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Study of Salt Hydrate-based Phase Change Materials Integrated into Thermal Energy Storage System for Air Pre-cooling in Hot Climate

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Abstract – The cooling of lightweight buildings is a major future challenge due to the consequences of global warming. Air conditioning (AC) systems are a major energy consumer, so even small improvements in AC performance can lead to significant energy savings. This numerical study investigates the use of thermal energy storage (TES) to improve AC performance in hot climates. TES is a technology that shows promise in meeting the rising energy demand while reducing greenhouse gas emissions. Latent heat thermal energy storage (LHTES) is a specific type of TES that aims to reduce the need for excessive cooling or heating in buildings. Researchers are currently exploring the use of phase change materials (PCMs) as potential LHTES materials to enhance energy efficiency in building systems. The primary objective of this paper is to explore the application of PCMs specifically salt hydrate (CaCl2.6H2O) with a melting range of 29–33°C in the pre-cooling of air, where they store night time ambient cooling and release it during the day to diminish peak cooling requirements. To accomplish this, a standard-size air-conditioning duct incorporated with the PCM enclosure has been modelled using ANSYS/Fluent. Results showed that a PCM-based air-pre-cooling model reduced peak cooling demand by 23% and air conditioning system capacity by 30%, achieving an 8.2°C drop in temperature at a velocity of 1 m/s. The findings of this study suggest that PCM-based TES systems are a promising technology for improving AC performance in hot environments.

Keywords: Phase change material, Salt hydrate, Energy efficiency, Air pre-cooling, Air-conditioning, UAE.

1. Introduction

The long-term viability of conventional energy sources, particularly fossil fuels, is under scrutiny due to their detrimental environmental impact [1]. In response to this pressing issue, the Paris Agreement was established, aiming to curb global CO2 emissions by 45% from 2010 levels by 2030 and ultimately achieve carbon neutrality by 2050 [2]. While generating a remarkable 80% of the world's GDP, urban centers cast a long shadow on the environment. These dense concentrations of human activity are responsible for a whopping 70% of all energy-related CO2 emissions, highlighting the need for innovative solutions to decouple economic prosperity from environmental harm [3,4]. This issue is further exacerbated by the rapid pace of urbanization, posing a growing environmental threat. The stark contrast in air pollution levels between urban and rural areas highlights the severity of this problem, with urban air pollution contributing to a significant number of deaths worldwide [5,6]. This alarming statistic underscores the urgent need for sustainable energy solutions to protect public health and the environment.

Buildings are one of the major contributors to worldwide energy consumption, accounting for approximately 25% to 30% of the total energy used worldwide [7, 8]. This substantial consumption generates considerable carbon emissions, which are projected to increase to nearly 50% in the next three decades [7, 8]. This alarming trend highlights the urgent need to enhance energy efficiency in the built environment. A significant portion of energy usage in buildings, approximately 75%, is attributed to space heating and cooling in both single-family and multi-family homes [9]. In next thirty years this demand is expected to grow by three times, driven by factors such as population growth, urbanization, and rising living standards [9]. This surge in energy demand necessitates the implementation of effective energy-saving measures. Among these measures, the utilization of TES holds considerable promise in reducing peak-time energy demand. When energy use is low, TES systems store thermal energy; when demand is high, they release the stored energy, thereby smoothing out the load on power grids and reducing the need for peak-capacity power plants [10, 11, 12, 13].

Phase Change Materials (PCMs) have emerged as a revolutionary technology with the remarkable ability to store significantly higher amounts of thermal energy [14]. This unique property allows lightweight buildings to achieve better thermal stability without adding extra weight. Consequently, the integration of PCMs into building envelopes has captured the attention of researchers worldwide, as it holds immense potential for improving indoor thermal comfort and energy conservation [15]. A PCM storage system can be easily incorporated into HVAC, cooling, and ventilation systems, just like a PCM-optimized building envelope can. This system efficiently stores thermal energy from the condenser or evaporator, resulting in improved internal temperature conditions. This makes Phase Change Materials (PCMs) popular as eco-friendly, energy-saving materials with a wide range of applications across several industries including HVAC, construction, clothing, healthcare, food preservation, and heating [16, 17]. The utilization of PCMs in building equipment facilitates the precise regulation of air temperature, leading to enhanced indoor thermal comfort and a marked improvement in the energy efficiency of HVAC systems [18]. This remarkable ability to store and release thermal energy makes PCMs a promising solution for addressing the growing energy demands of modern buildings while ensuring occupant comfort and environmental sustainability.

Durakovic et al.'s research highlights TES as a critical solution for building demand management [19]. In order to fully benefit from energy storage, it is important to have collaboration across different energy sectors. TES presents a variety of advantages, including significant energy savings, the ability to manage supply-demand imbalances, and the potential for large-scale substitution of energy [20]. PCMs have gained widespread recognition for their diverse applications within building structures. Their reversible properties and lightweight characteristics make them particularly well-suited for various applications [21,22]. A novel method for improving thermal efficiency has been developed, which involves integrating flat-plate solar collectors with TES modules [23,24].

Numerous research studies have been conducted on PCMs, such as the synthesis and manufacturing methods for encapsulated PCMs [27], the integration of PCMs into solar thermal systems [28], techniques to enhance the thermal conductivity of PCMs [29], and the selection and encapsulation of PCMs in hot climates [25,26]. There have been previous studies on using PCM for TES, but there is a lack of comprehensive research on their ability to reduce cooling load and manage peak demand in buildings. This study aims to design an innovative duct for air pre-cooling before entering the evaporation chamber of an air-conditioning system.

To provide colder air to the evaporator, a new air-pre-cooling system will be developed and tested as part of this research. The system will incorporate PCMs into the AC duct system. The selection of PCMs is critical for efficient and reliable TES. Because of the suitable thermos-physical properties of salt hydrates are chosen as a PCM. The TES unit will be used throughout the day to cool down the hot air from outside by directing it to the evaporator as it passes over it. We will use a duct design based on a single salt hydrate PCM series to measure how the air input speed affects the rates of PCM melting and solidification, as well as the temperature of the air. By employing the ANSYS software, a thorough mathematical representation of the physical model is created and solved.

2. Methodology

The main idea of the study is to make energy-efficient buildings by incorporating TES into air-conditioning ducts. Figure 1 shows the schematic diagram of the study where hot air enters the AC duct where the TES unit is embedded which cools the ambient air before supplying it to the AC evaporator which further cools the air and supply to the building. In this study the modelling and simulation of the AC duct contacting one series of salt hydrate as a PCM has been evaluated. Which quantifies the cooling effect and the duration of melting of PCM.

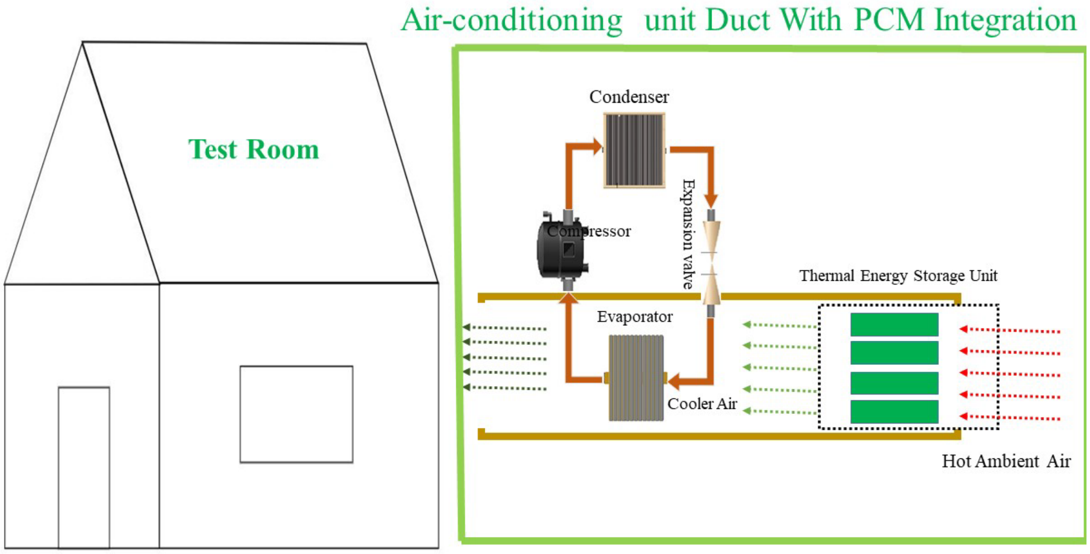

Fig 1. Schematic Diagram of AC unit with PCM Integration

2.1. Weather Data Analysis

The main purpose of installing a pre-cooling unit is to both lower energy usage and maintain a high level of thermal comfort. Phase Change Materials (PCMs) are essential for keeping indoor temperatures stable. To achieve these goals, several design factors need to be considered, such as ambient temperature, humidity levels, airspeed, and the specific cooling needs of the residential building. Finding a balance between these design considerations and reducing energy consumption is crucial. Maintaining stable indoor air temperatures and providing long-lasting thermal comfort are also important [4].

The United Arab Emirates (UAE) is renowned for its exceptionally hot and humid climate. During the summer months, daytime temperatures can soar to between 35°C and 50°C, with the hottest period extending from May to August. Peak temperatures during this time can reach a scorching 49°C. On average, daytime temperatures during the summer hover around 45°C, while night time temperatures in June dip to a still-warm 34°C. In contrast, the winter season, which runs from December to January, offers a milder reprieve, with temperatures ranging from 14°C to 27°C.

2.2. Material Analysis

This study is devoted to the topic of air pre-cooling AC duct systems. This implies that many PCMs may not satisfy the requirements for reliable and efficient thermal energy storage when employed across larger temperature ranges. The melting point range for the PCM was chosen slightly above ambient temperature in the morning. Therefore, a PCM with a melting range of 27–33 °C has been chosen. Inorganic salt hydrates were chosen as the ideal option due to their appropriate melting point range and excellent thermal energy storage capacity.

To effectively and predictably store thermal energy for air pre-cooling of air conditioning duct systems, phase change materials (PCMs) with specific properties are required. However, not all PCMs are suited for this application, especially those designed for larger temperature ranges. The criteria for selecting the PCM melting range was based on it being a few degrees higher than the given ambient air temperature in the morning. Therefore, a PCM with a melting range of 27.7 to 32.23 °C was chosen. The selection was based on the melting point and high thermal energy storage capacity of inorganic salt hydrates.

2.3. Materials Selection

The selection of an appropriate PCM requires careful consideration of various physical, chemical, economic, and thermal properties [5, 11]. Optimal properties of a PCM include a high heat of fusion, good thermal conductivity, high specific heat, high density, small volume changes during phase transitions, durability after freeze/melt cycles. For PCM uses, salt hydrates have desirable characteristics.

- Heat of fusion is around 210 kJ/kg
- Density is approximately 1.6 kg/m
- Thermal conductivity is approximately 0.6 W/m.K

These properties make salt hydrates promising candidates for a variety of PCM applications.

Table 1: Thermo-physical properties of salt hydrate.

Properties	Salt hydrate
Melting-Point-(°C)	27.7-32.23
Density-(kg/L)	1.5
Latent-Heat-(kJ/kg)	213.66
Heat-Conductivity-(W/m·K)	0.6
Specific-Heat-Capacity-(kJ/kg·K)	2

3. AC Duct Numerical Modelling

Using the finite-volume technique, a two-dimensional heat transfer model has been created for a set of four PCM enclosures inserted in an air duct. This model assumes that there will be no pressure-induced changes in volume inside the computational domain throughout the melting process and treats the PCM as an incompressible fluid. This simplistic model does not take into account several minute effects such as changes in PCM volume during a phase change, spontaneous convection, and buoyancy-induced movement of solid dendrites inside the molten PCM (Figure 2).

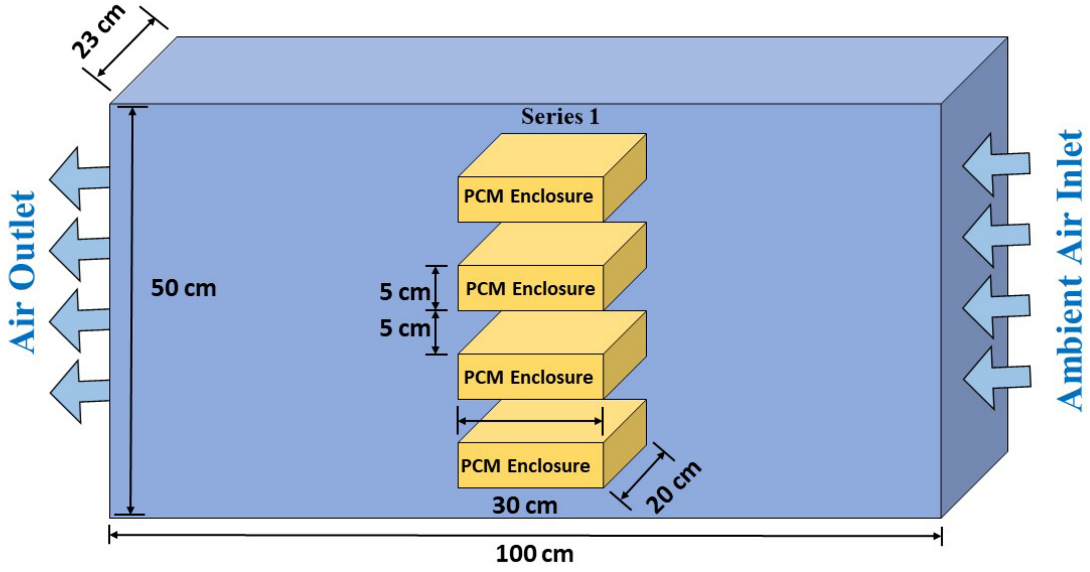

Fig. 2: Model of AC Duct containing PCM containers.

The input heat flow boundary accounts for external ambient conditions. The two-dimensional transient heat transfer is governed by differential equation (1), which calculate heat transfer rates.

$$\rho c\,\frac{\partial T}{\partial t}-\left[\frac{\partial}{\partial x_i}\left(k_{ij}\,\frac{\partial T}{\partial x_j}\right)\right]+Z_c+\,Z_r\;=0 \qquad (1)$$

Where c, T, k, ρ are heat capacity, temperature, thermal conductivity and density. Also time is denoted by t, and $x_i, and\ x_j$ represents unit vectors. Where heat convection and radiation losses are denoted by Z_c and Z_r given in Eq. (2) and (3):

$$Z_c = h_c\,A\,(T - T_{amb}) \tag{2}$$

$$Z_r = \sigma\varepsilon A(T^4 - {T_\infty}^4) \tag{3}$$

In above equation h_c stands for the convective heat loss coefficient, wall surface area is denoted by A, σ for the Stefan-Boltzman constant, T_{amb} represents the ambient temperature, and T_∞ represents the sky temperature.

The ANSYS (Computer software company, Cecil Township, PA, USA, 2015, Version 20) is used to model and solve the problem. The air inlet temperature has been chosen as the average maximum daytime temperature in the hot month of summer (July) in UAE.

4. Result and Discussion

The results show that the temperature drop decreases as air velocity increases. This is because the higher air velocity causes the air to flow more quickly over the cooling coils, which reduces the amount of time that the air has to absorb heat from the coils. As a result, the air temperature leaving the coils is not as low as it would be at a lower air velocity, and the temperature drop is also reduced.

The maximum temperature drop is observed at 1 m/s air velocity, which is 8.2 degrees Celsius. This is because at this velocity, the air has enough time to absorb heat from the coils without being blown away too quickly. However, as the air velocity increases, the temperature tends to drop less. At an air velocity of 4 m/s, the temperature drop is only 2.7 degrees Celsius (Figure 3).

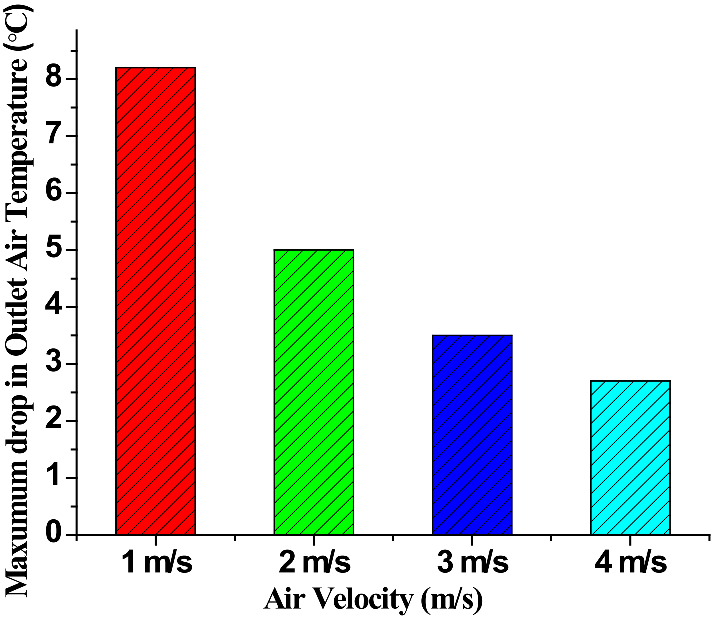

Fig. 3: Maximum drop in outlet air temperature using CaCl2.6H2O as PCM at air inlet velocities (1m/s, 2m/s, 3m/s, 4m/s)

Figure 4 shows the time taken to completely melt the PCM at different air velocities. At 1 m/s the time taken to melt the PCM has been observed to be the highest because less volume of air flows over the PCM enclosure as compared to high velocities. At 4m/s time taken to melt the PCM was the least because more volume of air flows over the PCM enclosure.

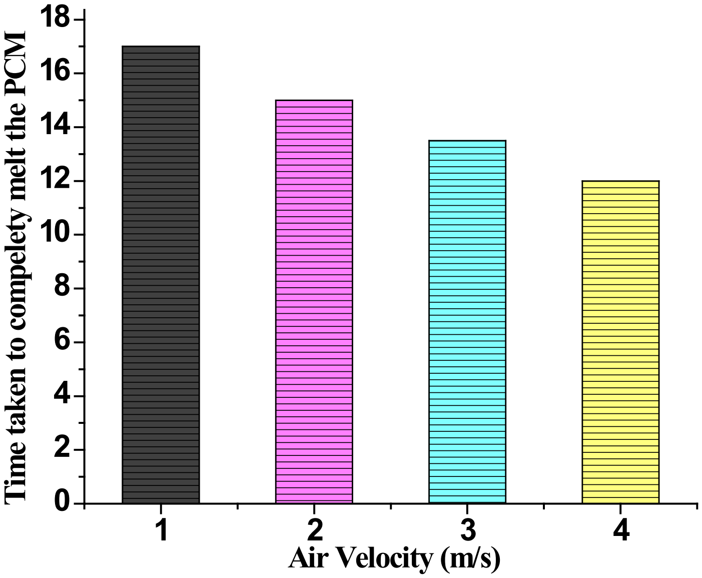

Fig. 4: PCM melting profile of CaCl2.6H2O based container at air inlet velocities (1m/s, 2m/s, 3m/s, 4m/s)

The findings of this study demonstrate the significant influence of air velocity on temperature drop in an air conditioning system. As air velocity increases, the temperature drop decreases, reflecting the reduced time available for air to absorb heat from the cooling coils. This observation aligns with the fundamental principles of heat transfer, where a higher flow rate leads to decreased residence time and diminished heat transfer efficiency. The maximum temperature drops of 8.2 degrees Celsius was achieved at an air velocity of 1 m/s, indicating optimal heat transfer under these conditions. This can be attributed to the balance between air flow rate and heat transfer time, allowing sufficient contact between the air and cooling coils for effective heat dissipation.

However, as air velocity increases beyond 1 m/s, the temperature drop progressively declines. At an air velocity of 4 m/s, the temperature drop drops to 2.7 degrees Celsius, highlighting the inverse relationship between air velocity and temperature drop. This phenomenon is attributed to the reduced residence time of air, which limits its ability to absorb heat from the cooling coils. The observed trend of decreasing temperature drop with increasing air velocity has practical implications for air conditioning system design and operation. Selecting an appropriate air velocity is crucial to achieve the desired cooling effect while balancing energy efficiency and performance. Excessively high air velocities may compromise cooling effectiveness, while excessively low velocities may lead to inefficient energy usage.

The findings of this study provide valuable insights into the relationship between air velocity and temperature drop in air-conditioning systems. Understanding this relationship is essential for designing and operating air conditioning systems that optimize cooling performance and energy efficiency.

5. Conclusions

In conclusion, addressing the cooling needs of lightweight buildings in the face of global warming presents a significant challenge. With air conditioning (AC) systems being major energy consumers, even modest enhancements in AC performance can result in substantial energy savings. The focus of this numerical study has been on leveraging thermal energy storage (TES) to enhance AC efficiency, particularly in hot climates. TES technology holds great promise in meeting the increasing energy demands while simultaneously reducing greenhouse gas emissions.

Specifically, latent heat thermal energy storage (LHTES), which aims to reduce the excessive cooling and heating requirements of buildings, has been a key area of exploration. Researchers are actively investigating the potential of phase change materials (PCMs), such as the salt hydrate CaCl2.6H2O with a melting range of 29–33°C, for pre-cooling air by storing night-time ambient cooling and releasing it during the day to reduce peak cooling demands.

The results of this study, using a standard-size air-conditioning duct incorporating a PCM enclosure modeled with ANSYS/Fluent, have demonstrated that a PCM-based air-pre-cooling approach can significantly reduce peak cooling demand by 23% and air conditioning system capacity by 30%. This resulted in a substantial 8.3°C temperature drop at an air velocity of 1 m/s. These findings strongly support the notion that PCM-based TES systems hold promise as a technology for enhancing AC performance in hot environments, thereby contributing to energy efficiency and environmental sustainability.

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