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Energy efficiency of PCM integrated in fresh air cooling systems in different climatic conditions

Octavian G. Pop, Lucian Fechete Tutunaru, Florin Bode, Ancuţa C. Abrudan, Mugur C. Balan*

Technical University of Cluj-Napoca, Bd. Muncii 103-105, 400641 Cluj-Napoca, Romania

HIGHLIGHTS

- Explicit equations of the PCM apparent heat capacity variation with temperature.
- Estimation of the required quantity of PCM in thermal energy storage systems.
- Evaluation of the energy efficiency of PCM in a fresh air cooling system.
- Specific energy indicators of PCM for feasibility studies are provided.

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ABSTRACT

The study provides novel and validated explicit equations of the apparent heat capacity variation with temperature for three phase change materials (**PCM**): RT20, RT25 and RT27. The developed models of **PCM** thermal behavior were successfully applied in the energy efficiency analysis of the fresh air cooling system with **PCM** latent heat storage system, serving a virtual office building considered to be located in different climatic conditions. Following the study, a practical guideline for estimation of the required quantity of **PCM** in fresh air cooling systems was provided. Two novel specific energy indicators were also proposed, which are useful for feasibility studies. The evaluation of **PCM** energy efficiency in fresh air cooling systems revealed that savings in the electric energy consumption of (7–41) % can be achieved, depending on the particular local conditions. Limits of the use of PCM in fresh air cooling systems were also provided.

1. Introduction

The study assumes that the integration of phase change materials (**PCM**) in the buildings' fresh air cooling systems can contribute to the enhancement of the energy efficiency of the buildings' air conditioning systems, in the context in which buildings account for about 40% of worldwide total energy consumption [1].

The importance and the opportunity of studying the effect of **PCM** integration in the fresh air cooling systems is suggested in [2] where it is shown that efficiency of thermal energy storage (**TES**) is demonstrated, but such system are not yet commercialized. In order to make possible the implementation of **PCM** based **TES**, more insights are needed into the behavior of **PCM** [3]. A particular major unsolved challenge refers to the amount of **PCM** needed for **TES** [4,5]. The importance of developing a simplified and experimentally valid mathematical models which are able to assess the energetic performance of **PCM** is also mentioned in [5].

The fresh air cooling load, as a component of the total cooling load of the buildings', can be determined by studying the thermal behavior of the buildings and this was approached in several studies with electrical analogy [6,7], with neural networks [8,9] or with specialized computer simulation software [8,10,11], with the use of stochastic differential equations [12] or with the use of mathematical modeling with finite differences [13]. A new trend integrates predictions and forecasts in the evaluation of the cooling demand [14]. The energy consumption of fresh air conditioning systems can be reduced by storing the cold occurring during summer nights and transferring it into the building during the day [15]. **PCM** have the ability to accumulate and release large amounts of cold [16] and to effectively reduce the cooling load of the buildings' [17,18]. Most studies present combinations between **PCM** based **TES** and classic air conditioning systems [4,19,20]. However long term stability issues of the **PCM** have been identified, such as corrosion or phase segregation [21]. The solidification phase for the **PCM** is considered to be the limit for the efficacy of the system [22].

Several studies focus on the **PCM** encapsulation method, on the geometry and on the type of materials [20,23,24]. A **PCM** packed bed provides high energy storage density [21]. Most studies recommend the

* Corresponding author.

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spherical encapsulation due to the high ratio between the exterior surface area of the spherical capsule and the interior volume [25]. An extensive review of the numerical models used in the study of **PCM** packed bed systems is presented in [26]. In [27] the behavior of a commercially available **PCM** is modeled in Fluent during melting. In the same study a “volume of fluid” model was developed to describe the **PCM**-air system. Analytical solutions for the moving boundary problems are described in [28] while a study of the transient response of a packed bed filled with a granular **PCM** is investigated in [29].

Modeling the behavior of latent heat thermal energy storage (**LHTES**) consisting of a large number of spheres by considering the behavior of each individual particle is difficult to implement [30] particularly because a significant number of **PCM** undergo phase change at different temperature ranges [30,31]. Some classical solutions do not take into account the variation of enthalpy and heat capacity of **PCM** with temperatures during phase change. Constant phase change temperature is considered in [25,32]. The thermal behavior of a cylindrical **LHTES** with spheres is modeled in [33] as a continuous porous medium. The same type of model is used in [30]. Based on a Fourier series, the dependence between the air inlet and outlet temperatures was determined [34] and was used in other case studies [35,36].

The selection of **PCM** is critical for any project and is influenced by both location and material behavior [17,37]. The optimal **PCM** peak melting temperature which serves as a function of the annual cooling energy consumption is provided in [38] for several locations worldwide.

Thermal properties of the **PCM** such as enthalpy or apparent heat capacity must be correctly implemented in the numerical models of the thermal behavior of **PCM**. The dependence of enthalpy and heat capacity of the **PCM** with temperature and the phase change temperature range [30] have a high influence on the accuracy of the models [31,39]. The enthalpy variation with temperature was determined by Differential Scanning Calorimetry (**DSC**) for several **PCM** in [40] while a novel function of enthalpy variation with temperature was proposed in [38]. The apparent heat capacity is considered constant at an average value in [2,41]. In contradiction, the apparent heat capacity was considered variable and modeled by using two exponential functions that meet at the peak value in [42] while in [43] the variation of the apparent heat capacity with temperature is assimilated with a triangle. In [39] a continuous mathematical function fitting the curve of the apparent heat capacity is used, where the function depends on the skewness of curve and the temperature range in which the phase change occurs. A different approach was considered in [44] where a Gaussian function was found to fit the variation of the heat flux of a micro-**PCM** with temperature. The variation of the apparent heat capacity during phase change as a polynomial function was proposed in [30]. Despite the large number of studies dedicated to the thermal properties of **PCM**, explicit equations capable of estimating the variation with temperature of the **PCM** apparent heat capacity are missing from literature.

The aim of this study is to provide explicit equations of the **PCM** apparent heat capacity variation with temperature, to provide a guideline for estimation of the required quantity of **PCM** in **LHTES** systems and to evaluate the energy efficiency of a fresh air cooling system equipped with an **LHTES**, in a virtual office building considered to be located in different climatic conditions. The following steps were taken in order to reach this goal: evaluation of the office building's cooling load considering different climatic conditions; proposal and validation of original mathematical equations capable to describe the variation with temperature of the **PCM** apparent heat capacity of three commercially available **PCM** during the phase change processes; numerical simulation of the thermal behavior of the **LHTES** integrated in the fresh air cooling system of the building that provides the amount of cold stored and released during seasonal operating periods; comparison between the cooling load covered by standard cooling coils and the amount of cold stored and released from the **LHTES**; comparison between the electrical energy absorbed by the fan and the electrical energy absorbed by the compressor of the chiller. Recommendations for the necessary specific quantities on required **PCM** and two new specific energy indicators of the **PCM** useful for feasibility studies are also provided.

Fig. 1. Real office building that inspired the study.

2. Material

2.1. Characteristics of the office building

The virtual office building investigated in the frame of the study is inspired by the real building located in Cluj-Napoca and presented in Fig. 1. The model used in the study is presented in Fig. 2.

The main characteristics of the considered office building are the following:

The length of the building: $L_B = 36.65$ m;
The width of the building: $W_B = 35.45$ m;
The height of the building: $H_B = 8$ m;
The total floor surface: $S_f = 1299.45$ m^2;
The total area of the walls: $S_{wall} = 711.61$ m^2;
The structure of the walls was considered composed of the following layers: autoclaved cellular concrete with the width of 300 mm and mineral wool with the width of 100 mm;
The structure of the flat roof was considered composed of the following layers: gypsum board with the width of 12.5 mm, concrete with the width of 150 mm, mineral wool with the width of 150 mm, cement and mortar with the width of 50 mm, bitumen membrane with the width of 5 mm;
The total area of the windows: $S_g = 439.60$ m^2;
The windows type: thermally insulated windows, equipped with 3 layers of glass with a thickness of 0.004 mm each and 2 layers of argon with a thickness of 0.009 mm each.

2.2. Locations and climatic conditions

The building was considered in 12 locations with the characteristics and the climates according to the Köppen-Geiger classification [45] indicated in Table 1.

The climatic data for each of the considered locations was taken

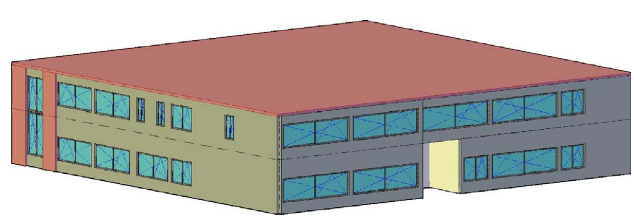

Fig. 2. 3D representation of the investigated building.