Numerical Study of a High Temperature Latent Heat Storage (200-300 ^{0}C) Using Eutectic Nitrate Salt of Sodium Nitrate and Potassium Nitrate

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Abstract: In this study, a small scale direct solar thermal energy storage unit for a parabolic dish system with a secondary reflector is designed and developed. The main advantage of thermal energy storage is that thermal energy is available also during times when there is little or no sun shine. In addition, no heat transport fluid is needed in this system. A well insulated heat storage should keep the heat for about 24 hours. KNO_3 and $NaNO_3$ in 60:40 percent ratio (mol %) is used as latent heat storage material (PCM). This type of salt is also used in large scale solar power plants producing electricity. Effects of the heat flux and the number of fins on the latent heat storage charging process were numerically simulated using COMSOL Multiphysics. During phase change (melting) of the PCM, large amount of energy in the form of latent heat of fusion is needed. The phase change heat transfer was implemented using the effective heat capacity method.

Keywords: Phase change material (PCM), Latent Heat Storage, Eutectic Salt

1. Introduction

Solar cookers, which convert solar radiation to heat, have been designed, developed and tested to cook foods since a few decades ago. This is introduced as an alternative energy source to reduce or solve the energy supply for cooking purposes, especially in rural area. There is currently a very large variety of solar cookers available, but most of them are based on direct use of the heat by positioning the food container at the focus point of the concentrator. A limitation of these solar cookers is that cooking can only be done when and where the sun is shining.

In order to improve the drawbacks of the traditional solar cookers, we propose to use phase change material (PCM) in the solar thermal energy storage system. PCM stores heat in the form of latent heat. Latent heat storage is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa. The capacity of the system with a PCM medium is given by Eq. (1) and Eq. (2) [1]:

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \quad (1)$$

$$Q = m\left[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)\right] \quad (2)$$

where Q is the quantity of heat stored, m is the mass of PCM, C_{sp} is the average specific heat between T_i and T_m, T_m is the melting temperature, T_i is the initial temperature, a_m is the fraction melted, Δh_m is the heat of fusion per unit mass, C_{lp} is the average heat capacity between T_m and T_f, and T_f is the final temperature.

PCM stores 5-14 times more heat per unit volume than sensible heat storage materials such as water, masonry or rock. In addition, PCM absorbs and release heat at a nearly constant temperature [1]. A large number of PCMs are known and have been tested. The main criteria for selection of PCM in latent heat thermal storage is given by A. Francis *et al.*[2].

Sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3) are inorganic PCM. The heat capacity and thermophysical data of these nitrate salts are available in the literatures. $NaNO_3$ and KNO_3 have the melting point of 310 ^{0}C and 330 ^{0}C respectively [3-4]. The molten salt consisting of $NaNO_3$ and KNO_3, or so called solar salt, with composition 60:40 wt.%, has a melting point of 238 ^{0}C and it has been used successfully as a thermal energy collection and storage fluid in a large scale solar central receiver (SCR) demonstration system at temperature up to 565 ^{0}C [5]. In addition, it is also interesting to know that the $NaNO_3$ - KNO_3 eutectic might find utilization in latent heat storage for cooking application as the melting temperature is in a suitable range.

Low thermal conductivity is a major challenge in PCM applications. Andrew *et al*. (2006) reported that various methods have been investigated to increase the thermal conductivity of PCMs such as dispersing high conductivity particles within the PCM, inserting a metallic matrix, impregnating a porous graphite matrix with PCM, and other methods [6]. In this study, heat penetration through aluminum fin was investigated to increase the thermal conductivity of PCM within the storage.

A small scale direct solar thermal energy storage system with secondary reflector was applied in this study as shown in Figure 1. The storage is illuminated directly, no heat transport fluid is needed in this system. A well insulated heat storage should keep the heat for about 24 hours. Eutectic nitrate salt was used as latent heat storage material. Thermal behaviour of the salt was studied using differential scanning calorimeter (DSC). During melting of PCM, a large amount of energy in the form of latent heat of fusion is needed. This effect is added into the phase change behavior simulation by using effective heat capacity method. The effects of varying heat flux and number of fins on the latent heat storage charging process is numerically simulated using COMSOL Multiphysics in this study.

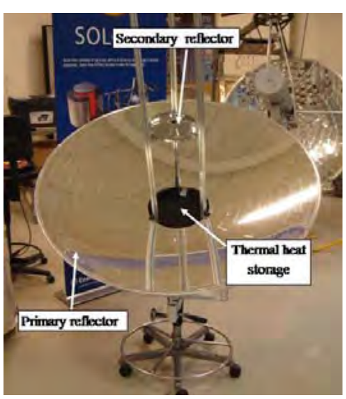

Figure 1. A direct solar thermal energy storage system.

2. Methodology

2.1 Differential scanning calorimeter (DSC) study

The preparation of $NaNO_3$-KNO_3 eutectic mixture for DSC analysis was done according to Foong *et al*. (2010a) [7].

A differential scanning calorimeter (DSC) series Q2000 equipped with finned air cooling system from TA instruments was used for the experimental measurement. The temperature scale was calibrated using high purity reference materials of Indium and Zinc. Heating rate of 10 ^{0}C/min was used for the heat capacity measurements. The sample mass was approximately 10 mg. All the samples were hermetically sealed in aluminum pans to ensure there is no loss of volatiles and the thermograms were recorded under pure argon atmosphere at flowrate of 50 mL/min. The pans and samples were weighed using Mettler Toledo XP6U ultra-microbalance with a detection limit of 10^{-6} g. The samples were used without any further purification. Heat capacity and the enthalpy of fusion of $NaNO_3$ - KNO_3 eutectic were measured by the DSC in the temperature range from 32 to 496 ^{0}C. Sapphire was used as reference material to measure heat capacity. All the experiments were done in triplicate and the mean values were taken.

2.2 Solar concentrator with thermal heat storage

A small scale direct solar thermal energy storage system is shown in Figure 1. A primary parabolic solar reflector was used to reflect the incident solar radiation onto a secondary solar reflector, which redirects the solar energy onto a solar thermal energy storage device. More information about the design concept of this system can be obtained from Foong *et al*. (2010b) [8]. Focus of this study is on the simulations of the latent heat storage unit using finite element model in COMSOL Multiphysics.

The latent heat storage unit which will be used in this study is shown schematically in Figure 2.

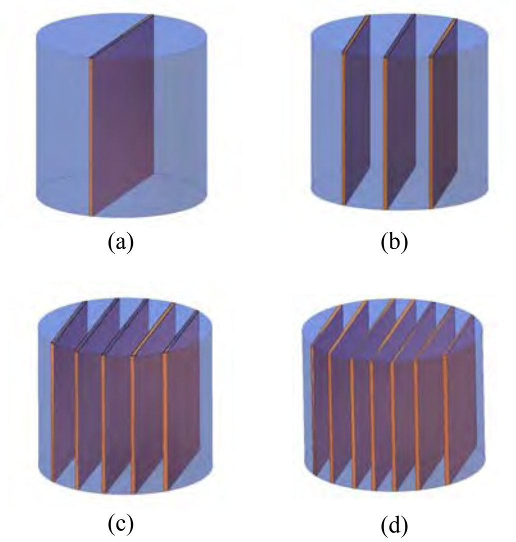

Figure 2. Latent heat thermal storage container with different number of aluminum fin; (a) 1 fin, (b) 3 fins, (c) 5 fins, (d) 7 fins.

The unit consists of a container of 0.19 m internal diameter and 0.20 m height made of stainless steel. The wall thickness was 0.005 m. Eutectic molten salt of $NaNO_3$ and KNO_3 is filled into the container until 90% of the container height. All surfaces except the top plate of the container are thermal insulated. In order to increase the heat transfer rate into the PCM, aluminum fin and top plate of 0.003 m and 0.004 m thickness respectively are used.

3. Use of COMSOL Multiphysics

The simulations of the latent heat storage unit were carried out using COMSOL Multiphysics 3.5a. A 2D model with transient analysis was chosen to solve the problem.

The governing equation for the heat transfer process within the PCM is the energy equation for conduction and convection. However, the effect of convection heat transfer within the PCM can be neglected when the volume of PCM used in between the fins is small [9]. Therefore, there is no convective term in our case and the energy equation for the analysis of thermal energy storage unit can be simplified and expressed in Eq. (3) below.

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) = \nabla (k \nabla T) \tag{3}$$

where ρ, C_p and k are the density, specific heat capacity, and thermal conductivity respectively of the PCM.

A brief description of the PCM heating process is given here. During the heating of PCM, sensible heat is added until the onset melting temperature is reached. In the phase change (melting) temperature range, extra energy in the form of latent heat of fusion is needed. This usually happens in a small temperature range [10]. After the PCM is completely melted, sensible heat gives a rise in the temperature. Solving the solid-liquid interface is one of the major problems in heat transfer calculations.

From the literature, there are two types of numerical methods usually used to solve the phase change problem; the enthalpy method and the effective heat capacity method. In this study, the phase change problem is solved using the effective heat capacity method. The effective heat capacity of the PCM during phase change is given by Eq. (4) [10].

$$C_{eff} = \frac{L}{T_1 - T_2} + C_p \tag{4}$$

where L is the latent heat of fusion, T_1 is the onset temperature of phase transition and T_2 is the end temperature of phase transition.

Eutectic nitrate salt of $NaNO_3$ and KNO_3 at 60:40 percent ratio (mol %) was prepared and used as latent heat storage material. The thermal behavior of this salt was determined using DSC in temperature range from 305.15 K to 769.15 K. Heat capacity as a function of temperature is shown in Figure 3. A phase transition in solid state and a phase change peak were observed. The enthalpy of phase transition and phase change were calculated. Table 1 shows the thermophysical properties of the eutectic nitrate salt used in this study.

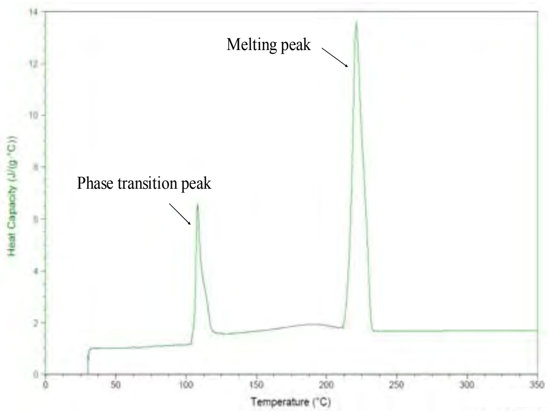

Figure 3. Thermal measurement of the eutectic nitrate salt using DSC.

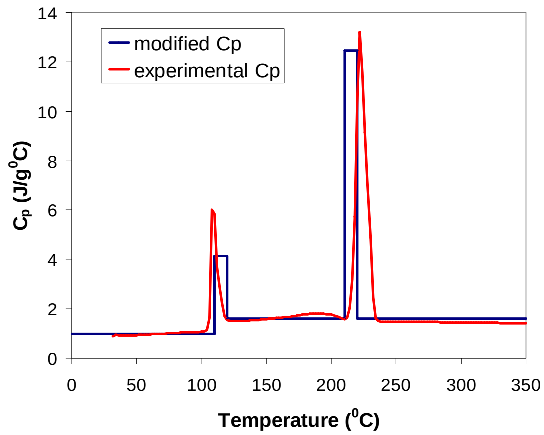

Figure 4. Experimental and modified heat capacity of the $NaNO_3 - KNO_3$ eutectic.

Table 1: Thermophysical properties of the $NaNO_3$ - KNO_3 eutectic (60:40 mol%)

Parameter	Value
Thermal conductivity (W/m·K)	0.5
Density (kg/m^3)	2000
Enthalpy of fusion (kJ/kg)	108.67
Phase transition enthalpy (kJ/kg)	31.91

By using effective heat capacity method to solve the phase change problem, heat capacity of the eutectic nitrate salt used in this study was modified and divided into 5 temperature regions. First of all, we assumed that the phase transition and melting occur within a temperature range from 383 K to 393 K and 483 K to 493 K respectively. The phase transition enthalpy and enthalpy of fusion were incorporated in the modified heat capacity which was stated in Eq. (5).

$$C_p = \begin{cases} 1 & T \prec 383K \\ 4.128 & 383K \le T \le 393K \\ 1.6 & 393K \prec T \prec 483K \\ 12.463 & 483K \le T \le 493K \\ 1.6 & T \succ 493K \end{cases} \quad \text{(kJ/kg)} \qquad (5)$$

The discontinuity of heat capacity as shown in Eq. (5) was done in COMSOL Multiphysics using logic function. A plot of experimental and modified heat capacity used in the simulation of the eutectic nitrate salt is shown in Figure 4.

After setting up the numerical method to solve the phase change problem, a 2D geometry of the latent heat storage unit was drawn as shown in Figure 5. The initial and boundary conditions are as follow:

- The top plate surface is subjected to constant heat input (solar radiation) and convection losses.
- A constant room temperature at 296 K and the heat transfer coefficient, h is assumed to be 10 W/m^2·K.
- The initial temperature of the thermal storage unit including PCM was 296 K.
- All other outside surfaces are thermally insulated.

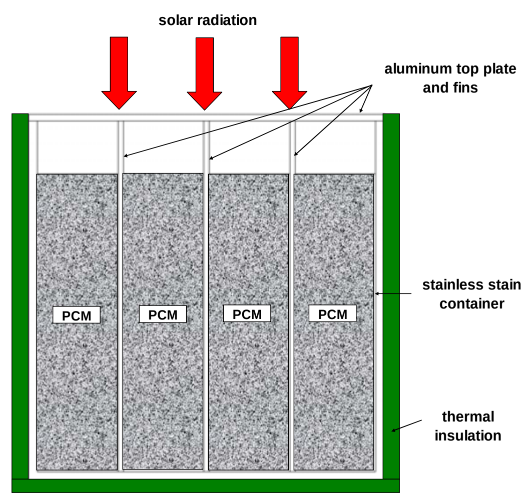

Figure 5. Geometry of the thermal storage unit used in this simulation.

Conductivity and density of the PCM are assumed to be constant. The phase change is accounted for by using effective heat capacity method. In addition, the solar intensity and the overall system efficiency are assumed to be at 850 W/m^2 and 35% respectively.

Due to the low thermal conductivity of PCM, the effect of different number of fins was investigated. In this case, 1 fin, 3 fins, 5 fins, and 7 fins system were simulated. Apart from the number of fins, the effect of heat flux at the top plate surface was studied. Two different heat fluxes were chosen based on the assumptions mentioned above. The chosen heat fluxes were 10 kW/m^2 and 20 kW/m^2. The aim of this study is to develop a high temperature (200 ^{0}C to 300 ^{0}C) latent heat storage unit which the complete melting of PCM is expected within 3 hours.

4. Results and discussion

Figure 6 shows an example of the computed temperature profile at a point in the PCM domain. It can be seen that the temperature profile of the eutectic nitrate salt during charging process is divided into 3 regions which represent the solid phase, phase change interface and liquid phase. The temperature rise in solid phase region and liquid phase region was due to the sensible heat added. Temperature between 483 K to 493 K was the phase change region where the melting of PCM started at 483 K and completed at 493 K. The temperature gradient of this region was smaller due to the large amount of energy, in the form of latent heat of fusion, was needed to melt the PCM.

Figure 7 shows the effect of different number of fins used to increase the PCM thermal conductivity at constant heat flux of 10 kW/m^2. The results showed that almost all the PCM within the container, regardless of number of fins, was not melted over the time of 3 hours. Only a small volume of PCM close to the fins at the top was melted or in the phase change temperature range. When fewer fins were used, heat was difficult to penetrate into the PCM.

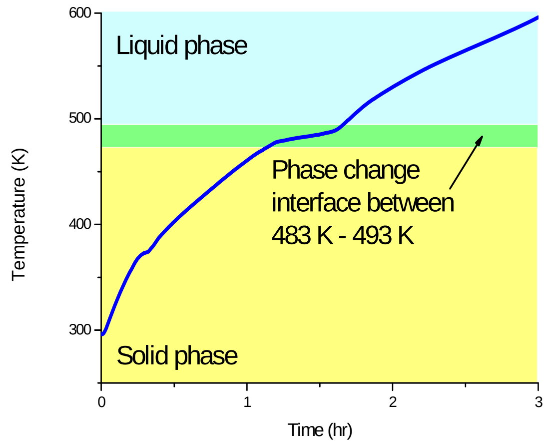

Figure 6. Temperature profile of the eutectic nitrate salt during charging process.

In this case, more heat is used to heat up the top plate which results in a higher temperature compared to the container with more fins. The number of fins play an important role in determining the heat transfer rate from the top to the bottom and into the PCM.

The results of simulations with higher heat flux at 20 kW/m^2 are shown in Figure 8. Higher heat flux corresponds to a larger parabola surface area in this case. As expected, temperature of the PCM was higher and the complete melting of PCM within the aluminum fins was observed in the container with 7 fins, except two small volumes close to the wall at the bottom. The temperature range of the PCM was found to be around 600 K at the top and 500 K at the bottom. The vertical temperature profiles in between the aluminum fins (the red line in Figure 8), except 1 fin case is illustrated in Figure 9. PCM in the top part of the container, around 0.02 m below the top surface, was melted regardless of the number of fins. For 7 fins case, the results showed that the PCM temperature was well above the complete melting region. On the other hand, most of the PCM was in solid phase for the 1 fin case.

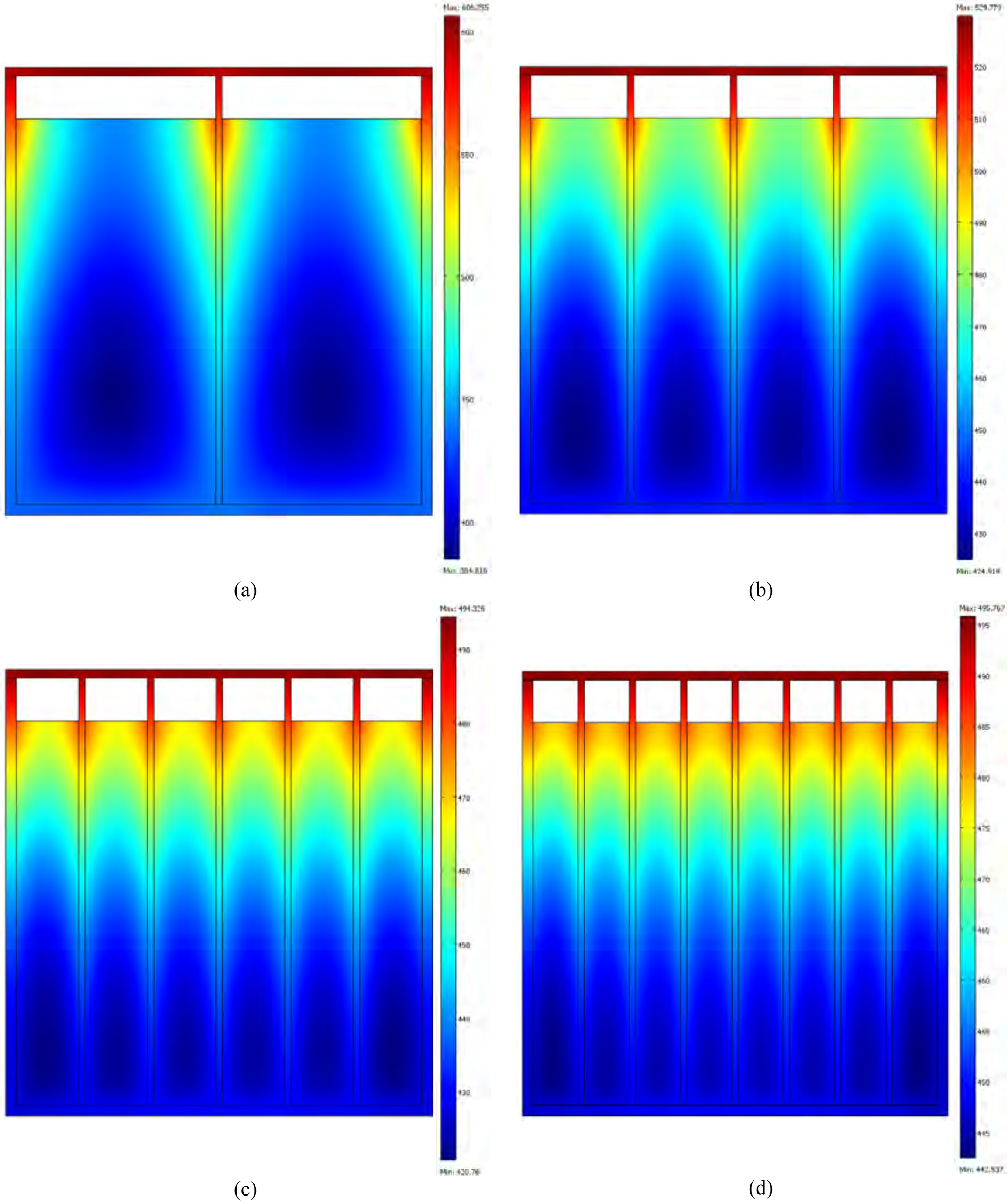

Figure 7. Temperature profiles of the PCM thermal storage unit at time = 3 hours and surface heat flux of 10 kW/m^2; (a) 1 fin, (b) 3 fins, (c) 5 fins, (d) 7 fins.

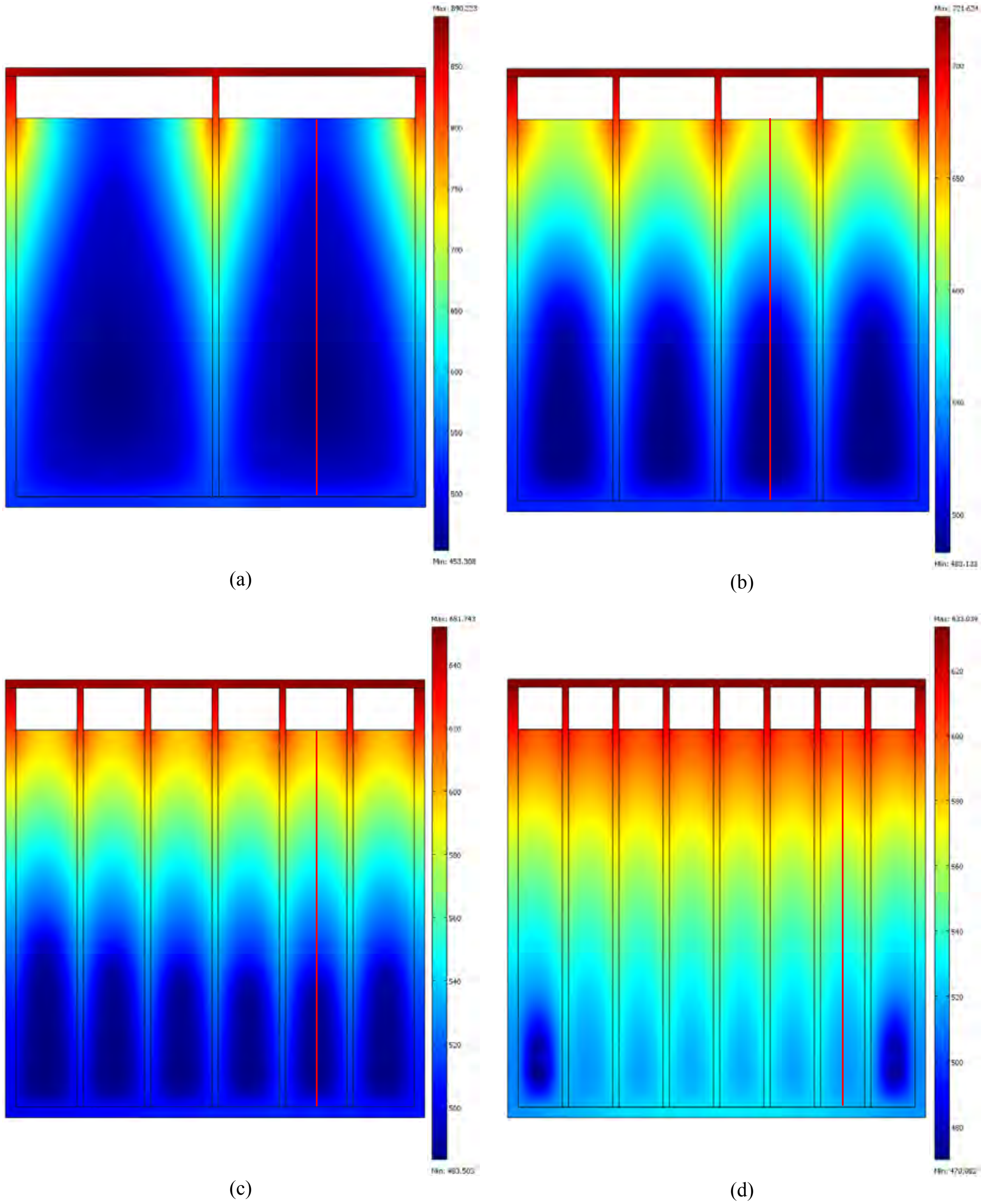

Figure 8. Temperature profiles of the PCM thermal storage unit at time = 3 hours and surface heat flux of 20 kW/m^2; (a) 1 fin, (b) 3 fins, (c) 5 fins, (d) 7 fins.

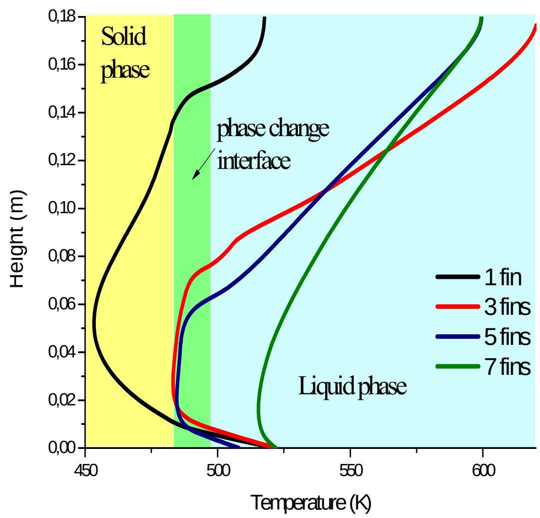

Figure 9. Vertical temperature profiles of the PCM at heat flux 20 kW/m^2.

5. Conclusions

The heat transfer in a small scale direct solar thermal energy storage system was analyzed with COMSOL Multiphysics. The latent heat storage unit was modeled numerically using a finite element model. Effective heat capacity method was used to simulate the phase change process which a large amount of energy in the form of latent heat of fusion is needed. The effects of heat flux and the number of fins were studied. It demonstrates how the model can be used to determine the number of fins and heat flux required in order to melt the PCM completely within 3 hours. For future works, optimization will be done on fin thickness, container dimension, and includes radiation heat loss. In addition, heat extraction also is an important study. Hence, heat extraction criteria will be considered as well in the design and development of the latent heat storage.

6. References

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7. Acknowledgement

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