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Numerical investigation of a cooling system with phase change material thermal storage for the energy savings in residential buildings

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Abstract

Energy consumption for cooling is the fastest-growing use of energy in buildings, and the space cooling systems have become one of the major end-users in building service systems. In recent years, phase change materials (PCM) have been increasingly adopted to reduce cooling energy consumption. This paper presents the simulations of an integrated latent heat thermal energy storage (ILHTES) system for residential buildings, which includes the PCM-to-air heat exchanger (PAHX) and air conditioner (AC). In this study, the Modelica language is adopted to develop the numerical model of the ILHTES system. A numerical heat transfer model has been used to simulate the performance of PCM-to-air heat exchanger, and it has been validated against data from the literature. Using the Modelica library AixLib, a simulation of the dynamic behavior and energy consumption of the building is performed. With the help of the ILHTES model, the optimal design of the system can be obtained using the results of the simulations throughout the cooling season. This study evaluates the energy savings potential of the ILHTES system over the conventional air conditioning system under realistic climate conditions in Budapest. The results show that an energy saving ratio of 32.4% can be achieved. The effect of PCM type on energy consumption of the ILHTES system is investigated, the results show that for three commercially available PCMs, RT25, RT20, and RT18, the ILHTES system using RT25 can utilize less energy and obtain a higher energy saving ratio.

Introduction

A large amount of primary energy is consumed by the building sector. As the major end-users in building service systems, heating, ventilation, and air conditioning (HVAC) systems account for over 40% of the total energy consumption of buildings (Kim et al., 2020). Space cooling, the fastest-growing end-use in building service systems, has tripled energy consumption since 1990 (IEA, 2018). It is estimated that space cooling consumed over 8.5% of the total electricity consumed in 2019 and emitted over 1Gt of carbon dioxide (CO_2). Over the next three decades, cooling energy demand will grow by an average growth of 3% (IEA, 2018).

A growing number of thermal energy storage systems is used in building service systems, which can be seen as a practical way to reduce waste and improve energy efficiency. There has been considerable interest in latent heat storage using phase change materials (PCM) in recent years. PCM can absorb and release large amounts of heat during the phase change process, and the temperature variation is relatively small, making them an excellent option for building applications.

A strong interaction exists between thermal energy storage units and buildings. It is important to note that occupant behaviors, climate conditions, operation strategies affect the performance of buildings. The optimal design of thermal energy storage units should therefore consider the integration of buildings in order to minimize energy consumption and economic cost. A co-simulation platform was developed to integrate latent heat thermal energy storage units with lightweight building envelopes (Rouault et al., 2016). In the MATLAB environment, a simulation model of the thermal energy storage unit was developed and validated using experimental data. The performance of a wooden building in Bordeaux, France, was developed with EnergyPlus. For passive building designed with latent thermal energy storage in Stockholm, the techno-economic analysis was presented (Chiu et al., 2013). The multi-objective optimization algorithm was used to find the economic solution to minimize the cooling demand and the life cycle cost of the integrated thermal system.

The above cooling systems (Rouault et al., 2016; Chiu et al., 2013) were designed for regions where nighttime outdoor air temperatures were lower than thermal comfort ranges for most of the cooling season. However, in hot climates, the lowest outdoor air temperature at nighttime still exceeds the comfort level. It is therefore crucial to integrate an air conditioner with the thermal energy storage unit and to maintain the indoor thermal comfort temperature. An integrated cooling system that incorporated an air source heat pump, PCM-to-air heat exchangers, and building was presented (Farah et al., 2019). Based on the manufacturer's performance catalog, the air source heat pump model was developed, and a two-dimensional numerical model was used to simulate the dynamic performance of the thermal energy storage unit. The cooling demand of the building was calculated using AccuRate, a NatHERS accredited software. Under three different operation modes, the cooling energy consumption and electricity consumption of the cooling system were compared. The effect of a price-based operation strategy on a cooling system with latent thermal energy storage was studied experimentally

(Gholamibozanjani et al., 2020). The room was kept comfortable by an air conditioner and PCM unit during the warm season. Using the proposed operating strategy, energy consumption can be reduced by up to 23% daily, and costs can be reduced by 42%. A dynamic model for integrating PCM-to-air heat exchangers with air-conditioned building was presented (Chen et al., 2019a). The in-house model for building cooling demand and thermal energy storage unit were developed and validated with commercial software and literature's data. By using thermal energy storage units in combination with air conditioner, the results showed that the energy saving ratio by using thermal energy storage unit over conventional system was found to be 16.9% - 50.8%

The above studies (Farah et al., 2019; Gholamibozanjani et al., 2020; Chen et al., 2019a) investigated the effect of different operation strategies on the performance of the integrated latent heat thermal energy storage system (ILHTES). Several key parameters, including PCM type, slab length, and slab thickness, have been fixed. However, for integrated energy systems, it is important to optimize the key parameters at an early design stage to ensure the efficiency of the system. Many computation tools for hybrid energy systems aim at optimizing design through long-term simulations, such as HOMER Pro (HOMER Energy, 2016), iHOGA (López, 2021), REopt (Simpkins et al., 2014), SAM (Blair et al. 2014). To determine the techno-economic outcomes of the energy systems, these tools conduct yearly simulations. Consequently, the optimization engines of the tools adjust the design variables to determine the optimal result. To the best of our knowledge, very few studies have tackled the optimization of the design of the ILHTES system based on the simulations of the cooling season. Thus, the main contribution of this paper is firstly, to determine the optimal values of key design parameters for cooling system of residential buildings using PAHX and air conditioner based on long-term simulations for cooling season. Secondly, we aim to evaluate the impact of PCM type on the performance of the ILHTES system under realistic climatic conditions.

System description

In this study, an integrated latent heat thermal energy storage (ILHTES) system, comprised of a PCM-to-air heat exchanger (PAHX) and an air conditioner (AC), has been proposed for space cooling of residential buildings. Figure 1 shows the schematic of the ILHTHS system.

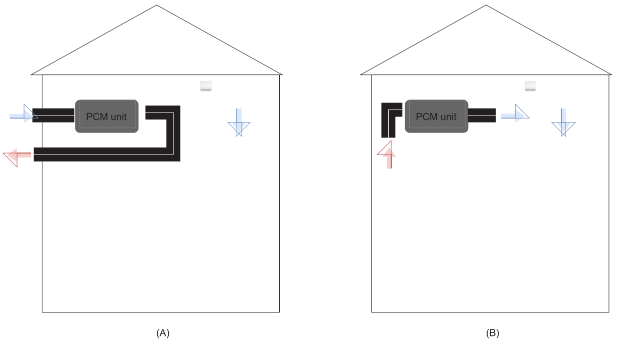

Figure 1 Schematic of ILHTES system: (a) charging mode and (b) discharging mode

A residential building of small size is taken into consideration, which refers to ANSI/ASHRAE Standard 140 (ASHRAE, 2004). The ANSI/ASHRAE Standard 140 is widely used worldwide for validating the accuracy of building performance simulation tools. Case 600 is a low-mass, single-zone building, with dimensions of 8 m × 6 m × 2.7 m and 12 m^2 of south-facing windows. A description of the reference building, such as its infiltration rate, internal gains, and construction material properties, is provided in the report (ASHRAE, 2004). PAHX is described in detail in the following section, the operation strategy for the ILHTES system is outlined below.

(1) At night, between 18:00 in the evening and 8:00 in the morning, as shown in Figure 1(a), the fan only operates if outdoor air temperature is less than 22 °C, so that the cold energy of the air can be stored into PCM slabs and solidify the PCM. The fan will turn off when the outside temperature rises above 22 °C.

(2) During the daytime, between 8:00 in the morning and 18:00 in the evening, as shown in Figure 1(b), discharging occurs when the room temperature has exceeded the set-point 24 °C, the indoor air flows through the PAHX and extracts the cold energy from PCM slabs, the outlet air is introduced for cooling. If the room temperature is below the set-point, the fan turns off and there is no air flows through PAHX.

For both daytime and nighttime, as backup, AC runs when room temperature is higher than 27 °C.

Modeling and validation

Based on the Modelica language, simulation environment Dymola is adopted to construct the simulation platform of the ILHTES system. Modelica is an object-oriented modeling language that simulates the behavior of transient systems.

Model of PCM-to-air heat exchanger

The PAHX is composed of parallel slabs containing PCM. This air moves through channels in between slabs. There is convection heat transfer between the air and the slab, and heat transfer through the slabs by conduction. Figure 2 illustrates the schematic of PHAX.

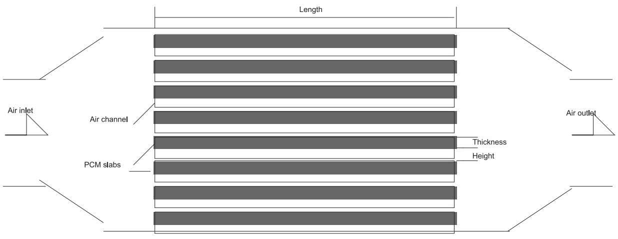

Figure 2 Schematic of PCM-to-air heat exchanger

Based on the assumptions below, the PCM-to-air heat exchanger model is developed:

- The storage unit does not consider heat loss to the surrounding environment.
- Radiative heat transfer between adjacent slabs is not considered.
- The density and thermal conductivity of the PCM are different for both solid and liquid phases, but it is considered to be constant within one phase.
- Using the Cp-T relationship, the specific heat capacity of the PCM can be determined as a function of temperature.
- Conduction dominates heat transfer in the PCM slab and natural convection is not considered during phase change.
- The heat conduction in PCM is treated as one-dimensional problem in the vertical direction.
- For horizontal air flow, one-dimensional assumption is employed, and convection heat transfer occurs between air and slabs.

The transport of energy through the air channels and the heat transfer to PCM are guided by energy balance equation, which can be defined by one-dimensional partial differential equations as a function of horizontal position and time:

$$\rho_a C_{p,a} A \frac{\partial T_a}{\partial t} + \dot{m} C_{p,a} \frac{\partial T_a}{\partial x} = q_e \quad (1)$$

Where ρ_a, $C_{p,a}$, T, $\dot{m}$ are the density, specific heat capacity, temperature, mass flow rate of air, A is the area of air channel, q_e is the convection heat transfer rate between air and PCM slabs.

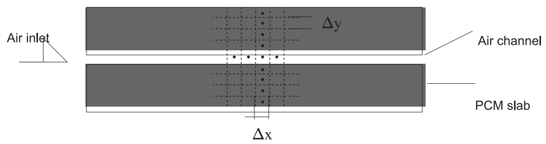

Figure 3 Numerical discretization grid of PAHX

As shown in Figure 3, by dividing the air channel into cells along the horizontal direction, the Equation (1) can be reduced to ODEs, the energy balance equation of each cell can be written as:

$$\rho_a V C_{p,a} \frac{dT_{cell}}{dt} = \dot{m} C_{p,a} (T_{cell} - T_{cell,eu}) + h_c \pi D \Delta x \, (T_{cell} - T_{PCM}) \quad (2)$$

Where V, Δx is the volume and length of the cell, D is the perimeter of the air channel. h_c is the convection heat transfer coefficient between air and PCM slabs. T_{cell}, $T_{cell,eu}$, T_{PCM} are the cell temperature, outlet temperature of the cell, temperature of adjacent PCM slab.

In order to determine the convection heat transfer coefficient of air in the channels, the following equation can be used:

$$h_c = Nu \frac{k}{D} \quad (3)$$

For laminar flow, the Nusselt number is a constant:

$$Nu = 7.54 \quad (4)$$

For fully developed turbulent flows, Nusselt number can be determined using the Dittus-Boelter correlation (Nellis and Klein, 2009):

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (5)$$

The heat conduction of PCM slabs is supposed to be one-dimensional, the numerical model which is shown as below:

$$\rho_{PCM} C_{PCM} \frac{\partial T_{PCM}}{\partial t} = \frac{\partial}{\partial y}\left(k_{PCM} \frac{\partial T_{PCM}}{\partial y}\right) \quad (6)$$

Where ρ_{PCM}, C_{PCM}, T_{PCM}, k_{PCM} are the density, specific heat capacity, temperature, thermal conductivity of the PCM. For the solid and liquid phases, the density and thermal conductivity of PCM are different, but they are considered constant within one phase. Thermal conductivity of PCM has the similar characteristic of density. DSC heat capacity method is used for calculating the specific heat capacity of PCM based on the Cp-T relationship (Hu et al., 2020).

As shown in the Figure 3, the one-dimensional equation can be solved by discretizing the PCM slab into layers, with heat storage capacity along the vertical direction, the energy balance of each layer can be described as follows:

$$\rho_{PCM} C_{PCM} \frac{dT_{PCM,i}}{dt} = \frac{k_{PCM} w \Delta x (T_{PCM,i+1} - T_{PCM,i})}{\Delta y} + \frac{k_{PCM} w \Delta x (T_{PCM,i-1} - T_{PCM,i})}{\Delta y} \quad (7)$$

Where w is the width of the PCM slab, Δx is the length of air channel cell, Δy is the height of the PCM slab layer along the vertical direction.

A validation study comparing the simulation results to experimental data from the literature (Arzamendia Lopez et al., 2013) have been carried out to determine the accuracy of the PAHX numerical model. There were two sets of experiments conducted under air flows of 240m^3/h and 330m^3/h. For each set of experiments, the inlet temperature was changed during charging and discharging. The mean absolute error (MAE) and the mean relative error (MRE) are used as indicators of the accuracy of the numerical model, which is expressed as follows:

$$MAE(°C) = \frac{1}{N} \sum_{i=1}^{N} |T_{exp,i} - T_{num,i}| \quad (8)$$

$$MRE(\%) = \frac{100}{N} \sum_{i=1}^{N} \frac{|T_{exp,i} - T_{num,i}|}{T_{exp,i}} \quad (9)$$

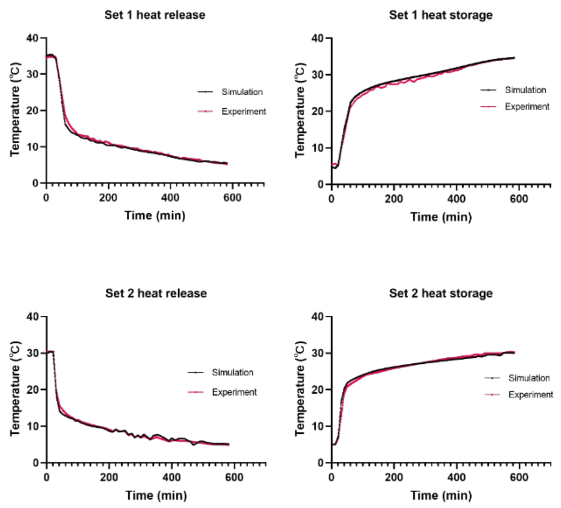

Figure 4 Validation results of PAHX

As shown in Figure 4, the simulation results and experimental data for the air temperature at PAHX outlet has been compared. With regards to the validation cases above, the MAE is 0.44°C, 0.55°C, 0.35°C, 0.46°C, respectively. The MRE between simulation results and experiment data is 3.88%, 2.66%, 4.34%, 2.20%, respectively. It is evident from the shown result that the predictions from the presented model have a good agreement with the experimental data.

Model of air conditioner

In this study, the typical split air conditioner is considered to remove heat from residential buildings in order to improve thermal comfort level. To determine the relationship between cooling energy and electricity consumption, the model of air conditioner is used (Verhelst et al., 2012; Lamaison et al., 2019):

$$COP = \frac{C_{AC}}{E_{AC}} \tag{10}$$

where COP is the coefficient of performance, it is assumed that COP does not vary based on operation conditions and is considered to be 2.3. C_{AC} is cooling energy provided to buildings, E_{AC} is the electricity consumption of the air conditioner.

Model of residential building

AixLib that is the calculation engine for building performance simulation developed by the RWTH is used in this study (Müller et al., 2016). The library is developed based on Modelica language, which follows the open-source approach. The AixLib library includes dynamic models for multi-zone buildings, electric systems, and HVAC equipment such as chillers, heat pumps, solar collectors, fans, and pumps. It has been adopted to design and evaluate building energy systems, develop and optimize control strategies, fault detection and diagnostics in building energy systems ranging from single buildings to urban scales.

The low-order approach of AixLib has been utilized to calculate the dynamic behavior of small-size residential buildings described in Section 2. More details about the LowOrder approach's validation results have been provided in the literature (Lauster et al., 2014).

Optimization

Optimization objective and design variables

The slab thickness and air flow rate are selected as design variables in this study. The slab thickness is related to geometry of the PCM-to-air heat exchanger, the air flow rate is related to operation condition of the system. Table 1 summarizes the range of design variables.

Table 1 Range of the design variables

Design variables	Lower Bound	Upper Bound	Units
Slab thickness	5	40	mm
Air flow rate	270	970	m^3/h

Slab length, slab width and air channel height are not selected as design variables, the values of these parameters are shown in Table 3. For slab length (Chen et al., 2019b) and slab width (Halawa et al., 2011), there is a clear trend that the energy capacity of PAHX increases with increasing the length and width. For air channel height, by lowering the air channel height, the heat transfer between air and slabs has been enhanced, thus increasing the energy capacity of PAHX (Dolado et al., 2011).

The optimization objective is to minimize the total energy consumption of the ILHTES system over the analysis period, which is expressed as following:

$$E_{with\ PCM} = \frac{C_{AC}}{COP} + E_F \tag{11}$$

Where $E_{with\ PCM}$ is the total energy consumption of ILHTES system, E_F is the electricity consumption of fan.

Surrogate modeling for ILHTES system

A system of differential-algebraic equations (DAE) can be constructed by using the Modelica language to represent the ILHTES system. The transient behavior analysis of the energy systems can then be performed. However, due to the large number of simulations over a long period of time, optimization of the ILHTES system based on DAE is time consuming. Due to the reasons stated above, the surrogate model is adopted to replace the original model. The surrogate model is a type of approximation model that can significantly reduce computational cost.

An artificial neural networks (ANN) surrogate model is developed based on input data and simulation results from Modelica to predict energy consumption of the integrated latent heat thermal energy storage unit, which is expressed in Equation (11). Figure 5 shows the structure of the ANN. This neural network has two inputs, ten neurons in the hidden layer, and one output. Finally, the surrogate model is used to find the optimal design variables with the minimum energy consumption.

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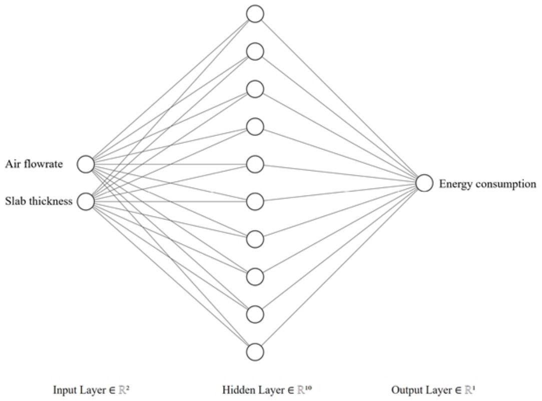

Figure 5 Structure of ANN model

Optimization process

Figure 6 shows the whole process of optimization. The Modelica model is used to perform long-term simulations covering the cooling season. With pre-defined operation strategy, the performance of the building cooling system can be predicted based on slab thickness, slab length, slab width, PCM type, and building dimension. As a result of the simulation, information such as energy consumption, room temperature, temperature at the PAHX outlet can be obtained. In addition, to reduce computation costs, a surrogate model has been developed. Figure 5 shows the structure of the surrogate model, which is the substitute for the Modelica model. Finally, to find the minimum energy consumption, the genetic algorithm is applied on the surrogate model to obtain the optimal design variables.

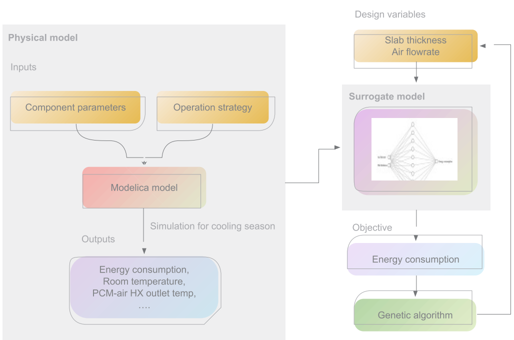

Figure 6 Flowchart of the optimization process

Case study

In this study, based on realistic climatic conditions, the energy saving potential of the ILHTES system for Budapest city is evaluated for a time period from July 1st to September 30th.

To determine the effect of PCM type on the performance of ILHTES system, three commercially available PCMs were selected (PCM RT25, PCM RT20, and PCM RT18). Table 2 provides the physical properties of selected PCMs (Liu et al., 2017).

Table 2 Physical properties of selected materials

	PCM RT25	PCM RT20	PCM RT18
Melting temperature $(^{\circ}C)$	23-25	18-20	16-18
Solid density (kg/m^3)	880	880	880
Liquid density (kg/m^3)	760	760	760
Thermal conductivity $(w/m.K)$	0.2	0.2	0.2

In Figure 7, the Cp-T curves of the three PCMs are shown (Liu et al., 2017).

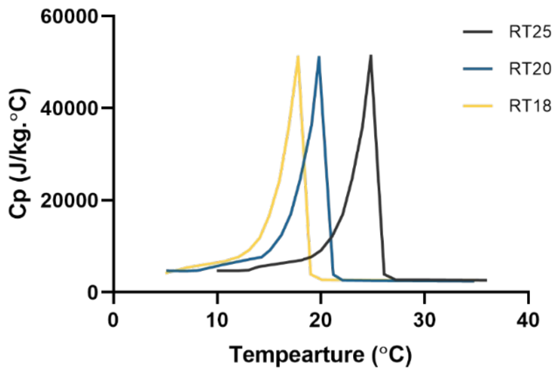

Figure 7 Cp-T curves for three PCMs

In addition to the two design variables (slab thickness, air flow rate), the other main parameters of PAHX are shown in the Table 3.

Table 3 Main parameters of PAHX

Item	Values
Slab length (m)	2
Slab number $(-)$	20
Slab width (m)	1.8
Air channel height (mm)	2.5

The energy saving ratio (ESR) is defined as the ratio between energy saving by using PCM in buildings in comparison with the traditional system and that of the traditional system. Accordingly, the equation of ESR is given by:

$$ESR = \frac{E_{without\ PCM} - E_{with\ PCM}}{E_{without\ PCM}} \times 100\% \quad (12)$$

Where ESR is the energy saving ratio, $E_{without\ PCM}$ is the total energy consumption of the building without PCM, $E_{with\ PCM}$ is the total energy consumption of the ILHTES system.

Results and discussions

Design optimization of the ILHTES system in Budapest

The performance of ILHTES system using PCM RT25 is analyzed in this section under Budapest's climate conditions.

It is important that the key parameters of the ILHTES system be sized properly to reduce the cooling energy consumption of residential buildings. Figure 6 illustrates the detailed optimization process for the key parameters based on simulation results of the cooling season. The optimal results for design variables, energy saving ratio, and energy consumption for buildings with and without PCM technology can be found in Table 4. The results demonstrate that by adding PCM RT25, the ILHTES system is more energy efficient during the cooling season and an energy saving ratio of 32.4% can be achieved.

Table 4 Comparison results between system with and without PCM in Budapest

	Slab thickness (mm)	Air flow rate (m^3/h)	Energy consumption (kWh)	ESR (%)
Without PCM	-	-	1090	-
RT25	10.1	594.7	737	32.4

After optimizing the ILHTES system, simulations have been conducted for the entire cooling season. As illustrated in Figure 8, the weekly AC energy consumption of the building without PCM, as well as the AC and fan energy consumption of the ILHTES system, shows that PCM plays a significant role in reducing AC energy consumption. The AC energy consumption of the ILHTES system has nearly dropped to zero during the weeks of week 10 to week 13 of the cooling season. The PAHX can almost meet the cooling demand independently.

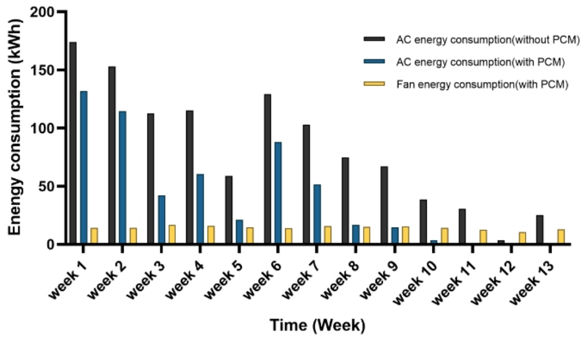

Figure 8 Energy consumption of the main components of system with and without PCM

Effect of PCM type on performance of the ILHTES system

As the melting temperature of PCM determines the performance of the ILHTES system, choosing the proper PCM is a crucial element in the design phase. Three commercially available PCMs, RT25, RT20, and RT18, were used to evaluate the effects of PCM type on system performance during the cooling season in Budapest. The surrogate model has been trained for each PCMs and used for the optimization process. The optimal results, energy consumption and energy saving ratio are presented in Table 5. It was found that ILHTES system using RT25 performed better during the study period than the system using RT20 and RT18. The energy consumption for the ILHTES system using RT25, RT20, and RT18 was respectively 737 kWh, 782 kWh, and 774 kWh. With 32.4% energy savings, the ILHTES system using RT25 are the most energy efficient. This is because that the PCM with higher melting temperature increases the temperature difference between ambient temperature during the nighttime and PCM melting temperature, which results in the larger amount of PCM being solidified, then more cooling energy can be released during the daytime.

Table 5 Effect of PCM type on the performance of ILHTES system

	Slab thickness (mm)	Air flow rate (m^3/h)	Energy consumption (kWh)	ESR (%)
Without PCM	-	-	1090	-
With RT25	10.2	594.7	737	32.4
With RT20	27.1	545.9	782	28.3
With RT18	26.6	505.9	774	29

Conclusion

Using a PCM-to-air heat exchanger and air conditioner, the energy performance of the ILHTES systems for residential buildings is investigated numerically in this study. The numerical models of the main components have been developed and validated with experiment data. Under realistic climatic conditions, long-term simulations of the studied system are carried out to determine the optimal design solution. A few conclusions can be made from this study:

- The optimal sized ILHTES system using PCM RT25 under climatic condition of Budapest leads to energy consumption reduction by 32.4% compares to the building without PCM.
- The ILHTES system using PCM RT20 and RT18 can achieve an ESR of 28.3% and 29% in Budapest, which is lower than the system using PCM RT25 with an ESR of 32.4%.

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