

## **Predicted Charging and Discharging Efficiency of a Latent Heat Thermal Energy Storage System Linked to a Solar Thermal Collector System**

**Philip C Eames**

Centre for Renewable Energy Systems Technology, Department of Electronic and Electrical Engineering,  
Loughborough University, LE11 3TU, UK

### **Abstract**

The high latent heat of phase change allows a small volume of phase change material (PCM) to store a significant amount of energy at constant temperature compared to simple sensible energy storage. This enables the size of thermal energy storage systems to be reduced. Charging and discharging rates of a PCM system are limited by the relatively low thermal conductivity of the PCM when solid. Two dimensional transient finite volume models have been developed that allow prediction of heat transfer to and from a PCM, with simulation of the progress of the phase transition front and the free convective heat transfer that occurs within the liquid phase. Simulation results are presented for a storage system geometry comprised of an outer shell containing PCM modules, a similar store in which the PCM in the modules is replaced with water and a water store. Isotherm plots are presented at selected times for both charging and discharging of the store geometry illustrating the effect of PCM melting and solidification on heat transfer to the PCM.

Key-words. Phase Change Energy Storage, Numerical Simulation

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### **1. Introduction**

There are many potential advantages that can be realized by the introduction of suitable thermal energy storage, it is possible to significantly extend the time of operation of systems that utilize intermittent energy sources, for example solar thermal collector systems, enable the reduction in peak load and thus plant size, for example in building cooling applications and improve system operational efficiency by maintaining operational parameters at design optimum levels. An example of this is the thermal regulation of building integrated photovoltaics, to achieve improvements in solar to electrical conversion efficiency, Huang et al (2004). The high latent heat of phase change allows a small volume of phase change material (PCM) to store a significant amount of energy over a small temperature range. This enables the volume of thermal energy storage systems to be reduced. High effective energy density can be realized if operational temperatures are close to phase change temperatures and charging and discharging occurs within a cycle. A wide range of suitable materials with different phase change temperatures are available for thermal energy storage and temperature control applications, reviews of both materials and systems can be found in Zalba et al (2003) or Agyenim et al (2010). In this paper simulations of charge and discharge of a thermal energy store using phase change materials with different phase transition temperatures potentially for use with a domestic scale solar hot water system are presented.

### **2. The Adopted Modelling Approach**

The numerical model developed and used in the current simulation work is based on the finite volume model used by Eames and Norton (1998), for modelling low speed laminar flows in stratified thermal storage tanks with adaptations incorporated to facilitate the solid to liquid and liquid to solid phase transitions. The developed two and three dimensional transient finite volume models with temperature dependant material properties allow prediction of heat transfer to and from a PCM, with simulation of the progress of the phase transition front and the free convective heat transfer within the liquid phase.

The variation in specific heat capacity of the PCM modelled in the current simulations associated with phase change during melting and solidification occurs over a pre-set temperature range and is presented in table 1, this approach is more realistic than that used in much previous work in which a constant specific heat capacity was assumed for the temperature interval in which phase change is occurring. The model allows the change from solid to liquid to be simulated in two ways, the dynamic viscosity can be allowed to decrease or increase in a predefined way over a specified temperature interval, with the PCM viscosity gradually changing, or the material can be changed from solid to liquid within each finite volume at a predefined temperature. For melting in the simulations presented the PCM is solid below 57°C and liquid above this temperature. For solidification the PCM is liquid above 55°C and solid below this. The thermal conductivity of the PCM is  $0.19\text{Wm}^{-1}\text{K}^{-1}$  and its density is  $820\text{kgm}^{-3}$ . The dynamic viscosity in the liquid state is  $0.026\text{Nsm}^{-2}$ .

The solution domain for the energy equations encompasses the phase change material and its enclosing container and insulation. The solution domain for the momentum and pressure equations is limited to that in which liquid phase change material or liquid heat transfer fluid exists, this domain changes with melting or solidification of the PCM. To enable convergence of the solution of the momentum and pressure equations to be achieved with the changing solution domain, it is necessary to reduce the simulation time-step when volumes change from solid to liquid or liquid to solid. Momentum, energy and pressure equations are solved using the Bi-CGSTAB iterative equation solver, Van der Vorst (1992). The model is currently implemented in Fortran 90 recently being converted to run in parallel allowing large systems of equations representing complicated geometries to be solved in a reasonable time.

The model at present does not allow for the increase in volume of the PCM when it changes from solid to liquid, other than that to drive free convection, and does not allow for the movement and settling of solid PCM when sufficient melting occurs so that the PCM is not attached to the PCM container walls.

**Tab. 1: The Specific heat capacity variation with temperature of the PCM used in the simulations**

<b>Temperature °C</b>	<b>Melting Specific Heat Capacity <math>\text{KJkg}^{-1}\text{K}^{-1}</math></b>	<b>Solidification Specific Heat Capacity <math>\text{KJkg}^{-1}\text{K}^{-1}</math></b>
<47	1.8	1.8
48	5	5
49	6	6
50	8	8
51	12	12
52	17	18
53	23	25
54	24	27
55	28	30
56	16	16
57	10	4
>58	1.8	1.8

The cross section of the thermal energy store design simulated is illustrated in figure 1. The store is comprised of an outer shell of internal dimensions 268mm by 486mm which is externally insulated. Four PCM modules are arranged in the store to provide a 4mm wide fluid flow path for the heat transfer fluid. Each module comprises of a 1mm thick aluminium envelope with internal dimensions of 480mm high by 60 mm wide. Modules 1 and 3 rest on the base of the store, modules 2 and 4 are supported 4mm above the base. To allow for PCM expansion, to be incorporated at a later date, an expansion space at the top of each module of 40mm or 8.3% is provided. To avoid simulation of air flow in the expansion space, the specific heat capacity and density of air are used, however the thermal conductivity is increased to  $10\text{Wm}^{-1}\text{K}^{-1}$ , to prevent the expansion space behaving like an additional insulation layer. Although the thermal conductivity of the solid PCM is low, for the simulations presented in this paper none of the heat transfer enhancement mechanisms, for example fins or carbon fibres, Agyenium et al (2009), Agyenium et al (2010) are included.

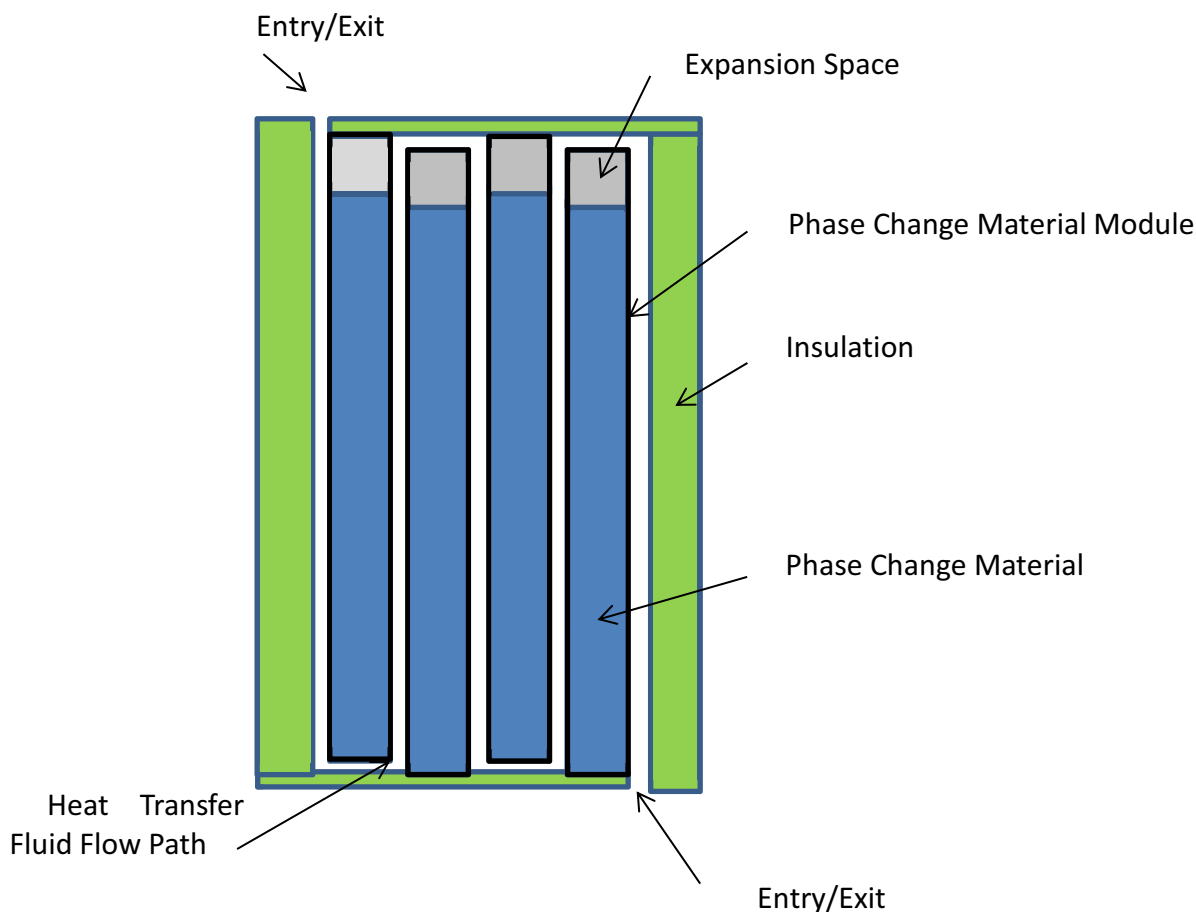


Fig: 1. A schematic of the cross section of the modelled PCM module storage system

Due to the uniform store cross section and assumed store length of 0.5m a two dimensional modelling approach was adopted for this analysis, based on the assumption that the 0.5m store length is sufficiently long so that end effects due to the end walls of the PCM modules and store will not influence greatly the heat transfer and fluid flow in the bulk of the modules and store. The insulation on the top and bottom of the store was 10mm thick and that on the sides was 50mm, the heat loss from the exterior surface of the insulation to an ambient temperature of 20°C was set to  $2.5\text{Wm}^{-2}\text{K}^{-1}$ .

During discharge at the inlet to the water filled fluid channel a fluid flow velocity of  $0.04\text{ms}^{-1}$  corresponding to a volume flow rate of  $0.08\text{ls}^{-1}$  and a temperature of 20°C were specified, the initial temperature of the store was set to 61°C. During charging at the inlet to the water filled fluid channel a fluid flow velocity of  $0.01\text{ms}^{-1}$  corresponding to a volume flow rate of  $0.02\text{ls}^{-1}$  was specified. The temperature of inlet was determined based on the outlet temperature from the store and a calculated temperature rise that would occur through a solar collector.

The solar collector was specified to have an area of  $3\text{m}^2$  and an optical efficiency of 0.75. The incident solar radiation was a constant  $700\text{Wm}^{-2}$  and the loss coefficient from the solar collector was  $3.5\text{Wm}^{-2}\text{K}^{-1}$ . The heat loss from the solar collector was calculated based on the assumption that the average flat plate temperature was 4°C greater than the average of the inlet and outlet temperature from the previous time step.

The heat gain from the collector  $H_g$  was thus,

$$H_g = 3 * (700 * 0.75 - \left(\frac{t_{out} + t_{in} + 4}{2} - 20\right) * 3.5) \quad (\text{eq. 1})$$

The variables  $t_{out}$  and  $t_{in}$  are the outlet temperature from the collector to the store and the inlet temperature to the collector from the store. The new outlet temperature from the collector to the store is then calculated based on the heat gain through the collector and the inlet temperature to the collector

$$t_{in} = H_g / (\text{vol flow rate} * 4200 * 1000) \quad (\text{eq. 2})$$

### 3. Results

#### 3.1 Charging

At the start of the simulated charging period of duration 5400 seconds it was assumed that the store was at a uniform temperature of 35°C. The predicted isotherm plots at times of 2700 and 5400 seconds can be seen in figure 2.

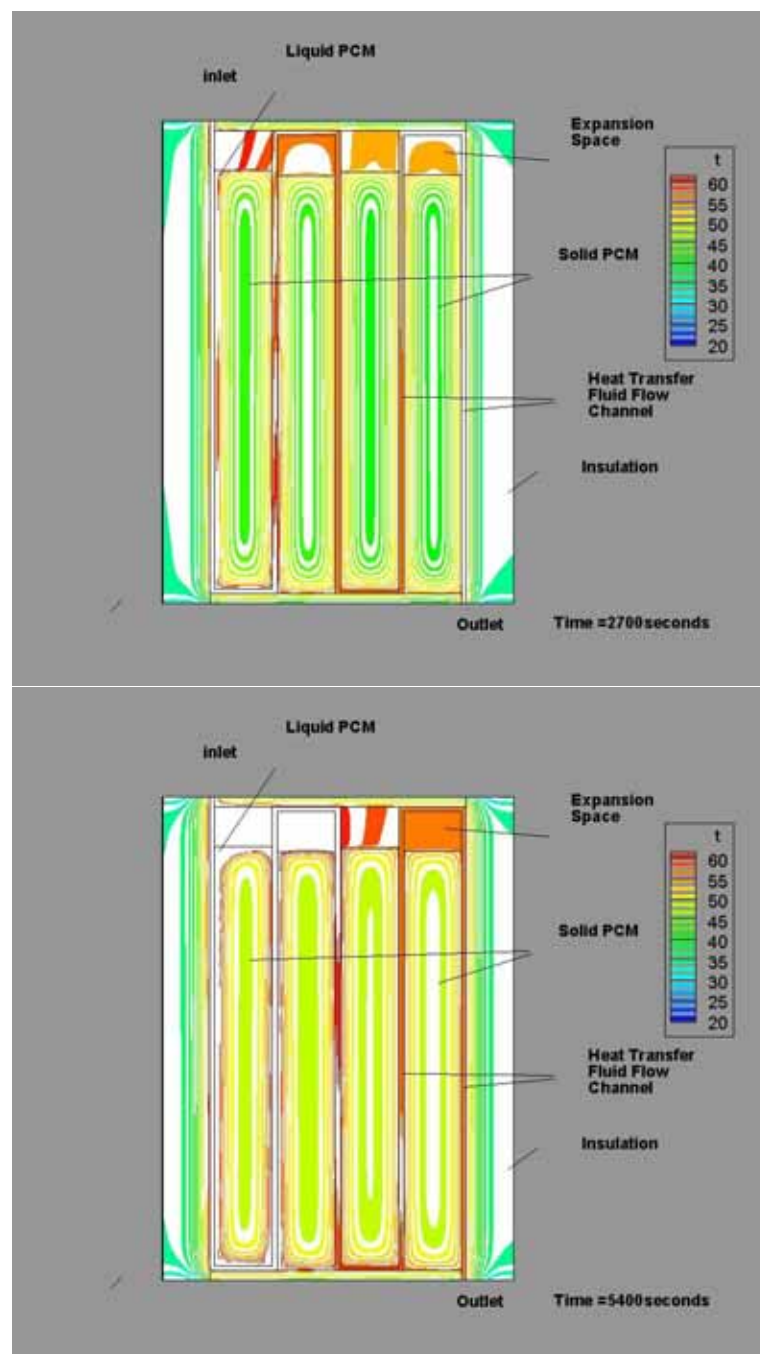


Fig. 2: Predicted Isotherms for the PCM module store at times of 2700 and 5400 seconds.

At 2700 seconds, melting of the PCM is only occurring on the left side of the first module, by 5400 seconds melting is seen all around the surface of the first module and over much of the surface of the second module. Enlargements showing the extent of melting at the top and bottom of the PCM module are presented in figure 3. There is a fluid circulation that flows around the solid un-melted PCM, this clearly shows a limitation of the model, in reality settling of the denser solid PCM would prevent this circulation.

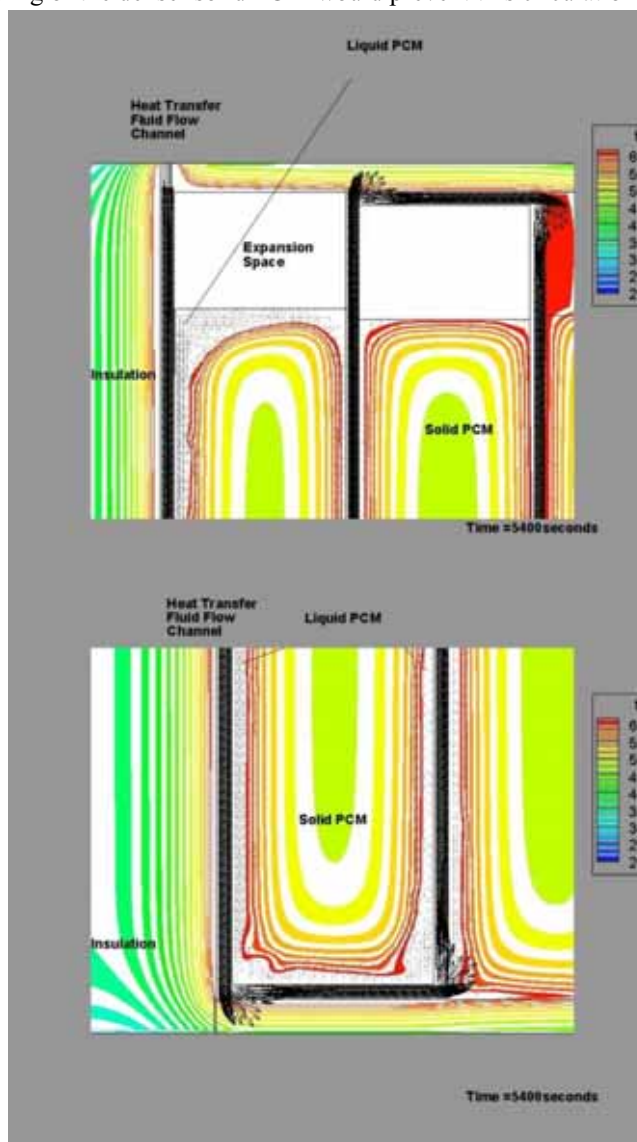


Fig. 3: Enlargements to illustrate the fluid flow at the top and bottom of the first PCM module.

To provide an element of comparison simulations were performed in which 1) the PCM was replaced by water within the aluminium containers and 2) a store was filled with water with no aluminium containers. The predicted isotherms for these simulations at a time of 5400 seconds are shown in figure 4. It is evident that the temperatures in the store in case 2 are significantly lower than the stores containing the modules. This is due to the reduced volume of fluid circulating to the solar collector for the stores including the modules. Thermal stratification can clearly be seen in both case 1, within the modules and case 2, within the store.

Figure 5 presents the variation of inlet and outlet temperatures to the store. It is clear that the inlet temperatures to the store with the PCM modules increases at a greater rate than the other stores. This is a result of the slower rate of heat transfer into the bulk of the PCM causing a more rapid rise in the PCM temperature adjacent to the heat transfer surfaces and thus the outlet temperature from the stores. The levelling out in the rate of temperature rise is due to the establishment of a pseudo steady state operating temperature gradient through the stores. The rate of increase of the outlet temperature to the water module store is greater than that for the PCM module store at 5400 seconds and indicates that the higher specific heat capacity of the PCM is having an effect. Simulations for longer time periods are required to determine if the

PCM store can provide an advantage in terms of lower solar collector operating temperatures and greater efficiency. It is also clear from this figure that for the water filled store the tank fluid is all circulated through the collector before the inlet temperature increases.

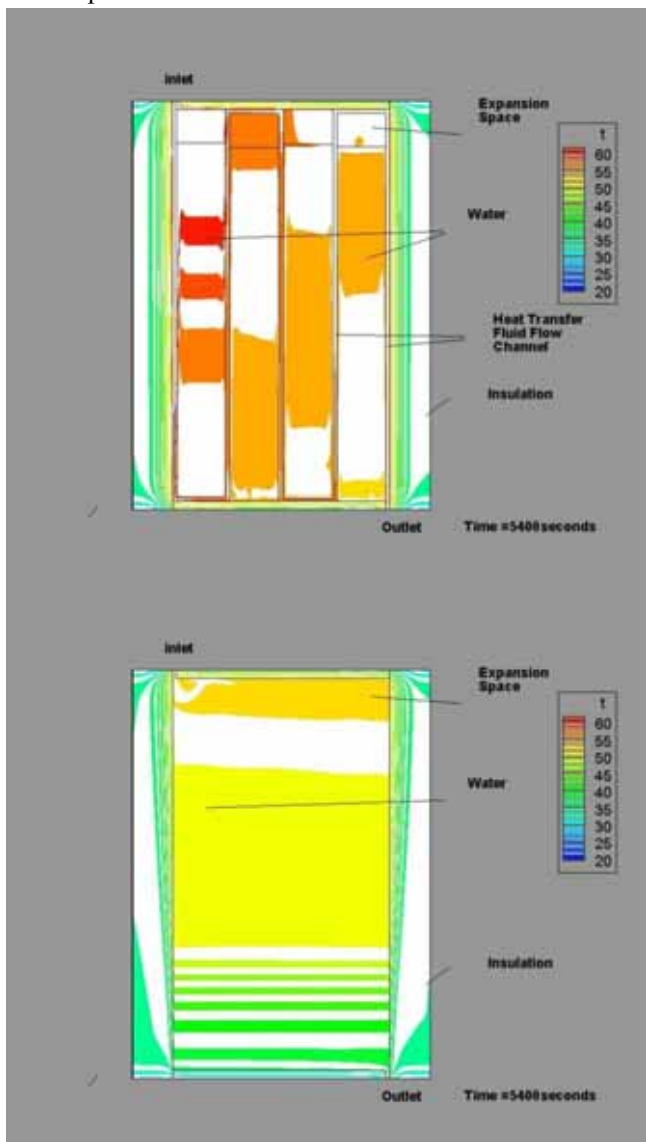


Fig. 4: Isotherm plots for the charging of the two different water based stores at 5400 seconds.

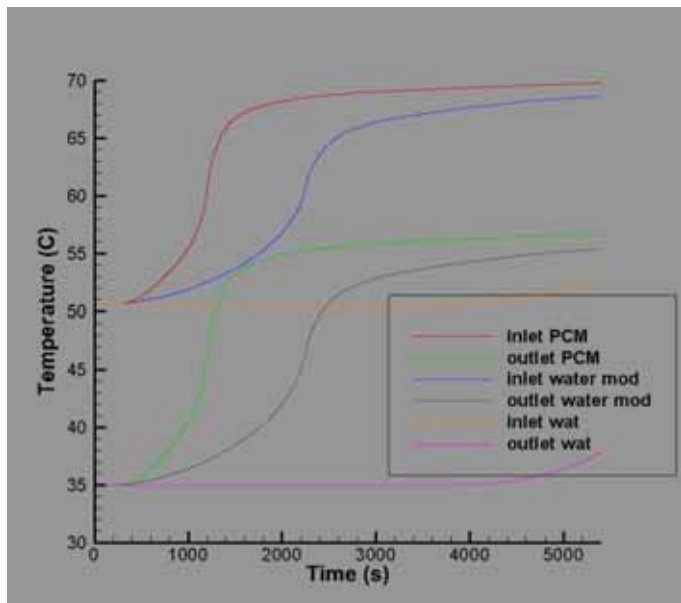


Fig. 5: Predicted inlet and outlet temperatures for the 3 stores simulated

### 3.2 Store Discharging

The predicted isotherms for discharging of the PCM store at times of 600 and 1200 seconds are presented in figure 6. It is evident that by 1200 seconds there is a layer of solid PCM on the internal surfaces of the modules. Due to the temperature difference that occurs across the modules resulting from the flow of the heat transfer fluid, a number of fluid circulations occur within the liquid PCM in each module. This results in non-uniform solidification across the surfaces. For comparison in figure 7 the predicted isotherm plots for the two different water based storage systems are presented. The thermal stratification is clear in the water module store. Due to the effective thermal stratification in the simple water store the majority of the hot water is discharged with little mixing. This can also be seen in figure 8 which presents the predicted outlet temperatures with time for the 3 stores.

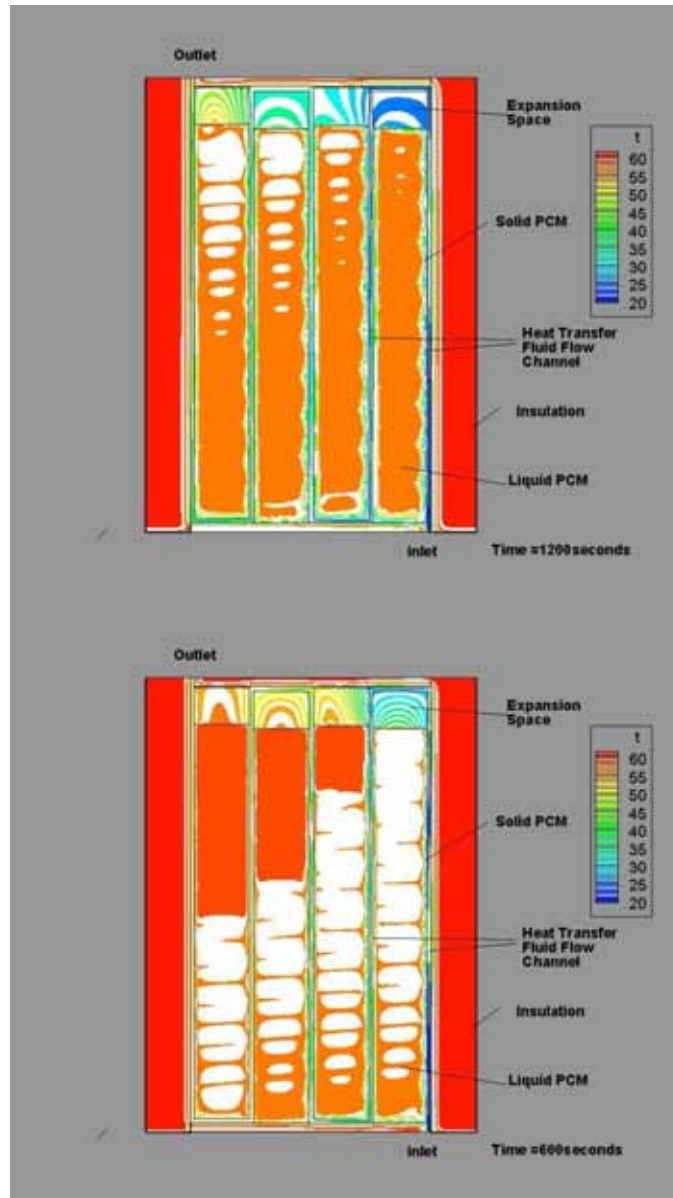


Fig. 6: The predicted isotherms for the PCM module store during discharging at times of 600 and 1200 seconds.

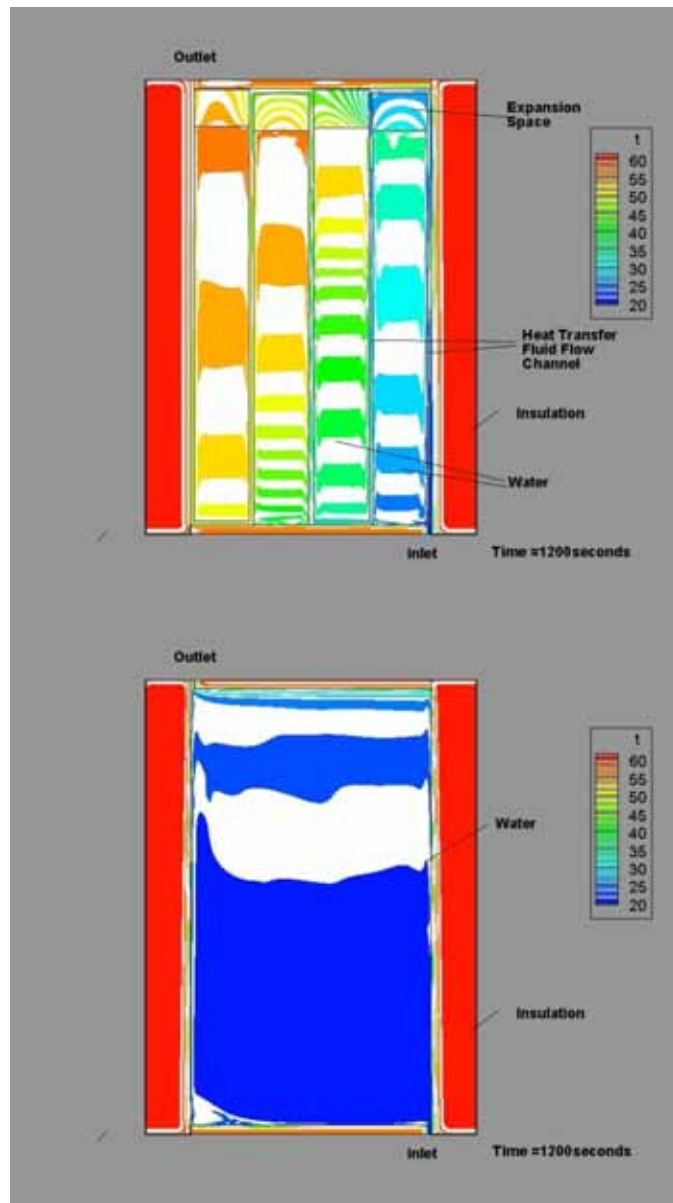


Fig. 7: The predicted isotherms for the water based store during discharging at a time of 1200 seconds

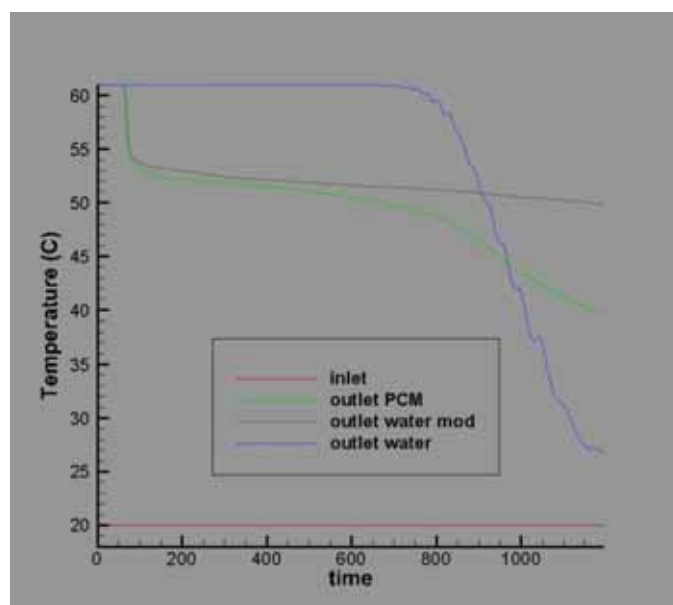


Fig. 8: The predicted outlet temperatures from the 3 stores during the 1200 second discharge period.



From figure 8 it can be seen that the simple water store effectively discharges at a constant temperature of 61°C for the first 800 seconds, the outlet temperature then rapidly decreases. This profile is due to the good thermal stratification that is maintained in the tank during discharge and the relatively small amount of mixing. The two stores that include modules deliver water at 61 °C for less than 75 seconds, corresponding to the hot water in the fluid flow channels being discharged, after this the temperatures drop to approximately 53°C with heat being transferred from the modules to the heat transfer fluid. Subsequently the PCM starts to solidify on the internal surfaces of the PCM modules reducing heat transfer and the fluid exit temperature below that of the water filled modules. At 800 seconds there is still significant heat within the PCM modules evident from the isotherm plot in figure 6, however it is not being effectively transferred to the heat exchange fluid.

#### **4. Conclusions**

Results from simulations of a PCM modular storage system using an enhanced PCM model and two water based stores are presented. Illustrative isotherm plots for selected times during charge and discharge of the stores were shown. The predictions indicated that for the PCM store, circulation temperatures, to and from the solar collector would rise more rapidly than for the water based stores. This would enable more heat to be generated and stored at higher potentially more useful temperatures. Discharging simulations indicated that although the PCM store contained more energy, due to solidification of PCM on the heat transfer surfaces it was not possible to realise the advantage of this.

#### **5. Acknowledgement**

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