Abstract— **Latent heat storage is one way of storing thermal energy that is capable of storing much more amounts of energy than the sensible heat storage. It has also the advantage of storing energy in a nearly isothermal phase change process. There are many phase change materials known, changing phase in a wide range of temperatures, which makes them suitable for different applications. In this study, temperature behavior of paraffin as a phase change material has been studied with two different numerical methods. Further the results have been verified with experimental data.**

Index Terms—**Phase change material, sensible heat, latent heat, numerical, experimental**

I. INTRODUCTION

he increasing need for energy is one of the most controversial and important issues of the human life. However, the resource of our current primary energy source, fossil fuel, is limited. Not only the rising value of these fossil fuels, but also their adverse effect on environment is alarming. All these issues increase the necessity of using renewable energy resources more effectively.

Therefore, many studies have been done on new and renewable energy resources in which one option is to develop energy storage devices, which are as important as developing new sources of energy. Energy storage plays an important role in improving a system to be more efficient. Moreover, one would be able to match supply and demand when they are not simultaneous, and when the energy resource is intermittent [1]-[3].

There are different methods for energy storage such as mechanical, electrical, thermochemical and thermal energy storage. Sensible heat storage and latent heat storage are two methods of thermal energy storage; however latent heat storage, which happens during a phase change, has the ability to store larger amounts of energy in a small temperature range compared to sensible heat storage. This provides two important advantage including energy storage and temperature control.

Phase transition could happen in different forms such as solid-solid, solid-liquid, liquid-gas etc. However, the most commonly used is solid-liquid transition that was reviewed by Sharma et al. [1] and Farid et al. [2] for different materials and their applications. Phase change materials, generally known as PCMs, can be sorted in three different categories, including organic, inorganic and eutectic compounds; so that each category includes its own subcategories such as paraffins, non-paraffins, salt-hydrates, fatty acids and so on. Different materials have been studied by many authors for several applications such as solar air and water heating systems, solar cookers, greenhouses and buildings [1]-[4].

It is important to understand the heat transfer and phase change mechanism in order to design or improve a system utilizing these storage materials. In this study, two different numerical models have been investigated for a horizontal rectangular container of PCM, which is exposed to constant

Soroor Karimi is M.Sc. student of Mechanical engineering at Amirkabir University of Technology, Tehran 15875-4413, Iran (e-mail: soroor.karimi@ aut.ac.ir).

Hassan Basirat Tabrizi is professor of Mechanical Engineering at Amirkabir University of Technology, Tehran 15875-4413, Iran (corresponding author, phone: +982164543455; fax: +9821 66419736; e-mail: hbasirat@aut.ac.ir).

Reza Hosseini Abardeh is associate professor of Mechanical Engineering at Amirkabir University of Technology, Tehran 15875-4413, Iran (e-mail:hoseinir@aut.ac.ir).

The heat flux will increase the PCM temperature rapidly through sensible heating until it reaches its melting temperature. Then the front surface of the PCM starts to melt and absorb latent heat. A thin layer of melted PCM will form on the front surface and starts to absorb sensible heat while the rest of the PCM continues to absorb heat until another layer melts. The melted layer has a lower conductivity compared to its solid phase leading to less heat transfer to the solid. Thus a temperature difference appears between liquid and solid parts of the PCM. In order to study the PCM heat absorption and temperature behavior, the energy equation (considering the conductive heat transfer) can be written as:

$$\rho C_P \frac{\partial T}{\partial t} = \nabla.(k\nabla T) \tag{1}$$

Where, ρ, C_p, k and T are density, specific heat capacity, thermal conductivity and temperature respectively.

On the upper surface of the PCM, the boundary condition is described as:

$$k\frac{\partial T}{\partial y}\bigg|_{y=0} = \dot{q} + h(T_\infty - T_0) \tag{2}$$

Where h and $\dot{q}$ are heat transfer coefficient and the constant heat flux exerted, respectively.

It is important to notice that the convection coefficient varies with surface temperature, so it should be calculated in each time step. However it should be determined whether this heat transfer convection is natural, forced or mixed. For a horizontal surface following formula is presented [6]:

$$\frac{Bo_y^{1/4}}{Pe_y^{1/2}} = \left(\frac{Gr_y}{Re_y^{2}}\right)^{1/4} \begin{cases} > O(1)\ natural \\ < O(1)\ forced \end{cases} \tag{3}$$

Where Bo is Boussinesq number, Pe is Peclet number, Gr is Grashof number and Re is Reynolds number.

The Nusselt number, Nu, for mixed convection over a horizontal surface can be calculated from (4), regardless of being local or average [7].

$$Nu_x^{3} = Nu_{FC}^{3} \pm Nu_{NC}^{3} \tag{4}$$

For a laminar flow, the forced Nusselt number can be calculated from (5) [6]:

$$Nu_x = 0.453 Pr^{1/3} Re_x^{1/2} \tag{5}$$

Where Pr is Prandtl number and the average Nusselt number is twice the local Nusselt.

In addition, the Natural Nusselt number for a horizontal plate with the hot surface facing upward is defined as (6) [6].

$$\overline{Nu_L} = \begin{cases} 0.54 Ra_L^{1/4}\ (10^4 < Ra_L < 10^7) \\ 0.15 Ra_L^{1/3}\ (10^7 < Ra_L < 10^{10}) \end{cases} \tag{6}$$

For the constant heat flux the Ra_L should be substituted with $Ra_L = Ra_{*L}/\overline{Nu_L}$, when Ra_* is Rayleigh number for constant heat flux.

III. MODELING

Two different schemes are presented in the following, with two different assumptions for the phase change problem. The finite difference model assumes that the phase change happens in a constant temperature, while the finite element model considers a temperature range instead. Further the PCM properties are considered constant. Thus they do not vary with temperature but they have different values for solid and liquid phase.

A. Finite difference Model

A constant melting temperature and conductive heat transfer through the PCM is assumed. The heat flux is exerted from the above; a one dimensional heat transfer in the PCM can be implemented. Therefore, an explicit finite difference method can be applied to (1) which gives (7).

$$T_i^{n+1} = T_i^n + \frac{k\Delta t}{\rho C_P \Delta y^2}(T_{i-1}^n - 2T_i^n + T_{i+1}^n) \tag{7}$$

Where $n+1$ and n indicate the values of parameters in the present and the previous time step, respectively and Δt is the time step. This form is applicable for both the solid and liquid phase, considering the properties related to that phase.

However, for the melting zones, the temperature is assumed constant until reached heat is less than the required latent heat. This can be modeled as a net sensible heat reaching that element in each time step accumulated with time. In other words, the heat reaching the element in any time step would melt a part of it; therefore, it is possible to predict the melting boundary based on following relation:

$$\begin{aligned} f_i^{n+1} = f_i^n &+ \frac{k_s\Delta t}{\rho_s L_f \Delta y^2}(T_{i+1}^n - T_i^n) \\ &+ \frac{k_l\Delta t}{\rho_l L_f \Delta y^2}(T_{i-1}^n - T_i^n) \end{aligned} \tag{8}$$

Where f_i is the melt fraction, L_f is the latent heat of the PCM and subscripts s and l refer to the solid and liquid phase respectively.

For every node, the melting fraction field can be defined as (9).

$$f_i = \begin{cases} 0 & T < T_m\ (solid) \\ f_i(t) & T = T_m\ (Mushy) \\ 1 & T > T_m\ (liquid) \end{cases} \tag{9}$$

Where, T_m is the PCM melting temperature.

For the boundary condition, the size of the element should be considered half the size of other elements. While the boundary element is absorbing sensible heat, whether it is solid or liquid, the temperature can be calculated from (10).

$$T_0^{n+1} = T_0^n + 2\frac{h\Delta t}{\rho C_P \Delta y}(T_\infty - T_0^n)$$
$$+ 2\frac{k\Delta t}{\rho C_P \Delta y^2}(T_1^n - T_0^n) + 2\frac{\dot{q}\Delta t}{\rho C_P \Delta y} \quad (10)$$

While the boundary node is melting, it remains at a constant temperature and the melt fraction is calculated from (11).

$$f_0^{n+1} = f_0^n + 2\frac{h\Delta t}{\rho_s L_f \Delta y}(T_\infty - T_0^n)$$
$$+ 2\frac{k_s\Delta t}{\rho_s L_f \Delta y^2}(T_1^n - T_0^n) + 2\frac{\dot{q}\Delta t}{\rho_s L_f \Delta y} \quad (11)$$

Where T_0 is the upper surface temperature and T_1 is the temperature of the next node in the PCM.

The time steps should be chosen small enough so that Fourier number becomes less than 0.5 and convergence occurs.

B. Finite Element Model

In this method, it is assumed that during the phase change, the specific heat capacity tends to infinity so the temperature would remain constant. In order to model the phase change, it is only needed to model the specific heat capacity change with temperature. Therefore model the latent heat with a substitute sensible heat. In this study is assumed in a small temperature range ($T_m \pm$ e), so the specific heat can be defined as:

$$Cp_\infty = L_f / 2e \quad (12)$$

Here e has been considered 0.5 °C.

The model is solved using Freefem software package. It is observed that by increasing the number of elements; the temperature of every element converges to its real value.

IV. RESULTS AND VALIDATION

A paraffin with dimensions 43*38*4.5 cm, melting point 58°C, latent heat 221 kJ/kg, exposed to heat flux 660 W/m^2 on the front surface and ambient temperature 44°C, is used. The predicted temperature change on the front surface, by the two stated methods is compared with the obtained experimental data in a two hours test shown in Fig. 2.

It is seen in Fig. 2 the experimental and modeling results agree with each other with a maximum error of 5.6°C. This error is mainly due to the change in properties of the PCM as temperature rises in reality. However, the results of two models are slightly different. It is noticed that the temperature change in Freefem results is smoother. This is caused by the fact that phase change is assumed to happen in a small temperature range and not at a sharp point.
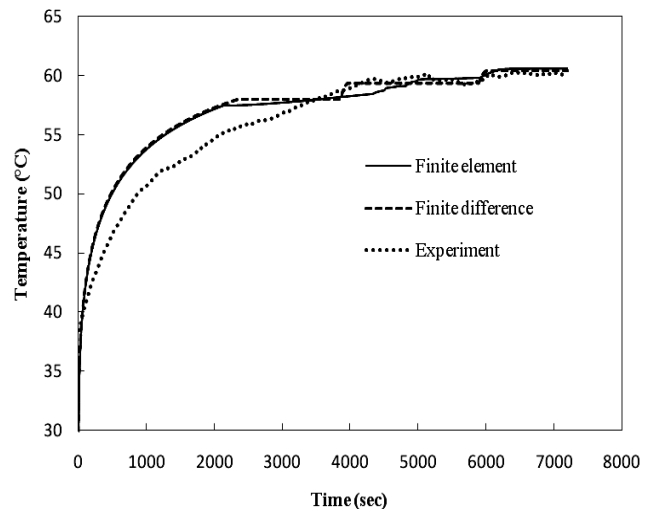

Fig. 2. Temperature for the upper surface of the PCM

Fig. 3 shows the temperature distribution in the cross section of the PCM for the finite difference model and obtained experimental data. The maximum error in temperature prediction is 5.4°C and average error is 2.3°C.

Moreover, Fig. 4 compares the predicted temperature by finite difference model in 3cm depth with the experimental data of the same depth.
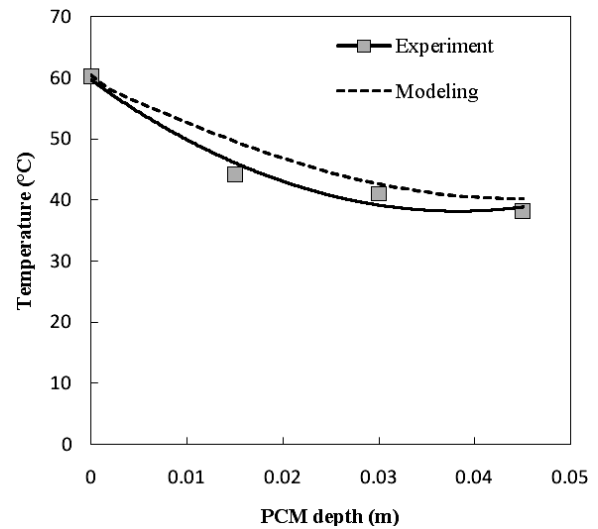

Fig.3. Comparison between predicted temperature distribution in PCM depth by finite difference model and experiment after two hours test.

It can be seen that at the beginning of the process, the modeling results are deviated from the experimental one; this is caused by three factors. First, the temperature has been considered the same for the whole PCM volume in the modeling, but it does not exactly occur in reality. Second, the surrounding surfaces have been assumed adiabatic so the predicted temperature is constant at the start, but there is heat exchange with the environment, regardless of insulation, therefore the temperature starts to increase immediately. Third, the properties of the PCM vary with rise in temperature, which leads to a smaller rate in temperature increase. However, the maximum error in predicting the temperature for this point is 4.2°C and the average error is 2.1°C.
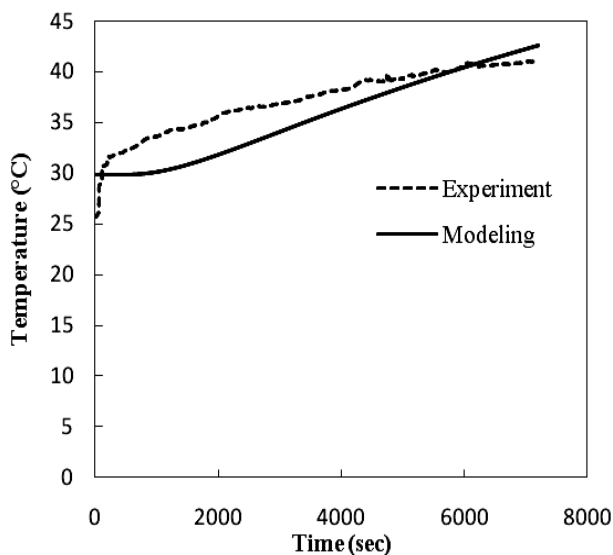
Fig.4. Predicted temperature in 3 cm depth of PCM from the upper surface, by finite difference modeling

V. CONCLUSION

Two different numerical models for temperature distribution of phase change problem were studied for a rectangular container filled with PCM under a constant heat flux. Further, the proposed models have been validated with obtained experimental data for paraffin. It was shown that both methods are suitable for modeling of phase change problem. Moreover, it is appropriate to assume a constant melting temperature for the PCM or to model the phase change in a small temperature range with defining a specific heat capacity for the PCM based on its latent heat. In addition, it is observed that not only the PCM stores large amount of energy, but also its surface temperature remains constant, which could be applicable for temperature control.

REFERENCES

[1] A. Sharma, V.V. Tyagi, C.R Chen and D. Buddhi, " Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable Energy Reviews 13,* pp. 318–345, 2009.
[2] M.M. Farid, A.M. Khudhair, S.A.K. Razack and S. Al-Hallaj, "A review on phase change energy storage: materials and applications," *Energy Conversion and Management 45,* pp. 1597–1615, 2004.
[3] H. Mehling and L.F. Cabeza, *Heat and cold storage with PCM* (An up to date introduction into basics and applications), Springer-Verlag Berlin Heidelberg, 2008.
[4] M.M. Alkilani, K. Sopian, M.A. Alghoul, M. Sohif and M.H. Ruslan, "Review of solar sir collectors with thermal storage units," *Renewable and sustainable Energy Reviews 15*, pp. 1476-1490, 2011.
[5] http://www.freefem.org/ff++/
[6] A. Bejan, Convection heat transfer, 3rd ed.*, John Wiley & Sons, INC., 2004.*
[7] B.F. Armaly, T.S. Chen and N. Ramachandran, "Correlations for laminar mixed convection on vertical, inclined and horizontal flat plates with uniform surface heat flux," *Heat* Mass *Transfer.* Vol. 30, No. 2, pp. 405-408, 1987.