CONEM 2010 VI Congresso Nacional de Engenharia Mecânica

ABCM COMPROMETIDA COM A PROMOÇÃO DO DESENVOLVIMENTO DA ENGENHARIA E DAS CIÊNCIAS MECÂNICAS
ASSOCIAÇÃO BRASILEIRA DE ENGENHARIA E CIÊNCIAS MECÂNICAS

VI CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
VI NATIONAL CONGRESS OF MECHANICAL ENGINEERING
18 a 21 de agosto de 2010 – Campina Grande – Paraíba - Brasil
August 18 – 21, 2010 – Campina Grande – Paraíba – Brazil

A MODEL FOR PREDICTING THE PERFORMANCE OF PARALLEL PLATE LATENT HEAT STORAGE

Kamal Abdel Radi Ismail[1], kamal@fem.unicamp.br
Fátima A. M. Lino[1], fatimalino@fem.unicamp.br
Carlos Teófilo Salinas[2], csalinas@unitau.br
Raykleison Igor dos Reis Moraes[1], raykleison@fem.unicamp.br
Tiago H. Machado[1], tiago@fem.unicamp.br

[1]Departament of Thermal and fluids Engineering-Faculty of Mechanical Engineering-UNICAMP, P.O.Box 6122, CEP13084-970, Campinas (SP), Brazil.
[2] Departament of mechanical Engineering, UNITAU, CEP 12060-440, Taubaté (SP) Brazil.

Abstract. *Parallel plate latent heat storage units are simple in construction and equally efficient as any other system of latent heat storage. Usually these systems are susceptible to variation of the gap between plates as well as the temperature uniformity over the plates surfaces. These parameters can lead to reducing the rate of solidified mass, presence of convective currents, reduction of the total solidified mass, increase of the time for complete solidification as well as the reduction of the solidification velocity. A simplified model is formulated based upon one dimensional heat transfer conduction discretized by using the finite difference approximation and solved by adopting the modified variable time the step scheme. The numerical predictions are results for the two cases of constant and variable wall temperature. The numerical for the two cases were compared with experiments and it was found that the variable temperature case indicated good agreement with the experimental results. Additional numerical predictions and experimental results were realized and compared to establish the validity of the model and its predictions. Both the experimental and numerical predictions are used to investigate the effects of the gap between the plates and the plate surface temperature on the time for complete solidification, the solidification velocity and the total solidified mass. The results are presented and discussed.*

Keywords: *Solidification, PCM, Phase change, Latent heat storage.*

1. INTRODUCTION

The process of heat transfer with phase change is associated with many engineering application such as metal processing ice fabrication, food preservation and latent heat storage systems. In the latent heat storage systems, the PCM is subjected to high temperature absorbing heat and changing to phase from solid to liquid. When required to liberate its latent heat energy content, the PCM is subjected to lower temperature than its phase change temperature. The PCM is usually free or encapsulated depending upon the application. One of these possible geometries for energy storage is the parallel plate storage unit. In this unit the parallel plates are the heat transfer surfaces to exchange heat between the PCM and the working fluid circulating within the plate.

The literature is rich with analytical, numerical, experimental and applications publications, (Erek, Ilker and Acar 2005; Poots, 1962; Cho and Sunderland, 1969; Prud'homme *et al.* 1989; Eckert *et al.* 1997; Lin and Jiang, 2003 and Dincer and Rosen, 2002; Saito, 2002; Stritih, 2004; and Ozisik, 1980) and many others.

In this paper we are interested in developing a simplified model for the heat transfer with phase change between parallel plates submersed in PCM. The model will be used to estimate in a rapid way the performance of latent heat storage units of the parallel plate type. In order to validate the proposed model experimental rig is constructed and instrumented to enable the experimental investigation of the different working and geometrical parameters affecting this problem.

2. FORMULATION OF THE PROBLEM

The physical problem to be analyzed is composed of a set of parallel cold plate separated by equal gaps between the plates. The plates are cooled by a flow of cold secondary flow where temperature can be verified according to the working conditions. The set of plates are submersed in a PCM (water) generally maintained at the solidification temperature.

The text block that contains the title, the authors' names and affiliation, the abstract and the keywords must be indented 0.1 cm from the left margin and marked by a leftmost black line border of width 2 1/4 pt.

The first page must have a top margin of 5 cm and all the other margins (left, right and bottom) must have 2 cm. All the other pages must be set with all margins equal to 2 cm.

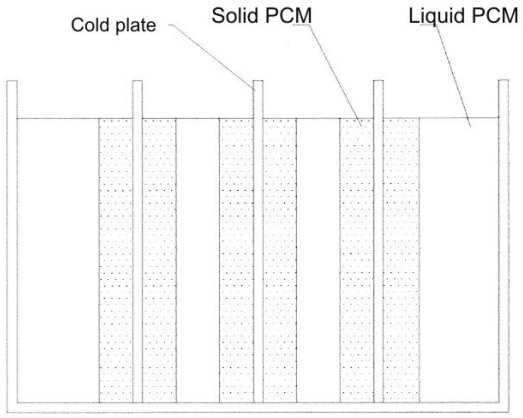

Figure 1. Simplified layout of a parallel plate latent heat storage unit.

The layout of the problem is shown in Fig (1). The treatment of the problem is restricted to the solidification of the PCM between the plates. Considering the symmetry of the problem, our attention will be concentrated on between one plate and half the gap. They the liquid PCM is confined in a semi infinite region determined by half the gap and the cold surface of the plate where the liquid is at the phase change temperature, while the plate temperature is smaller than the phase temperature due to the cold secondary fluid circulation within the plate. As a result, the time layer of solidified PCM is formed on the surface and the solid liquid interface starts to move in the positive x direction as seen in Fig (2).

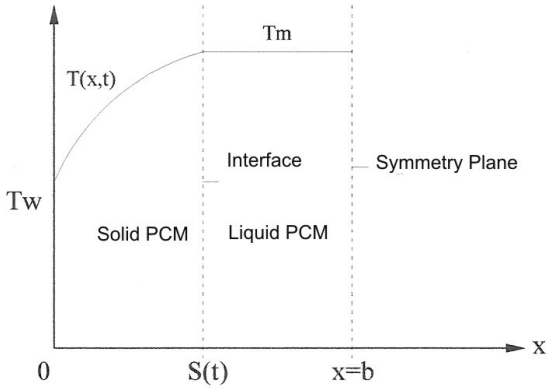

Figure 2. Model for the solidification between parallel plates.

Assuming constant physical properties for the PCM, Cho and Sunderland (1969) the phase change is one dimensional and governed by pure conduction with the wall temperature being constant or variable, one can write the governing equation and the associated boundary conditions as below Equations 1 to 4.

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \text{ at } 0 < x < S(t) \tag{1}$$

with the following boundary and interface conditions

$$T = T_w(t) \text{ at } x = 0,\ t > 0 \tag{2}$$

at the interface

$$T = T_m(t) \text{ at } x = S(t),\ t > 0 \tag{3}$$

$$k\frac{\partial T}{\partial x} = \rho L\frac{dS(t)}{dt} \text{ at } x = S(t),\ t > 0 \tag{4}$$

where S(t) is the Interface position, L is the Latent heat of the PCM, k is the thermal conductivity of the PCM, $T_m$is the phase change temperature, x is the distance measured normal to the plate and t is the time.

The equations are discretized using the finite difference approximation and the modified variable time step MVTS scheme proposed by Gupta and Kumar (1981). In the present problem, the PCM is initially considered at the phase change temperature T_m and is confined in the region $0 \le x \le b$ where b is half the gap. For $t > 0$, the control surface at x=0 is submitted to temperature below T_m while the boundary at x=b is kept isolated as a symmetry condition. The solidification starts at x=0 and advances along the x direction as shown in Figure 2. To solve the problem by finite difference approximation, the domain (x-t) is subdivided into small intervals of Δx and Δt as shown in Fig (3). The space approximation of variable time requires that in each time instant t_m, the time step Δt_m is selected such that the interface move exactly a distance Δx during the time interval Δt ,in this way it will always be at a node. Consequently it is necessary to determine the time step $\Delta t_n = t_{n+1} - t_{n-1}$, such that in the time interval t_n a t_{n-1}, the interface moves from the position $n\Delta x$ to the following position $(n+1)\Delta x$.

The basic equations and the associated boundary and initial conditions are discretized by using finite difference implicit scheme as below Equations 5 to 11.

$$\frac{T_{i-1}^{n+1} - 2T_i^{n+1} + T_{i+1}^{n+1}}{(\Delta x)^2} = \frac{1}{\alpha}\frac{T_i^{n+1} - T_i^n}{\Delta t_n} \tag{5}$$

such that

$$T(x, t_n) = T(i\Delta x, t_n) \equiv T_i^n$$

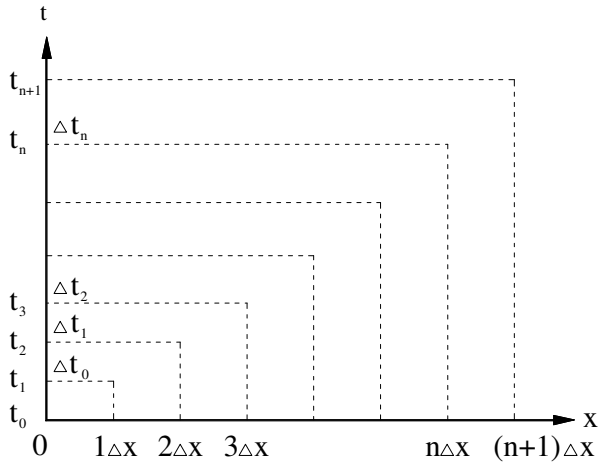

Figure 3. Subdivision of the domain "x-t" with constant Δx and variable Δt.

Rearranging the above equation one has

$$\left[-r_n T_{i-1}^{n+1} + (1+2r_n)T_i^{n+1} - r_n T_{i+1}^{n+1}\right]^{(p)} = T_i^n \tag{6}$$

Define the parameters r_n

$$r_n = \frac{\alpha \Delta t_n}{(\Delta x)^2},\ n = 1,2,3,\ldots \quad \text{e} \quad \Delta t_n = t_{n+1} - t_n \tag{7}$$

Boundary condition at x=0

$$T_0^{n+1} = f(t) \tag{8}$$

Interface condition

$$T_{n+1}^{n+1} = T_m \tag{9}$$

which is valid for all time instants

The equation of energy balance at the interface is discretized as

$$\frac{T_{n+1}^{n+1} - T_n^{n+1}}{\Delta x} = \frac{\rho L}{k}\frac{\Delta x}{\Delta t_n} \tag{10}$$

Or

$$\left[\Delta t_n\right]^{(p+1)} = \frac{\rho L}{k}\left[\frac{(\Delta x)^2}{T_m - T_n^{n+1}}\right]^{(p)} \tag{11}$$

where p is the number of iterations.

Determination of Δt_o

Here me describe the algorithms to determine the time step Δt_n such that during this internal the interface moves exactly the distance Δx.

To start the process, set n=0 in eq. (8) and (11) to obtain the following explicit expression for Δt_o according to Equations 12.

$$\Delta t_0 = \frac{\rho L}{k}\left[\frac{(\Delta x)^2}{T_m - T_0^1}\right] \tag{12}$$

Determination of Δt_1

Set i=1 and n=1 in eq. (6) we have

$$\left[-r_1 T_0^2 + (1+2r_1)T_1^2\right]^{(p)} = \left(1 + r_1^{(p)}\right)T_m \tag{13}$$

set n=1 in eq. (8) we have

$$T_0^2 = f(t) \tag{14}$$

In order to solver Eq. 13 and 14 it is necessary to know the value of $r_i(p)$ defined by eq. (7) and depends upon $\Delta r_i^{(p)}$. Iteration is necessary in this case to initiate the process put:

$\Delta t^{(o)} = \Delta t_0$

using the value of $r_i^{(0)}$,calculated by eq. (7), solve eq. (13) and (14) and calculate Δt_i^1 from eq. (11). Continue the iteration process until the differences between two consecutive times satisfy the convergence condition

$$\left|\Delta t_1^{p+1} - \Delta t_1^p\right| \le 10^{-5}$$

Determination of Δt_n

The above results are used in the following algorithms to calculate the time steps Δt_n in each time level t_n, n = 2, 3,…

a) the time steps Δt_n at the time levels t_n, n = 2, 3, 4,… are calculated by iteration, where one choose a value for $\Delta t_n^{(0)}$ according to Equation 15.

$$\Delta t_n^{(0)} = \Delta t_{n-1},\ n = 2,3,... \tag{15}$$

The system of eq. (6) to (8) with the condition (9) is solved for i = 1, 2, 3,…,n.
Setting p = 0, one can obtain the first value estimated for the nodal temperatures according to Equation 16.

$$\left[T_i^{n+1}\right]^{(0)},\quad \text{for i = 1, 2,...,n} \tag{16}$$

Since the system of equations is tridiagonal it can be solved by TDMA.

b) the value of $\left[T_i^{n+1}\right]^{(0)}$ obtained from equation (16) are now introduced in equation (11) for p= 0. In this way, one an obtain the first estimated value for the time step $\Delta t_n^{(1)}$;

c) this value of $\Delta t_n^{(1)}$ is used to calculate the first value $\Delta t_n^{(2)}$, respecting the steps (a) and (b) of the algorithms;

The steps (a), (b) and (c) are repeated until the convergence criterion between two successive time steps is satisfied $\left|\Delta t_1^{p+1} - \Delta t_1^{p}\right| \leq 10^{-5}$

In order to validate the numerical model and its predictions, an experimental set-up is constructed and instrumented. This experimental rig is designed to enable a realization of experiments necessary to investigate three important parameters for phase change of PCM between parallel plates. These parameters are the gap between the plates, temperature and mass flow of the secondary working fluid. The secondary fluid used in the experiments is ethanol.

3. RESULTS AND DISCUSSION

In the numerical model two boundary conditions were used constant wall temperature and variable wall temperature.

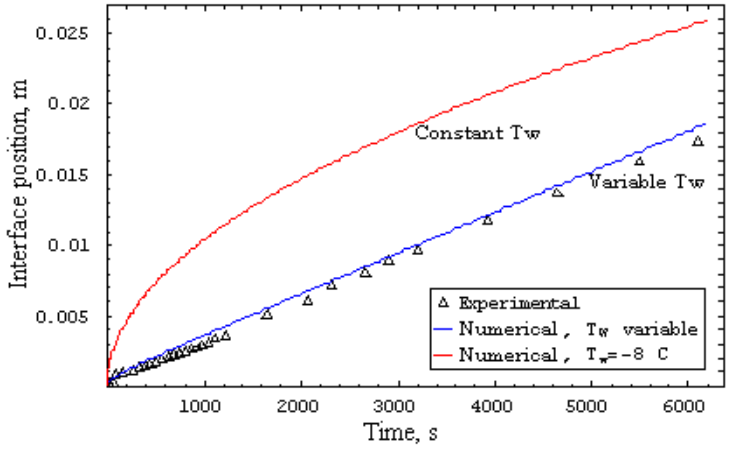

Figure 4. Variation of the interface position as function of time for T_f=-16 °C, E=0,051m, M= 0.0793 kg/s.

Figures (4) to (6) show the behavior of the solidification for the true boundary conditions. As can be seen the experimental measurements agree well with the condition of variable wall temperature.

For Figures (4) and (5) every thing is the same except the mass flow rate of the secondary fluid. As can be seen, increasing the mass flow rate increases the rate of solidification the velocity of the interface predicted numerically and determined experimentally is show in Fig. (7). As can be seen initially the velocity of the interface due to the fact that the solidified layer is very small and hence the over all thermal resistance is small and consequently the thermal gradient is high leading to high velocity of the interface. As the time passes, the thicknesses of the solidified layer increase and the over all thermal resistance too leading to a smaller thermal gradient and consequently smaller interface velocity. One can verify from both Figs. 6 and 7 that the agreement is fairly good.

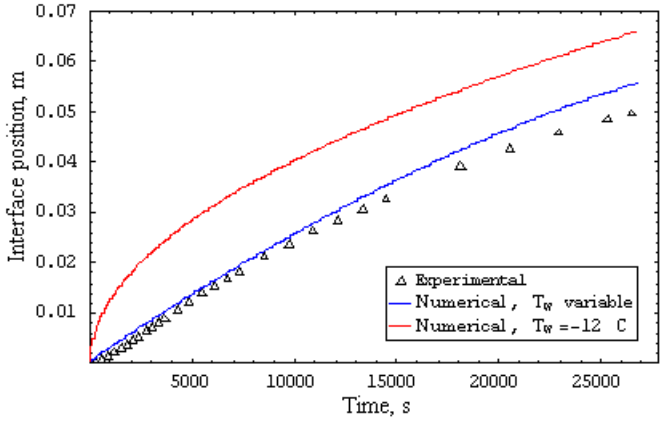

Figure 5. Variation of the interface position as function of time for T_f=-16 °C, E=0,105 m, M= 0.102 kg/s.

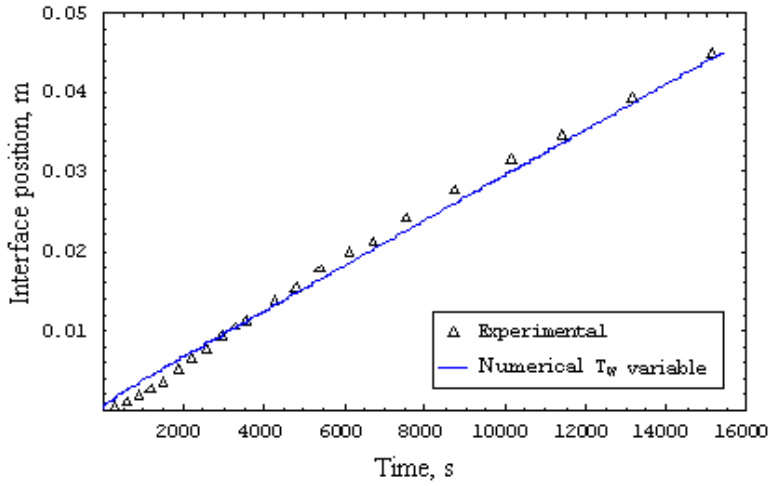

Figure 6. Variation of the interface position as function of time for T_f=-26 ºC, E=0,105 m, M= 0.0793 kg/s.

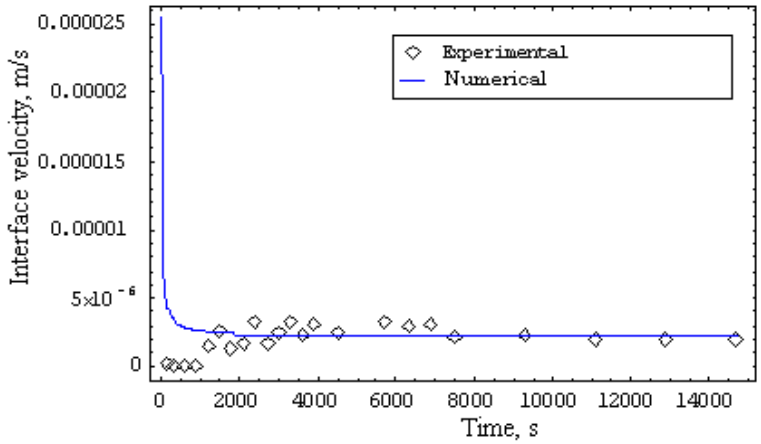

Figure 7. Variation of the interface position as function of time for T_f=-16 ºC, E=0,073m, M= 0.0656 kg/s.

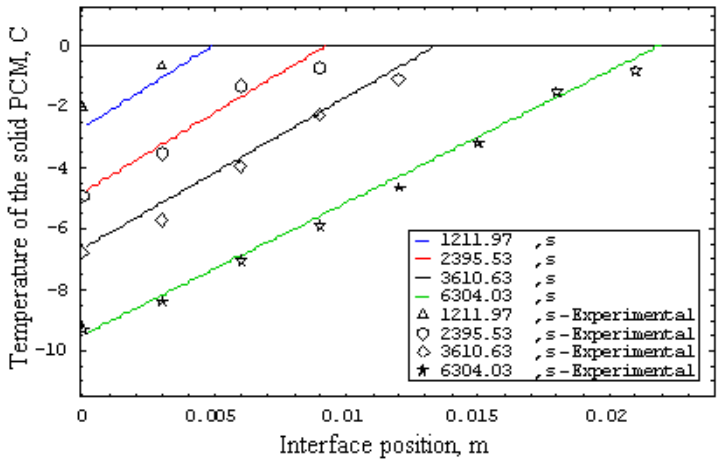

Figure 8. Experimental and numerical temperature distribution in the solid phase for T_f=-22 ºC, E=0,051m, M= 0.0656 kg/s.

The temperature distribution in the solidified layer is presented in Fig. (8). Both the predicted numerical temperature and the measured distributions are compared and as can be seen the agreement is good. From these comparative results one can observe that the agreement is good indicating that the proposed model with variable wall temperature can represent fairly well the phase change process between parallel plates submersed in the PCM and hence can be used to predict the performance of storage units of the parallel plate type.

4. CONCLUSION

From the above discussion one can conclude that the proposed simplified model is adequate and reasonably accurate to predict the phase change characteristics of the PCM between parallel plates as confirmed by comparisons with the experimental measurements.

Also the experimental results showed that the increase of the gap between plates reduces the interface position and hence the interface velocity but increases the time for complete solidification. Reducing the secondary fluid working temperature is shown to have the opposite effects that is, increase the interface position, enhance the interface velocity are reduce the time for complete solidification. The variation of the secondary fluid mass flow rate has similar effects as reducing its temperature but to small extent.

5. ACKNOWLEDGEMENTS

The authors acknowledge the CNPQ for the PQ research scholarship to the first author and the doctorate scholarship for the second author and Capes for the doctorate scholarship for the fourth author.

6. COPYRIGHT

7. REFERENCE

Cho, S. H., Sunderland, J. E., 1969, “Heat conduction problems with melting or freezing”. Transactions of ASME J. of heat transfer, pp. 421-426.

Dinçer, I., Rosen, M. A., 2002, “Thermal energy storage”. Chichester: John wiley & Sons, 577p.

Erek, A., Ilken, Z., Acar, M. A., 2005, “Experimental and numerical investigation of thermal energy storage with a finned tube”. Int. J. Energy Research, Vol. 29 No. 4, pp. 283-301.

Eckert, R. J., et. al., 1997, “Heat transfer – a review of 1994 literature”. Int. J. Heat Mass Transfer, Vol.40, No. 16, pp. 3729-3804.

Gupta R. S., Kumar D., 1981, **“**Variable time step methods for one-dimensional Stefan problem with mixed boundary condition”. Int. J. Heat Mass Transfer, Vol. 24, pp. 251-259.

Lin, S., Jiang, Z., 2003, “An improved quase-steady analysis for solving freezing problems in a plate, a cylinder, and a sphere”. Journal of Heat Transfer, Vol.125, pp. 1123-1128.

Ozisik, M. N., “Heat conduction”. 1980,USA: John Wiley & Sons, 540p.

Poots, G., 1962, “On the application of integral methods to the solution of problems involving the solidification of liquids initially at fusion temperature”. Int. J. of Heat Mass Transfer, Vol.5, pp. 525-531.

Prud’homme, M., Hung Nguyen, T., Long Nguyen, D., 1989, “A heat transfer analysis for solidification of slabs, cylinders and spheres”. Journal of Heat Transfer, Vol. 111, pp. 699-705.

Stritih, U., 2004, “An experimental study of enhanced heat transfer in rectangular PCM thermal storage”. Int. J. Heat Mass Transfer, Vol.47, pp. 2841-2847.

Saito, A., 2002, “Recent advances in research on cold thermal energy storage’. Int. J. of Refrigeration, v.25, pp 177-189.