Performance Investigation of An Air Source Heat Pump for Residential Heat Supply Through PCM Underfloor Heating

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Summary

Phase change materials (PCMs) incorporated into building underfloor structure material for regulating the heat supply by effective storing the heat from Air source Heat Pump (ASHP) to meet the building demand side requirement are becoming ever-growing factor for installing renewable energy to building heating system.

A two dimensional temperature based finite volume numerical simulation model has been theoretically and experimentally validated for PCM underfloor heating system. A detailed theoretical investigation and analysis of PCM underfloor heating system driven by ASHP have been carried out. The dynamic performance of the heating system for the domestic building has been predicted with different ASHP operation conditions. An optimized operation condition has been suggested.

Key words: Numerical simulation, Phase Change Material (PCM), Underfloor Heating, Air source Heat Pump.

1. Introduction

Buildings account for more than 40% of the total energy consumption in the UK and in cold climate the heat loss to the ground might be responsible for up to one third or even a half of total heat losses (UKEB, 2019, Zoras et al., 2002). Improving low energy application with heavy thermal mass and utilising renewable energy in buildings in the UK are vital in order to create a sustainable and dependable energy market as well as cutting CO_2 emissions. The flexibility in choosing heat sources, reduction of fuel consumption and increased indoor environmental quality, enhanced community energy management will also reduce costs for end users.

Air source heat pumps (ASHP) utilise energy stored in the surrounding ambient at low temperatures and convert it to high temperature useful energy is considered good practice for building heating with high efficiency and lower cost. Kelly and Cockroft (2011) studied the performance of an ASHP when retrofitted into a dwelling in UK and predicted that the ASHP produced 12% less carbon that an equivalent condensing gas boiler system in annual. However except electricity consumption there are three main problems with air source heat pumps: 1) lower temperature heat supply than the traditional convective radiator heating system required; 2) heating capacity decreases as outdoor air temperature drops and 3) when there is frost formation on the outdoor heat exchanger (evaporator) coil surfaces in humid climates (Kelly and Cockroft (2011) and Huang and Hewitt (2011)). This can cause the system oversized for the periods of warmer weather and the system short cycles, further leading to reduction in compressor lifetime. Field trials with on-off cycle control have provided valuable information on the system operation optimisation with PCM storage. More simulation has predicted on using phase change material as buffered tank for load shifting have been carried out to improve the ASHP performance in the UK climate. Figure 1 shows a schematic diagram of some applications using PCMs in residential buildings for a series of applications (Huang, 2016). The capacity of a PCM for energy storage and temperature control depends on its properties, heat transfer methods and system configuration. The low thermal conductivity for most of the commercial available organic PCMs frequently makes an anticipated level of thermal storage untenable within an acceptable time period.

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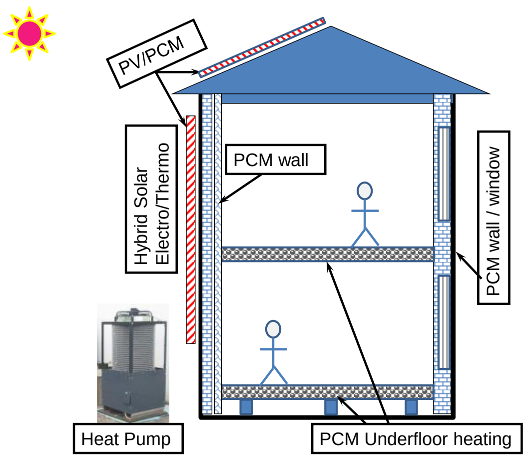


Figure 1. Renewable energy for low energy residential building with PCMs (Huang, 2016)

Underfloor heating is an efficient and economical method for home heating compared which can use the low temperature heat supply from HPs. Research on using heat pump with integrated phase change materials layer for underfloor heating has shown that this can save operating cost and improve the thermal comfort. The solar thermal energy stored in the PCM can provide a low grade heating source for the HP and also has potential to overcome the impact of frosting to the ASHP. The previous research has shown that in 81% of the daily time the floor surface temperature is higher for the PCM layer floor than the concrete floor at an average of 1 ºC. The heat flux from the floor surface with PCM layer is 22.4 % higher than the original concrete floor during the 24 hrs operation. It is only in 19 % of the 24 hours period the floor surface temperature for the concrete layer is higher than the PCM layer floor with the average higher temperature less than 0.3 ºC. The benefit of using PCM layer floor is clear with reduced floor material and steady desirable floor surface temperature and heat supply (Huang et.al., 2015).

The purpose of the current research is to study the performance of the PCM Underfloor-ASHP system for the domestic building heat supply. One of the main barriers for this application is how to utilize the high energy storage of the PCM in order to achieve a quick thermal response with longer thermal store performance in the buildings. Therefore a comprehensive system has been investigated to use PCMs for the underfloor thermal energy storage and thermal regulation in the domestic buildings with floor heating system.

A two dimensional temperature based finite volume numerical simulation model has been developed and experimental validated for PCM energy store and underfloor heating system (Huang et. al. 2015). In the current work the model has been modified to predict the thermal performance of the PCM Underfloor-ASHP system with the stored thermal energy for the HP energy absorption and stored the heat to the underfloor structure for heating supply to the buildings. In a residential building, the dynamic response with thermal energy charge and discharge from the PCM material is important in relation to the thermal behaviour of the heat gain and loss. A good understanding of the fundamental heat transfer processes involved with different heating modes is essential for accurately predicting the thermal performance of a PCM augmented building underfloor system and for avoiding costly system over design.

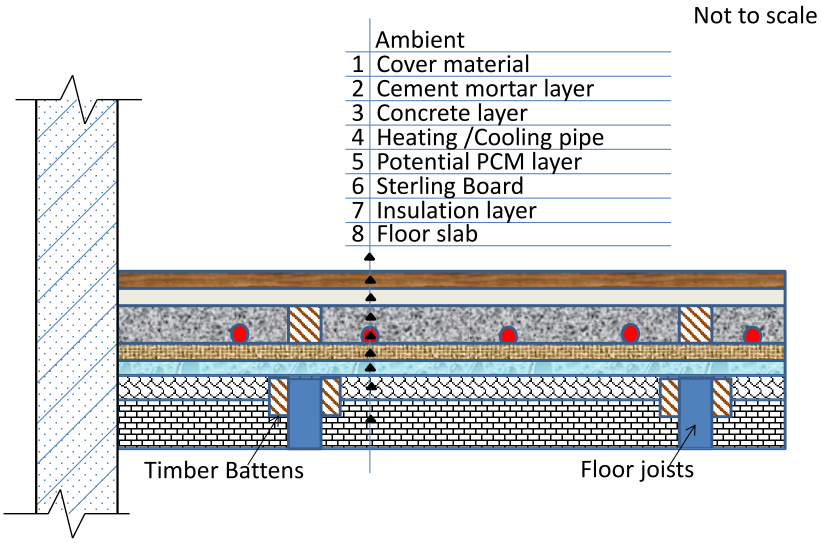


Figure 2. A schematic diagram of underfloor heating system structure with potential layers and joists (Huang etc al., 2015)

Description of the numerical simulation model for pcm underfloor heating

A schematic diagram of current common used underfloor heating system structure with cover layers is shown in Figure 2. In this work a previous validated two-dimensional numerical simulation model used for PCM underfloor heating system thermal performance (Huang et al, 2015) has been modified for the ASHP driven PCM floor heating applications with indoor ambient dynamic responding during heating process. The modified PCM underfloor-ASHP model can be used to predict the thermal performance of the underfloor heating system with transient temperature distribution inside of the underfloor structures under heat charge and discharge processes. The effect of the thermal mass material with and without PCMs under different supplied water temperature, heat flux supply, underfloor system structure, hot water pipe spacing, floor layer materials and dynamic ambient boundary conditions have been predicted. The following assumptions are made:

(1) Advection, not conduction, dominates the heat transfer in the fluid. Therefore, thermal conduction in the axial direction in the fluid is negligible. The heat conduction in the PCM combined underfloor heating system is two-dimensional.

(2) The end sides at the simulated floor system are adiabatic.

(3) The floor materials and PCM are homogeneous and isotropic.

(4) The convection effect in the molten PCM is neglected due to limited thickness.

(5) The thermophysical properties of the floor materials are constant except the specific heat capacity and density of the PCMs during phase changes.

(6) There is no solar radiation gain on the floor and assuming the natural ventilation is constant. A constant heating load set as 50Wm^{-2} for the heat demanding. The room temperature is affected through the floor surface heat transfer.

(7) The interfacial resistances between the pipe and filling material are negligible. Average water temperature in the pipe is used without temperature reduced along the water pipe.

(8) The thermal resistance of the pipe wall can be neglected due to the pipe wall is thin and its material has good thermal conductivity. Thus, the model assumes that the heat transfer fluid directly contacts the solid filling layers and the pipe thickness can be assumed to be zero.

The potential material properties with thicknesses used in the underfloor thermal mass layers are shown in Table 1 (Wang et al., 2014) unless presenting as different. The selected PCM for the current study is RT42 from Rubitherm. The external diameter of the hot water heating pipe is 20mm. Assuming the hot water temperature and heat flux from the pipe are constant in this study. The pipes spacing at 150 mm, are studied. The supplied hot water temperature by the pipe in this study are 40, 45, 47, 50 and 55 ºC, the heat flux from the pipe is the same for all of the simulations as 360W m^{-2}. The concrete layer thickness is 30 mm and the insulation layer is 30 mm. The initial temperature for the underfloor system and ground is 16 º C respectively.

Table 1 Thermo-physical properties of floor materials (Wang et al., 2014)

Structure layers	Thermal conductivity	Thickness	Density	Specifc thermal conductivity
	$Wm^{-1}K^{-1}$	mm	kg m^{-3}	J $Kg^{-1}K^{-1}$
Wood layer	0.14	10	650	1200
Tile layer	1.1	10	1900	1050
Cement mortar layer	1.51	10	2300	920
Concrete layer	1.28	40	2400	
PPR-pipe	0.22	20		325
Insulation layer	0.027	20	30	2000
soil	2		1500	1350
Sterling board	0.13		800	1700

2. Numerical Simulation Predictions and Discussions

2.1. The dynamic performance of ASHP on the underfloor heating system

The predicted temperature on the surface of the floor with realistic date for hot water from Heat Pump under winter clime in Belfast, UK at January is presented on the Figure 3. The heat pump can effective heat the room through the underfloor heat system. It can charge the floor mass efficient and quickly rising the floor surface temperature to a steady state. After four hours heating the PCM layer can store the thermal energy and continue release the heat for later use for longer period. The floor with integrated PCM in the underfloor structure has also been studied. The thermal mass of floor layers plays an important role on the underfloor heating along with floor structure, heating pipe system layout, costs and thermal response to the indoor environment. Amb represents the ambient temperature; HP-HW represents the hot water temperature supplied by the heat pump; Floor-surface means the temperature on the floor surface and inso represents the solar incident radiation. The underfloor heating system with PCM surrounding the water heating tubes can store more thermal energy during the charging process. The heat loss through the below layer is limited. A improved underfloor structure to enhance the heat charge and discharge effect have been carried out in the following study.

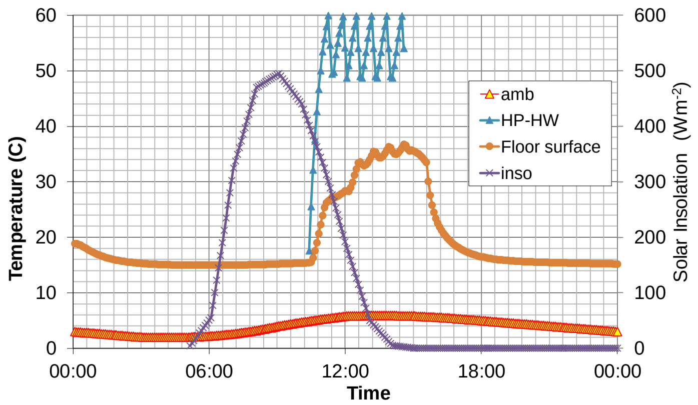


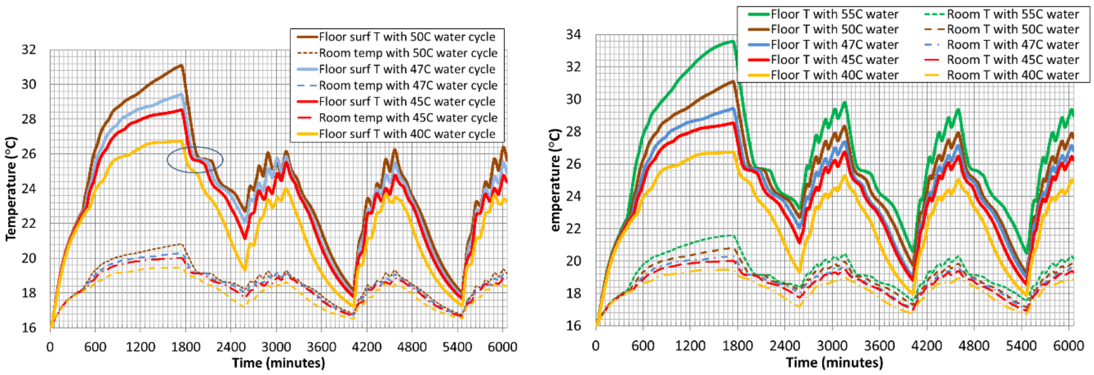
Figure 3. Predicted floor surface temperature using the realistic hot water supply from heat pump running under the local ambient conditions in 24hrs

2.2. The effect of the PCM with underfloor heating system

The effect of heating by heat pump for the underfloor heating system is predicted. The thermal isotherms for the cross-section of underfloor concrete layer with PCM layer at different time during heating process are predicted. The underfloor heating system with PCM surrounding the heating pipe can store more thermal energy during the charging process. The heat loss through the below layer is limited.

The thermal performance of the underfloor system with daily heating and off heating routine has been analysed. In the PCM layered underfloor heating system, the 30 mm insulation layer and 30 mm concrete are replaced by

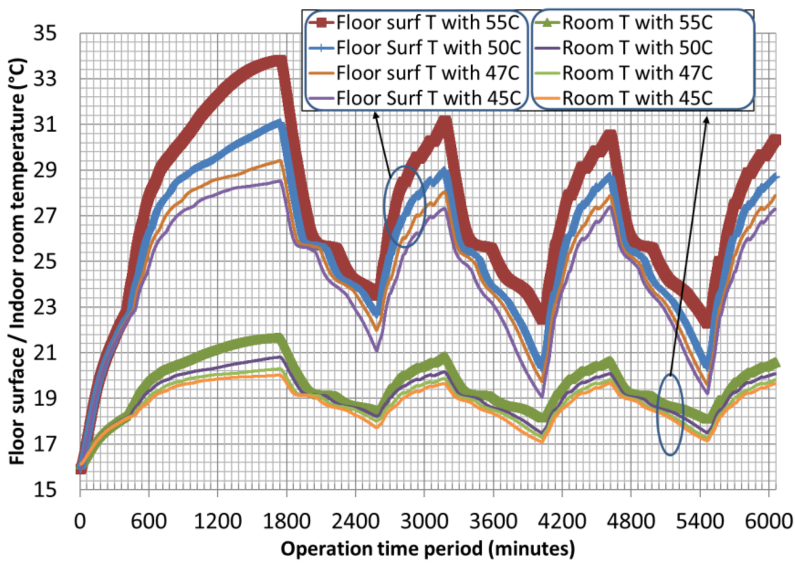
30 mm PCM layer with supporting. In order to reduce the impact from the initial and boundary conditions, the system has been preheated for 29 hours to reach a steady state before carrying on the heating schedule for three days. In each day it involves 14 hrs off heating and five on-off heating cycles. The underfloor heating mode can effectively lead to different heating performance. In the current study the heating operation each day there are five heating cycles be involved, which each cycle has two hours on-off period, there are three heating modes: 1) 1hr heating and 1hr off; 2) 1.5hrs heating and 0.5hr off; 3) 1hr and 55mins heating and 10 mins off.



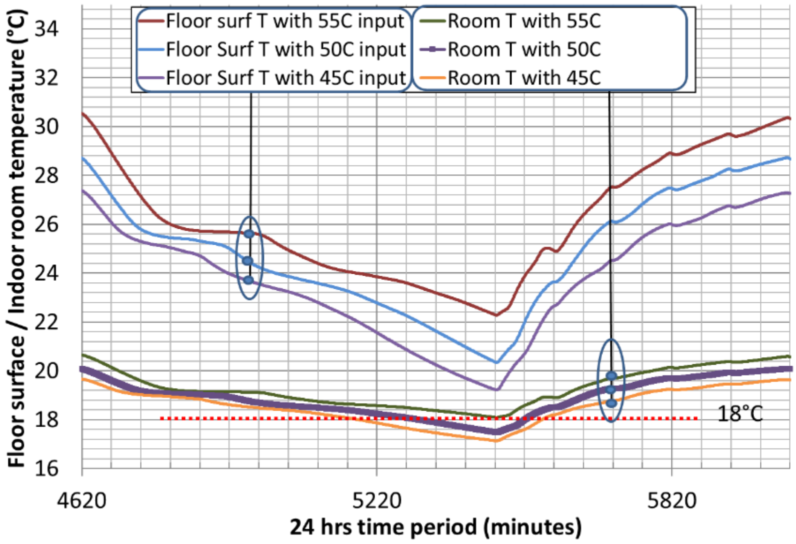
(mode 1) (mode 2)

Figure 4 Floor surface temperature and indoor room temperature variation with different water inlet temperatures under mode 1 and 2 operations

Figure 4 represents the variation of the floor surface temperature and the indoor room temperature with the different hot water input temperatures at 40, 45, 47, 50 and 55°C under ASHP operation modes 1 and 2. For the water inlet temperature 50°C, the highest floor surface temperature can reach to 26.4°C in the third day with mode 1 operation while in the mode 2 operation, the highest temperature on the floor surface can reach to 28°C. Based on EN 15377-1 (2008), the floor surface temperature can up to 29°C for the walking area. It can be seen that due to the short heating period of 1hr in the each cycle, there is not enough heat can be supplied to the room to keep the room temperature above the standard 18°C for longer time than the mode 2. For the mode 2, when the supplied water temperature reaches to 55°C, there is less than half hour of time the floor surface temperature is above 29°C which meets the requirement for the heat demanding.



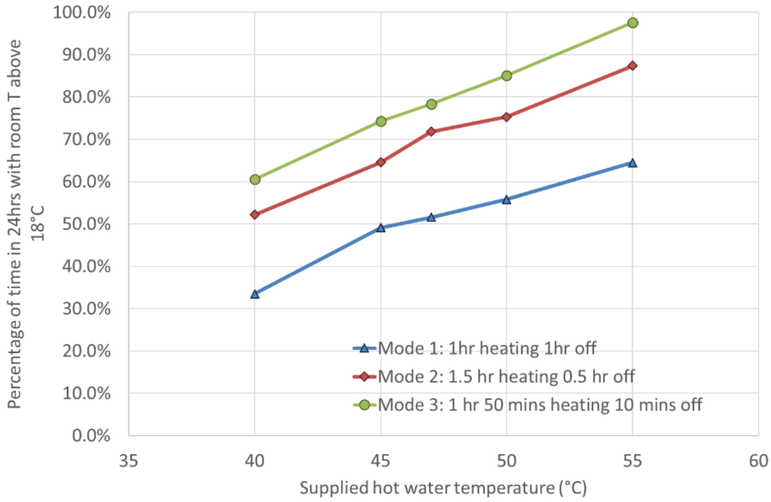
(a) Whole process with preheating



(b) 24hrs operation after preheating in the third day

Figure 5 Floor surface temperature and indoor room temperature variation with different water inlet temperatures under mode 3 operation

Figure 5 represents the variation of the floor surface temperature and the indoor room temperature with the different hot water input temperatures under the heating mode 3 operation. After the preheating operation, most of the time the floor surface temperature is beyond 30°C while the room temperature can be kept at above 18°C with the 55°C hot water inlet. During the 24hr in the third day it has a short period that the room temperature is below 18°C with the input water temperature at 45, 50 and 55°C under mode 3 heating operation.



Heating period during 2 hrs cycles	Supplied water temperature for underfloor heating cycle (°C)				
	40	45	47	50	55
1hr	**33.5%**	**49.1%**	**51.6%**	**55.8%**	
1.5hr	**52.2%**	**64.6%**	**71.8%**	**75.3%**	**87.4%**
1hr and 50 mins	**60.60%**	**74.3%**	**78.3%**	**85.1%**	**97.6%**

Figure 6 Percentage of time when the floor surface temperature is above 18C with different hot water inlet temperature and three heating modes

Figure 6 represents the relationship of keeping indoor room temperature at 18°C with five different water supply temperatures. The effect of keeping room temperature above 18°C with three heating modes have been summarized. The heating mode 1 can meet more than 50% of the 24hrs time to keep the room above 18C when the inlet water temperature is above 45°C or so. Under the heating modes 2 and 3, the more than 50% and 60%

of the 24hrs time, the room temperature can keep above 18C with the hot water inlet temperature is above 40°C respectively. For 75% of the time, the room temperature can be kept above 18°C within 24hrs when the heating system is operated under the mode 2 with inlet water is 50°C and the mode 3 with inlet water is 45°C.

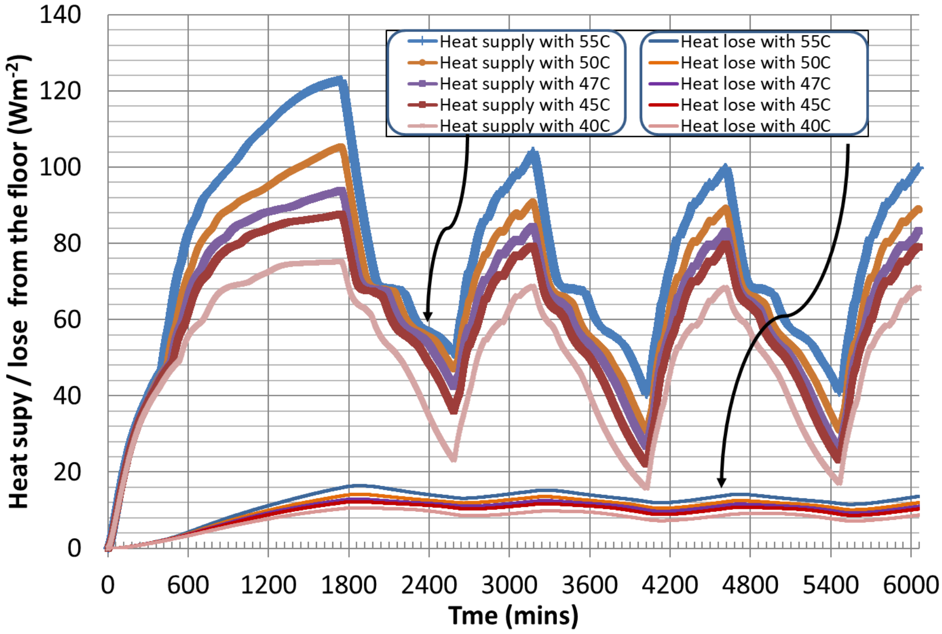
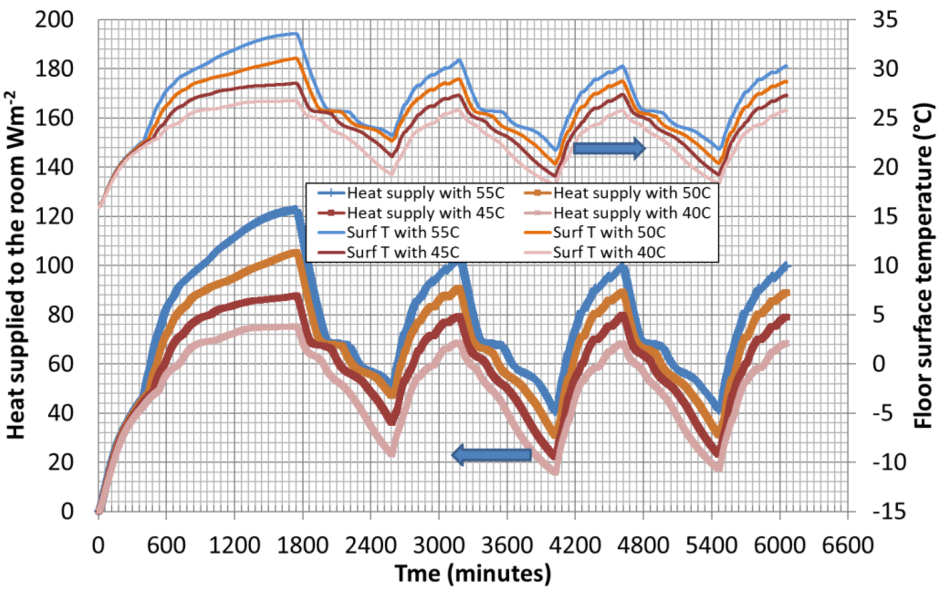
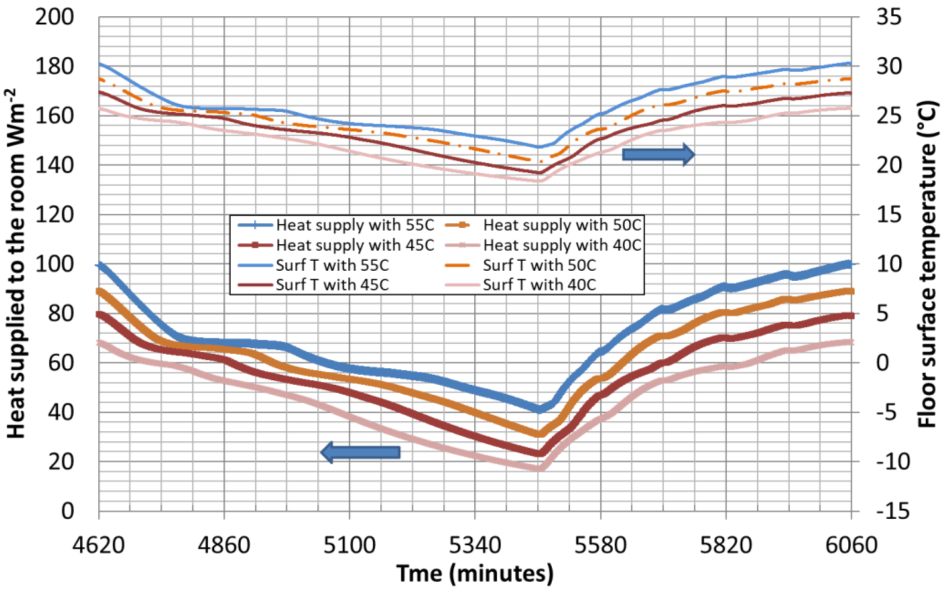


Figure 7 Heat supply from the floor surface to the room and lose from the bottom of the floor under different water inlet temperatures

Figure 7 represents the heat lose from the floor surface to the room and heat lose from the bottom of the floor under the five different water inlet temperatures. The heating mode is under mode 3, i.e. 1hr and 50mins heating and 10 mins off. During the heating period the heat supplied to the room increased sharply and the ratio of heat supply is increased with hot water inlet temperature increased from 40 to 55 degree. The effect of long lasting heat release from the PCM can be seen during the off cycle. However the effect can be kept only for the water temperature at 55°C after three day cycles with the current floor structure. The heat lose from the bottom of the floor toke about 14% of the highest heat supply to the room for each level of the water inlet. There is no significant variation with the heat lose during the heating and off heating period.



(a) with three days performance



(b) with 24 hrs operation

Figure 8. Predicted heat supplied to the room through the floor surface by hot water inlet temperature at 40, 45, 50 and 55°C under the operation mode 3

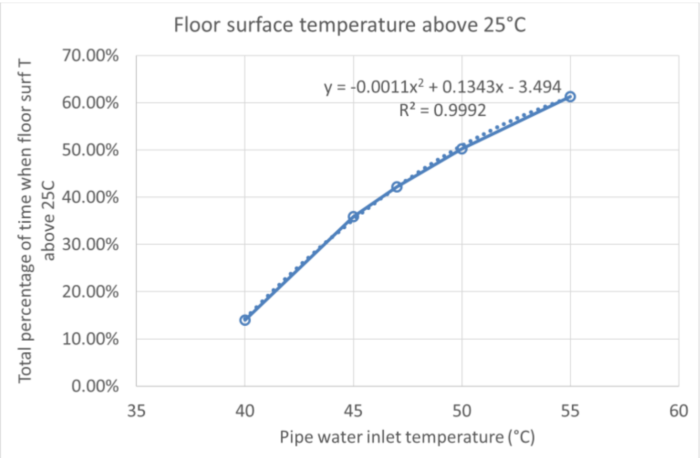


Figure 9 The total percentage of the time when the floor surface temperature is above 25°C in each day with five difference hot water inlet temperatures of 40, 45, 47, 50 and 55°C

The Figure 8 (a) representented the predicted heat supplied to the room through the floor surface by hot water inlet temperature at 40, 45, 50 and 55°C. The operation of heat supply to the room is under 29 hrs preheating and followed with five cycles of 1hr and 50mins heating and 10 mins off heating for three days. The effect of heat energy stored in the phase change material can be seen clearly on the preheating period. During the discharge period with the three days opeation, the stablise heat supply to the room can also be seen with the phasee change effect at the water inlet above 45°C. A detailed 24 hrs performance is enlarged in the Figure 8(b). Figure 9 represented the total percentage of the time when the floor surface temperature is above 25°C in the 24hrs. Five average hot water supply temperatures at 40, 45, 47, 50 and 55°C are examied. Considering the lasting time for the floor surface temperature above 25°C, the hot water temperarture at 50°C or above will have a good performance for the selected PCM RT42 underfloor structure with the selected heating mode.

3. Conclusions

The thermal performance of the PCM underfloor-ASHP heating system for buildings has been predicted and analyzed. The effect of integrating ASHP for the PCM underfloor structure shows potential application with improved energy management strategies. It presents an evaluation of the effects of PCM underfloor-ASHP heating system on heat transfer with different system operation modes. The improved fundamental understanding of the processes within the PCM underfloor-ASHP system provided by this work can be used to optimise the design of underfloor structure for buildings heating to improve the total energy efficiency. At the current simulation the constant heat load is used, however the variable ambient conditions will be accepted in the future applications. In addition the variation of the floor surface temperature maybe able to be improved with increasing the mass of PCM while reduce the molten temperature to reach a high comfortable operative temperature for users with this system.

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