in solidification.**



(a) Variation of the thermal energy during solidification of nano PCM.



(b) Variation of total, sensible and latent stored energy with Al_2O_3 nanoparticles fraction.

Figure 8: **Variation of the stored energy with time.**

6. CONCLUSION

In this work, a thermal model based on pure conduction was analyzed for the phase change process of nano PCM in a latent energy storage system with a parallel flat plates configuration. From the numerical results, it was possible to evaluate the solidification process through its thermal parameters such as interface position, interface velocity, stored energy, and complete solidification time. As the temperature on the surface of the plate decreases, there is an increase in the heat transfer rate. There is too a decrease in the full solidification time due to the growth in the gradient between the temperatures. The predictions from the home built numerical code written in *GNU OCTAVE* is compared with available experimental and numerical results to establish the validity of the model and method of calculation. When compared to the work of Ismail *et al.* (1999), this study presented a different solution method through the finite difference approach in the solution of the governing equations that describe the solidification process. Also, the present manuscript includes nanomaterials as PCM. To attenuate the effects of large spacing between the flat plates and facilitate the use of moderate cold temperature nanoparticles of Al_2O_3 were added to PCM as base fluid. Thus, the analyzed model contributes some data that can be considered relevant in these types of flat plate latent heat storage configurations and be useful for designers in the area. As suggestions for future work, it would be appropriate to develop a new thermal model and implement a computational code evaluating the case of flat finned plates in the study of storage units from the two-dimensional heat conduction formulation involving enthalpy methods. One of the advantages of including fins in a rectangular cavity is the improvement in heat transfer, which results in shorter times for the solidification process of the nano PCM. This improvement is due to the possibility of using materials with high thermal conductivity in these geometries. The major disadvantage of extending this study to two-dimensional configurations is the infeasibility of the MVTS method in calculating the exact location of the interface position in the 2D domain of the rectangular geometry. Some geometric parameters of the rectangular cavity, such as width, fin length, fin thickness and thickness of the top and bottom, are used in the phase change processes in two-dimensional configuration.

7. REFERENCES

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8. AUTHORSHIP RESPONSIBILITY

The authors are solely responsible for the content of this work.