EFFECT OF FINS ON ENHANCING ICE FORMATION IN COLD STORAGE APPLICATIONS

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***Abstract*:**Phase change materials (PCMs) are attractive options as thermal energy storage media due to their reduced storage volume and isothermal behavior during charging and discharging processes. Their main drawback is the slow thermal response due to the low thermal conductivity. Various methods for PCM thermal conductivity enhancement have been investigated by many researchers. The present study has the objective of investigating fins to meliorate the thermal performance of PCM storage systems. The formulated model for the horizontal radial finned tube is based on pure conduction in the PCM, the enthalpy approach was used and the resulting equations were treated by the finite difference technique. The numerical code is optimized and the numerical predictions were validated against experimental results. Comparisons with the results of a bare tube show the beneficial effect of fins on enhancing the thermal behavior during phase change process by increasing the position and velocity of the interface and consequently the solidified mass fraction and stored energy.

Keywords: Finned tube, Latent heat storage system, PCM, Phase change, Solidification, Thermal conductivity enhancement.

1. INTRODUCTION

Phase change materials (PCMs) are attractive as thermal energy storage media due to their high thermal capacity and their isothermal behavior during the phase change processes compared with sensible heat storage systems. However, latent heat storage technology is still not widely implemented in practical applications because of the difficulty to find PCM that possesses high thermal conductivity, large latent heat, low supercooling and good stability among other characteristics. Organic PCMs are good candidates but have slow thermal response due to their low thermal conductivity. Therefore, effective enhancement methods for the liquid–solid phase change are the key issue that limits their practical application in latent heat energy storage technology. Some works are worth mentioning because they treated certain aspects of the phase change process in the early developments stages as (Henze and Humphrey, 1981, Padmanabhan and Murthy, 1986, Ismail *et al*., 2001). Padmanabhan and Murthy (1986) presented a numerical study for the phase change process occurring in a cylindrical annulus in which rectangular, uniformly spaced axial fins, spanning the annulus are attached to the inner isothermal tube. The time-wise evolution of the interface profile, phase-change fraction and energy stored/discharged were presented. Later,Ismail *et al.*(2001) presented the results of a numerical and experimental investigation on finned tubes. The number of fins, fin length, fin thickness, the degree of super heat and the aspect ratio of the annular spacing were found to influence the time for complete solidification, solidified mass fraction and the total stored energy.

Ismail and Silva (2003) presented the results of a numerical study on melting of PCM around a horizontal circular cylinder in the presence of the natural convection in the melt phase. A two dimensional unsteady model was formulated in terms of primitive variables and a coordinate transformation technique has been used to fix the moving front. The finite volume approach was used to discretize the system of governing equations, boundary and initial conditions. The numerical predictions were compared with available results to establish the validity of the model and the numerical approach.

Liu *et al.* (2005) studied experimentally the performance of a thermal storage unit using stearic acid as the heat storage medium. The thermal performance of the unit was measured, and the heat transfer characteristics of the melting process were studied under different heat flux conditions to determine the influence of heat flux on the melting processes. It was shown that the fin effectively improved both heat conduction and natural convection.

A numerical and experimental investigation was realized by Kayansayan and Acar (2006)on a cold thermal energy storage system involving phase-change process dominated by heat conduction. The problem involved a fluid flowing inside a horizontal finned tube surrounded by PCM. Comparison between the numerical predictions and the experimental data showed good agreement.

Yuksel *et al.* (2006) proposed a theoretical approach for the prediction of time and temperature during phase change in the latent heat storage. By the use of the average values of the mean specific heat capacities for the phase-changed materials, analytical solutions are obtained and compared with the available experimental data in the literature. The agreement between the theoretical model results and the experimental data was good.

A different approach to enhance thermal conductivity of the PCM was investigated by Jegadheeswaran and Pohekar (2010). They presented the results of a numerical study to investigate the performance enhancement of a latent heat storage unit of shell and tube configuration due to the dispersion of high conductivity particles in the PCM during charging process. Later, Chintakrinda *et al*. (2011) analyzed the thermal performance and energy storage capabilities of a 54 ^{o}C organic paraffin wax and directly compared using three common different thermal conductivity enhancement methods including the use of graphite foam with infiltrated PCM, aluminum foam with infiltrated PCM, and PCM with 10 wt% graphite nano-fibers.

The concept of storage of any type of energy can have a positive impact on greenhouse–gas emissions. The urgent need to control greenhouse–gas emissions and better use of energy and other resources can boost up and extends the applicability of PCM to other areas. Anisur *et al.*(2013) emphasized the opportunities for energy savings and greenhouse-gas emissions reduction with the implementation of PCM in TES systems. About 3.43% of CO2 emission by 2020 could be reduced through the application of PCM in building and solar thermal power systems. Similarly, energy conservation and GHGs emission reduction by other PCM applications for thermal comfort of vehicles, transport refrigeration, greenhouse and waste heat management are also presented.

Ismail *et al*. (2015) presented the results of a numerical study on internally and externally finned annulus in which the internal tube has external fins while the external tube has internal fins. This arrangement was investigated with the objective of increasing the heat transfer rate, reducing the time for complete phase change and allowing for simultaneous charging and discharging processes. The proposed model was based upon pure conduction and its validity was established by comparison with available data. In another work Ismail *et al*. (2016) presented the results of an investigation on axially finned tubes to enhance the processes of charging and discharging thermal storage units. The proposed model was based upon pure conduction in the solid and liquid phases. The enthalpy approach and the finite volume method were used in the numerical treatment. The numerical predictions were compared with experimental results and relatively good agreement was observed.

The objective of the present paper is to investigate the effect of fins on the enhancement of solidification, the interface velocity and stored energy during the phase change process. A pure conduction model was formulated and solved by finite difference. The numerical predictions and method of solution were validated against experimental results showing reasonably good agreement.

2. FORMULATION OF THE MODEL

The present problem treats the solidification of PCM inside a storage tank of the latent heat type composed of a bundle of horizontal tubes fitted with radial fins and extending along along the length of the storage tank. Since the objective of the investigation is to study the process of phase change around tubes with radial fins, a representative section of this configuration which is composed of the finned tube surrounded by a symmetry circle and extending from entry to exit along the storage tank is shown in Fig. 1. The symmetry circle is defined as the limiting boundary beyond which there is no heat transfer or phase change. The PCM is placed in the space between the finned tube and the boundary of the symmetry circle while the cold cooling fluid flows inside the finned tubes solidifying the PCM externally around them. Fig. 1 shows a general layout of the problem and the instantaneous interface between the solidified and the liquid PCM.

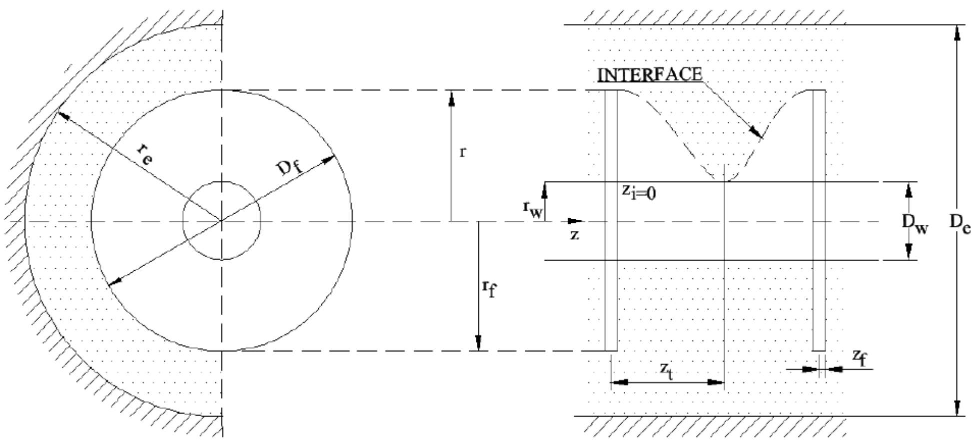

Figure 1. Sketch of the problem of phase change around a finned tube

In order to formulate the model a two dimensional coordinate system is used, where the z direction is along the finned tube axis and the radial coordinate is along the radial direction. Some assumptions are admitted to be able to formulate the model. For example, the PCM is considered as a pure substance, incompressible, has constant phase change temperature, and initially in the liquid fase. The physical properties such as density, specific heat and thermal conductivity of the solid and liquid phases are known. The mechanism of heat exchange during the phase change process is controlled by pure conduction and convection in the PCM liquid phase is neglected.

At any instant, one can write the governing equations and the associated boundary conditions in cylindrical coordinates as the energy equation of the solid PCM is:

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_s \frac{\partial T_s}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_s \frac{\partial T_s}{\partial r}\right) \quad (1)$$

the energy equation of the liquid PCM:

$$\rho_l c_l \frac{\partial T_l}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_l \frac{\partial T_l}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_l \frac{\partial T_l}{\partial r}\right) \quad (2)$$

the boundary conditions at the solid / liquid interface:

$$\left(k_s \frac{\partial T_s}{\partial r} - k_l \frac{\partial T_l}{\partial r}\right)\left(1 + \left(\frac{\partial s}{\partial z}\right)^2 \right) = \rho_s L \frac{\partial s}{\partial t} \quad (3)$$

$$T_s = T_l = T_m \;\; r = s(t) \quad (4)$$

boundary condition at the wall of the tube:

$$r = r_w \;\; T = T_w \quad (5)$$

boundary condition at the symmetry circle:

$$r = r_e \;\; \frac{\partial T}{\partial r} = 0 \quad (6)$$

boundary condition at the tube entrance section:

$$z = z_i \;\; \frac{\partial T}{\partial z} = 0 \quad (7)$$

boundary condition at the tube exit section:

$$z = z_t \;\; \frac{\partial T}{\partial z} = 0$$

the initial and final conditions can be written as:

$$T(r, z, t_{=0}) = T_m + \Delta T$$
$$T(r, z, t_f) = T_m - \Delta T \quad (8)$$

where ΔT is half of the phase change temperature range.

Following Bonacina *et al*. (1973) introducing new variables and using the same numerical treatment as in Ismail *et al* (2016) one can write

Eq. 3 in terms of the new variables becomes:

$$\overline{C}(\phi)\frac{\partial \phi}{\partial \tau} = \frac{1}{R}\frac{\partial}{\partial R}\left(R\overline{k}(\phi)\frac{\partial \phi}{\partial R}\right) + \frac{\partial}{\partial Z}\left(\overline{k}(\phi)\frac{\partial \phi}{\partial Z}\right) \quad (9)$$

while the boundary conditions for tube wall:

$$\phi_w = 0 \;\; R = 1$$

symmetry circle:

$$\frac{\partial \phi}{\partial R} = 0 \;\; R = R_e \tag{10}$$

initial interface position:

$$\frac{\partial \phi}{\partial Z} = 0 \;\; Z = Z_i = 0$$

final interface position:

$$\frac{\partial \phi}{\partial Z} = 0 \;\; Z = Z_t$$

Initial and final conditions are respectively:

$$\phi = 1$$
$$\phi = 1 - 2\xi \tag{11}$$

The set of equations of the model and the boundary and initial conditions were implemented in a computational code. Numerical tests were realized to ensure that the results are independent of the choice of the number of grid points. The grid points which make the results independent according to the numerical tests is found to be 45 along the tube while the number of grid points along the radial fin is taken as 33 points. The time step is taken as 10^{-3} s. These values are used in all the numerical simulations.

3. EXPERIMENTAL ANALYSES

In order to validate the model and the numerical predictions an experimental set up is constructed and instrumented as shown in Fig. 2. The test set up is composed of a compression refrigerant circuit, secondary fluid circuit, coiled tube heat exchanger submersed in the secondary fluid tank, the test section of the finned tube which is connected to the secondary fluid circuit. The secondary fluid is Ethanol cooled by the refrigerant flowing through the coiled tube heat exchanger and its temperature and mass flow rate are controlled as required. The test section is of rectangular shape built from 15 mm thick acrylic sheet with the test tube extended across the test section filled with PCM (water) whose initial temperature can be varied as desired. High resolution digital camera is used to photograph the finned tube and the reference scale to be used to convert the image dimensions to real values as will be explained later. Calibrated thermocouples type K, are fixed at entry and exit of the finned tube, in the PCM test tank, along the finned tube and in the secondary fluid tank. The thermocouples were calibrated to within ±0.5 ^{o}C, image conversion precision to within ±0.1mm while the mass flow rate (measured by a calibrated orifice plate) to within $\pm 10^{-4}$ kg/s.

Measurements were usually taken when the desired testing conditions were achieved, that is the temperature of the working fluid in the finned tube, temperature of the Ethanol tank, temperature of the PCM, and the mass flow rate of the secondary fluid. Under these initial conditions the chronometer is started after all initial conditions are registered. During the first two hours each 5 minutes period all measurement points are registered and a photograph of the finned tube is taken. During the third hour measurements are registered each 15 minutes interval. After that the time interval is increased to 30 minutes until the end of the test. The test is considered terminated when no change in temperature or interface position is registered during three successive time intervals.

A typical photograph of the finned tube is shown in Fig. 3 where the interface position is tracked and converted to real dimension by using the program Tracker as shown in Fig. 4.

Figure 2. Photograph of the experimental installation

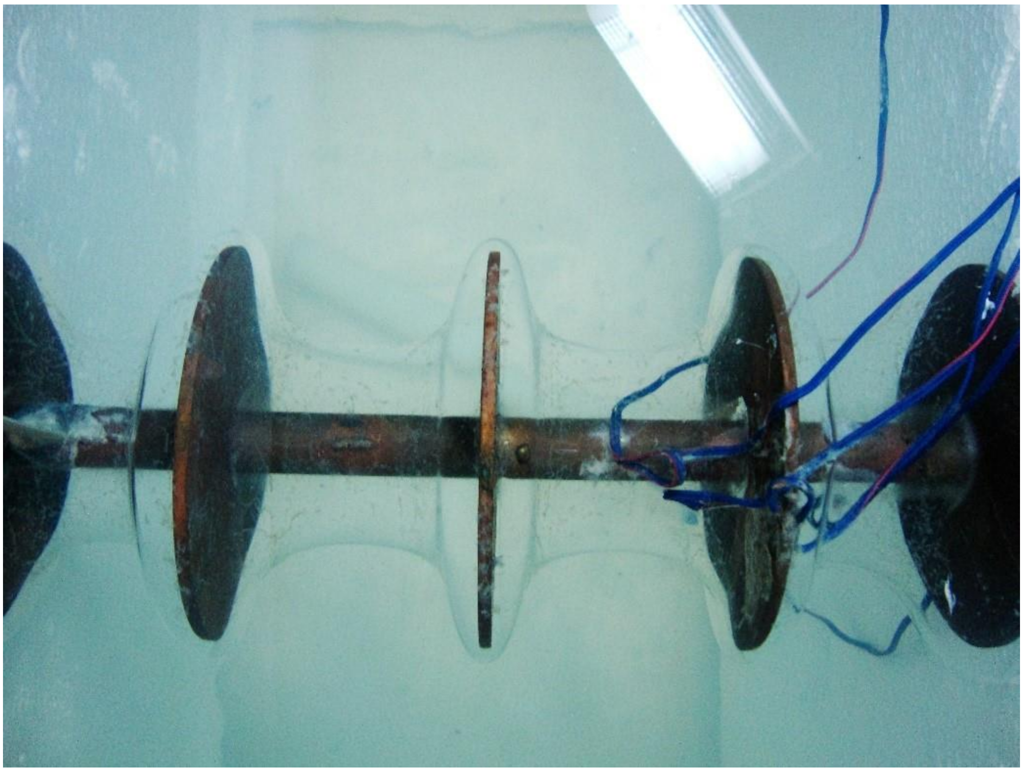

Figure 3. Photograph of the finned tube showing the solidified PCM and thermocouples for temperature measurements

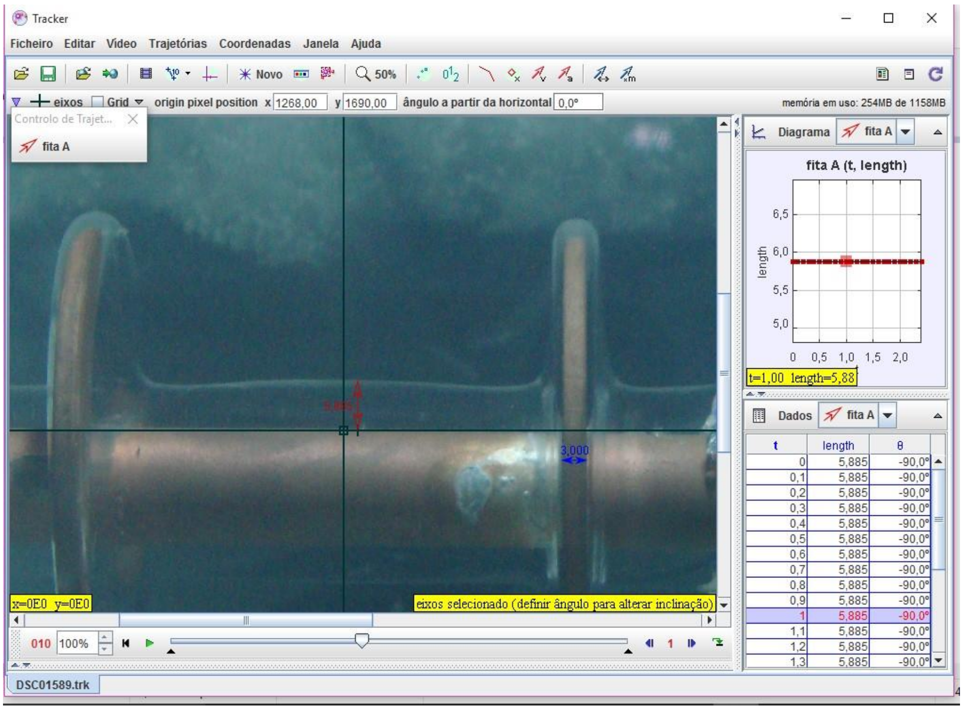

Figure 4. Tracker soft ware with the finned tube photograph positioned for digitalization of the interface position

4 RESULTS AND DISCUSSION

4.1 Validation of the results

The model and the numerical predictions were validated against experiments conducted by the authors. Fig. 5 shows a comparison between the numerical predictions of the interface velocity and the experimental measurements for the case of tube with 95 mm fin diameter. As can be seen the agreement is good. Fig. 6 shows a similar comparison for the case of fin with 75 mm diameter indicating a relatively good agreement.

Comparative results for the solidified mass fraction are shown in Figs. 7-8. Fig. 7 shows a comparison of the predicted solidified mass fraction and the experimentally determined mass fraction. As can be seen the agreement is good confirming the suitability of the model and the method of solution to handle the problem of solidification around finned tubes.

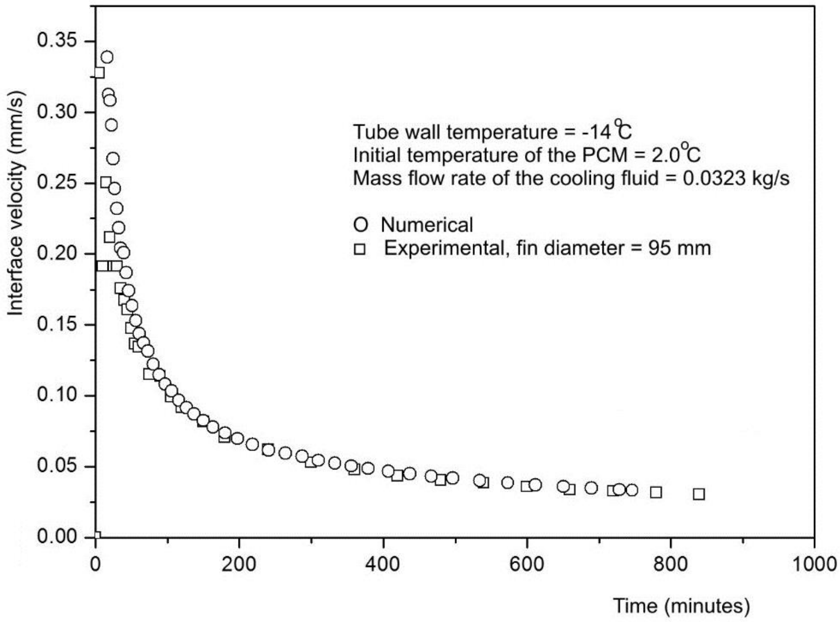

Figure 5. Numerical and experimental comparison of the instantaneous interface velocity for a finned tube of 95 mm diameter

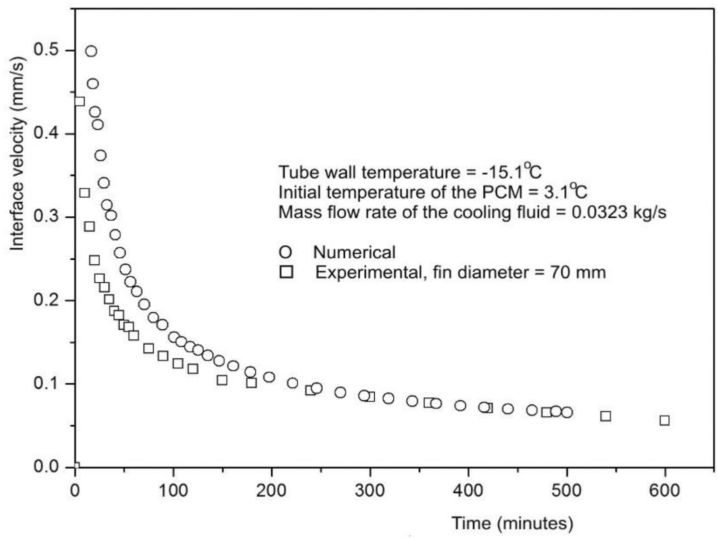

Figure 6. Numerical and experimental comparison of the instantaneous interface velocity for a finned tube of 70 mm diameter

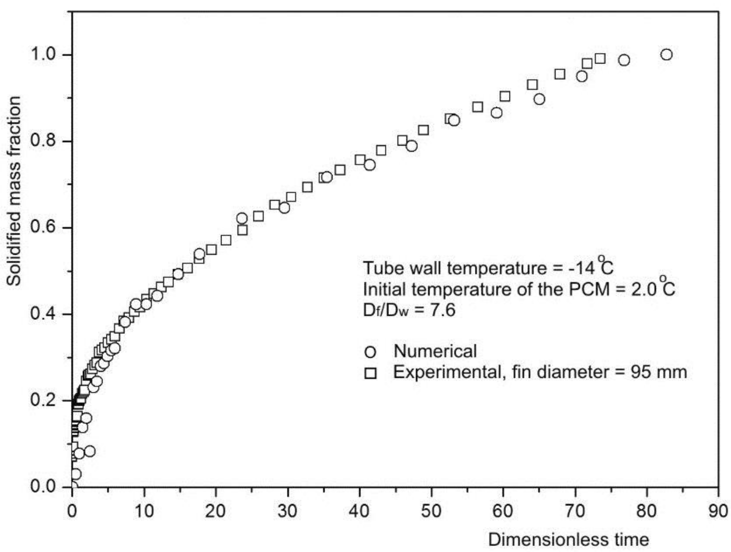

Figure 7. Numerical and experimental comparison of the solidified mass fraction against dimensionless time for a finned tube of 95 mm diameter

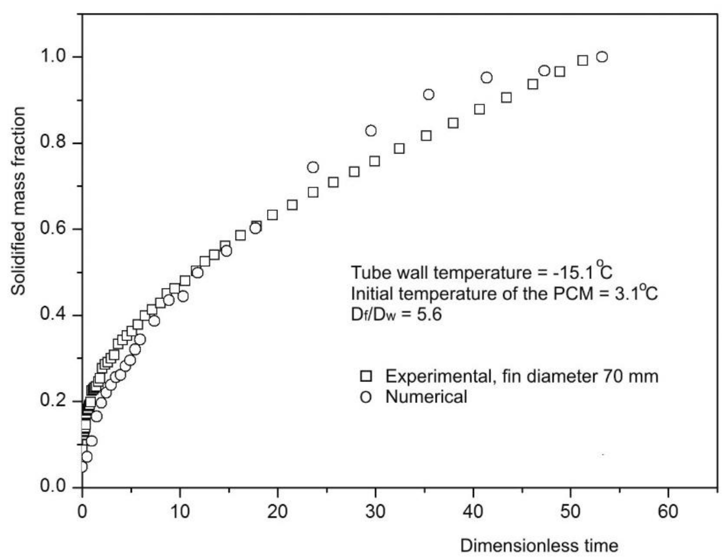

Figure 8. Numerical and experimental comparison of the solidified mass fractionagainst dimensionless time for a finned tube of 70 mm diameter

Fig. 8 shows a similar comparative result for the case of tube with 70 mm fin diameter. As can be seen the agreement is relatively good except in the final part of the process where the experimental results are lower values due to possible losses from the tank insulated top.

4.2 Comparison with bare tube

In order to show explicitly the effect of incorporating fins on the tube submersed in PCM, experiments were realized with finless tube and the results were compared with the results of finned tube as in Fig. 9 which shows the variation of the interface velocity with time. One can observe the beneficial effect of the fins on enhancing the interface velocity and hence reducing the time for complete solidification.

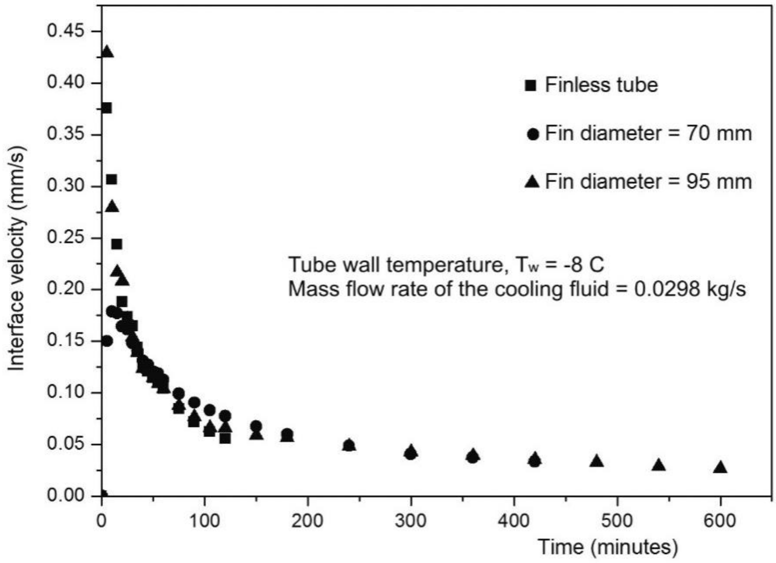

Figure 9. Experimental interface velocity for finned and finless tubes

Fig. 10 shows a comparison of the measured instantaneous interface position of the finned tubes with the results of the bare tube. As can be seen finned tubes show greater interface positions, more solidified mass fraction than the bare tube and higher interface velocity and shorter time for complete solidification. Also from Fig. 11 one can observe that the increase of the fin diameter increases the solidified mass as explained before.

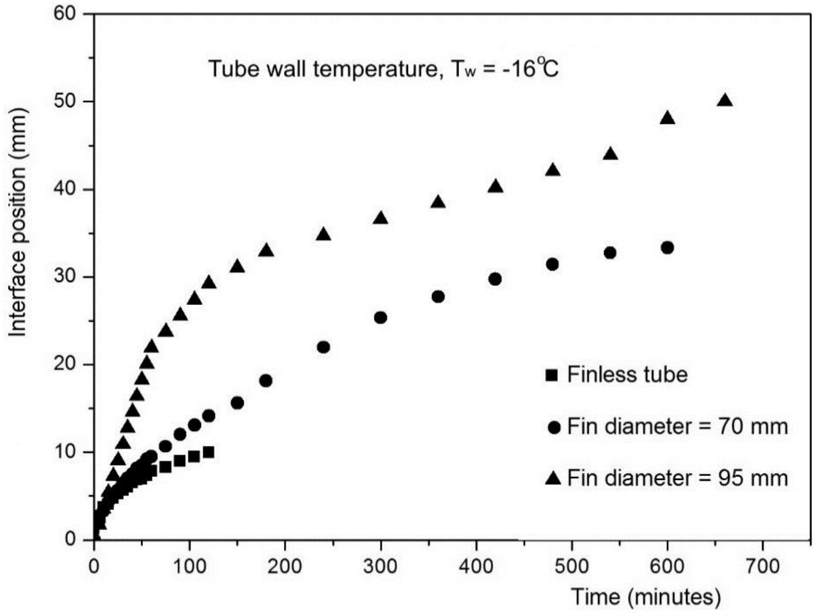

Figure 10. Experimental interface position for finned and finless tubes

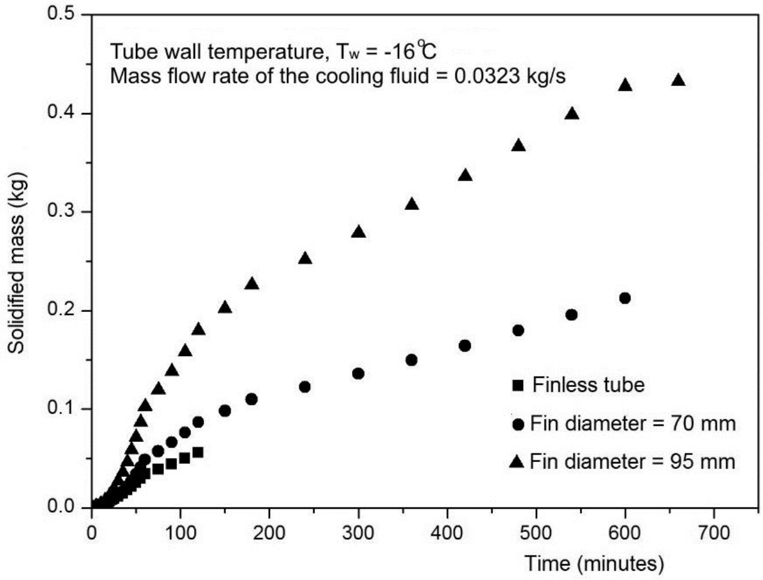

Figure 11. Experimental solidified mass for finned and finless tubes

Fig. 12 shows the energy stored in the cases of bare and finned tubes. As can be seen the fins strongly increase the stored energy and make the tube elements highly efficient.

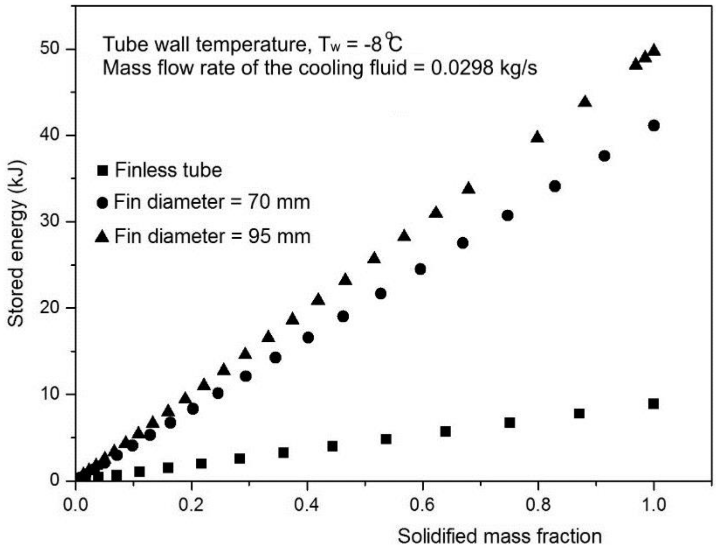

Figure 12.Experimental stored energy for finned and finless tubes

5. CONCLUSION

A model is developed for the solidification of PCM around a tube with radial fins and is validated against experimental measurements. The numerical predictions and the experimental measurements revealed that incorporating fins enhances the process of solidification. Comparisons with the results of a bare tube show the beneficial effect of fins on enhancing the thermal behavior during phase change process by increasing the position and velocity of the interface and consequently the solidified mass fraction and stored energy.

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EFEITO DAS ALETAS NA APLICAÇÃO DE MELHORIAS NO ARMAZENAMENTO DE GELO

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***Resumo*:**Materiais de mudança de fases (MMFs) são opções atraentes como meios de armazenamento de energia térmica devido ao seu volume de armazenamento reduzido e comportamento isotérmico durante a carga e descarga do processo. A sua principal desvantagem é a resposta térmica lenta devido à baixa condutividade. Vários métodos para a melhoria da condutividade térmica do MMF foram investigados por muitos pesquisadores. O presente estudo tem o objetivo de investigar as aletas para aperfeiçoar o desempenho térmico de sistemas de armazenamento por MMF. O modelo formulado para o tubo horizontal com aletas radiais é baseado em condução pura do MMF, a abordagem da entalpia foi usada e as equações resultantes foram tratadas pela técnica de diferenças finitas. O código numérico foi otimizado e as previsões numéricas foram validados a partir dos resultados experimentais. As comparações com os resultados de um tubo liso, mostram o efeito benéfico das aletas na melhoria do comportamento térmico durante o processo de mudança de fase, aumentando a posição e a velocidade da interface e, consequentemente, a fração de massa solidificada e energia armazenada.

Palavras-chaves: Tubo aletado, Sistema de armazeamento por calor latente, MMF, Mudança de fase, Solidificação, Aumento da condutividade térmica.