Numerical Study of Application of PCM for a Passive Thermal Energy Storage System for Space Cooling in Residential Buildings

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Abstract. In this paper, effectiveness of phase change materials (PCMs) for application in passive thermal energy storage (TES) system for space cooling in residential buildings is investigated numerically. PCM is encapsulated in steel containers and integrated into the building interior under a ceiling slab. Thermal response of two phase change materials with different melting/solidification temperatures under the typical summer conditions of the Baltic States is analysed by using computational fluid dynamics (CFD) software Ansys Fluent. The results showed that integration of the passive TES system can reduce the overheating problem and improve thermal comfort; however full advantage of the PCM storage capacity cannot be taken without active regeneration of the PCM.

1. Introduction

In the European Union, buildings account for approximately 40% of total energy consumption and over 36% of greenhouse gas emissions [1]. Therefore, one of the priorities of the EU is the improvement of the energy performance of buildings [2, 3]. The introduced legislative instruments drive engineers and scientists to develop new building concepts that contribute to achieving these goals.

Conventional heating, ventilating, and air conditioning (HVAC) systems are responsible for most of the energy use in buildings as well as for associated greenhouse gas emissions [4]. Hence, there is a demand for alternative energy technologies such as thermal energy storage systems that can reduce the energy consumption in buildings and at the same time provide thermal comfort indoor. The recent developments in TES show that latent heat thermal storage systems with the application of phase change materials have received considerable attention due to their ability to provide high volumetric heat capacity and their ability to store thermal energy at relatively constant temperatures [5-7]. While energy storage capabilities of traditional building materials are restricted to sensible heat, the PCM ability to store energy is defined by latent heat of fusion. PCM absorb or release the energy equivalent to their latent heat during the phase change process thus providing a large heat capacity over a limited temperature range [6].

In general, latent heat thermal storage systems for buildings can be categorized into two main application methods which are active and passive methods. Active TES systems [8-11] such as solar...
heat pumps, air-conditioning units, floor heating, and thermally active ceiling panels use fans and pumps to transfer energy to air or water, which serve as the working fluids to move thermal energy of the PCMs. Passive application methods, on the other hand, are technologies where the TES system is operated without the external supply of energy. This way phase change material will simply store or release energy if the adjacent air or surface temperature is above or below the melting point. Typically, PCM melts during the daytime thus absorbing the heat and solidifies during the night by dissipating the stored energy. In passive applications, phase change materials can be integrated into a building envelope as separate components (encapsulation) or integrated directly (immersion and impregnation) into conventional building materials. Typical applications of the direct integration into building materials include PCM-impregnated wallboard, concrete, floors, ceiling and roofing materials [16]. Encapsulation (micro or macro), on the other hand, involves containing the PCM with another material. Micro-encapsulated PCMs are typically contained by microscopic polymeric capsules which then are incorporated into various building materials [16]. The macro-encapsulation is the technique in which PCMs are contained in a wide range of containers such as tubes, spheres and panels that interact with other building materials through conduction and convection. Many studies [12-15] have reported that PCM integrated passive application systems for buildings can reduce overheating problems and increase building energy efficiency; however, their effectiveness largely depends on the thermophysical properties of PCM, internal gains and local climatic conditions [13].

In this paper, application of PCM for a passive thermal energy storage system is investigated numerically. Stand-alone PCM storage units installed between the concrete ceiling slab and the ceiling finishing layer is proposed for space cooling in a multi-storey nearly zero-energy residential buildings. The macro-encapsulation technique is adopted for the storage unit as a steel tray serves as a container for phase change material. Two types of PCMs (salt hydrate and paraffin) with different melting/solidification temperatures are analysed in this research. The main focus of this study is on the thermal response of a passive TES system under the typical summer conditions of the Baltic States. The investigation is carried out by using computational fluid dynamics (CFD) software Ansys Fluent.

2. Materials and methods

The present study is carried out in the frames of the project aiming at the development of a new concept for sustainable nearly zero-energy buildings. Nearly zero-energy energy requirements in northern climate demand the thermal storage and insulation properties of the building envelope to be designed in order to delay and decay the outdoor temperature and to reduce the heat loss during winter. On the other hand, a well-insulated building envelope and highly glazed façade cause overheating of the building in summer time and therefore a comfortable indoor air temperature cannot be maintained without space cooling. Considering the latest developments in the field of TES systems, the aim of this study was to design a PCM incorporated passive system with thermal storage capacity approximately equal to the heat gains within the space during a daily cycle. The macro-encapsulation technique is adopted for the system as PCM is contained in stand-alone steel containers. This way the TES system is suitable for local installation in the building interior as the stand-alone units can easily be added or removed without affecting the building structure.

2.1. Numerical modelling

The object of the present study is a living room with dimensions of 6 x 6 x 3 m located on the second floor of a multi-storey residential house designed according to the nearly zero-energy requirements. The external walls are constructed from three layers of bio-based materials with total thickness of 0.37 m [17]. The internal walls and floors are made of 0.12 m thick high performance cement composite [18]. Façade side contains 40% fenestration which comprises 7.2 m². The windows feature three layers of glazing (4mm) with an air gap (9 mm) between the layers. Detailed properties of all materials used in this study are listed in table 1.
Table 1. Material thermal properties.

| Domain                     | Material     | Density, kg/m³ | Specific heat, J/(kg·°C) | Thermal conductivity, W/(m·°C) |
|----------------------------|--------------|----------------|--------------------------|--------------------------------|
| indoor air                 | air          | a              | 1000                     | 0.0267                         |
| inner wall and slabs       | concrete     | 2322           | 850                      | 1.7                            |
| external wall              | outer layer (30 mm) | 452.2       | 1650                     | 0.112                          |
|                            | middle layer (290 mm) | 210.1       | 1250                     | 0.062                          |
|                            | inner layer (50 mm) | 332.5       | 1450                     | 0.077                          |
| window                     | glass (4+4+4 mm) | 2500         | 840                      | 0.76                           |
|                            | air (9+9 mm)  | 1.3            | 1000                     | 0.0267                         |
|                            | **lumped**   | 1000.8         | 840.1                    | 0.7441                         |
| finishing layer of ceiling| gypsum       | 800            | 950                      | 0.15                           |
| walls of PCM container     | steel        | 8030           | 502.5                    | 16.27                          |

a Air density is temperature dependent: \( \rho = 1.292 - 0.00466T(°C) + 0.000013677T²(°C) \)

Numerical model of the room is reduced to a 2D problem due to negligible changes in z-direction. Therefore, a two dimensional finite element model is developed and the related heat-transfer problem is solved. Since the room is taken as a part of multi-storey building, only a half of the thickness (0.06 m) of the internal walls and floors is modelled and symmetry boundary conditions (zero heat transfer) are applied to the corresponding sides of the computational domain. Outer surface of the external wall is described as convective boundary with a convection heat transfer coefficient \( h = 25 \text{ W/(m}² \text{°C)} \) at the surface. Air flow inside the room due to natural convection is expected to be turbulent, and standard \( k-\varepsilon \) model is used to describe this flow. Surface-to-Surface (S2S) radiation model is used to simulate radiative heat exchange among indoor surfaces of solid domains.

The meteorological parameters (figure 1) in Riga during the period of 5th to 12th August 2018 were chosen to represent the typical weather conditions of a hot summer in the Baltic States. In order to account for the hottest possible scenario, it is assumed that the fenestration façade is south oriented. Solar radiation incident on the south oriented vertical plane is recalculated according to the numerical weather forecast models available at [21]. Absorption coefficient of 0.44 for solar radiation incident to external wall surfaces is selected. The fenestration transmission coefficient of 0.6 is adopted. Solar radiation absorbed by glazing equals 10% while the indoor air and interior surfaces absorbs 50%. Absorbed energy is simulated by equivalent time-depending heat sources distributed in a thin outside layer of the external wall, in a window domain and in a thin boundary layer between room air and floor, respectively. Internal gains of 5W/m² due to people, lighting and equipment are taken into account. Indoor loads are applied as an equivalent heat source homogenously distributed in the air domain. A ventilation and infiltration rate of 1 air changes per hour (ACH) is included in the simulation.

2D model of the TES system is assumed to be built of 11 steel containers with external dimensions of 500 x 25 mm and wall thickness of 0.5 mm. The storage unit is filled with phase change material which corresponds to 25 mm thick layer of the PCM within the unit. Two types of PCMs - salt hydrate SP24E [19] and paraffin RT22HC [20] are considered in this research. PCM properties according to the manufacturer data are given in table 2. The storage units are located under the concrete ceiling slab at the distance of 50 mm and covered by the 10 mm thick gypsum board set at the fixed distance \( d \) from the unit. Dimensions and the schematic diagram of the 2D domain used in this investigation are depicted in figure 2.
### Table 2. Phase change material thermal properties.

| Phase               | Temperature, °C | Density, kg/m³ | Specific heat, J/(kg·°C) | Thermal conductivity, W/(m·°C) | Heat storage capacity, J/kg |
|---------------------|-----------------|----------------|--------------------------|-------------------------------|-----------------------------|
| **RT22HC**          |                 |                |                          |                               |                             |
| Solid               | < 20            | 760            | 2000                     | 0.2                           | -                           |
| Melting/congealing  | 20… 23          | 1160-207°C     | 2000                     | 0.2                           | 160 000                     |
| Liquid              | > 23            | 700            | 2000                     | 0.2                           | -                           |
| **SP24E**           |                 |                |                          |                               |                             |
| Solid               | < 21            | 1500           | 2000                     | 0.6                           | -                           |
| Melting             | 24… 25          | 2025-257°C     | 2000                     | 0.6                           | 150 000                     |
| Congealing          | 23… 21          | 2000           | 0.6                      |                               |                             |
| Liquid              | > 25            | 1400           | 2000                     | 0.6                           | -                           |

**Figure 1.** Outdoor air temperature and solar radiation.

**Figure 2.** Schematic representation of the 2D simulation domain.

Characteristic size of the finite elements varies from 3 to 40 mm depending on simulation domain (smaller elements are used for window, gypsum board and PCM domains, larger – for walls, concrete...
slabs and inner air). Total number of 4-nodal planar elements used in the building model is 21440. Transient analysis with initial temperature of 20 °C for all domains and with constant time step size of 5 s is carried out for 192 h or 8 days. Selected time step provides a stable solution convergence, and is based on the results of the convergence study of inner air temperature.

2.2. Governing equations for PCMs

Two methods - the Enthalpy Method [32] and the Effective Thermal Capacity Method [22, 33], are generally employed for numerical simulation of phase change process. Since in the present study the phase change is interesting only as a macroscopic phenomenon, the latter method is selected. The selected method describes the PCM thermal capacity as a function of temperature in the phase change range. The method considers that the PCM is fully charged above the solidification temperature and fully discharged below the melting temperature. In order to mathematically describe the process inside the PCM storage unit, the following assumptions have been made:

1. The PCM is homogeneous and isotropic.
2. PCM properties are assumed to be constant in both solid and liquid phase except for the mass density.
3. Convective flow of PCM is taken into account due to density change during melting/solidification.

The enthalpy of PCM is computed as the sum of the sensible enthalpy, $h$, and the latent heat, $\Delta H$:

$$ H = h + \Delta H $$

(1)

where

$$ h = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT $$

(2)

and $h_{ref}$ is reference enthalpy;
$T_{ref}$ is reference temperature;
$C_p$ is specific heat.

The latent heat content according to Ansys Fluent model is calculated in terms of the latent heat of the material, $L$, and liquid fraction, $\beta$:

$$ \Delta H = \beta L $$

(3)

![Figure 3. Heat capacity and melting model of RT22HC](image1)

![Figure 4. Heat capacity and melting model of SP24E](image2)
Figure 5. Dependence of the indoor air temperature on time

Figure 6. Dependence of the PCM liquid fraction on time

The latent heat content can vary proportionally to temperature change between zero (for a solid) and $L$ (for a liquid), since it is assumed that $\beta = 0$ if the material temperature is lower than solidus temperature, $\beta = 1$ if the material temperature is above the liquidus temperature, and varies linearly for temperatures between the solid and liquid state. Graphical representations of the used melting/solidification and heat capacity models for partial enthalpy together with experimental data for heating and cooling provided by the material manufacturer are given in figures 3 and 4 for RT22HC and SP24E, respectively. The idealised models correspond to the Effective Thermal Capacity Method and are built according to the nominal heat storage capacity guaranteed by the manufacturer (table 2).

3. Results and discussion

The objective of the present work was to investigate numerically effectiveness of two types of PCMs for application in passive thermal energy storage system for space cooling in residential buildings. The simulations were carried out for the time period of 5th to 12th August 2018 to represent the typical summer conditions in the Baltic States. For analyses purposes, in the first stage building thermal condition simulation for the room without installed TES system is performed. Figure 5 shows that the indoor air temperature reaches 40.9 °C at the maximum without the space cooling during a hot summer week in Riga. In order to compare the thermal behaviour of the PCMs, in the second stage the room with integrated PCM storage units is modelled for building thermal condition simulation. In this simulation storage units are introduced under the concrete ceiling slab at the distance of 50 mm. The ceiling finishing layer is not considered for this stage. Results presented in figure 5 show that both types of the PCM succeeded in reducing the indoor air temperature. Application of the PCM paraffin RT22HC resulted in the average reduction of indoor air temperatures around 2.3 °C with a maximum reduction of 4.6 °C compared to the simulation results of the building with no TES system installed. Figure 5 also shows that the indoor air temperature was reduced by an average of 4.5 °C with a maximum reduction of 8.1 °C due to the passive application of the PCM salt hydrate SP24E. However, as it was expected, in both cases the PCM suffers from a poor solidification rate at night (figure 6), thus the full storage capacity of the phase change material is not used during the day. Although the outdoor air temperature drops below the solidification temperature of both PCMs every day, due to a well-insulated building envelope the indoor air temperature never drops below 23 °C. As it is evident in figure 6, the indoor air temperature does not allow the PCM to solidify overnight; moreover, it keeps on melting during the night only at a slower rate. Figure 6 shows that the PCM paraffin RT22HC melts completely during the third day of the analysis period, nevertheless, it still provides sensible heat storage as the average reduction of 1.9 °C in air temperature is observed during the following days. The PCM salt hydrate SP24E undergoes phase change for 5 days due to its higher
melting point and approximately twice larger volumetric heat capacity. Average reduction of the indoor air temperature in post-melting time is 4.2 °C in comparison to the simulation results of the building with no TES system installed.

Due to aesthetic reasons the indoor finishing layer of the ceiling covering installations is a necessity in residential buildings. In order to analyse the effect of the air gap between the PCM storage unit and the ceiling finishing layer (gypsum board), two different installation configurations are considered in this study. In the first case, a gypsum board is closely attached to the storage unit leaving no air gap between them, while in the second case a gypsum board is fixed at the distance of 50 mm. Results of this investigation are presented in figure 5. The figure demonstrates that the air gap works as insulation decreasing the heat exchange between the indoor air and the PCM storage unit. This results in a lower daily heat absorption rate which is confirmed by both - the lower liquid fraction of the PCM and higher indoor air temperatures. This effect is especially noticeable when the PCM is still able to provide the latent heat storage. Thus, in the first 3 days, the average reduction of the indoor temperature is 3.1 °C with the maximum reduction of 4.0 °C when the finishing layer is closely attached to the storage unit filled with the PCM RT22HC. When the finishing layer is installed with the air gap, the average reduction of 2.1 °C with the maximum reduction of 2.4 °C is achieved. In the case of the PCM SP24E, the average reduction of 2.4 °C and 1.1 °C with the maximum of 3.8 °C and 2.0 °C is obtained for installation configurations with and without the air gap, respectively.

On the other hand, the air gap extends the PCM’s ability to perform the passive cooling as it takes approximately 22 hours more for RT22HC and 53 hours more for SP24E to melt completely. Therefore, in the last day of the analysis period, the indoor air temperature was reduced by an average of 5.7 °C when the PCM SP24E was installed with the air gap compared to a reduction of 3.8 °C when the ceiling finishing layer is closely attached to the storage unit. For PCM RT22HC values of reduction are significantly smaller, but the pattern is the same: 2.4 °C for the installation configuration with the air gap and 1.8 °C without it. Overall, the installation configuration without the air gap is more effective in reducing overheating considering the whole analysis period. Application of the PCM RT22HC results in average of 3.0 °C reduction of indoor air temperature for the installation configuration without the air gap, while reduction of 2.4 °C is obtained when the finishing layer is attached with the distance to the storage unit. Maximum reductions are 4.0 °C and 3.1 °C, respectively. In the case of the PCM SP24E, the average temperature reductions are 4.4 °C and 3.5 °C for the installation configurations without and with the air gap, respectively. Maximum reductions are similar: 7.1 °C and 7.3 °C, respectively, but they are observed on different days. In summary, application of the PCM SP24E for the passive space cooling is more effective in comparison to the PCM RT22HC due to its higher volumetric heat capacity caused by approximately two times greater mass density and almost the same specific heat and heat storage capacity per mass unit.

4. Conclusions
In this study, a numerical investigation of the thermal behaviour of two PCM types for integration in a passive cooling application was carried out. A 2D numerical model of the room with an installed PCM thermal energy storage system was built in computational fluid dynamics software Ansys Fluent. The transient thermal simulations were executed for two PCMs with different phase transition rates and three different PCM storage unit installation configurations. The results showed that the passive application of PCM can have a positive effect on thermal comfort and reduce the indoor air temperature of the studied room; however, the PCM suffers from a poor solidification rate at night due to continuous heat loads owing to the indoor air temperature being above the solidus temperature of the PCM. Considering that PCMs are a form of thermal energy storage that requires dissipation of stored heat to return to a solid state in order to begin a melt-freeze cycle again, the obtained results suggest that additional dissipation of stored heat is required to take entire advantage of the PCM’s storage capacity. One way to achieve that is to employ methods for active regeneration of the PCM. In
active application methods, PCM storage units are commonly used in connection to air- or water-based systems [8-11]. The main advantage of the macro-encapsulation technique is that PCM storage units can be retrofitted by integrating a pipe network suitable for both active regeneration systems. Further investigations will include designing and performance analysis of an active control of the PCM thermal energy storage for the developed concept of TES system of stand-alone storage units.

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