PREDICTED CHARGING EFFICIENCY OF A LATENT HEAT ENERGY STORAGE SYSTEM LINKED TO A SOLAR THERMAL COLLECTOR SYSTEM

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1. 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. Finned metal heat transfer surfaces or an embedded metal matrix may effectively address this problem. Two and three 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 selected system geometries with and without fins incorporated to enhance heat transfer to the PCM. Isotherm plots are presented for both charging and discharging of PCM modules within a thermal energy store.

2. 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. 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. The application considered in the present work is a thermal energy store using a phase change material with a phase transition temperature of 55˚C for use with a domestic scale solar hot water system.

3. Methodology

3.1 The Thermal Energy Store Design

The configuration of the thermal energy store design simulated is illustrated in figure1. The store is comprised of an outer metal shell which is externally insulated. Inside the store is divided into three sections, an upper plenum chamber, the central storage region housing PCM enclosed within an array of aluminium containers and a lower plenum chamber. When charging the store, hot water from the solar collector enters at the top of the upper plenum chamber. Due to its temperature being greater than that of the fluid already present in the plenum chamber and a baffle plate, buoyancy forces lead to thermal stratification with the new fluid distributed to the upper part of the plenum chamber. This results in a low velocity plug flow developing through the main part of the store. As the hot water flows down through the store heat is transferred from it into the PCM containers. At the base of the store a second plenum chamber with baffle plate is included to allow the plug flow hypothesis to be extended to flows in which hot or cold water enters at the base of the store.

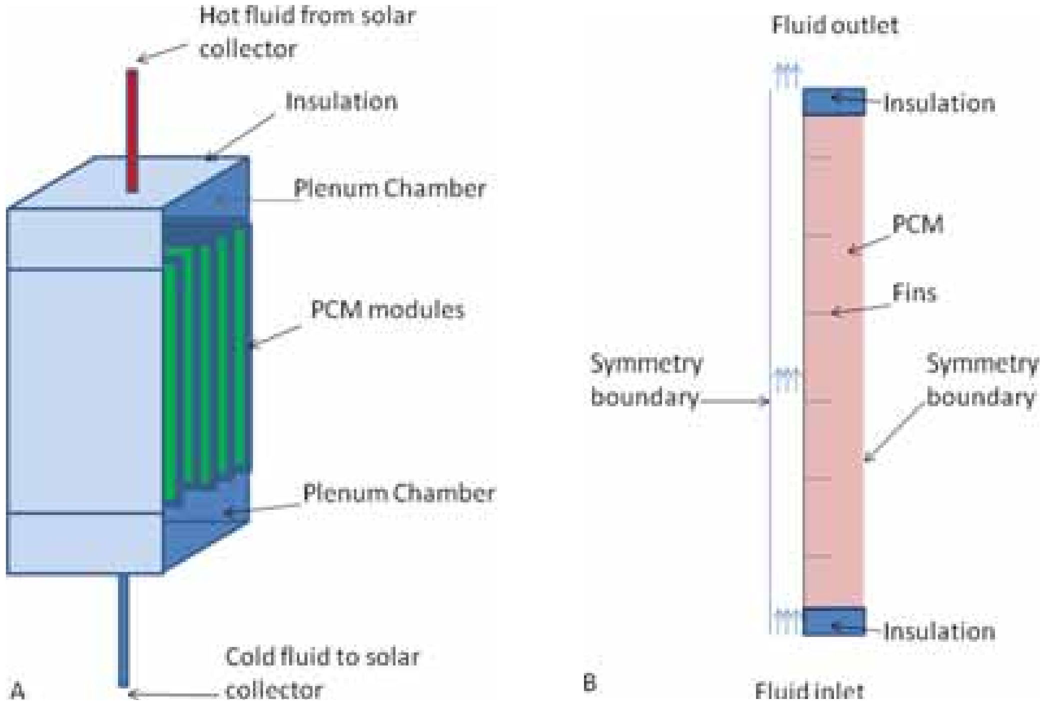


Fig 1: A schematic diagram of the proposed PCM thermal energy storage system (A) and a schematic of the modelled computational domain adopted for the PCM storage unit (B).

2.2 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. Two and three dimensional transient finite volume models with temperature dependant material properties have been developed to predict 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. Phase change occurs over a preset temperature range, 55-56˚C, the model allows the enthalpy to be varied within the temperature of phase change to more accurately simulate real phase change behaviour. The solution domain for the energy equations encompasses the phase change material and its enclosing container, the solution domain for the momentum equations is limited to that in which liquid phase change material or liquid heat transfer fluid exists. The models employ reduced time steps when rapid melting of the phase change material is taking place which enables a stable solution to the equations to be obtained. All equations are solved using the Bi-CGSTAB iterative equation solver (Van der Vorst, 1992), thus allowing significantly larger systems of equations to be solved in a reasonable time when compared to that required for direct solution methods.

The modelled computational domain is illustrated in figure 1B. A two dimensional modelling approach was adopted for this analysis, based on the assumption that the modules are sufficiently long so that end effects due to the end walls of the PCM modules will not influence greatly the heat transfer and fluid flow in the bulk of the modules. The symmetry boundaries indicated are at the vertical centre line of the PCM module and at the vertical centre line of the water filled heat transfer fluid channel, this boundary is adiabatic and the horizontal u-component of velocity is zero. At the inlet to the water filled fluid channel a fluid flow velocity and temperature are specified. A layer of insulation 10mm thick is simulated at the base and top of the module with a heat loss rate from the exposed external boundary of 5 $Wm^{-2}k^{-1}$ specified. The PCM container is 300mm tall and 60mm wide with walls and fins made from 1mm thick aluminium. The heat transfer fluid channel is 10mm wide. The properties of the materials used in the simulations are summarised in Table 1.

Tab. 1: Properties of Materials used for simulation of the phase change energy storage module.

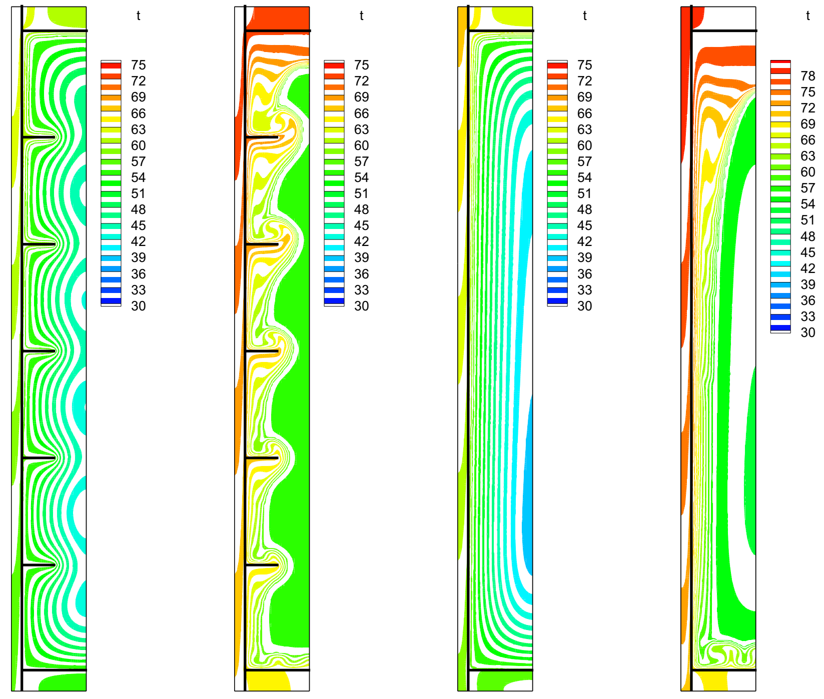
Material	*Thermal Conductivity $Wm^{-1}K^{-1}$*	*Specific Heat Capacity $Jkg^{-1}K^{-1}$*	*Density kgm^{-3}*	*Dynamic Viscosity Nsm^{-2}*
PCM Solid	0.19	1800	820	n/a
PCM Transition	0.19	124960	820	n/a
PCM Liquid	0.18	2400	820	0.026
Insulation	0.04	2012	24	n/a
Aluminium	237	2702	903	n/a

PCM transition temperature range is between 55 and 56˚C. When melting the PCM is assumed fluid above 56˚C and solid below this. When solidifying the PCM is assumed fluid above 55˚C and solid below this.

3. Results

3.1 Charging

For a store with a cross section 490mm wide and 500mm long the fluid flow cross sectional area with the PSM module dimensions and flow channels specified above will be 0.035m^2, the fluid flow velocity through the PCM modules simulated was 0.0011ms^{-1} giving a volume flow rate of 0.0385 ls^{-1}. If the store is linked to a 2m^2 area of solar collectors working at an assumed efficiency of 60% with an incident solar radiation of 800W/m^2 the temperature rise from inlet to outlet of the solar collector will be approximately 6˚C. When undertaking the charging simulations, initially the store is all assumed to be at 25˚C, the inlet fluid temperature to the store is set at 31˚C, for the duration of the simulation the inlet fluid temperature is maintained at 6˚C higher than that at the outlet from the store. Figure 2 shows the predicted isotherms for 2 store configurations, with and without fins, after one and two hours of charging with the fluid inlet at the top.



Time = 1 hour **Time = 2 hours** **Time = 1 hour** **Time = 2 hours**

Fig. 2: Predicted isotherms for PCM modules with and without fins for a fluid inlet velocity of 0.0011ms^{-1} at the top of the fluid flow channel. Fluid inlet temperature is maintained 6˚C higher than fluid outlet temperature

From figure 2 it can be seen that at 1 hour the heat transfer to the PCM in both systems is by conduction with all of the PCM still in its solid state. After 2 hours the PCM adjacent to the aluminium heat transfer surfaces is molten with the clear effects evident of convection in the fluid PCM. The movement of the fluid PCM adjacent to the surface leads to a degree of thermal stratification in both systems. Significant differences in temperature isotherms and the melt front location can be seen between the two systems resulting from the presence of the fins.

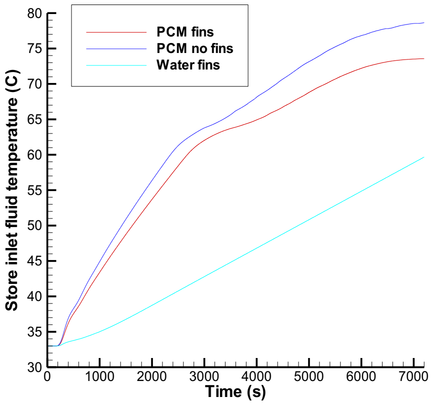
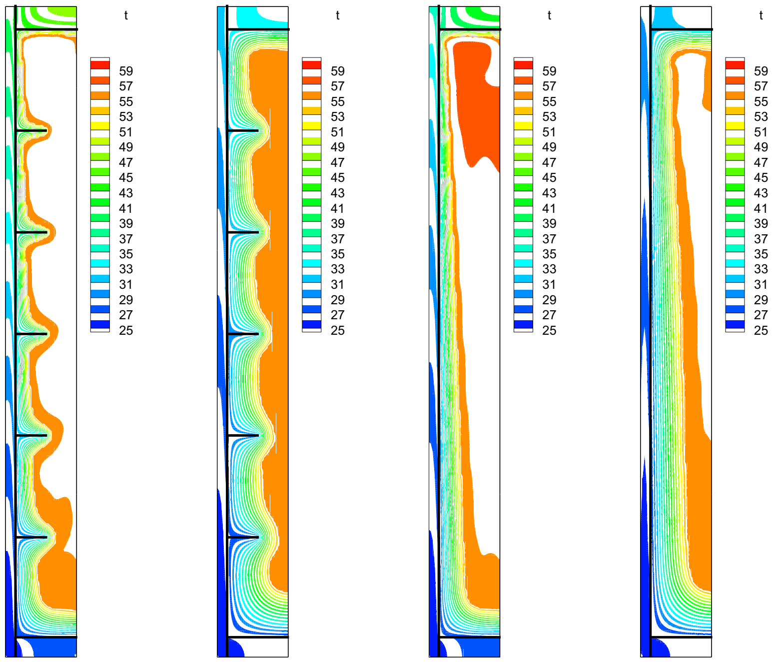


Fig. 3: The predicted change in inlet fluid temperature with time when charging a PCM module with and without fins and a water filled module.

From figure 3 the predicted variation of inlet fluid temperature with time can be seen for the PCM modules with and without fins and a water filled module with fins. The gradient of the lines is an indication of how well heat is being transferred from the circulating collector fluid to the storage module, shallower gradients indicating higher rates of heat transfer. Heat is transferred more rapidly to the water filled modules than to the PCM filled modules for the first three thousand seconds, after this because the PCM is melting and changing phase the rate of increase in inlet fluid temperature decreases significantly. The fin arrangement selected provides a slight improvement in heat transfer to the PCM compared to the system with no fins. Between 6000 and 7000 seconds the store inlet fluid reaches a steady temperature, this implies that the temperature drop of the fluid though the storage module is 6˚C. A potential benefit of using a PCM store of this design is that significantly less energy is required to elevate the store to the melt temperature of 55˚C, more energy is then stored at higher temperatures, i.e. in the 55 to 60˚C temperature range.

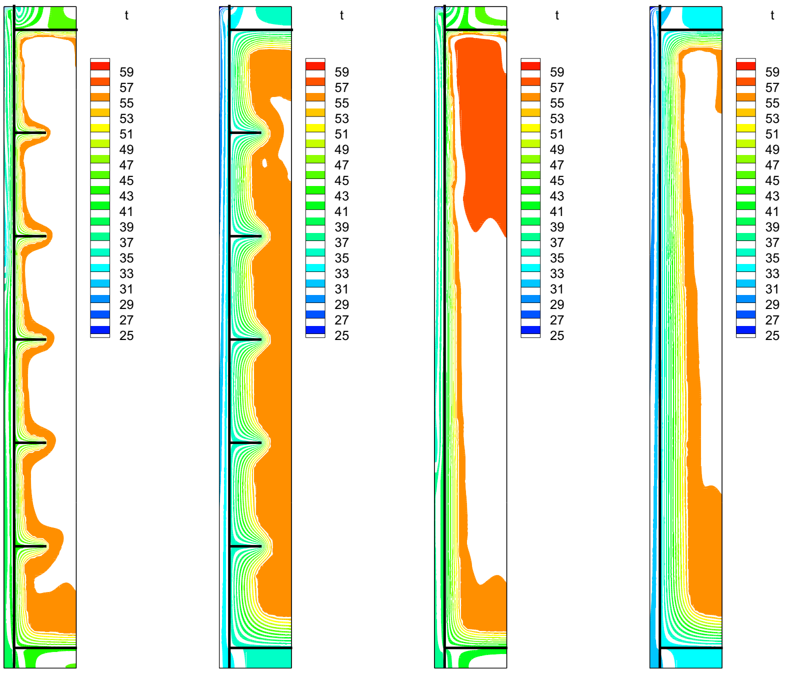
3.2 Discharging

The simulations performed for discharging the storage unit again used an inlet flow velocity for the fluid of $0.0011 ms^{-1}$, the temperature at inlet was set to a constant value of 25˚C. The store was initially assumed to be at a uniform temperature of 60˚C, 4°C above the commencement of phase transition and 5°C above solidification. The predicted isotherms at times of 30 minutes and one hour for modules with and without fins are presented in figure 4 for fluid inlet flow at the base of the system and in figure 5 for fluid inlet flow at the top of the system. It can be seen from figure 4 that the fins increase the rate of heat extraction from the PCM compared to the system with no fins, leading to a more uniform slightly lower liquid PCM temperature. At the time of one hour a greater volume of PCM has solidified in the finned system and the liquid PCM temperature is lower than that in the non finned system. At one hour the temperature difference between the hot liquid PCM and the aluminium heat transfer surfaces is high due to the low thermal conductivity of the solid PCM leading to a low level of heat removal even though a significant volume of PCM is still in the liquid state. In both cases, with and without fins, the thickness of solidified PCM is greater in the lower section of the storage module. This is a consequence of the cold fluid entering the store at this point, and the hotter PCM rising to the top of the store with cooler PCM falling to the bottom where it solidifies. In both cases due to the large amount of molten PCM remaining in the systems a significant amount of high temperature energy remains available if it can be effectively extracted.



Time = 30 minutes **Time = 1 hour** **Time = 30 minutes** **Time = 1 hour**

Fig. 4: Predicted isotherms at 30 minutes and 1 hour for PCM modules with and without fins, initial module temperature of 60˚C and inlet flow of 0.0011ms-1 at the base of the store with a constant temperature of 25˚C.



Time = 30 minutes **Time = 1 hour** **Time = 30 minutes** **Time = 1 hour**

Fig. 5: Predicted isotherms at 30 minutes and 1 hour for PCM modules with and without fins, initial module temperature of 60˚C and inlet flow of 0.0011ms^{-1} at the top of the store with a constant temperature of 25˚C.

Comparing figure 5, the case when the cold inlet fluid is introduced at the top of the PCM module, with figure 4 the two major differences that can be seen are that the aluminium heat transfer surface is at a more uniform temperature with little temperature gradient between the top and the bottom of the module and that a smaller volume of PCM has solidified, in particular the volume solidifying at the base of the module is much reduced. Due to the thinner layer of solidified PCM the thermal resistance between the molten PCM and the heat transfer fluid is lower and more heat is removed from the molten PCM. The inlet of cold water from the top results in a fluid circulation in the PCM that leads to the cooled PCM adjacent to the wall sinking with hotter PCM replacing it and reducing solidification. The result of this is that the average temperature of the molten PCM after one hour in figure 5 when the cold inlet fluid is introduced from the top of the store is lower than that shown in figure 4.

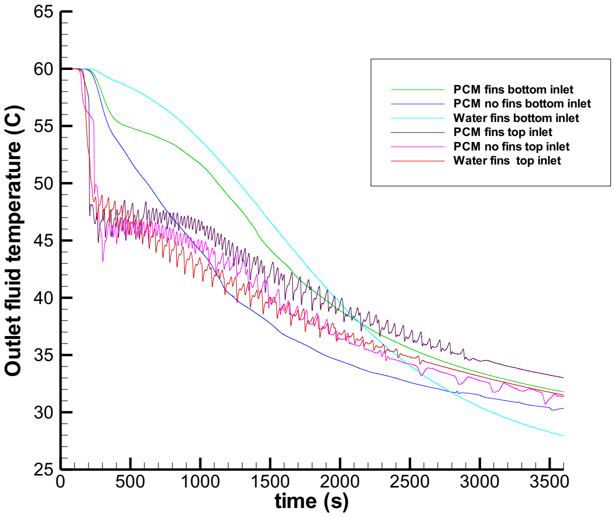


Fig. 6: The variation of outlet temperature with time for an inlet flow velocity of 0.0011ms^{-1} at a temperature of 25°C for PCM modules with and without fins. Predictions are shown for fluid inlet at the top and base of the store and for a module filled with water.

From figure 6 it can be seen that the discharge temperature of the system in which the module is filled with water remains higher than the PCM filled modules for the first 1800 seconds when cold water is introduced at the base (69.3 l discharge), after 2700 seconds all PCM modules are maintaining higher discharge temperatures, and after one hour the water filled system is effectively discharged while the PCM systems are still providing water at temperatures between 33 and 37°C. The PCM module with cold fluid inlet at the base initially maintains higher water outlet temperatures than all systems with cold water inlet at the top of the store, the finned PCM system performing similarly to the water filled system and maintaining higher outlet temperatures than other systems for approximately 1600 seconds. When the cold inlet fluid is introduced at the top of the store the outlet fluid temperature is characterised by a rapid drop in temperature of approximately 15°C. This is followed by a period in which the outlet fluid temperature reduces steadily with a superimposed oscillation of 1 to 1.5°C which decreases in frequency with reducing average outlet temperature. This oscillation is a result of a recirculation flow that forms in the fluid flow channel: the introduced cold water sinks in the centre of the channel and warm water rises adjacent to the heat transfer surface, the non steady nature of this circulation and fluid mixing leads to an effective pulse in the outlet temperature. This can be seen in the predictions for the water filled module also.

4. Conclusions

A detailed simulation model for a phase change filled module forming part of thermal energy store in a domestic solar hot water system has been developed. Charging predictions indicate that if sized correctly the variable thermal capacity at different temperatures that a PCM module provides will allow more heat to be stored at higher more useful temperatures. When charging the inclusion of fins only aids charging marginally, when discharging the inclusion of fins allows heat to be more effectively transferred from the store to the heat transfer fluid, the fin system simulated transferring heat only slightly less quickly to the heat transfer fluid than for a water filled module while storing significantly more energy.

5. References

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