Inorganic PCMs applications in passive cooling of buildings - A review

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Abstract. Buildings consume around 40% of total world energy and are responsible for 30-35% greenhouse gas emissions globally. Latent heat thermal energy storage is one of the most promising techniques being investigated currently to reduce the thermal load of buildings. Different types of phase change materials (PCMs) i.e. organic, inorganic and eutectics with different thermophysical properties have been investigated for passive cooling of buildings showing great potential for saving energy. Due to their higher thermal conductivity and high heat storage capacity per unit volume, inorganic phase change materials take advantage over organic ones. They can be used as stand-alone heat storage systems for free cooling, embedded in building walls, windows, roofs and ceilings etc. Studies have shown that there are some drawbacks of inorganic PCMs as well like corrosion of container material, phase separation and supercooling which require solutions.

1. Introduction
Buildings around the world (both used for residential as well as commercial purposes) consume 35-40% of world’s energy. More than half of the energy consumed in buildings is because of heating, ventilation and air conditioning systems to provide comfortable environment [1][2]. Many techniques have been developed to decrease the energy consumption for the above-mentioned processes and improve energy efficiency of the buildings. One of the most widely investigated techniques is Thermal Energy Storage (TES) which, in fact, is a passive cooling method used to lower the thermal load of buildings. Passive cooling does not utilize conventional energy like HVAC systems. Rather it utilizes the natural energy from the environment by storing the cold during the night time in specific materials and then supplies this cold during the hot daytime to lower the indoor temperature [2].

Latent Heat Storage (LHS) is one of the thermal energy storage techniques in which material stores heat by changing its phase from solid to liquid almost isothermally [3]. LHS has very large energy storage density with a very small volume change and the energy can be taken back almost at a constant temperature. The materials used for LHS (solid-liquid) applications are termed as Phase Change Materials (PCMs). These materials initially store sensible heat until reaching their melting temperature, then phase change starts at almost constant temperature by absorbing huge amount of heat (heat of fusion) until the material is completely melted [4]. The energy stored by PCM can be evaluated by equation 1 [5].
\[ Q = \int_{T_1}^{T_f} m c_{p,s} \, dT + m a_m \Delta h_m + \int_{T_1}^{T_f} m c_{p,l} \, dT \] (1)

Where \( T \) is the temperature, \( c_{p,s} \) and \( c_{p,l} \) are the average specific heats for solid and liquid phases respectively, \( m \) is the mass of PCM, \( a_m \) is the melted fraction of the PCM, \( \Delta h_m \) is the latent heat of fusion required for the phase change to take place.

2. Inorganic Phase Change Materials

Phase change materials are mainly divided into three types; Organic, Inorganic and Eutectic mixtures [1]. In this study we will just review inorganic PCMs and their applications in building cooling. Inorganic PCMs consist of salts, salt hydrates, metals and metal alloys [4][6]. Among all inorganic PCM types, salt hydrates are most common for energy storage applications which are usually metal nitrites, sulphates, phosphates, carbonates, chlorides, acetates etc. attached with "n" number of water molecules e.g. \( \text{CaCl}_2.6\text{H}_2\text{O} \). The value of "n" varies from compound to compound. During the melting process, salt hydrates loose water molecules partially or completely by absorbing latent heat. Similarly, during the solidification process, these water molecules are attached again with the salt anion and latent heat is released [4]. Based on phase transition characteristics, salt hydrated inorganic PCMs can be placed in three groups: 1) salt hydrates which show congruent melting behaviour, 2) salt hydrates which show semi-congruent melting behaviour and 3) which show incongruent melting [7].

Inorganic PCMs are more advantageous for energy storage applications because they have almost double heat storage capacity per unit volume than organic PCMs. Also, they have higher thermal conductivity, high latent heat of fusion, and they are non-flammable [8][9]. But, despite their advantages, inorganic PCMs have some drawbacks as well. Salt hydrates in particular are corrosive to metallic storage containers which result in shorter life of the system and leakage problems. They also show the phenomena of phase segregation and supercooling which affect their heat storing capacity. They also have higher vapour pressure, higher volume change and their chemical stability is variable [4][8]. Some inorganic PCMs are listed in table 1 with their properties which are commercially available in the market for building cooling applications.

### Table 1. Examples of inorganic PCMs used in building cooling applications [10][11][12]

| PCM material | Melting Temperature (°C) | Latent heat of fusion (kJ/kg) | Thermal conductivity (W/(m K)) | Manufacturer |
|--------------|--------------------------|-----------------------------|-------------------------------|--------------|
| S17          | 19                       | 155                         | 0.43                          | Environmental Process Systems (EPS) limited |
| S21          | 21                       | 220                         | 0.54                          | Environmental Process Systems (EPS) limited |
| SP21EK       | 22-23                    | 140                         | ~ 0.5                         | Rubitherm GmbH |
| S23          | 23                       | 200                         | 0.54                          | Environmental Process Systems (EPS) limited |
| ClimSel C24  | 24                       | 126                         | 0.74 (solid), 0.93 (liquid)   | Climator AB |
| SP25E2       | 24-26                    | 180                         | ~ 0.5                         | Rubitherm GmbH |
| S27          | 27                       | 185                         | 0.54                          | Environmental Process Systems (EPS) limited |
| ClimSel C28  | 27                       | 154                         | 0.98 (solid), 0.72 (liquid)   | Climator AB |

3. Applications of inorganic PCMs in passive cooling of buildings

The term passive cooling of buildings includes all the techniques used to cool the buildings by utilizing minimum or zero electric energy [2]. These techniques utilize ambient cooling sources like water, night sky, air, material of the building etc. to minimize the indoor temperature [13]. Some of the applications where PCMs are used for building cooling are given below:
3.1. Free cooling
In the process of free cooling, a standalone thermal storage (PCM storage) is used to store the cold at night-time (charging of PCM) by passing the air through the storage when temperature of ambient air is lower than the temperature of the storage. When there is a need of cooling (usually during the day time) i.e. the indoor temperature is higher than the storage temperature, then the stored cold is therefore extracted (discharging the storage) in the same way by passing the air through the storage [2]. Mosaffa et al. [14] studied numerically the performance of multiple PCM (KF.4H$_2$O and Climsel C24) based thermal storage system for optimization purpose for free cooling as shown in figure 1. They concluded that the method of energy storage effectiveness optimization could be applied to latent heat thermal storage systems to investigate optimum design for free cooling.

![Figure 1. PCM based thermal storage for free cooling [14]](image)

3.2. PCM in walls and wallboards
There are several methods of using PCM in building walls to improve energy efficiency of the building. Some of them are microencapsulation of PCM particles in the construction material, macro-encapsulation where PCM (enclosed in containers) is installed in the building walls, and direct use of PCMs in walls in the form of wallboards [8]. A. Bontemps et al. [15] investigated experimentally and numerically a small scale test cell having two rooms separated by a wall made of glass bricks filled with PCM as shown in figure 2. They compared the performance of three PCMs including organic and inorganic PCM and found that the maximum temperature reduction was achieved with inorganic salt hydrate because of its higher melting point and higher heat of fusion.

![Figure 2. PCM wall with 16 glass bricks filled with PCM [15]](image)

3.3. PCM in ceilings and roofs
Roofs receive most of the heat coming from sun and are responsible for most of the thermal load carried by a building [16]. PCMs are very useful in reducing the thermal load of buildings by embedding them
in roofs and ceilings. PCM can be placed in the layers of concrete in roof in the form of slabs, by drilling cylindrical holes and filling them with PCM, in suspended ceilings with PCM encapsulated in ceiling plates etc. [5]. In one of the studies, A. Pasupathy and R. Velraj [17] investigated numerically and experimentally, first a single layer PCM system in which inorganic PCM enclosed in a steel container was placed between the top and bottom slabs of the roof as shown in figure 3 for year round application. For the hot summer season in Chennai India, single layer of PCM did not provide any promising results. Then they numerically investigated a double layer PCM system (second inorganic PCM panel layer on top of the first layer) with higher melting point and variable second layer thickness. They concluded that the comfort temperature of 27 °C was maintained during the summer season.

![Figure 3](image1.png)

**Figure 3.** (a) PCM panel placed between the layers of roof. (b) Roof without PCM layer [17]

### 3.4. PCM in windows

PCMs can be used in windows by filling them between the layers of glass, in window curtains, window blinds etc. to improve comfort conditions inside. Wang and Zhao [18] investigated a system of window equipped with PCM based curtain. They investigated a cloth/PCM curtain with variable PCM layer thickness placed on the inner side of the glass window with air gap between glass layer and PCM curtain as shown in figure 4. They found that the solar heat gain was reduced to almost 31% for 15 mm thick PCM layer for hot summer conditions of Shanghai, China.

![Figure 4](image2.png)

**Figure 4.** PCM curtain used with glass layer for a window [18]

### 4. Conclusions

This paper provides a brief and state-of-the-art insight in passive cooling technology for buildings using inorganic PCM based energy storage techniques. Different numerical and experimental studies have shown that inorganic PCMs are very effective in energy saving applications in buildings because of their higher heat of fusion, high thermal conductivity and non-flammable nature but problems of corrosion,
phase segregation and supercooling need to be investigated more in detail to maximize their energy storing potential.

References

[1] Akeiber H, Nejat P, Majid MZA, et al 2016 A review on phase change material (PCM) for sustainable passive cooling in building envelopes Renew Sustain Energy Rev 60 1470–97
[2] Waqas A, Ud Din Z 2013 Phase change material (PCM) storage for free cooling of buildings - A review Renew Sustain Energy Rev 18 607–625
[3] Rathore PKS, Shukla SK 2019 Potential of macroencapsulated pcm for thermal energy storage in buildings: A comprehensive review Constr Build Mater 225 723–744
[4] Mohamed SA, Al-Sulaiman FA, Ibrahim NI, et al 2017 A review on current status and challenges of inorganic phase change materials for thermal energy storage systems Renew Sustain Energy Rev 70 1072–89
[5] Faraj K, Khaled M, Faraj J, et al 2020 Phase change material thermal energy storage systems for cooling applications in buildings: A review Renew Sustain Energy Rev 119 109579
[6] Zeinelabdein R, Omer S, Gan G 2018 Critical review of latent heat storage systems for free cooling in buildings Renew Sustain Energy Rev 82 2843–68
[7] Xie N, Huang Z, Luo Z, et al 2017 Inorganic salt hydrate for thermal energy storage. Appl Sci 7
[8] Memon SA 2014 Phase change materials integrated in building walls: A state of the art review Renew Sustain Energy Rev 31 870–906
[9] Wong-Pinto LS, Milian Y, Ushak S 2020 Progress on use of nanoparticles in salt hydrates as phase change materials Renew Sustain Energy Rev 122 109727
[10] Product data sheets https://www.climator.com/en/pcm-climsel/product-data-sheets
[11] Environmental Process Systems Ltd http://www.epsltd.co.uk/pcm.htm
[12] Rubitherm GmbH https://www.rubitherm.eu/en/index.php/productcategory/anorganische-pcm-sp
[13] Bhamare DK, Rathod MK, Banerjee J 2019 Passive cooling techniques for building and their applicability in different climatic zones—The state of art Energy Build 198 467–490
[14] Mosaffa AH, Infante Ferreira CA, Rosen MA, et al 2013 Thermal performance optimization of free cooling systems using enhanced latent heat thermal storage unit Appl Therm Eng 59 473–479
[15] Bontemps A, Ahmad M, Johannis K, et al 2011 Experimental and modelling study of twin cells with latent heat storage walls Energy Build 43 2456–61
[16] Song M, Niu F, Mao N, et al 2018 Review on building energy performance improvement using phase change materials Energy Build 158 776–793
[17] Pasupathy A, Velraj R 2008 Effect of double layer phase change material in building roof for year round thermal management. Energy Build 40 193–203
[18] Wang Q, Zhao CY 2015 Parametric investigations of using a PCM curtain for energy efficient buildings Energy Build 94 33–42