XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Numerical and Experimental Study of Phase Change Around Cold Flat Plate Submersed in PCM

Michel P. Machado[1], Kamal A. R. Ismail[1]

[1]*Department of Thermal and Fluids, State University of Campinas*
Mendeleyev Street, 200, Cidade Universitária "Zeferino Vaz", 13083-860, Barão Geraldo, Campinas - SP, Brazil
michel.p.machado@hotmail.com, kamal@fem.unicamp.br.com

Abstract. The global demand of energy is ever increasing due to the continuous increase of the world population, industrial growth, transport, cooling and heating and similar activities which are strongly energy or electricity dependents. During the last decades electricity was mainly generated by combustion of fossil fuels such as coal, petroleum products and similar energy sources. On a global scale this resulted in huge amounts of greenhouse gases which led to global warming of the planet with the disastrous consequences that humanity is facing in recent years including melting of snow in the Poles, increasing water level in oceans, uncontrollable heating and cooling seasons occurrence and duration and many other uncommon changes. In addition to this, fossil fuels fields are deemed to be exhausted in the near future which leaves mankind without adequate alternatives for survival. This possible scenario urged the nations to look for other energy alternatives resources to substitute fossil fuels and at the same time do not degrade the environment. Solar and wind energy appear at the top of the list of possible alternatives that are well developed and reasonably easy to implement but suffers from intermittency. To solve this problem, many energy storage systems and technologies are investigated and developed to improve the efficiency and widen the acceptability of these systems. One of these energy storage systems is energy storage in latent heat. In the present study it is proposed to investigate latent heat storage with flat plate geometries using water as a Phase Change Material (PCM). A model based on pure conduction is developed for the solidification of PCM between flat cold plates. Experiments were done to validate the model. The wall temperature, spacing between plates and the material of the plate are found to strongly affect the solidified mass, the interface velocity and the time for complete phase change.

Keywords: Energy storage, PCM, Modeling of solidification, Time for complete phase change, Interface velocity;

1 Introduction

Energy is vital element for the survival, development and comfort of humans. As a result of long periods of extensive use of fossil based fuels, intensive industrialization activities, serious overlooking of the noxious impacts on the environment, deforesting native forests to explore natural resources and degrading water bodies and rivers scenarios of eminent exhaust and collapse of our eco system became very clear. In front of this threat, worldwide unified efforts were directed to reduce pressures on the eco system and look for alternatives sources of energy that offend and impact less the environment, use better and efficiently available sources and revitalize natural systems where it is fragile because of past human activities.

To alleviate the energy problem and its ambient impacts many worldwide research and development activities were devoted to use better available energy via conservation and integration schemes, search for new and renewable energy sources beside rigorous vigilant and surveying the environment. Two aspects are related to the present investigation: energy conservation and integrated use and renewable energy sources. To integrate the thermal systems energy storage is usually a key element for the optimized use of energy and its conservation. Most of the viable energy sources are intermittent especially solar. Hence for good management and better and efficient use energy storage is a key element.

For most of the thermal energy applications thermal storage is the most adequate to integrate different systems and solve the problem of intermittence of generation and use of energy. Thermal energy storage is normally classified into two wide categories, namely sensible and latent heat storage. Sensible heat storage is widely used in thermal application on short time base as in solar water heating, or on medium and long terms as in seasonal storage for district heating and cooling. Materials for latent heat storage applications usually have high thermal capacity and nearly isothermal charging and discharging characteristics but have subcooling and low thermal conductivity which makes them less favorable for some important applications.

Because of the importance of the theme in the current scenario, there is a growing interest from researchers on the subject. In current publications, it is possible to find works on different types of PCM, such as Hosseini [1], for example, made a numerical and experimental investigation on the influence of the internal temperature of the tube during the processes of solidification and melting in a shell and tube heat exchanger using Paraffin RT50 as PCM. This work showed is a 37% reduction in the total melting time when the heat fluid transfer (HFT) temperature is raised from 70 to 80°C.

Xie [2] uses water as a PCM and made a numerical investigation on the influence of the material, thickness and disposition of the thin layer ring on the formation of ice and found that the thickness of the ring is the element that has an insignificant influence on the formation of the ice.

Another point of interest is the storage of different geometries, Seddegh [3], for example, studies the thermal behavior during the solidification and melting process in shell and tube heat exchangers in two configurations, vertical and horizontal. The results indicate that the horizontal orientation presents greater thermal performance during loading. In addition to this type of latent heat storage, there are studies on other geometries, such as cylindrical geometry, studied by Ismail [4] and Cherfi [5], flat geometries, studied by Ismail [6], spherical geometry, studied by Kenisarin [7] and Pop [8], among others.

Finally, there are several types of mathematical methods, from analytical to numerical methods. Caldwell [9], for example, made a study using two methods: Heat Balance Integral Method and Enthalpy Method. In this work, he studies the position of the solidification front by the two methods and compares the results, showing that the results are close to a wide range of Stefan's numbers, except when it is low.

In this work, a numerical investigation was made, based on two methods, the Enthalpy Method and the Heat Balance Integral Method, developed by Goodman [10]. In this investigation, the influence of the temperature of the flat plate on the position of the solid liquid interface, the solidified mass of PCM, the stored energy and on the advance velocity of the interface was evaluated. The validation of the mathematical models developed is done by comparing the results obtained with the results of an experimental investigation.

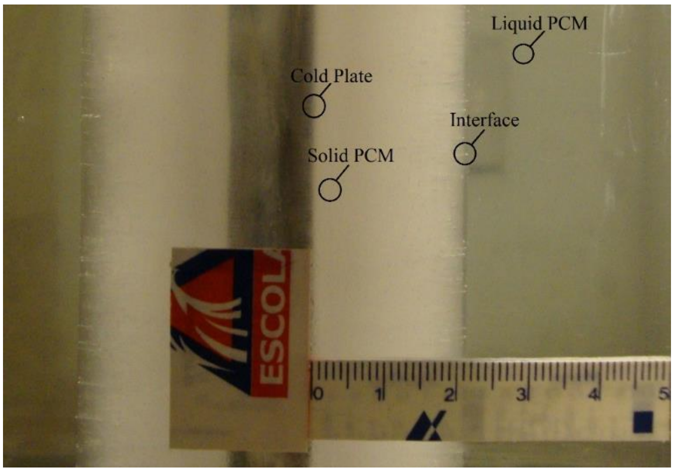

Figure 1. Experimental workbench layout

2 Formulation of the Problem

To produce a mathematical model that represents the phenomenon of solidification, the following considerations are made: PCM is at the temperature of solidification at the initial moment of the process; one-dimensional heat transfer; the heat transfer is perpendicular to the cooling wall; heat transfer by conduction only; the effects of convection are disregarded; the temperature of the cooling wall is constant throughout the process.

2.1 Enthalpy Method

The numerical method adopted is the Enthalpy Method, which is based on the Law of conservation of energy, being expressed in terms of enthalpy and temperature. Considering that the water density is the same for the solid and liquid phases, the following governing equation is:

$$\rho \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) \tag{1}$$

The variables are: ρ refers to density (kg/m³), h refers to enthalpy (kJ/kg), t refers to time (s), T refers to temperature (°C), x refers to space (m) and k refers to thermal conductivity (kW/m. °C). Water is a pure substance, the phase change happens at a constant temperature. If enthalpy is a function of temperature, we have:

$$h(T) = \begin{cases} c_{ps}\left(T - T_m\right) & T < T_m \\ c_{pl}\left(T - T_m\right) + L & T > T_m \end{cases} \tag{2}$$

The variables are: C refers to specific heat (kJ/kg. °C), L refers to latent heat (kJ/kg).The subscripts are: pl refers to constant pressure for liquid phase, ps refers to constant pressure for solid phase and m refers to phase change, in this case, solidification. The numerical method applied in the governing equation is the method of finite differences by the implicit formulation. The space-time domain will be divided into discrete points, with the space mesh is fixe and the time mesh is changeable. If conductivity is constant in the solid and liquid phases, we have:

$$\rho \frac{h_j^{n+1} - h_j^n}{\Delta t} = \frac{k\left(T_{j+1}^{n+1} - 2T_j^{n+1} + T_{j-1}^{n+1}\right)}{\Delta x^2} \tag{3}$$

Boundary conditions

To solve the above equation, three boundary conditions are required: Temperature of the liquid PCM before the start of the freezing process is constant and equal to the phase change temperature.

$$T_x^{t=0} = T_m \qquad x \ge 0 \tag{4}$$

The cold plate is kept at a temperature below the phase change temperature throughout the experiment. The subscript “p” refers to the cold plate position.

$$T_{x=0}^t = T_{x=p}^t < 0 \tag{5}$$

The external walls of the tank are insulated, so there is no exchange of heat with the environment.

$$\frac{\partial T(x,t)}{\partial x} = 0 \qquad x = l \tag{6}$$

Determining the time step

To calculate dt_0 we start from equation 3. Making the substitutions and reorganizing the equation, we have:

$$\mathrm{d}t_0 = \rho \frac{L}{k_s} \cdot \frac{\mathrm{d}x^2}{T_m - T_P} \tag{7}$$

To calculate the subsequent time slots, the following equation is used:

$$\mathrm{d}t_n = \rho \frac{L}{k_s} \cdot \frac{\mathrm{d}x^2}{T_m - T_j^{n+1}} \tag{8}$$

The time interval above is calculated iteratively, the process is repeated until the following convergence criterion is reached:

$$abs\left(dt_{n-1}-dt_n\right)<10^{-5} \tag{9}$$

2.2 Heat Balance Integral Method

The analytical method adopted is the Heat Balance Integral Method, developed by Goodman [10]. For the application of this method, a governing equation for solidification problems is written below:

$$\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right)=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{10}$$

Integrating the previous equation and applying Leibniz's theorem we will obtain the following equation, which is the heat balance integral equation for solidification problem. The term S refers to the position of the interface, t refers to time, T refers to temperature and x refers to position.

$$\alpha\left[\left(\frac{\partial T}{\partial x}\right)_{x=S(t)}-\left(\frac{\partial T}{\partial x}\right)_{x=0}\right]=\frac{d}{dt}\left[\theta-T_m.S\left(t\right)\right] \tag{11}$$

Where:

$$\theta=\int_0^{S(t)}T.dx \tag{12}$$

To determine the position of the interface, it is necessary to choose a temperature profile to be applied to equation 11. Therefore, a quadratic profile was chosen:

$$T_{(x,t)}=a+b\left[x-S\left(t\right)\right]+c\left[x-S\left(t\right)\right]^2 \tag{13}$$

For the determination of the coefficients and, subsequently, the equation that describes the position of the interface, three boundary conditions are necessary, presented below. The subscript only refers to the solid and p refers to the cold plate.

$$T_{(s,t)}=T_m \tag{14}$$

$$T_{(0,t)}=T_p=T_0 \tag{15}$$

$$\left(\frac{\partial T}{\partial x}\right)^2=-\alpha.A.\frac{\partial^2 T}{\partial x^2} \tag{16}$$

Where:

$$A=\frac{\rho.L}{K_s} \tag{17}$$

Applying the previous boundary conditions, the following coefficients are obtained:

$$a=T_m \tag{18}$$

$$b=\frac{\alpha.A}{S}.\left(\sqrt{1-\mu}-1\right) \tag{19}$$

$$c=\frac{\left(T_0-T_m\right)+b.S}{S^2} \tag{20}$$

$$\mu=\frac{2.\left(T_0-T_m\right)}{\alpha.A} \tag{21}$$

To determine the position of the interface, the temperature profile is replaced in the heat balance integral equation. The result obtained is an equation that depends only on the time variable:

$$S(t)=\sqrt{12.\alpha.\frac{\left(\mu+\sqrt{1-\mu}-1\right)}{\left(\mu-\sqrt{1-\mu}-5\right)}.t} \tag{22}$$

3 Results and discussion

3.1 Interface position

The home built numerical codes based on the two numerical methods developed here are used to predict the interface position for different working conditions as used in the experimental measurements and indicated in the respective figures. The predicted results are compared with the experimental results as shown in Figure 2. One can observe that the interface position varies with time. During the first instants of solidification the thickness of the solidified mass of PCM is small and hence the thermal resistance between the cold plate and the bulk PCM is also relatively small. As a result the heat transfer rate is high which results in a big interface position. Also one can observe a high gradient of interface with time. For longer solidification times the thickness of the solidified mass is bigger and hence higher thermal resistance and slower rate of heat transfer and hence slower rate of increase of the interface position. This process continues but with a continuously decreasing rate of increase of interface position with respect to time as can be confirmed from Figure 2. When the rate of increase of the interface position reaches zero the solidification process stops and the time is called the time for complete solidification and the interface position is the maximum that can be achieved, usually referred to as symmetry line.

The results indicate that the heat balance integral method over predicts the interface position due to the approximate temperature distribution assumed in the solution. The enthalpy method agrees closely with the experimental results. The differences can be attributed to experimental measurements and also that the numerical method considers zero heat losses while the experiments have some losses from the top part of the test section.

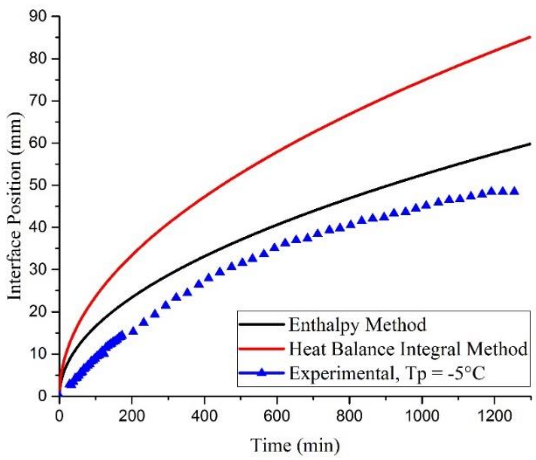

Figure 2. Interface position over time for Tp = -5°C, flow rate of 0.04832 kg/s

3.2 Solidified mass of PCM

Figure 3 shows the variation of the solidified mass with time. As expected the solidified mass variation with time has the same trend as the instantaneous interface position with time multiplied by the surface area of the cold plate (0.3x0.505 m²). As can be seen, the solidified mass predicted by the enthalpy method agrees better with the experimental results having a maximum difference of about 1.43 kg. The simple heat balance method with assumed quadratic temperature profile overestimates the interface position and consequently the solidified mass of PCM.

These differences are due to the thermal losses at the top of the test tank which are not included in the numerical model.

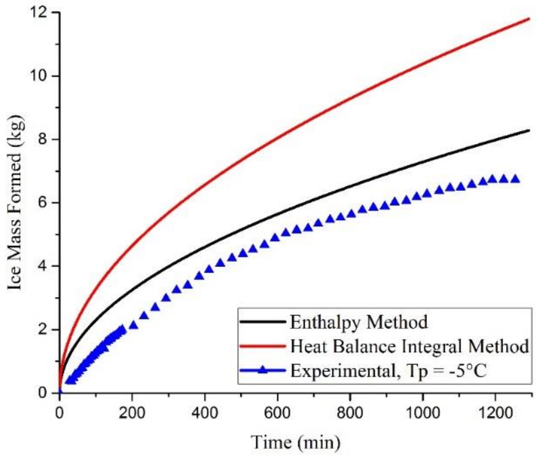

Figure 3. Ice mass formed over time for Tp = -5°C, flow rate of 0.04832 kg/s

3.3 Interface velocity

Figure 4 shows the predicted interface velocity determined by the enthalpy method and the heat balance integral method and the experimental interface velocity. As can be seen, the heat balance integral method overestimates the interface velocity in comparison with the enthalpy method and that the enthalpy method seems to agree better with the experimental results. The scatter in the experimental results is due to possible errors in measuring the interface position and image processing.

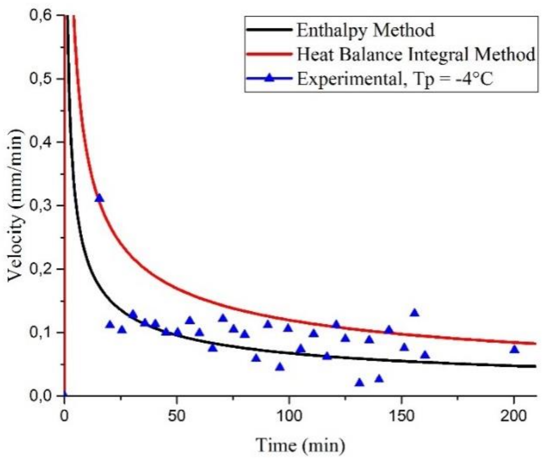

Figure 4. Initial 200 minutes advance velocity of interface for Tp = -4°C, flow rate of 0.04832 kg/s

3.4 Stored energy

Figure 5 shows the variation of the predicted stored energy with time compared with the experimental results. As can be seen, the agreement is good with maximum difference of about 520.36 kJ. The differences at the initial part of the solidification process are attributed to the thermal losses from the top of the cold tank to the ambient which are not included in the numerical model.

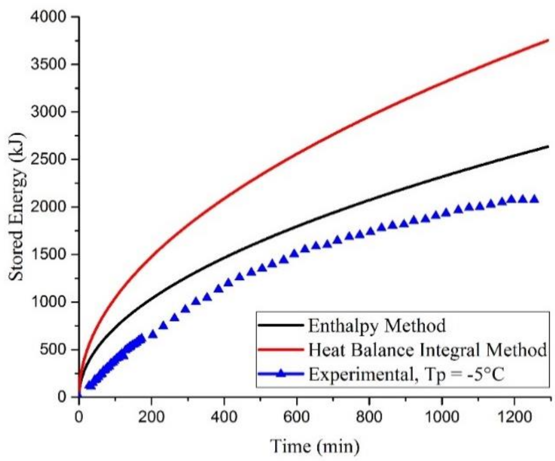

Figure 5: Stored Energy over time for Tp = -5°C, flow rate of 0.04832 kg/s

4 Conclusions

This article reports the results of numerical and experimental study on the effects of the temperature of the cold plate on the interface position, the solidified mass of PCM, the energy stored and the interface velocity. The numerical code was developed based on pure conduction and formulated using the enthalpy method and discretized using finite difference approximation. Another simple numerical solution based on the Heat Balance Integral Method was also solved numerically. The numerical predictions from the two methods were compared and it was found that the numerical predictions from the Enthalpy Method agree more closely than the predictions from the Heat Balance Integral Method.

The simulation results confirmed the trend of the behavior of the interface position. During the initial instants, the ice layer formed is small. Consequently the thermal resistance between the cold plate and the liquid PCM is also small. Because of this, the heat transfer is bigger in the initial moments and hence a bigger interface position. This tendency is also observed in the PCM solidified mass and the stored energy.

Although the Enthalpy Method shows better agreement with the results of the interface position, solidified mass of PCM, stored energy and the interface velocity. The differences between experimental and numerical results are due to thermal losses from the top of the cold tank to the ambient which are not included in the numerical model.

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