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Research Article

Heat Transfer Modeling of Phase Change Materials in Multiple Plates Heat Exchanger

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Abstract: Nowadays, given the increasing importance of energy sources, the possibility of energy storage in the heat exchangers through the Phase Change Materials (PCM) and releasing it when needed have been extremely essential. This study seeks to model the domestic water heat system in which the paraffin is as the phase change material and it stores the solar energy. The behavior of a PCM plate was studied by writing the governing equations and solving them as the one-dimensional, implicit method and through numerical calculation of the method equations. Given the confirmed accuracy of performed modeling by the results of similar studies for the complete melting and solidification of PCM, the application of this system seems appropriate for the solar domestic water heaters.

Keywords: Heat transfer, modeling, phase change materials

INTRODUCTION

Nowadays, the need for using the renewable energy resources is increased according to the enhanced need for the energy and limited fossil fuels as the environment-polluting and running out resources. Heat energy is one of the energies with increasing application. Energy storage has become essential with relying on the Phase Change Materials and using the nano technology. Different methods such as the Phase Change Materials, which store the thermal energy while changing the phase and release it if necessary (Hamdan and Elwerr, 1996). Different types of nanomaterials with effects such as the heat capacity, increased heat transfer coefficient and thermal and chemical stability have been investigated through various studies in order to increase the efficiency of PCMs (Phase Change Materials). For commercialization of studied materials, the use of machines, which are applied for them, should have the technical feasibility as well as the economic feasibility (SheikhJaberi and ShariatiNiasar, 2011). Thermal energy storage machine is one of the most modern technologies in which various heating and cooling application shave been used. This technology has a lot of supporters in most of the countries especially Canada, the United States of America and European countries. Applying this machine in the heating systems will lead to the transfer of electrical energy consumption from the high to low load hours as well as saving the electricity consumption. Energy storage machine has several applications in applying the solar energy and in the aerospace industry. All these examples are the evidence for the great importance of this technology in today industry (Dolado *et al*., 2011). Therefore, our aim in this study is to investigate and model the heat transfer in the energy storage systems with the phase change materials.

Numerous studies have been conducted in the field of modeling the heat transfer; some of them are noted as follows. Springer numerically solved the problem of freezing and melting of a cylinder containing the phase change material under the boundary conditions of clear wall temperature (Springer, 1969). Hsu and Sparrow (1981) conducted an analytical solution for the freezing issue on the outside of a coolant carrying tube. Hsu *et al*. (1981) introduced a numerical method for solving the non-permanent and two-dimensional issue of melting and freezing solidification in which the network boundaries moved along with the retaining wall over time. Shamsundar (1982) obtained an analytical solution for freezing problem on the outer surface of a tube with the boundary condition of variable temperature in the tube axis in which the intuitive energy and the axial conduction were neglected in the Phase Change Material. Cao and Faghri (1991) studied the performance of thermal energy storage system and finally investigated the optimized terms and conditions of system. They did not believe in using the empirical relations for determining the rate of heat transfer from the carrying fluid and believed that applying them would lead to the error in designing (Vakilaltojjar and Saman, 2001). Furthermore, Bellecci and Conti (1993) solved the same problem by using the empirical relations in obtaining

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the carrying fluid heat transfer coefficient and standard enthalpy in phase change problem; and their use of empirical relationships slightly limited the solution for the geometry of machine. Obviously, there is no research conducted in the field of energy storage systems like the solar exchangers in which the phase change materials are used.

Nowadays, designing the heat exchangers, in which the Phase Change Material (PCM) is used as the energy storage, has been taken more into account by the researchers because these kinds of exchangers have higher energy storage capacity than the conventional exchangers according to the phase change in them (Dolado *et al*., 2006). In this study, a mathematical model of a PCM water heat exchanger, in which the parallel plates have been used due to the enhanced heat transfer area and they contain paraffin as the energy storage (PCM), is introduced and its equations is solved numerically and by finite difference method and in unstable conditions. Given the obtained time for melting and solidification times obtained for complete solidification of paraffin and its other properties, mentioned in the text and the temperature proportion to the temperature of water required for domestic consumption in the heater, this material seems suitable for this application and this exchanger can be used as the energy storage in current solar energy heaters (Najarzadeh *et al*., 2012). Therefore, this study seeks to model the domestic water heat system of a PCM plate in which the paraffin is as the phase change material and it stores the solar energy.

SYSTEM MODELING

Properties of modeled heat exchanger: Studied heat exchanger in this research composes of 8 parallel plates. The plates were vertically put next to each other in a distance of 3 cm. Length, width and thickness of each of the plates were 90, 50 and 3 cm, respectively. Total temperature of exchanger was equal to 35°C at the first time and water entered the exchanger with the speed equal to 0.1 m/sec and at 70°C and exited the exchanger after the heat exchange.

Phase change material: Among the phase change materials, paraffin is considered as one of the ideal materials for applying in energy saving due to the properties such as appropriate melting point, high latent heat of fusion, cost effective and being non-toxic and non-corrosive materials. In this model, paraffin was used as the PCM. Properties of this paraffin are presented in Table 1. Since the temperature of water, needed for domestic consumption in heaters, is between 50 to 60°C, it seems appropriate for this application.

Numerical solution:

Governing equations: The equations, governing this system, are presented in Table 2 (Holman, 2002).

Solution method: Given that the ratio of length to the thickness of PCM plates ismore than 10, the heat transfer has been considered one-dimensional (Incropera and DeWitt, 1996). The behavior of a PCM plate was studied by writing the governing equations and solving them by the one-dimensional, implicit method and through the finite difference method. In this model, it was assumed that there was only the heat conduction transfervertical to the direction of water movement. Equation, governing the fluid flow, was also studied in one dimension. Theequations in the present study were solved by the software MATLAB R2009B and through the Matrix method (Dolado *et al*., 2011). In writing the equations, thewall resistance between thewater and PCM is neglected due to its low thickness and high thermal conductivity coefficient.

Calculating the overall water heat transfer coefficient: The properties of fluid should be calculated more accurately for obtaining the highest accuracy in modeling. The density, thermal conductivity coefficient and water dynamic viscosity were calculatedat the temperature range from 30 to 80°C, on average (Golub and Charles, 1989).

Convective heat transfer coefficient: Given the geometry, dimension and velocity of water, flowing

Table 1: Thermo-physical properties of paraffin as PCM

Property	Value	Property	Value
Melting point temperature	53°C	Fluid phase density ($\frac{kg}{m^3}$)	790
Melting range	10°C	Specific heat of solid ($\frac{J}{kgK}$)	2175
Solid phase density ($\frac{kg}{m^3}$)	910	Specific heat of fluid ($\frac{J}{kgK}$)	2150

Table 2: Equations governing the system with PCM

Location	Governing equations
Fluid flow	$v\frac{\partial T_{water}}{\partial y}+\frac{2h_{water}}{\rho_{water}C_{p_{water}}\delta}\left(T_{water}-T_{Surface}\right)=\rho_{water}C_{p_{water}}\delta\frac{\partial T_{water}}{\partial t}$
Surface of PCM	$2h_{water}\left(T_{surface}-T_{water}\right)+2k\frac{\partial T_{surface}}{\partial x}=\rho_{pcm}C_{p_{pcm}}\frac{\partial T_{surface}}{\partial t}$
Inside of PCM	$\frac{\partial}{\partial x}\left(k\frac{\partial T_{pcm}}{\partial x}\right)=\rho_{pcm}\frac{\partial H_{pcm}}{\partial t}$
Center of PCM	$\frac{\partial T}{\partial x}=0$

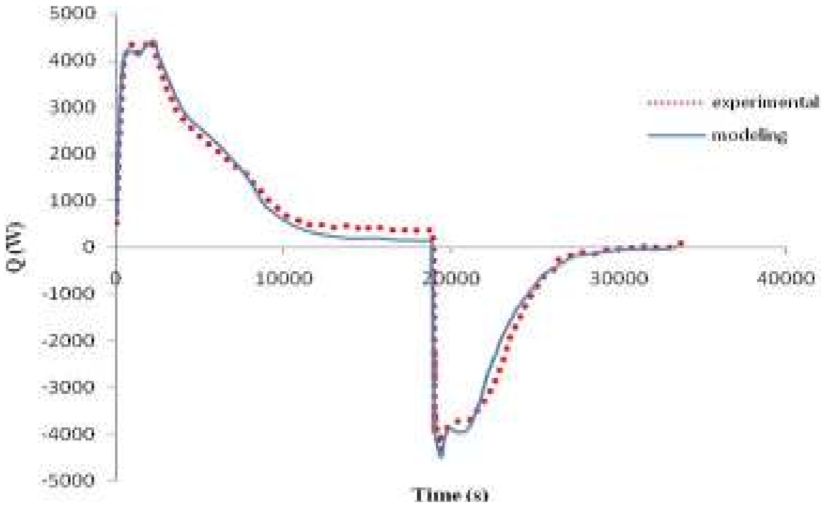

Fig. 1: Comparison of experimental results (Incropera and DeWitt, 1996) and simulation of heat transfer flux from the PCM during the freezing process

among the PCM plates, Nusselt number was calculated by the help of reference (Dolado *et al*., 2011).

PCM properties: Specific heat capacity of PCM in this model has been considered as a function of temperature during the whole process. Also, twodistinct values have been consideredfor these properties in themathematical model in order to take into account the difference between the thermal conductivity coefficientand density of PCM both in solid and liquid phases. In the range ofphase change, the value of thiscoefficientwas calculatedby the linear interpolation ofenthalpy. The thermal conductivity coefficientand density is obtained equal to the solid thermal conductivity coefficientand density in the solid phase, equal to andthermal conductivity coefficientand density in the liquid phase and through the Eq. (1) and (2) in the range of phase change:

$$k_{s/l} = k_{solid} + \frac{k_{liuid}-k_{solid}}{h_2-h_1}[H(T)-H_1] \tag{1}$$

$$\rho_{s/l} = \rho_{solid} + \frac{\rho_{liquid}-\rho_{solid}}{h_2-h_1}[H(T)-H_1] \tag{2}$$

RESULTS AND DISCUSSION

Comparison of numerical solution and experimental results of the heat transfer flux changes with time in a full cycle of melting and freezing: Figure 1 shows the comparison among the experimental results of reference (Incropera and DeWitt, 1996) and the numerical solution of existing study. As indicated in this figure, there is a reasonable agreement among these results.

Investigating the behavior of a PCM plate:

Melting and solidification processes: Figure 2 and 3 show the behavior of a PCM plate for paraffin during the melting and freezing process. Concentration oftemperature profile in the range of 50 to 58° indicates the melting zone in this range.

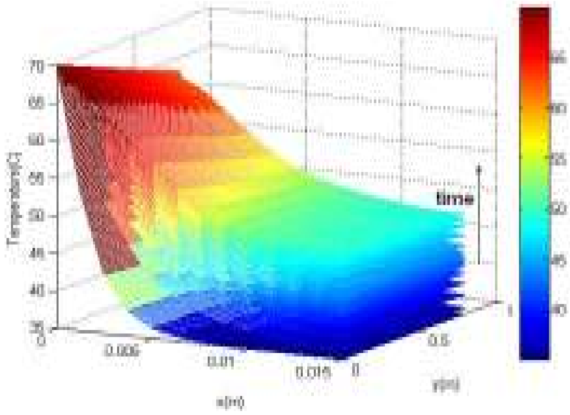

Fig. 2: Temperature profile at different times during the melting process

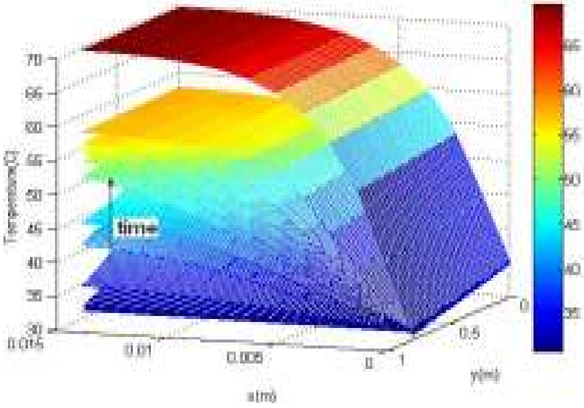

Fig. 3: Temperature profile at different times during the freezing process

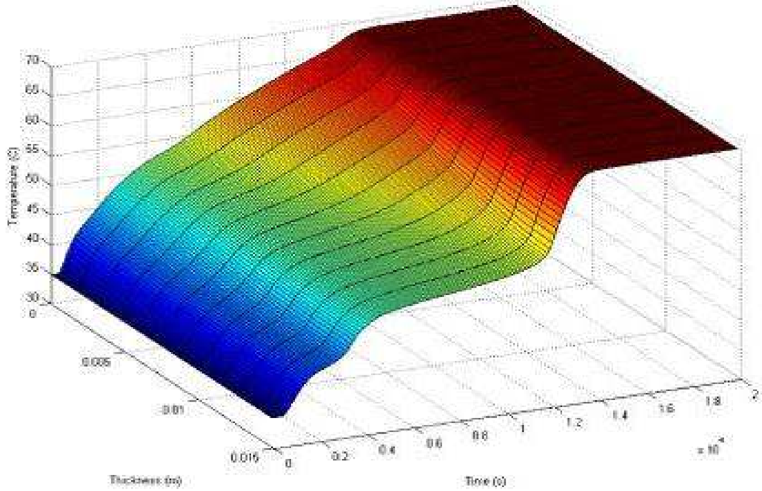

Fig. 4: Temperature profile in terms of time during the melting process

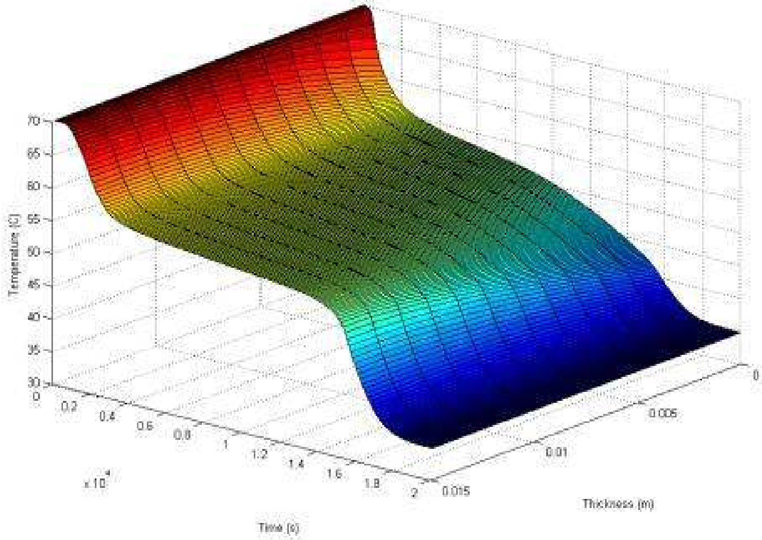

Fig. 5: Temperature profile in terms of time during the freezing process

PCM temperature change with the time during the melting and freezing processes: Figure 4 and 5 show the PCM temperature change with the time during the melting and freezing processes of Paraffin. The phase change region is obvious in this figure.

Given the obtained results, the necessary time for complete melting and freezing of PCM was obtained about 5 h. It seems an appropriate time. Therefore, this unit can be used for saving the energy in solar water heaters.

CONCLUSION

In this study, the application of phase change materials was studied in the domestic water heating system and the modeling of energy storage system was predicted through the numerical solution of model equations:

- The accuracy of conducted modeling was tested by the results of other works in this regard and a good agreement was obtained.
- The time required to complete the melting process is higher than freezing.
- Given the obtained time for complete melting and freezing of PCM, this system seems suitable for use in solar water heaters.

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