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Research Paper

Experimental investigation of the PCM-EG radiant floor heating driven by ASHP with advanced heat transfer enhancement

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ABSTRACT

Radiant floor heating systems (RFHSs) provide superior indoor thermal comfort environment compared to other exist heating methods. Recently the integration of phase change materials (PCMs) as thermal mass within underfloor heating structures has demonstrated potential to reduce operating costs and enhance thermal comfort by enabling a quicker heating response due to their excellent heat retention properties during the heating period. For domestic buildings, Air Source Heat Pumps (ASHPs) recognised as a highly efficient heating technology, are increasingly adopted to meet heating and cooling demands while contributing to CO_2 emissions reduction targets. This study focuses on leveraging ASHPs to supply heat for the PCM-enhanced RFHSs, introducing an improved heating method for residential buildings to address heat demand and reduce the power consumption of ASHPs. The research aims to advance scientific understanding and establish a foundation for future studies on sustainable and efficient heating technologies. This study investigates the development of a novel sustainable and highly efficient thermal energy retention system through laboratory engineered composite PCMs integrated into RFs powered by ASHPs. Such systems are crucial to addressing current and future heating demands in the UK. This work examines the impact of system configuration, constituent materials and design parameters on the thermal and energy performance of RF heating systems incorporating composite PCM with enhanced expanded graphite (PCM-EG). The study has shown that PCM-EG used as thermal mass in RFHSs can achieve 37 % higher heat retention capacity compared to systems utilising a metal mesh. Additionally, PCM-EG combined with copper powder maintains the floor surface temperature 0.7 °C higher than PCM-EG alone, further reducing the power consumption of the ASHP.

1. Introduction

About 46 % of the total heat consumed in buildings is used for space and water heating [1]. Air Source Heat Pumps (ASHPs) are highly efficient heating systems that are rapidly gaining popularity in domestic buildings to meet the heating and cooling demands. This growth aligns with the goals of reducing CO_2 emissions and achieving nearly Zero-Energy Buildings (nZEB) by 2050. However, ASHPs typically supply heat at around 55 °C for most commercially available products, which is significantly lower than the conventional heating system design temperature at 80 °C. Therefore, the heat emitter area must be increased, or indoor spaces will take much longer time to warm during the high demand heating seasons. In addition, the high power demand by ASHPs during peak periods places additional strain on the grid network.

1.1. *Challenge of radiant floor heating*

Radiant floor heating systems (RFHSs) offer significant advantages in compatibility with heat pumps (HPs) and potential thermal sources such as solar energy. However, several challenges need to be addressed to integrate ASHPs with RFHS heating effectively and maintain the floor surface temperature below 29 °C [2]. These challenges include: 1) improving the efficiency of RFHS heating during charging and discharging phases by utilising suitable floor thermal mass materials; 2) developing efficient energy storage technologies to store excess energy with minimal heat loss and recover it during periods of high space heating demand. 3) evaluating the operational modes of HPs for compatibility with RF heating systems.

Latent heat systems, such as those incorporating phase change materials (PCMs) possess higher energy densities than sensible heat stores and operate over a wide temperature range. Due to their suitable

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Nomenclature

Abbreviations

ASHP	Air Source Heat Pump
COP	Coefficient of Performance
DSC	Differential scanning calorimeter
EG	Expanded Graphite
EU	European Union
LHTES	Latent Heat Thermal Energy Storage
nZEB	Net or Nearly Zero Energy Buildings
PCM	Phase Change Material
PE	Polyethene
RFS	Radiant Floor Heating System
SAT	Sodium Acetate Trihydrate
SEP	Sepiolite fibre
SSPCM	Shape-Stabilised Phase Change Material
TES	Thermal Energy Storage
UTES	Underground Thermal Energy Storage

Symbol

H	Latent Heat, $kJ \bullet kg^{-1}$
λ	Thermal Conductivity, $W\bullet m^{-1} \bullet K^{-1}$
T	Temperature, °C
T_m	Melting Temperature, °C
ρ	Density of phase change material, $kg \bullet m^{-3}$
c_p	Specific Heat Capacity, $kJ\bullet kg^{-1}\bullet K^{-1}$
T_{amb}	Ambient temperature, °C

properties, including suitable phase change temperatures, high latent heat, specific heat capacity, high energy density, thermal and chemical stability, PCMs are increasingly being explored for applications such as building integration for thermal management [3] and space heating and hot water production [4]. The thermophysical properties of the PCM significantly influence the optimisation of heat exchanger designs. Efficient heat exchangers for PCM aim to maximise heat storage within a shorter period, enhance heat transfer, and minimise heat loss. Extensive research has been conducted on heat exchanger design criteria and optimization for different operational and geometric parameters [5]. For example, it demonstrated that inlet flow temperatures significantly affect system charging time while flow rates have minimal influence on discharging time [6]. Similarly, studies revealed that mass flow rates have a negligible effect on thermal energy storage and heat transfer rates compared to the inlet temperature of the heat transfer fluid [7,8].

Despite the desirable properties of PCMs, their low thermal conductivity, shape stability, leakage, compatibility with other materials and volume expansion during phase change are drawbacks which limit their wider application and acceptance in RFHSs. The enhancement of the thermophysical properties of PCM has included strategies such as the dispersion of high conductivity nanoparticles and the preparation of shape stabilized composites using expanded carbon graphite [9]. The most commonly used nanoparticles for modifying the thermophysical properties of PCMs include graphene [10,11], alumina [12], titanium dioxide [13], and copper oxide [14]. Graphite composites with paraffin to enhance the thermal conductivity of pure paraffin have been investigated [10]. Their results showed an appreciable enhancement in the thermal conductivity of the composite compared to the pure PCM. Paraffin/EG composites, prepared by absorbing liquid paraffin into EG, have also been studied for their thermophysical properties. The exploration of composite PCM with EG to improve thermal conductivity particularly for heating sources compatible with HPs have been conducted [15,16].

1.2. State of the research on PCM for RFHSs

Research on the incorporation of PCMs into RFHSs is experiencing growing interest due to their potential to improve buildings energy efficiency and thermal performance [17]. A comprehensive literature review covering the last decade of PCM applications in RFS, emphasising their role as latent heat storage materials [17]. These materials act as thermal reservoirs equipping RFHS with enhanced thermal energy storage capacity and enabling a better alignment between energy demand and renewable energy supply.

Experimental studies of the use of slag cement combined with 0–10 % PCM to improve the heat storage performance of radiant floors [18]. It concluded that 7 % PCM was the optimal addition. Numerical simulations have been conducted to predict the performance of RFHSs using cascaded PCMs with distinct phase change temperatures [19]. These studies demonstrated energy savings is more than 19 % during heat charging and an elevation of the floor surface temperature by ~2 K during heat release compared to single-stage PCM systems.

The development of composite inorganic PCMs has also advanced to enhance thermal conductivity through the addition of EG or modified EG [20,21] and the use of sepiolite fibre (SEP) to develop form-stable composites [22] for RF heating. However, inorganic materials such as salt hydrates (either shape stabilised or eutectic mixtures) face challenges including supercooling and phase separation. Commercial products utilising inorganic hydrated salts as PCMs with a melting temperature of 27 °C, have demonstrated improvements in indoor thermal comfort and energy savings. These systems successfully shifted energy consumption from peak to off-peak periods, as observed in hydronic systems incorporating inorganic PCM encapsulated in thin high-density polyethylene HDPE containers installed beneath of above heating pipes [23]. Studies of Shape-Stabilised Phase Change Material (SSPCM) systems with 45 °C supply water temperature [24] and hydronic RFHS with paraffin-based (n-eicosane) PCM (35 °C melting temperature), coupled with an ASHP, have further highlighted the potential of PCM-RFHS for energy efficient heating [22].

1.3. Use of organic PCMs with EG for indoor heat supply

The use of organic PCMs (paraffin) with graphite encapsulated within an epoxy matrix to produce shape-stable PCM composites suitable for HP applications has been studied [25]. These properties were completely preserved during phase change cycling and no leakage occurred, indicating the successful development of a thermally and shape-stable PCM with significantly enhanced thermal conductivity. Sodium acetate trihydrate for HP applications for a melting temperature range of 45–48 °C is conducted [26]. Characterization studies revealed that PCM-EG composites possess high thermal conductivity, excellent shape stability without leakage, relatively high latent heat and strong thermal reliability. The phase change temperatures were minimally affected by the presence of EG [27]. However, the phase change enthalpies obtained through DSC analysis were slightly lower than the theoretical values calculated based on the wt % of PCMs.

The Underground Thermal Energy Storage (UTES) with ASHP is a promising solution for energy savings in buildings. Current research focuses on developing a modified latent heat thermal energy storage (LHTES) system to enhance the thermal performance of RFHSs. This system is integrated with an ASHP to enable demand-side management for domestic space heating and hot water production. The performance of thermal regulation and heat retention in organic PCM-EG composites has been further improved by adding copper powder along with different heat transfer enhancement. Common approaches include incorporating fins, high density metal meshes and constructing heat conduction channels. The effectiveness of these methods depends on the design and layout of the heat conduction pathways, which are critical for improving heat transfer efficiency. An enhanced heating method for residential buildings has been introduced to address heating demands while reducing the power consumption of ASHPs. This study investigates the development of a sustainable and highly efficient thermal energy retention method through lab engineered composite PCMs integrated into RFHSs with ASHPs which is imperative for meeting current and future heating demands throughout the UK.

2. Experimental platform design and methods

2.1. Design of experimental platform

A composite PCM-EG underfloor heating system driven by an ASHP was designed, fabricated and constructed in the Ulster University campus at Jordanstown, Northern Ireland (Fig. 1). The total room floor area is 25 m^2 with the PCM-EG RFHS installed at the centre of the room covering a heating area of 9.5 m^2 as shown in Fig. 2. The layout of the RFHS structure complies with EN1264-1:2021 [28] and ISO 11855-2:2021 [29].

2.2. PCM selection for the RFHS

PlusICE A36, an organic paraffin-based PCM was chosen due to its high latent heat capacity, consistent performance and operational reliability [30]. The initial selection of PlusICE A36, with a melting point of 36 °C, was based on the need to maintain the desired temperature range for energy retention. This ensures that the PCM remains effective over a wider range of HP operation modes in the RFHS. The selected PCM enhances both the overall efficiency and thermal stability of the RFHS, contributing to consistent thermal comfort for occupants. The melting point of 36 °C allows for the gradual and controlled release of heat, maintaining a uniformly warm surface without overheating. The phase change temperature aligns well with domestic heating requirements, optimising energy storage and release for maximum efficiency.

Expanded Graphite (EG) SIGRATHERM GFG 600 with an average particle size of 600 μm [31] was incorporated into PCM as a thermal enhancement material. The composite formation method is presented in Fig. 3 [15]. The composite properties including phase change temperatures and enthalpies were evaluated using differential scanning calorimetry (DSC Mettler Toledo DSC1/700) based on our previous work [15]. The thermal conductivity of pure PCM is 0.22 $Wm^{-1}K^{-1}$. In comparison, the thermal conductivity of the PCM-EG composite was studied for different EG wt % (20 %; 25 % and 30 %) and densities [15] (Fig. 4). The study demonstrated that the thermal conductivity of the PCM-EG composite increases with both EG wt % and packed density. The enhanced thermal conductivity can exceed 22 times that of pure PCM. It was also determined that the PCM and EG do not chemically react to form the composite; instead they are physically blended, ensuring no new substance are produced [15].

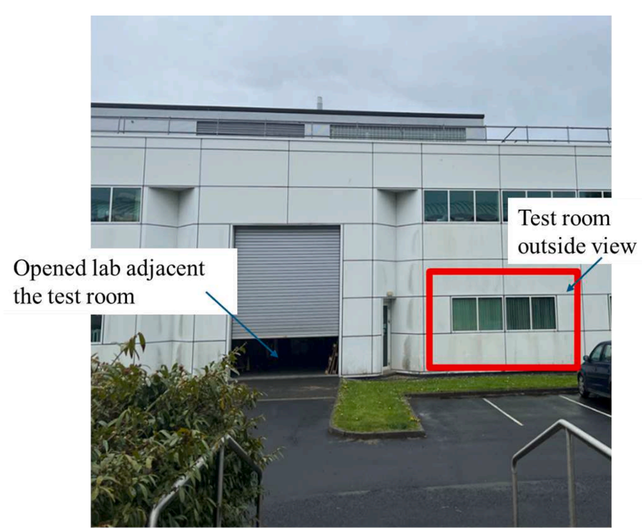

Fig. 1. Office/lab building used for ASHP driven PCM-EG RFHS in the Ulster University, Jordanstown campus, UK.

2.3. Water pipe configuration with RFHS

The pipe configuration strongly affects the performance of RFHSs. In this design, water heating pipes with a total length of 5 m (Fig. 5a) are distributed through channels arranged in a serpentine configuration. The pipes are positioned towards the perimeter wall, with a pipe spacing of 150 mm within the channels. The composite PCM-EG is filled into the channels, surrounding the water heating pipes to enhance heat transfer efficiency. The detailed floor layer structure and dimensions are presented in Fig. 5 (b). The materials used for the floor construction, along with their thermophysical properties are listed in the Table 1. This configuration ensures even heat distribution across the floor area. Wooden joists provide structural support and divide the RFHS space into seven distinct compartments, facilitating controlled heating zones. These joists also secure the water pipes in place ensuring system stability.

2.4. PCM RFHS layer structure configuration

The selection of floor finishing materials and the location of the PCM layer relative to the piping system, are critical factors for optimising the system's performance. Fig. 5 (c) illustrates the heating pipe system configuration, where pipes are embedded within the PCM composite layer and covered with the floor finish.

To ensure system efficiency and durability, the base of the RFHS was insulated to prevent leakage. The installation process begins with a protective, water-resistant layer (Fig. 5 (c)), to shield the floor from potential leaks or spillages. Above this layer, 50 mm thick insulation boards were installed to minimise heat loss to the ground. These boards have a thermal conductivity of $\lambda = 0.022$ $W\bullet m^{-1}\bullet K^{-1}$, ensuring efficiency thermal management. Finally, the PCM-EG underfloor heating system was completed with a vinyl floor covering, providing a durable and visually appealing finish. This layered configuration enhances thermal efficiency and ensures the longevity of the system.

2.5. PCM-EG RFHS under installation

Fig. 6 shows the RFHS during construction, showing the installation of pipes and the filling of PCM-EG composite. The water pipes, made of high-density polyethylene (PEX) with an internal diameter of 17 mm were secured in place using plastic rails and clipped onto the insulation board. The testing area was enclosed with plastic foil for protection. The PCM-EG composite was filled into the channels and compressed to ensure optimal contact with the pipes. The completed PCM-EG underfloor heating system was leveled using a galvanised steel wire mesh panel and finished with vinyl, a cost effective flooring material.

2.6. Monitoring the system performance

Temperature of the RFHS is monitored using high accuracy and stability PT100 sensors for the control of hot water inlet and outlet at the entrance to the RFHS and a network of strategically placed type-T thermocouples (Fig. 5a). The heating area by the RFHS is enclosed by greenhouse foil to form enclosure to reduce the heat loss to the surrounding in the room. These thermocouples measure temperature within the PCM layer, on the floor surface, within the test area and across the system's piping. All sensors are connected to a DT85 data

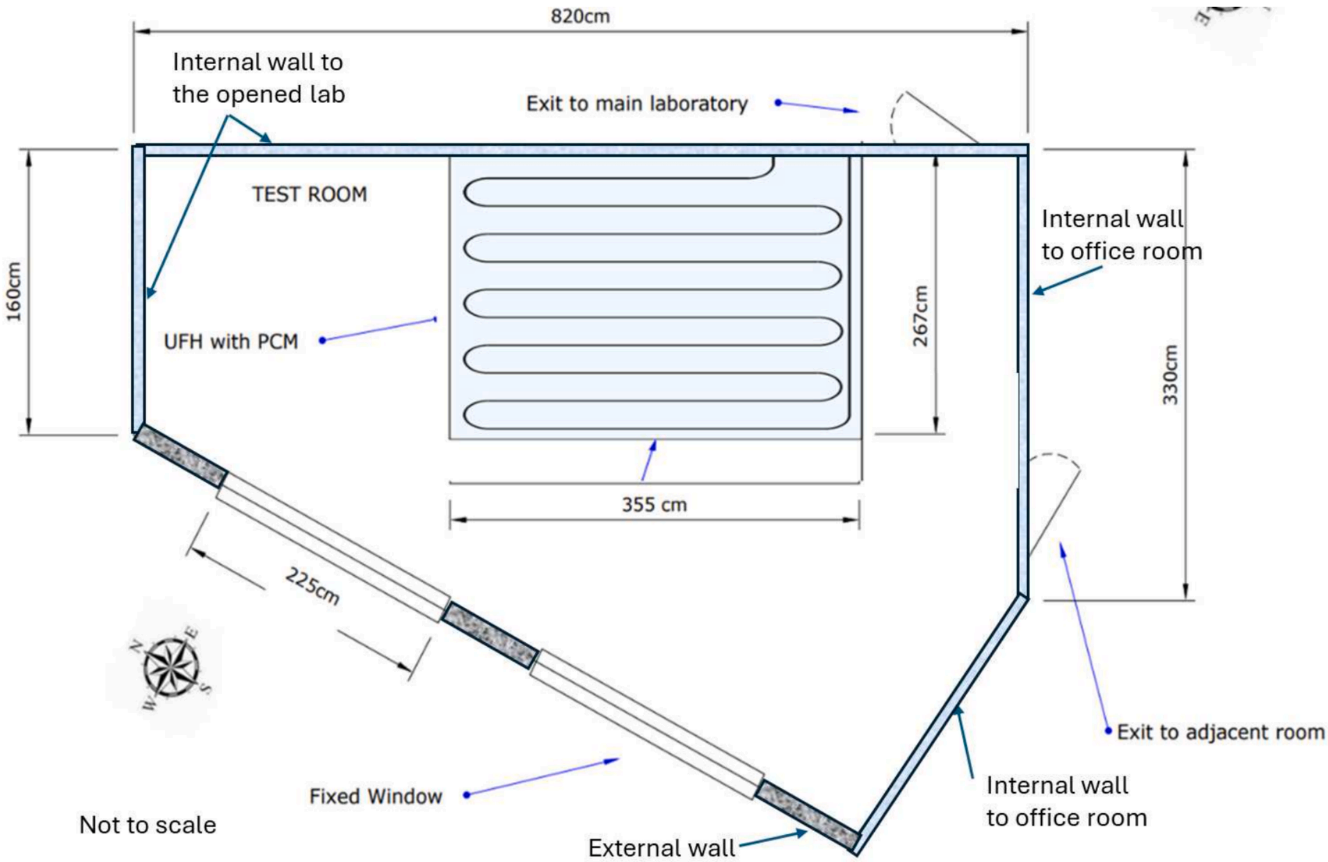

Fig. 2. Layout of the 25 m^2 room area with PCM underfloor heating system.

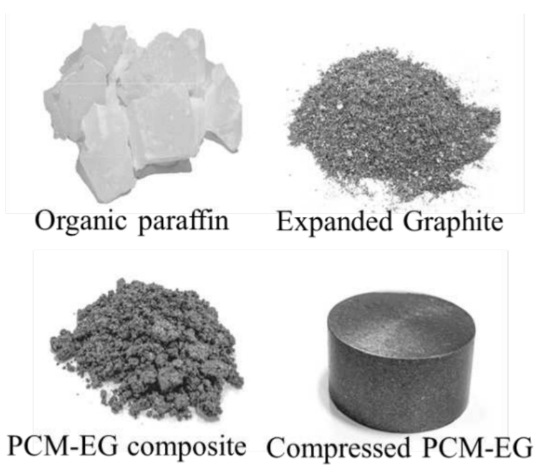

Fig. 3. Organic PCM with EG powder formed for composite [15].

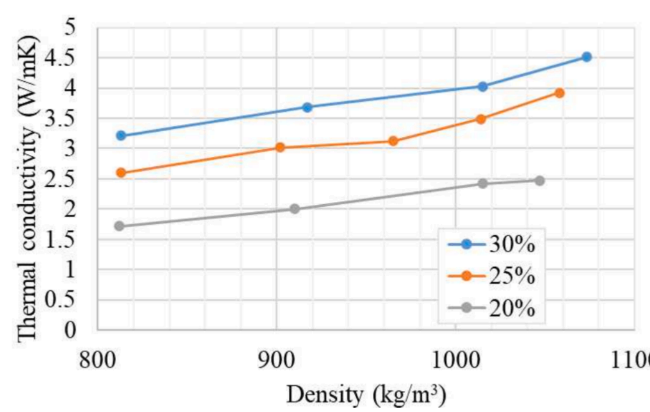

Fig. 4. Composite of PCM-EG thermal conductivity with three different ratios of EG at 20 %, 25 % and 30 % and densities from 800 to 1100 kg•m^{-3}.

logger, to ensure accurate data collection for system performance analysis. Table 2 shows the specific locations of the thermocouples used to monitor the RFHS performance.

3. Experimental analysis and discussions

A comprehensive study was conducted to evaluate the performance of the RFHS with various heat transfer enhancement methods applied to the PCM layer structure. The primary objective was to investigate efficiency improvements and optimise thermal performance. The experimental procedure along with a schematic of the experimental setup is presented in Fig. 7. An appropriate PCM-EG composite was prepared and used in the experiments to assess the thermal performance of the RFHS. Different heat transfer enhancement techniques were tested and analysed.

3.1. PCM-EG composite development for the RFHS

To evaluate the stability of the PCM-EG for RFHS in buildings, a composite of PCM-EG with organic based paraffin wax and EG wt. 25 % was produced and incorporated into the RF system layer for heat supply using an ASHP. After two months of operation, the PCM-EG composite exhibited segregation within the RF PCM layer (Fig. 8). Although this segregation did not significantly impact the heat supply to the room, it raised concerns about the long term stability of the PCM composite

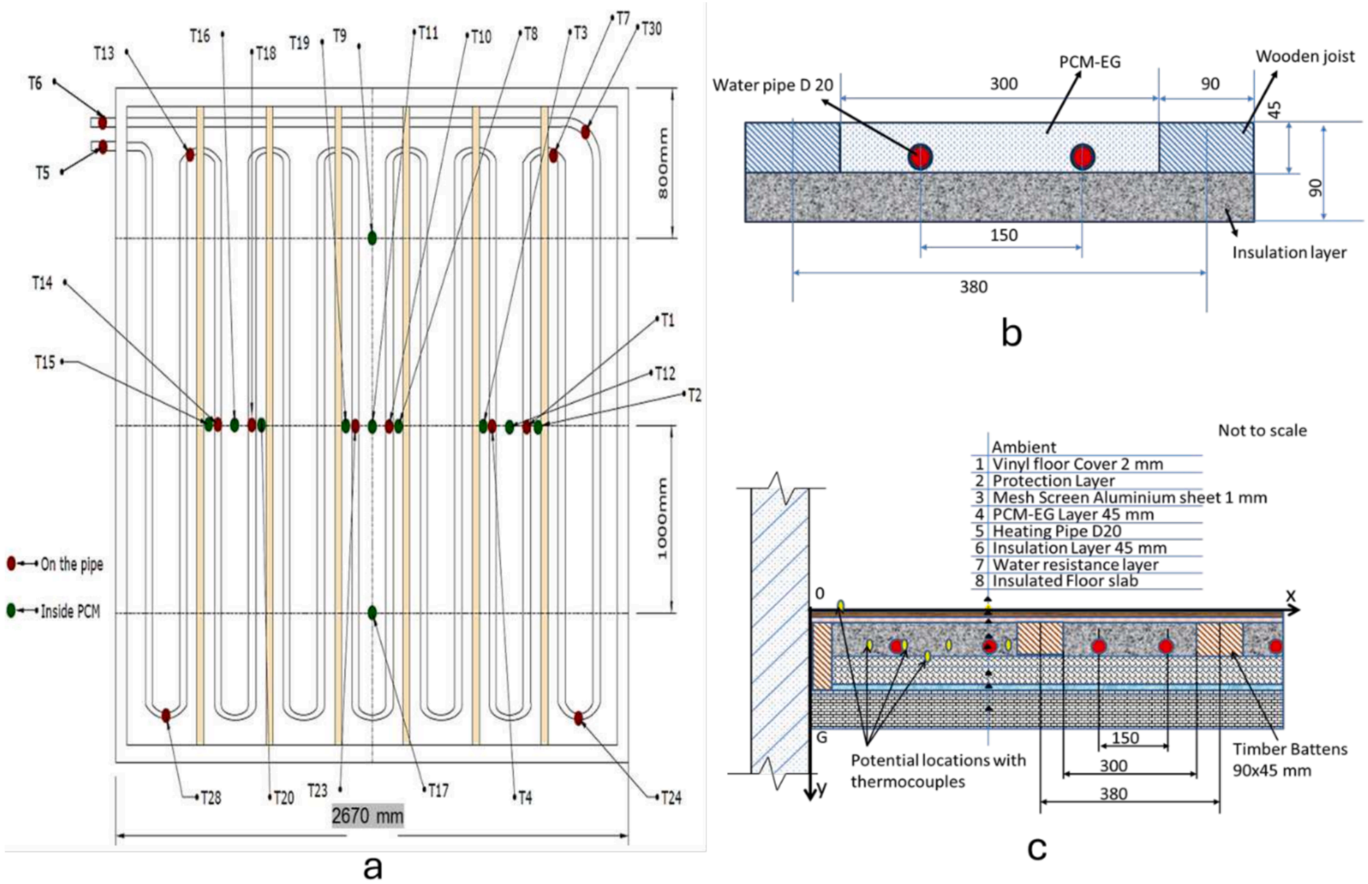

Fig. 5. Hydraulic connection of water heating pipes in the underfloor heating system with temperature sensors positioned along the water pipes and within the PCM-EG composite.

Table 1
PCM-EG floor structure materials and their thermophysical properties.

	Melting Temp T_m [°C]	Density ρ [kg•m^{-3}]	Latent heat H [kJ•kg^{-1}]	Specific Heat Capacity, c_p [kJ•kg^{-1}•K^{-1}]	Thermal Conductivity, λ [W•m^{-1}•K^{-1}]	Thickness δ [mm]
A 36	36	776	250	2.3	0.22	
PCM-EG	33–36	840	180	2.1	3.8	45
Vinyl cover		700		0.9	0.17	2
RF water pipe		938		2.4	0.41	DO 20/17
Insulation Board		31		1.4	0.022	45
Sand filling		1602		0.83	0.25	45
Wooden joists		1800		1.2	0.2	45x90mm

layer. During the warming up stage, the PCM composite softened, resulting in a slight ramping up effect on the floor surface above the heating pipes. To address this issue, subsequent RF heating system constructions employed a PCM-EG composite with. EG 30 wt%. This revised composition was selected to enhance the structural stability of the PCM layer and ensure consistent performance in the RF heating system configuration.

3.2. Initial operation condition set up for testing

The ASHP operates to maintain a room floor surface temperature of up to 29 °C, ensuring the desired indoor thermal comfort. The supply water temperature is a critical factor influencing buildings' primary energy consumption [32]. It recommend supply water temperatures between 25 and 40 °C for low-temperature heating systems with embedded pipes in radiant floor system (RFS). It has been suggested that, for low-energy buildings, radiant low-temperature heating systems should operate with supply water temperatures below 45 °C to efficiently achieve indoor thermal comfort [33].

When PCMs are incorporated into RF heating systems, the supply water temperature becomes a critical factor for inducing phase transitions and enabling efficient thermal energy storage and release. The optimum supply water temperature must maintain the desired floor surface and indoor air temperatures. Numerical simulations and experimental testing show water supply temperatures in the range of 35–55 °C for RF heating [23,34,35]. The impact of the heating source supplied by an ASHP with a 55 °C operation set point for the organic PCM-EG RF heating system requires detailed investigation.

An initial test was conducted to assess the temperature distribution on the PCM-EG floor surface with an ASHP heat source set to 50 °C. Infrared imaging showed that during the heating process (60 min) and after heating cessation (60 min) (Fig. 9), the PCM-EG underfloor heating system maintained a uniform temperature distribution on the floor surface. During the period of the HP switched off, the system effectively retained higher surface temperatures for extended periods with consistent heat distribution.

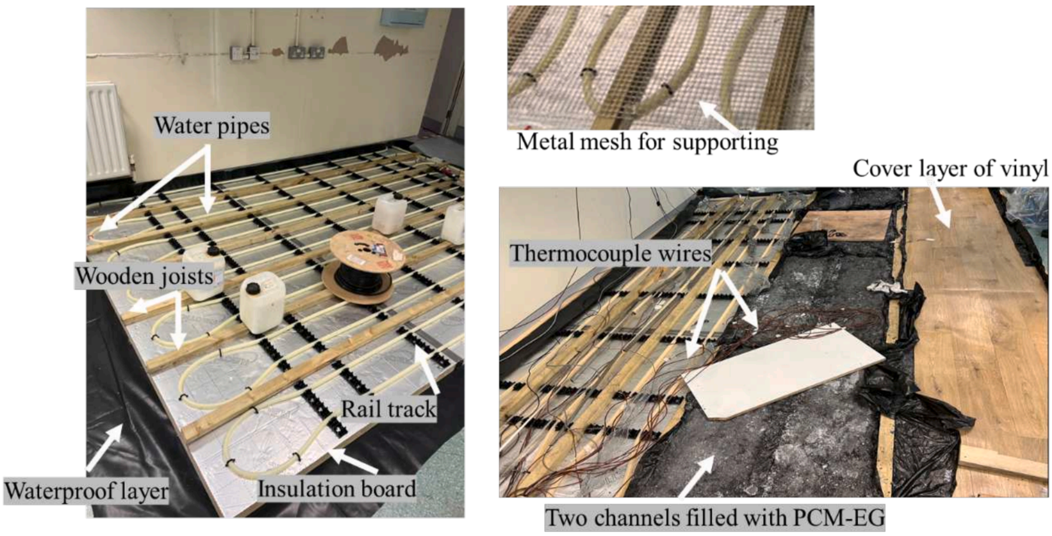

Fig. 6. Preparation of the PCM-EG underfloor heating system under installation.

Table 2
Location of thermocouples for RFHS performance monitoring.

Thermocouple locations		Label of thermocouple	Type of thermocouple
Water pipe inlet / outlet to the RFHS		T5, T6	PT100
Channel A	Along the tube	T13, T28	T-type
Channel B	Along the tube	T14, T18	T-type
	Inside of the PCM layer	T15, T16, T20	T-type
Channel D	Along the tube	T10, T23	T-type
	Inside of the PCM layer	T8, T9, T11, T17; T19	T-type
Channel F	Along the tube	T1, T4	T-type
	Inside of the PCM layer	T2, T3, T12	T-type
Channel G	Along the tube	T24, T30	T-type
Floor surface		T50-T55	T-type
Test Chamber		T40-T48	T-type
Room		T27, T25	T-type
Ambient		Tamb	T-type

A 24-hour monitoring study was conducted to assess the systems performance, focusing on the supplied water temperature from the HP, the temperature within the PCM layer, and the room temperature (Fig. 10). The PCM-EG RF heating system maintained room temperatures above 20 °C during heating operation and above 18 °C for 450 min after heating was turned off. The thermal regulation of the floor surface temperature, achieved through heat retention by the PCM during the phase transition process at 33–35 °C, has been accomplished. Monitoring data show that within 500 min of HP operation, the room temperature remained above 20 °C, with the floor surface temperature remaining below 27.5 °C when the ambient temperature was ~15 °C. Beyond 500 min, the phase transition completed, causing the floor surface temperature to rise sharply above 30 °C. During the period of the ASHP switched off, with ambient temperature at around 12 °C, the floor surface temperature remained above 25 °C and the room temperature stayed above 18 °C for over 600 min.

3.3. PCM-EG RF heating system configurated with different heat transfer cases

The operation of the ASHP leverages off-peak electricity tariffs, such as the Off-Peak F scheme, which provides 10.5 h of cheaper- rate electricity for driving the ASHP to store /supply heat each day. This strategy optimises energy costs and aligns with the energy providers Economy 7 tariff in Northern Ireland, offering reduced rates during low-demand hours. The ASHP is operated to maintain a floor surface temperature of up to 29 °C, ensuring indoor comfort.

To investigate the effects of enhanced heat transfer in the PCM-EG underfloor heating system, with the four different configurations (Fig. 11):

- Case I PCM-EG composite with EG wt. 30 %.
- Case II PCM-EG composite with EG wt. 30 % mixed with copper powder wt. 10 %.
- Case III PCM-EG composite with an integrated metal mesh entangle the pipe.
- Case IV PCM-EG composite with thin metal fins.

These configurations were evaluated for their thermal performance and efficiency under the low energy tariff scheme. The HP was operated to keep the room floor surface temperature up to 29 °C to maintain the room temperature at the comfort level.

3.4. Effect of heat transfer enhancement in the PCM-EG layer with different configurations

The thermal performance of the underfloor heating system was monitored over three days (Fig. 12), with outdoor temperatures ranging from ~9 to 12 °C The room temperature was maintained between ~19 and 22 °C. The results showed that the temperature fluctuation on the floor surface was smoother in Case I (pure PCM-EG composite) compared to Case III (PCM-EG with metal mesh). This indicates that the pure PCM-EG composite produced more consistent thermal regulation while configurations with metal meshes exhibited greater temperature variation due to enhanced but localised heat transfer.

The heat retention comparison between the two PCM structures on Day 2 is presented in Fig. 13. The superior thermal retention performance of Case I over Case III is evident with quantitative details presented in the Table 3.

From Table 3, it can be seen that Case I demonstrates 37 % longer heat retention time than Case III, when maintaining the floor surface temperature above 25 °C. However, Case I required 13 min longer than Case III to initially reach 25 °C on the floor surface. From this comparison, the importance of balancing heat transfer capacity with heat retention for energy saving can be seen.

Fig. 14 shows the detailed comparison of thermal control for the four

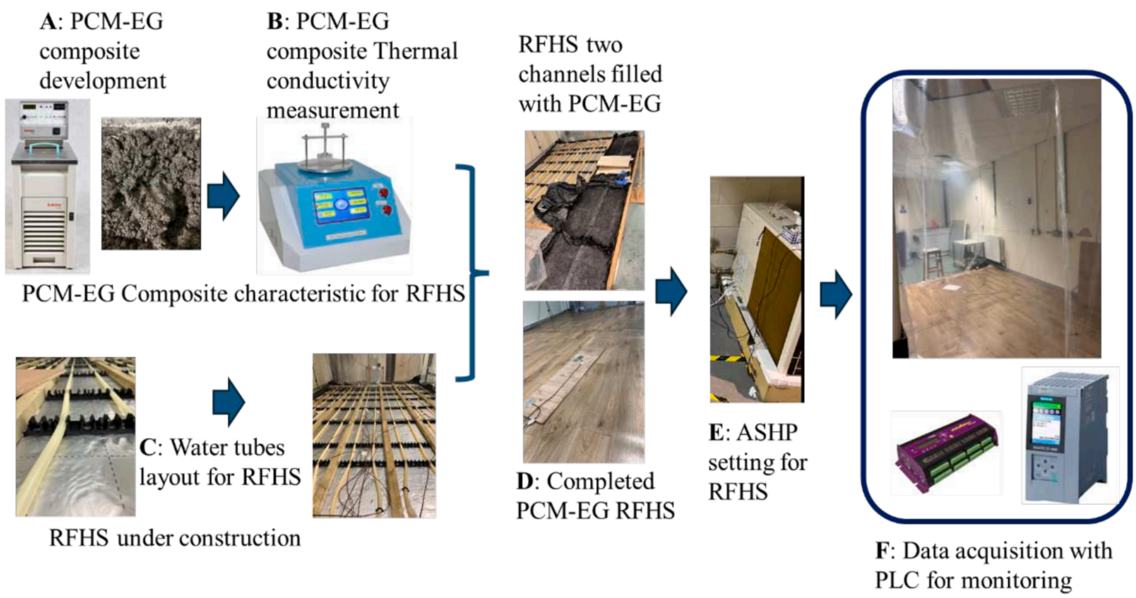

Fig. 7. The experimental procedure and schematic of the experimental setup.

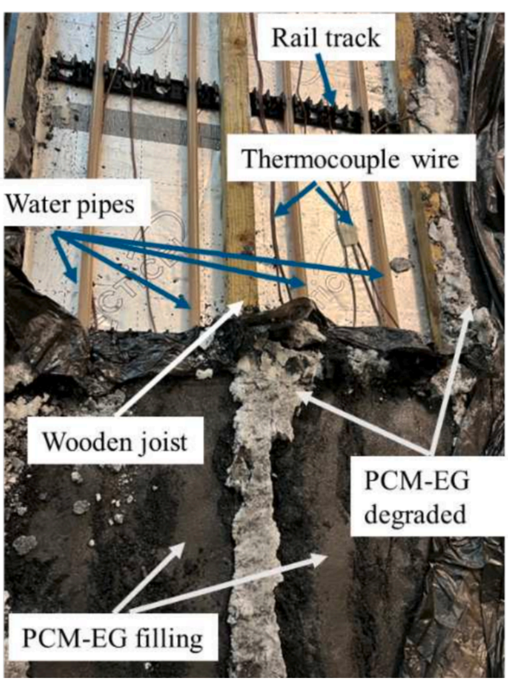

Fig. 8. PCM-EG composite with EG wt. 25 % degraded with repeated heating operation after two months.

cases on the floor surface of the underfloor. Each case utilises a PCM-EG composite with 30 wt% EG. The system was heated for two hours with HP setting point at 55 °C hot water supply and subsequently allowed to cold naturally. The thermal performance of Case I and Case II is comparable during the heating process, with both cases showing gradual increases in floor surface temperature and effective temperature retention after the heating was turned off. Case II which incorporates 10 wt% copper powder into the PCM composite, exhibits a peak floor surface temperature 0.7 °C higher than Case I which is PCM-EG composite used only. The added copper powder in Case II enhances heat transfer, increasing the capacity of heat storage around the PCM and causing a time lag before the thermal energy is reflected on the floor surface.

Case III demonstrates a faster heat response than Case IV during the ASHP operation and shutdown periods, indicating lower thermal retention. The ability of Case III to charge the floor to a higher temperature rapidly suggests that the system is more efficient in delivering heat to the floor, potentially reducing the need for higher water temperatures from the Air Source Heat Pump (ASHP). This reduction in the required hot water temperature could result in energy savings.

3.5. Thermal performance of water storage and PCM-EG RF heating system under designed operation schemes

The system is designed to provide space heating between 7:00–9:00 and 17:00–23:00, while charging the 120 L hot water storage from 3:00–5:00 AM. The RF heating system is controlled by a PLC device, following a tariff scheme for the heat pump (HP) to deliver heat with 55 °C setting point, ensuring the room temperature remains above 20 °C, while the floor surface temperature stays below 29 °C with deviation. The heating source supplied is a combination of direct heating from the ASHP and reserved heat from the thermal storage, depending on the tariff scheme. The thermal performance of the water storage and PCM-EG RF heating system under the three operational schemes is shown in Fig. 15, which illustrates temperature variations and electricity consumption by the ASHP. From Fig. 15, it is evident that the ASHP begins operating at 3:00 to charge the water storage, raising the temperature from 30 to 50 °C within 130 min. At 7:00, the ASHP switches to providing space heating through the PCM-EG underfloor heating system. Within 2 h, the room temperature reached 21.5 °C while the floor surface temperature continues to rise to 28 °C and remains above 22 °C throughout the daytime, with the room temperature maintained at 21 °C till 17:00.

In the evening, space heating requirements are met by two heat sources: 1) Heat retained in the water storage until its outlet temperature drops below the setpoint temperature of 30 °C and 2) Heat supplied by the ASHP to the RF heating system to maintain the designed thermal comfort levels in the room. This operation scheme demonstrates efficient thermal management, ensuring indoor comfort while optimising energy use. From the Fig. 15, it can be seen that the system employs two discharging periods during the evening (17:00–18:00 and 20:00 to 21:30) to maintain room temperatures above 20 °C while the floor surface temperature stabilises around 24 °C. During the first discharging period (17:00 to 18:00), the water storage outlet temperature decreases from 45 °C to 34 °C, raising the floor surface temperature from 21 °C to 25 °C. This heat supply maintains the room temperature above 20 °C for

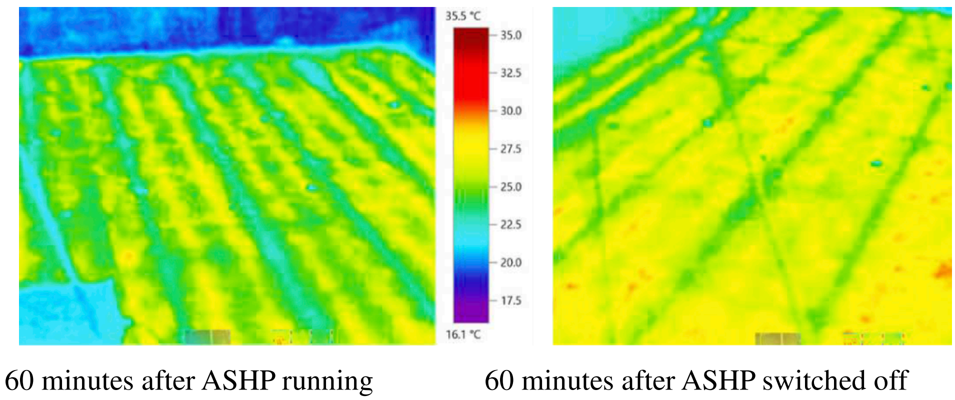

Fig. 9. Thermal images of the PCM-EG with 30 % EG by weight, integrated into the underfloor system, with the ASHP heating for 60 min and switching off after 60 min.

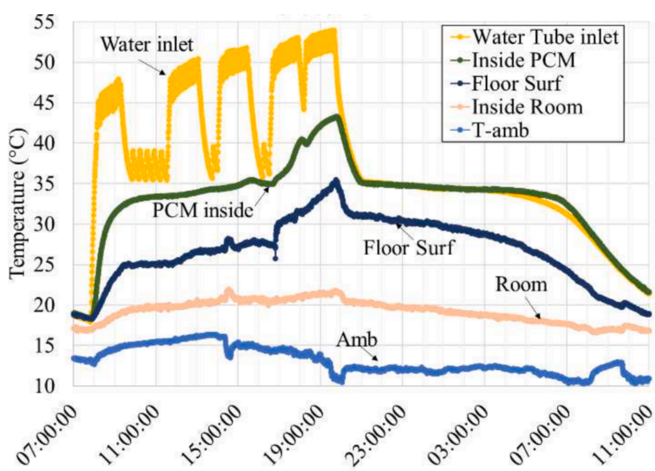

Fig. 10. PCM-EG Underfloor heating system operated by the ASHP for heat supply.

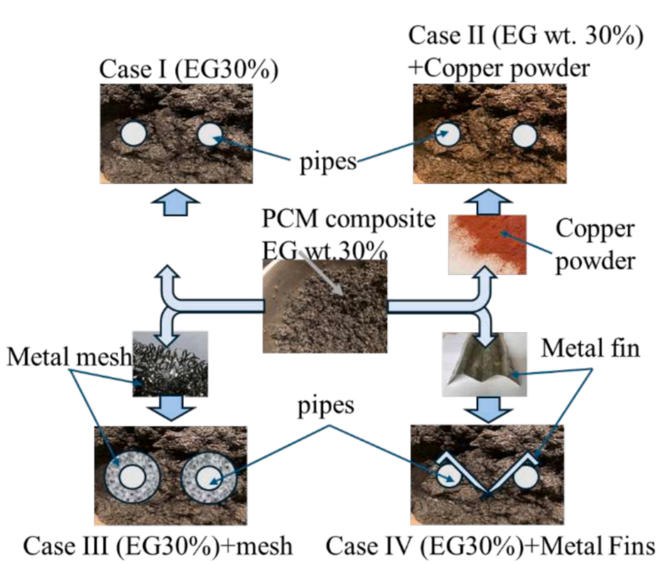

Fig. 11. Cases of PCM-EG underfloor heating system with different structures in the channels.

~2.5 h before it begins to decline.

During the second discharging period, heat is still supplied from the water storage until the water outlet temperature drops below 30 °C in

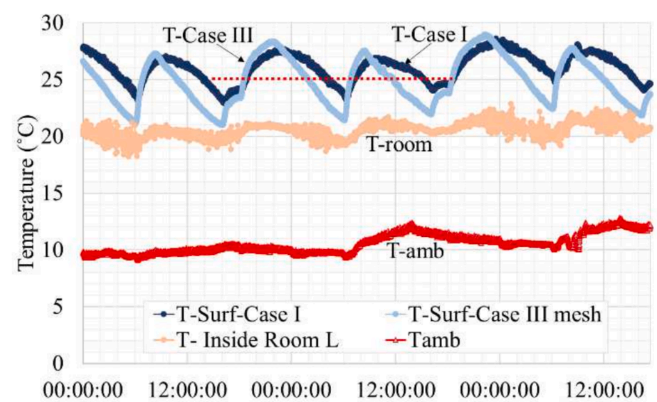

Fig. 12. Thermal performance of PCM EG RF heating system over 3 days.

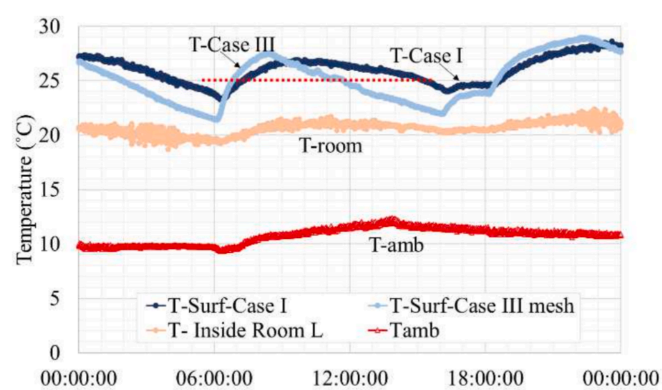

Fig. 13. Detailed thermal performance of the ASHP driven underfloor heating system on Day2.

Table 3
Comparison of two RFHS structures in terms of time taken to reach and retain floor surface temperature above 25 °C over 24 h.

Cases	Time for raising floor surface temp. to 25 °C (minutes)	Time for retain the floor surface temp. above 25 °C during off heating	Comparison %
Case I	57	8 hrs 15 mins	37 %
Case III	44	5 hrs 12 mins	

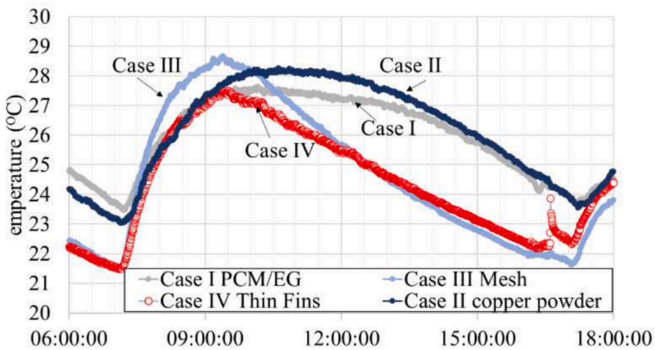

Fig. 14. Thermal control comparison of four PCM-EG cases. with two hours heating.

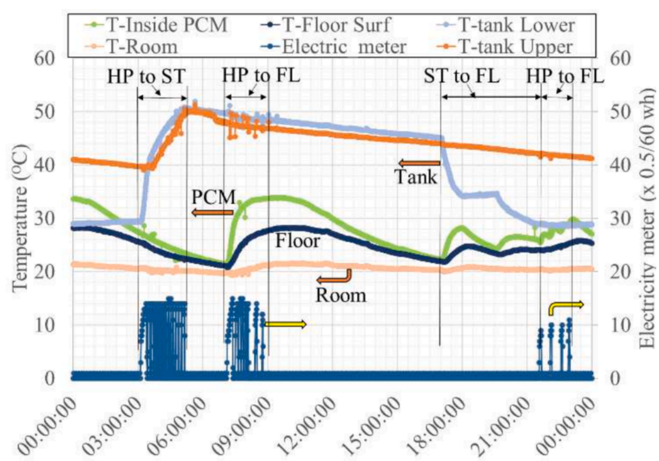

Fig. 15. Typical 24 h system operation with charging/ discharging, temperatures of indoor environment, floor surface and water thermal storage.

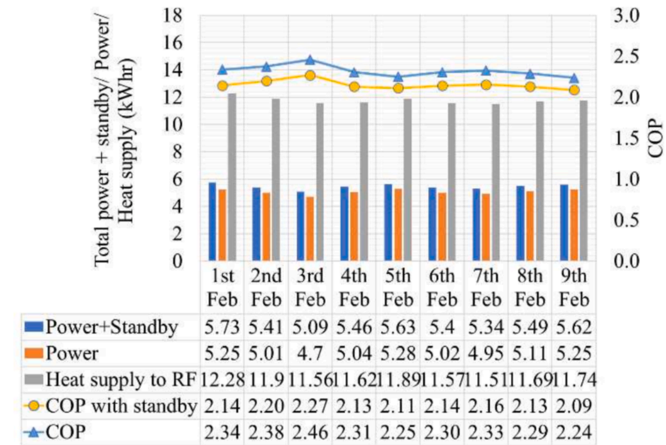

Fig. 16. The total thermal energy and power performance with nine hours operation with the PCM-EG as thermal mass filled in the underfloor heating system during winter.

the water storage, after which the ASHP resumes operation to maintain room temperatures above 20 °C until 23:00. Early morning heating by the ASHP ensures sufficient heat input to the underfloor system, enabling the PCM-EG to melt at its phase transition temperature of 33–36 °C. The stored latent heat within the PCM-EG keeps the floor surface temperature above 22 °C till 17:00. The benefits of using PCM for stabilizing indoor thermal comfort are clearly demonstrated in this operation cycle.

3.6. ASHP thermal performance with nine hours of operation using PCM-EG as thermal mass filled in the underfloor heating system during winter

Fig. 16 presents the total thermal energy and power performance of the ASHP-driven RF heating system with PCM-EG as thermal mass during a nine-hour operation period in winter, Northern Ireland. During the coldest season in Northern Ireland, the integrated ASHP with PCM-EG underfloor heating system, achieves a coefficient of performance (COP) of ~2.3. This represents a significant improvement in ASHP efficiency compared to systems without PCM-EG integration for longer period with daily routine. The PCM-EG acts as an effective thermal mass, enhancing heat retention and reducing energy consumption for residential heat supply.

4. Conclusions

This study has experimentally investigated and analysed the characteristics of various enhanced heat transfer approaches for the RF-PCM-EG system under variable conditions. Extensive onsite data were collected thoroughly discussed. The findings revealed that the thermal conductivity of the PCM-EG composite improves with increasing EG wt % and compression density. Specifically, a composite with 30 wt% EG and a density of 950 kg•m^{-3} provided optimised thermal conductivity improvements and structural stability for RF heating system applications. However, for broader implementation in building applications, the potential of shape stable composites such as PCM epoxy-graphite warrants further investigation to enhance the mechanical stability and durability of the system. The ASHP performance, integrated with new sustainable and highly efficient thermal the PCM-EG underfloor heating system was evaluated under these optimised conditions. The study also analysed the optimal operational routines combing heat pumps and thermal storage for residential building applications, demonstrating significant energy savings for keeping a thermal comfort environment in longer period. Results show that PCM-EG composites improve the thermal energy retention capacity of the system by 37 % compared to systems using a metal mesh with PCM-EG. Additionally, PCM-EG composites mixed with copper powder maintained floor surface temperature 0.7 °C higher than PCM-EG alone, further reducing ASHP power consumption. This research provides valuable insights for integrating thermal storage with ASHPs in energy efficient building applications. However future work should focus on long-term durability and reliability of PCM composites, addressing challenges such as thermal degradation and cycling durability to ensure cost-effectiveness and sustainability over time with optimising control.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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