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ADVANCED HEAT PUMPS WITH THERMAL STORAGE FOR DEMAND SIDE MANAGEMENT

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ABSTRACT

Air source heat pumps are easy to install, and in particular for those units capable of achieving higher temperatures, are able to be directly retrofitted into the higher-temperature hot water heating systems typically found in UK homes. Phase change materials (PCMs) are attractive for use in thermal energy store applications due to their high-energy storage density over a small temperature range, therefore allowing the air-source heat pump to operate during winter warmer afternoon ambient air conditions. This energy is then stored for evening use, with the added benefit of delaying the air-source heat pump start until after the peak electricity demand time of early evening. A finite-volume numerical simulation model has been used to examine the thermal performance of PCMs augmented hot water thermal energy store for a heat pump energy storage application. These simulation results will be used to improve the system operation in winter and identify limitations when used for heat pump on-off control application.

Keywords: finite-volume, phase change material, heat pump, energy storage.

1. INTRODUCTION

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Domestic heating and hot water systems typically consume 50% of the energy demand for building during the winter months. Heat pumps are proven energy efficient space heating devices for homes in the UK. Ground source heat pumps require extensive ground preparation and under-floor heating systems to attain higher efficiencies. They are used primarily for low-temperature (<40 ◦C) space heating applications. Air source units are easier to install, and in particular for those units capable of achieving higher temperatures such as economised vapour injection, are able to be directly retrofitted into the higher-temperature hot water heating systems typically found in UK homes. However, considering the heating capacity decreases when the outdoor air temperature becomes lower and when there is frost formation on the outdoor heat exchanger surfaces in humid climates, the result is that the system is oversized for periods of warmer weather and the system short cycles, leading to reduction in compressor lifetime. As boiler replacements their role is that of “on-demand” space heating and therefore the increased electrical demands can result in challenges for an already weak electricity distribution network.

As an alternative to complex load management systems such as variable speed compressors, a buffer tank with high energy store capacity can ease up the on-off cycle problem and also shift the heating systems to off peak periods. The role of energy storage is therefore to allow the air-source heat pump to operate during warmer afternoon ambient air conditions. This energy is then stored for evening use, thus delaying the air-source heat pump start until after the peak electricity demand time of early evening. Further a load is always provided for the heat pump which reduces short cycling of the compressor and increases product lifetime.

Phase change materials (PCMs) are attractive for use in thermal energy storage and temperature control applications due to their high-energy storage density over a small temperature range (Abhat, 1981; Duffie and Beckman, 1991; Ismail and Goncalves, 1999; Wirtz, 1999; Huang et al., 2004; Khudhair A. M. and Farid M.M., 2004). The key benefits of using the PCM storage system as a component of a heating system can be summarised as a reduction in equipment size, capital cost savings, energy cost savings, peak energy savings and improved system operation (ASHRAE, 2003). However the low thermal conductivity of PCMs limits their application when needs quick response to heat charge and discharge. The use of a PCM as the storage medium stabilizes the output temperature of the water supply system by storing heat near the melting temperature. The latent heat of a PCM, such as paraffin wax, can be over 30 times greater than water sensible heat capacity. Therefore less space is required to store the same amount of heat. The smaller volume also reduces the heat loss from the storage. The latent heat storage can reduce short cycling of the compressor especially when the heat demanding is reduced in summer.

So far only the water storage systems have been commercially used in space heating systems for residential buildings. There have been no detailed investigations into the modifications resulting from using phase change materials for thermal energy storage systems for heat pump applications, although some work has been carried out to achieve high rates of heat transfer and rapid charging on PCMs (Huang et al 2004). The experimental and simulation results showed that fins in contact with the PCM could greatly improve the heat transfer of the melting process of the thermal storage unit. The analysis of their experimental results showed that the enhancement mechanism of the fin was attributed to its ability to improve both heat conduction and natural convection very effectively. Solid-liquid transition PCMs have been incorporated into gypsum wallboards and augmented to building cavity walls to provide passive energy storage in buildings (Paris et al, 1999, Huang et al., 2006). The thermal performance of solar-aided latent heat storage systems have been theoretically and experimentally studied by Esen (2000) and Comakli et al. (1993).

Reviews of the general numerical techniques for the solution of solid-liquid phase change problems have been undertaken by Dincer and Rosen (2002) and Voller (1997). For the conduction-dominated phase, in some models the effects of natural convection in the melt phase is incorporated in the model by using an enhanced thermal conductivity (or thermal diffusivity) for the melt (Brousseau and Lacroix 1998; Farid and Hussian, 1990). Studies have been undertaken that focus on the melt process inside containers using three-dimensional (Huang et al., 2007) and two-dimensional numerical models for rectangular cross section containers (Bertrand et al.1999, Binet and Lacroix, 1998) and for cylindrical containers (Sasaguchi et al.1997). In spite of the impressive number of articles published on the subject over the last twenty years, simulation of PCMs for real thermal applications with cyclic melting and solidification subject to realistic boundary conditions remains a challenging task.

The new designed heat storage for heat pump heat management is described and its basic thermal characteristics are evaluated. It is a kind of PCM pin-fin water storage. The vessels filled with phase change material (PCM) are vertical augmented to the water storage. This design combines two important features of heat storage – high heat transfer surface (due to large number of PCM vessels/fins) and high thermal capacity (which results from the use of PCM). Such a heat sink can be very effective in removing heat from heat pump in steady states, and simultaneously it can stabilize the temperature of the heat dispassion. Thermal characteristics of the device in steady conditions, i.e. overall thermal demanding, were estimated by simple energy balance. Thermal performances of heat storage in transient conditions were determined base on numerical simulation of transient heat transfer, including melting process of PCM. These results show the benefits of the use of different PCMs in the different structure of heat storages.

In this paper, an experimental validated finite volume numerical simulation model used for PCM temperature regulation application (Huang et al., 2004) has been adopted to examine the thermal performance of PCM for a novel heat pump energy storage with on-off cyclic application. The performance of the heat pump PCM water storage has been modelled which the running conditions used the experimental data from laboratory experiments and field trials. As yet untried PCM applications will now be modelled and this will be then coupled to the dynamic simulation of the heat pump to understand the performance of a heat store in this system. The thermal processes occurring in the integrated PCM storage heat pump system can be predicted and the time lag for pre-heating could be used for economic analysis of heat pumps in the future. These simulation results will be used to improve heat pump system size selection and identify design limitations for energy storage.

2. HEAT PUMP PCM-WATER STORAGE SYSTEM CONFIGERANTIONS AND CONDITIONS

2.1 PCMS selection for PCM water storages

The selection of the PCM is a crucial point. There are problems associated with the volume expansion of the PCM and the density change in the PCM that takes place upon melting/solidification (Dincer and Rosen, 2002). The most suited PCM for the desired application should have a fixed or relative close range of melting point close to the maximum heating supply point of the heat pump with high latent heat of fusion to absorb maximum heat before phase change, high thermal conductivity for efficient heat removal, low or no corrosive behaviour, non combustible, phase congruence, low cost and ease of availability. Unfortunately none of the available PCMs possesses all of the desired properties altogether so a trade off is necessary. Based on the stated properties, a PCM was selected prioritising melting point, latent heat of fusion, combustibility and thermal conductivity and was evaluated for the system performance. Phase change material enclosed in vessels start to absorb additional amount of heat. Thus, PCM protects against excessively rapid increase of temperature. In order to obtain such performance characteristics, phase change material should be chosen so that its melting temperature was lower than temperature of heat pump condenser 5⍰C during normal operation. In those conditions the whole amount of PCM should remain in phase change state.

Table 1 Physical properties of the materials used for simulations

	RT42	RT52	Water	Copper
Latent heat of fusion (kJ / kg)	174	173	N/A	N/A
Melting temperature (°C)	41	52	N/A	
Solid phase density (kg / m^3)	880	880	N/A	8795
Liquid phase density (kg / m^3)	760	760	983	N/A
Thermal conductivity (W / m K)	0.2	0.2	0.609	385
Specific heat (kJ / kg K)	2.1	2.1	4.185	0.385

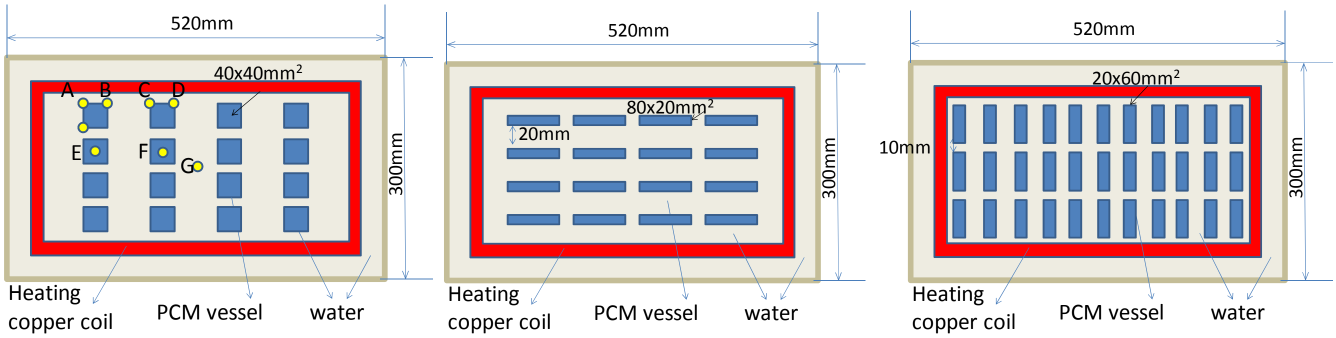
The melting point of the high melting point PCM should be higher than comfort temperature but less than the maximum temperature obtainable from the heat pump. Thus for a residential application PCMs should be in the range of 55 °C. Solid-liquid phase change material RT42 and RT52 (paraffin based phase change material) (Anon, 2011) that is available commercially have been used for simulation in this study. Two types of PCM with different meting points 41 and 52°C have been studied for the two system configuration and compared with the full water storage. The closed PCM vessel allows for volume expansion of the PCM to take place within the structure. The heated PCM material will be melted during the off peak time, then during the night peak time or in the morning heating time it is solidified and the stored latent heat is released to meet some parts of the space heating load. Physical properties of the PCM RT42 and RT52, copper coils and water used as input data in the simulations are summarised in Table 1.

2.2 Heat Pump PCM storage configuration

The rectangle water storage with 30cm by width, 52cm by length and 100 cm by height is designed for residential home heating store. Copper tube helix heat exchanger is situated inside the water storage along the storage wall with gap through which to heat the water for the hot water supply for residential application. Two copper tube with diameter of 20 to the gaps of wall at 40 is invested. The PCM is filled in different square or rectangle shaped vessels and augmented into the water storage vertical in case I to V (Table 2). The detailed schedules of the system for case II, IV and V are listed in Figure 1. In order to meet the challenge of low heat conductivity, the coils must have a high surfaces area in order to (a) heat the storage effectively doing off-peak heating; (b) heat the home effectively during heat demand times; (c) heat the home directly with the heat pump in times of greater demand. During the heating period the heating load is firstly met by the storage system, and if the load exceeds the storage system capability, then the heat pump system will meet the rest of the load.

Table 2 Heat pump heat storage configurations

	PCM vessel number	Single PCM vessel size (cmXcm)	PCM area (cm^2)	Water area (cm^2)	PCM perimeter (cm)	PCM/water area ratio	PCM/heating coil pipe perimeter ratio
Water storage	N/A	N/A	0	1236	0	0	0
Case I	8	4X4	128	1108	128	0.116	0.485
Case II	16	4X4	256	980	128	0.261	0.485
Case III	16	4x8	256	980	192	0.261	0.727
Case IV	16	2X8	256	980	320	0.261	1.212
Case V	33	2X8	528	708	660	0.746	2.500



Case II Case IV Case V

Figure 1. A horizontal cross-section of the simulated water storage with cooper tube helix heat coils and PCM vessels for HP system heat water store

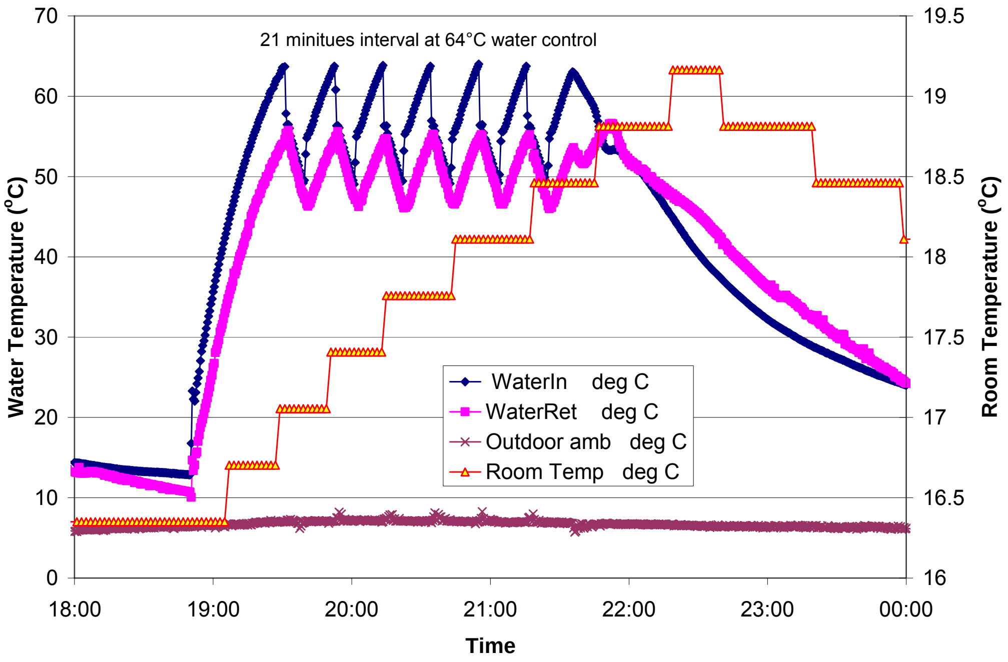


Figure 2 Temperatures of on-off control HP system with indoor and outdoor ambient temperature

3. MATHEMATICAL MODEL

The basic mathematical model used is based on two dimensional model (Huang et al., 2004). A schematic of the system modelled is illustrated in Fig. 1. It is assumed that the heat Hsupply supplied by heat pump is transferred to the heating copper coil in the water storage, therefore the PCM in the vessels inside of the heat store is heated.

Assuming (i) the heat transfer coefficients from the coil surface to the surrounded water has the fixed values, (ii) that in time Δt the temperature change within the PCM is from TPCM,t to TPCM,t+Δt and within the water in the storage is from Twater,t to Twater,t+Δt (iii) there is no heat lost from the adiabatic boundaries of the storage system to the surrounding. The energy balance for a storage system when the calculated temperature TPCM,t+Δt is smaller than the PCM melt temperature Tm is:

$$H_{\sup ply,\Delta t} = \sum (T_{water,t+\Delta t} - T_{water,t})\rho_{water} c_{p,water} V_{water} + \sum (T_{PCM,t+\Delta t} - T_{PCM,t})\rho_{PCM} c_{P,PCM} V_{PCM} + Q_{demand} \quad (1)$$

where, VPCM and Vwater are the water and PCM volumes in the storage respectively. When the calculated water temperature TPCM,t+Δt is greater than Tm , thermal energy is used for phase change and the temperature in the PCM remains constant at Tm until the phase change is completed, i.e. the absorbed energy in the PCM is larger than the latent heat of fusion H. The total time for phase change is ΔΔt for which this condition holds. The energy balance for the phase transition is:

$$H_{\sup ply,\Delta t} = \sum (T_{water,t+\Delta t} - T_{water,t})\rho_{water} c_{p,water} V_{water} + \sum (T_{PCM,t+\Delta t} - T_m)\rho_{PCM} c_{P,PCM} V_{PCM} + HV_{PCM} + Q_{demand} \quad (2)$$

In this study, the thermal performance of the storage with the constant heat input for water only storage has been compared with those PCM augmented water storage. The detailed configurations of the PCM storages have been detailed are presented in table 2. The storage is insulated. The surrounding temperatures along with the initial store temperature were set to 10 °C.

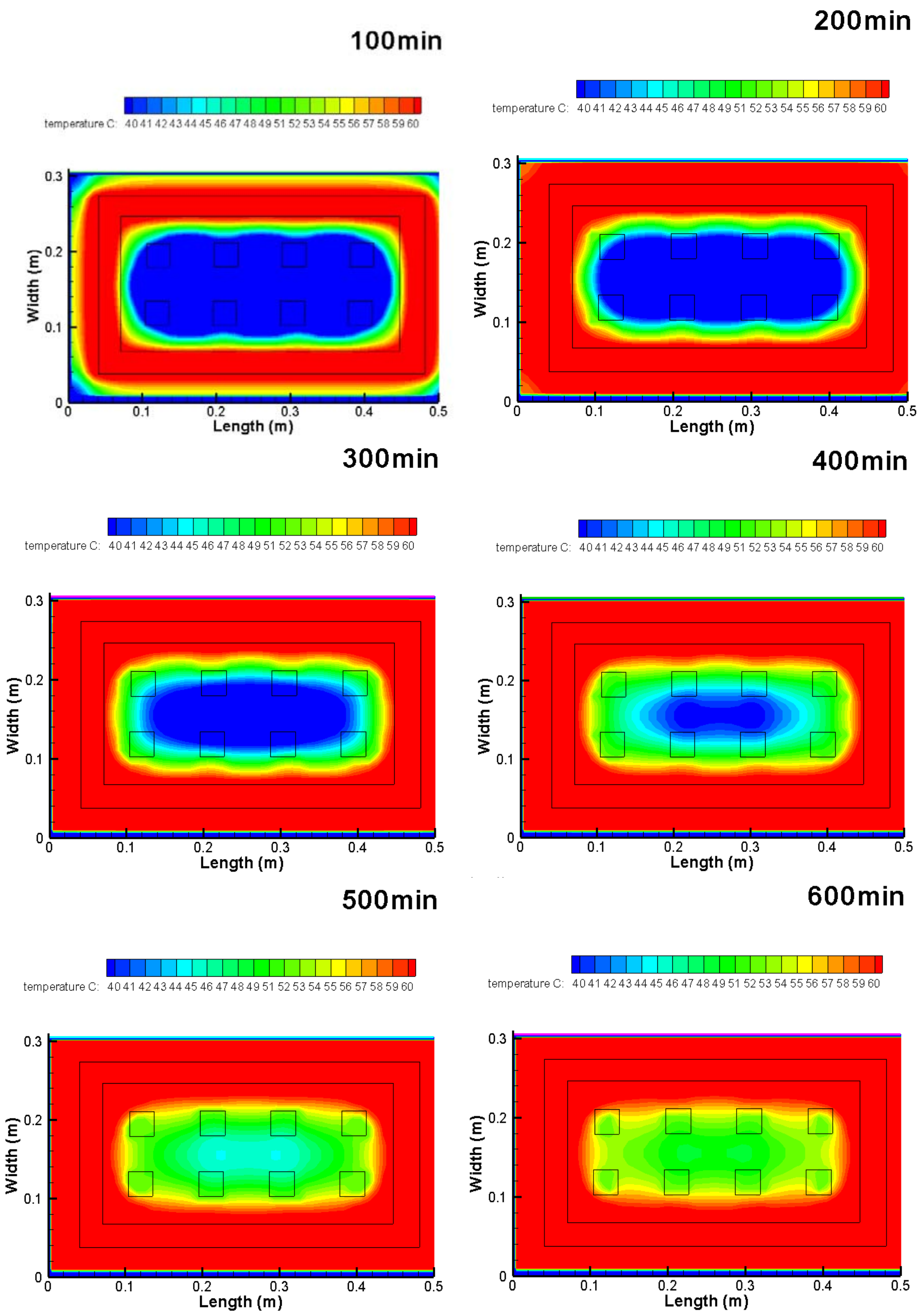


Figure 3 Cross-section isotherms of the water heat storage with 65°C heating coils and RT52 vessels for different time process

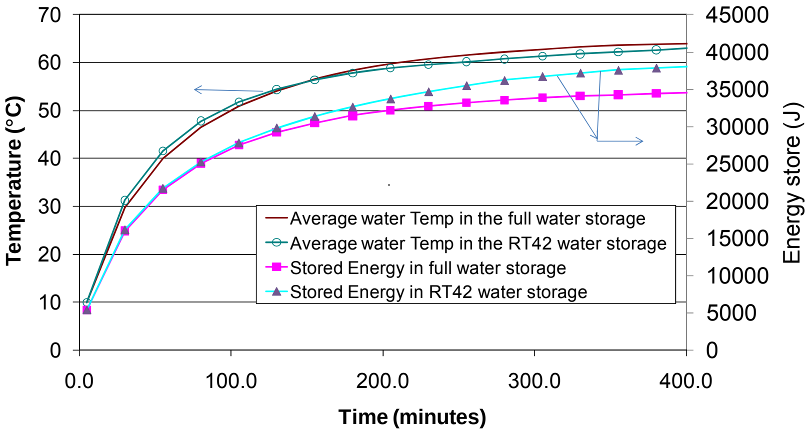


Figure 4 Energy stored and average temperature with time evolution in the full water storage and PCM RT42 water storage in Case I.

4. PREDICTION RESULTS ON THE HEAT PUMP STORE

4.1 Performance of the PCM Water Storage with Constant Heat Pump System Supply Temperature

To improve the thermal comfort of indoor environment, a pre-heating run may be needed. The heat charge progress in the storage can be predicted by the simulation. PCM water storage with PCM RT52 vessels was investigated regarding the temperature distributions. The heat exchanger coil can provide hot water from HP in constant temperature of 65°C. Figure 3 shows the cross-section isotherms of the water heat storage with 65⍰C heating coils and eight RT52 vessels (Case I) for different time process. The input heat by the coil heats up the surrounded water. Due to the PCM inside of the copper vessels can absorb the latent heat in its phase change temperature, therefore the water temperature around the vessels can keep in lower phase transient temperature and absorb the latent heat. Due to the water high thermal conductivity and convection effect the water around the PCM vessels can enhance the heat transfer from the heating coil to the PCM vessels for heat store. However with the Case I the effect of PCM heat store is not significant. Figure 4 presents the energy stored and average temperature with time evolution in the full water storage and PCM RT42 water storage. From the prediction it can be seen that although there is no significant difference between the temperatures for the two water storages, the energy stored in the PCM RT42 augmented water storage can store more energy than the full water storage.

4.2 The Effect of PCM Temperature Stabilisation in the Heat Pump Water Heat Store with Different PCMs

The heat store capacity has been studied and compared with the water only and PCM-water stores. Two types of PCMs RT42 and RT52 with different melting temperatures have been simulated in the Case II store which has doubled amount of PCM compared with Case I. The average water temperatures in the water only store and PCM-water stores are presented in Figure 5 and 6. The temperatures inside of the PCM vessels on point E and F along with the central point G are also listed. The effect of PCM temperature stabilisation in the water storage can be seen in the points E, F and G for RT42 and RT52 PCMs. The average water temperature in the PCM-water store can be held in lower temperature than the heat pump on-off temperature for longer time to charge the heat from heat pump. The stabilised temperature in the water can reduce short cycling of the compressor. The stored latent heat in the PCM can be released to meet the peak time heating requirement. During the discharge, when the water return temperature dropped to 30°C, the PCM-water storage can provide higher temperature for longer time than the water only store. There is no significant effect from the type of PCMs for the simulated conditions.

The doubled PCM vessels than Case I increases the heat transfer area, however the increased heat transfer from the heat pump through the copper heat exchanger to the PCMs inside of the PCM-water store is not clear. A simple increase in volume does not improve performance due to the low thermal conductivity of PCMs. It must be combined with the improvement of heat conductivity of PCMs.

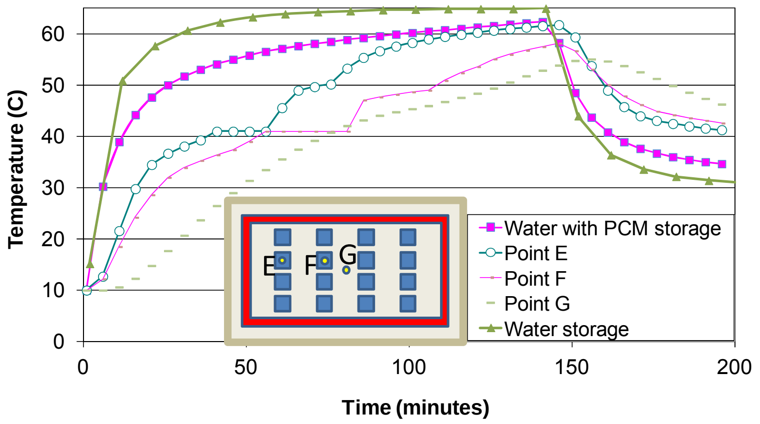


Figure 5 The comparison of the average temperature progress on heat charge and discharge in the water only storage and the PCM-RT42 water storage along with the PCM temperatures in points E, F and G

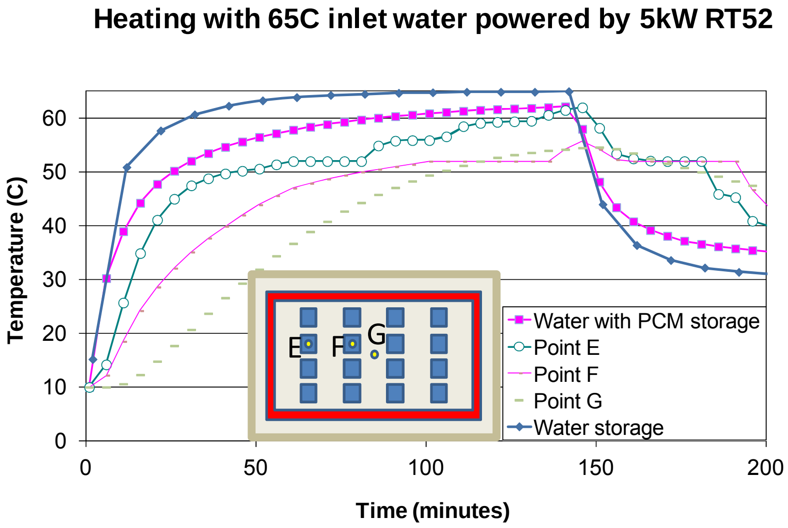


Figure 6 The comparison of the average temperature progress on heat charge and discharge in the water only storage and the PCM-RT52 water storage along with the PCM temperatures in points E, F and G

4.3 The Effect of PCM Temperature Stabilisation in the Heat Pump Water Heat Store with Realistic Heat Demanding

The realistic heat demanding and heat loss conditions have been used to study the performance of the PCM-water store. The average water temperature variations inside of the heat storage have been compared between the water only storage and the water-PCM heat storage in Case II situation in Figure 7. At the start stage there is a bit time delay on the first cycle. However due to the small amount of the PCM with low thermal conductive limited the temperature regulation effect. The reduced water volume by the PCM vessels makes the on-off cycle been reduced.

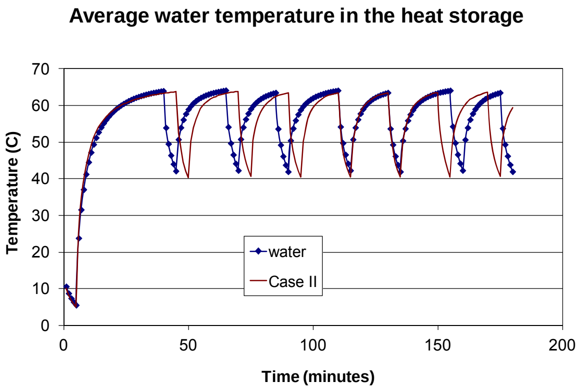


Figure 7 The average water temperature variations inside of the heat storage with water only and the PCM water storage with case II

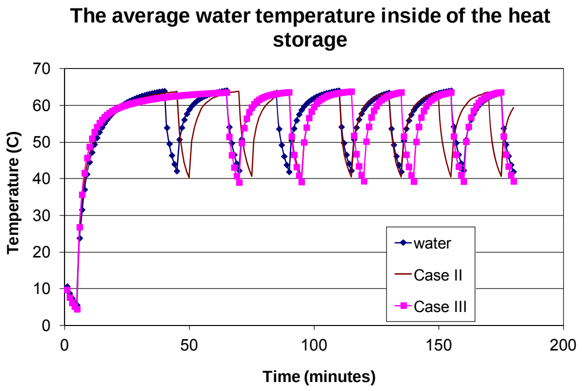


Figure 8 The average water temperature variations inside of the heat storage with water only and the PCM water storage with case II and III

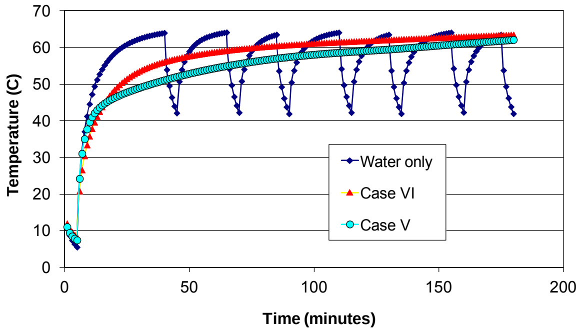


Figure 9 The average water temperature variations inside of the heat storage with water only and the PCM water storage with case IV and V

Figure 8 presents the simulated average water temperature variation in the storage with full water case, case II and case III with the inlet water temperature from the HP water supply scheme. From the figure 8 it can be seen that with the increased PCM and contact area the temperature stabilised effect is increased. Case III can absorb more energy therefore to reduce short cycling of the compressor and increase product lifetime. Further improvement can be seen in Case IV and Case V from Figure 9.

5. CONCLUSIONS

In conclusion, using a heat pump system with integrated PCMs storage can improve the heating capacity and it is believed that it will reduce the electricity cost for a residential home. It also can shift a portion of the heating loads to off peak hours, when electricity cost is potentially lower. PCM storage can be used to stabilise the house water temperature during the day time, while the storage unit can be used as a thermal barrier against heat loss during the night time because of its relatively high melting temperature and low heat conduction coefficient in its solid phase. The simulation results have also indicated that the thermal characteristics of the PCM and the configuration of the PCM storage vessel can result in advantageous control of the water temperature rise and drop during both day and night time operation. In the future, the thermal performance of the heat store with different defrosting strategies and set point temperatures will be studied. Furthermore, a realistic range of climate conditions will be simulated to study the thermal application of PCM in heat pump residential applications.

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