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Thermal Comfort, Humidity, and Air Quality in Passive Cooling Systems Using Phase Change Materials

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Abstract

The global demand for energy consumption is rising at an alarming rate. This increase is driven by economic growth, population expansion, and escalating temperatures due to climate change. Cooling energy demand is projected to rise by 275% globally by 2050, with the Middle East and North Africa (MENA) region being one of the most affected. In Kuwait, buildings account for approximately 90% of electricity consumption, and air conditioning alone constitutes over 70% of this usage during peak summer months. Kuwait's electricity demand is expected to reach 30,000 MW by 2030, primarily driven by cooling needs. With a population reliant on fossil fuel-based energy, there is an urgent need to find sustainable solutions that can mitigate this rising demand. This paper investigates the use of phase change materials (PCMs) to improve thermal comfort. Two portable cabins were constructed in Kuwait, one equipped with PCMs and the other serving as a control. The study evaluates the combined impact of PCM integration on perceived indoor thermal index, humidity, and air quality during the month of March 2023. Results show that PCM application reduced indoor temperature peaks by 3.31°C on average and stabilized humidity fluctuations by 10%. Moreover, daily particulate matter (PM 2.5) concentrations were reduced by 6.12 µg/m³, indicating an improvement in air quality. These findings suggest that PCMs offer a promising passive cooling solution that can enhance thermal comfort, improve indoor air quality, and the potential to reduce energy consumption in hot climates like Kuwait.

Keywords
Thermal Comfort, Building Energy Consumption, Phase Change Materials, Passive Cooling

1. Introduction
Energy consumption from cooling and heating systems represents a significant portion of global energy usage, with buildings contributing up to 36% of the total demand (Mastrucci et al., 2021; Wan et al., 2011). In regions with hot and humid climates, such as the Gulf Cooperation Council (GCC) countries, maintaining indoor thermal comfort is crucial, particularly as global temperatures continue to rise due to climate change (Khourchid et al., 2023; Kutty et al., 2023). For example, Kuwait experiences prolonged summers with temperatures exceeding 50°C, making air conditioning essential for comfort and productivity (Sedaghat et al., 2024; Sedaghat, Mahdizadeh, et al., 2023; Sedaghat, Salem, et al., 2023).

Cooling systems consume significant amounts of energy, leading to high electricity demand and greenhouse gas emissions. To address these challenges, sustainable alternatives, such as passive cooling techniques, are increasingly being researched and implemented (Yang et al., 2023). Among the most promising technologies is the use of phase change materials (PCMs), which can store and release heat, thereby moderating indoor temperatures (Sedaghat et al., 2024; Sedaghat, Mahdizadeh, et al., 2023; Sedaghat, Salem, et al., 2023; Yang et al., 2023).

The reliance on energy-intensive air conditioning systems is unsustainable in the long term, particularly in regions that face extreme climatic conditions. Traditional cooling systems have high operational costs, consume large amounts of electricity, and contribute to environmental degradation. As population growth and urbanization increase, so will the demand for cooling solutions (Sivak, 2009). Therefore, exploring passive cooling techniques that reduce energy consumption while maintaining thermal comfort is essential for mitigating these challenges (Chetan et al., 2020).

Thermal comfort is a multifaceted concept that involves not only temperature regulation but also the control of humidity and air quality (Grassi et al., 2022). While PCMs have been proven effective in regulating indoor temperatures, their role in controlling humidity and improving air quality remains underexplored. This study fills this gap by investigating how PCM-based passive cooling systems impact these additional aspects of thermal comfort.

1.1 Objectives
The objectives of this research are threefold: I) To evaluate the performance of PCMs in reducing indoor temperature fluctuations in a hot, humid climate. II) To assess the impact of PCM integration on perceived thermal comfort, particularly in terms of humidity regulation. III) To investigate the role of PCMs in improving indoor air quality by analyzing particulate matter (PM 2.5) concentrations.

2. Literature Review
Phase change materials (PCMs) are substances that absorb and release heat as they change phases between solid and liquid (Wang et al., 2022). This characteristic enables PCMs to moderate indoor temperatures by storing thermal energy during periods of heat and releasing it when temperatures drop. Over the past two decades, several studies have highlighted the potential of PCMs in improving the energy efficiency of buildings (Abdel-Mawla et al., 2024; Álvarez et al., 2013; Osterman et al., 2012; Sedaghat, Mahdizadeh, et al., 2023; Yang et al., 2023).

For instance, a study by Sedaghat et al. (2023a) demonstrated that incorporating PCMs in portable cabins reduced temperature fluctuations by up to 4.25°C, contributing to significant energy savings. Al-Rashed et al. (2021) reported that PCM integration in building envelopes reduced heat gain by 15.37% during the summer months in Kuwait. These findings align with previous simulations conducted by (Zeinelabdein et al., 2018), which showed that PCMs could reduce cooling demands in hot-arid climates.

Thermal comfort is often defined as “that condition of mind which expresses satisfaction with the thermal environment” (Zhao et al., 2021). In building science, achieving thermal comfort typically involves maintaining optimal indoor temperatures. However, comfort is not solely dependent on temperature; factors such as humidity, air movement, and radiant heat also contribute to how an occupant perceives comfort (Grassi et al., 2022).

Humidity plays a crucial role in thermal comfort, as high humidity levels can increase the perceived temperature, making environments feel warmer than they actually are. Conversely, low humidity levels can lead to discomfort, such as dry skin and respiratory issues. Studies have shown that maintaining humidity within the 40-60% range contributes to enhanced comfort levels (Liu, 2022).

Indoor air quality is another key factor influencing comfort, health, and well-being. Poor ventilation or temperature fluctuations can lead to an accumulation of pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and other indoor pollutants. Particulate matter, specifically PM 2.5 (particles with a diameter of 2.5 micrometers or less), poses significant health risks as these particles can penetrate deep into the lungs and even enter the bloodstream (Dominski et al., 2021).

Stable indoor climates, particularly in terms of temperature and humidity, have been shown to positively impact indoor air quality. Maintaining consistent indoor conditions helps reduce the emission of pollutants from building materials, furnishings, and appliances, which can release volatile organic compounds and particulate matter when subjected to extreme or fluctuating temperatures. Stable climates reduce the infiltration of outdoor pollutants, such as PM2.5 and ozone (Mansouri et al., 2022). To this end, studies on how PCM-based systems affect air quality remain scarce.

3. Methods

The experiment was conducted in Kuwait during the month of March (March 3rd, 2024 to March 28th, 2024), a period characterized by mild but gradually warming temperatures. Two portable cabins were constructed to study the effects of PCMs on indoor climate conditions. Each cabin measured 2.15 meters in width, 2.15 meters in length, and 2.96 meters in average height. The cabins were built using polyurethane sandwich panels with a thickness of 75mm, providing thermal insulation. The cabins had one aluminum door and a double-glazed window, Figure 1 (a). One cabin served as the control, while the second, serving as the treatment, was outfitted with PCM sheets on all walls and the ceiling, Figure 1. (b).

(a) (b)

Figure 1. The experimental setup with two identical portable cabins (a), the left cabin is equipped with PCM slabs on all interior walls and the ceiling (b), while the right cabin serves as control.

The PCM used was a nano-graphite composite with a PCM content of 90%, a graphite content of 7%, and a resin content of around 3%. It has an approximate melting point of 24°C that was selected for its high latent heat storage capacity (~200 kJ/kg) and excellent thermal conductivity (18-30 W/mK). In the chosen PCM energy storage initiates at approximately 10°C, reaches its peak at 24.53°C and continues until 29.5°C, Figure 2. The PCM was placed on all the walls of the treated cabin using suspension ropes extending from the ceiling to the floor.

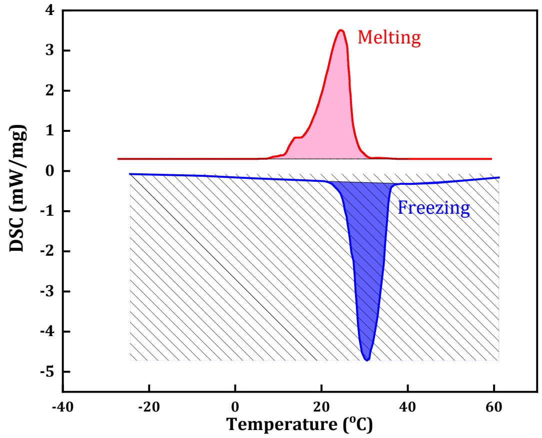


Figure 2. DSC analysis of the utilized PCM material (Sedaghat et al., 2024)

Two identical Davis Airlink devices were installed in both cabins, one each, to measure indoor conditions. These devices were chosen for their ability to measure multiple environmental parameters, including temperature, humidity, and air quality (PM 2.5). The sensors were placed on stands at a height of one meter, centered in the middle of each cabin, Figure 3. (a). Outdoor climate data, including temperature, relative humidity, and wind speed, were recorded using a weather station installed on the roof of a nearby building, Figure 3. (b). Data points were collected every hour and transmitted to an online platform for storage and analysis.

(a) (b)

Figure 3. The experimental setup with Davis Airlink to measure indoor air conditions (a), and a weather station to monitor the outdoor climate data.

4. Data Collection

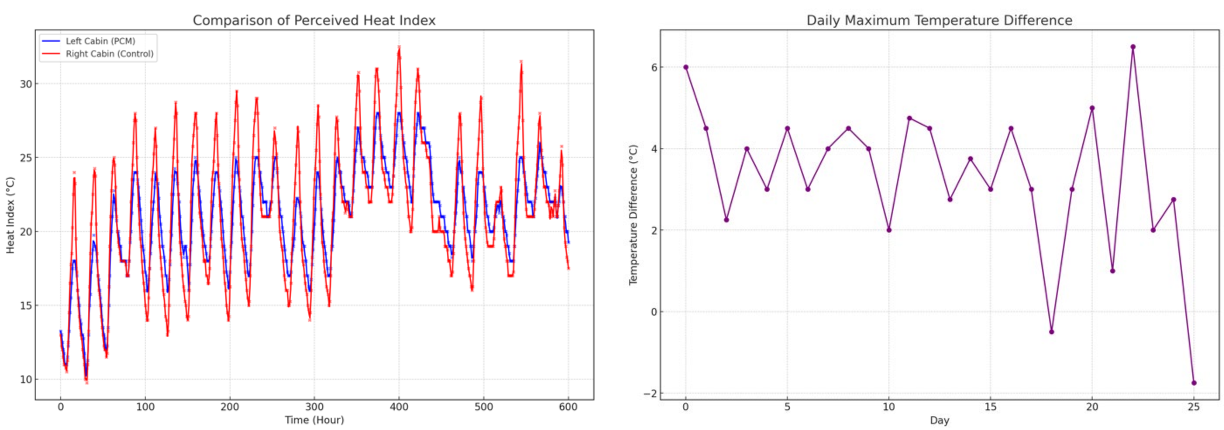
For the purposes of this study, indoor data markers were collected during the month of March 2024, a period chosen for its transitional weather conditions. March in Kuwait typically experiences moderate daytime temperatures, ranging from 15°C to 30°C, with rising temperatures toward the end of the month. The air conditioning systems in both cabins were turned off during this period to allow for monitoring and comparison of indoor conditions using PCM as the passive cooling system.

5. Results and Discussion

Perceived heat index, often called the feels-like temperature or simply heat index, combines air temperature and humidity to determine the human-perceived equivalent temperature (Zhao et al., 2021). The variation in heat index has significant implications, especially when considering human comfort, health, and activities that are sensitive to temperature and humidity levels (Nagashima et al., 2018). Fluctuations in heat index can stress the human body, particularly in the elderly, young, and those with pre-existing health conditions. Sudden increases in heat index can raise the risk of heat strokes, dehydration, and other heat-related illnesses. Furthermore, variations in heat index influence the load on heating, ventilation, and air conditioning systems. Higher heat index values may cause systems to work harder to maintain comfortable indoor temperatures, potentially increasing energy consumption and costs (Kim et al., 2006).

5.1 Heat Index

Analysis of the experimental data revealed significant differences between the left (PCM) and the right (control) cabins across all the markers of interest. Figure 4. (a) plots the hourly indoor heat index for both cabins during March 2024. Hourly results are smoothed by a moving average function with a 3-hour window width to reduce visual noise in the trend lines. As observed, covering all walls of the left cabin with PCM slabs reduced the temperature variations compared to the control cabin. This effect is more pronounced at maximum and minimum temperatures during the day. PCM's ability to absorb and release heat at its transition temperature reduced the maximum daily temperature in the left cabin by 3.31°C on average, which can significantly contribute to enhancing the comfort factor and reducing energy consumption in active cooling. Figure 4. (b) shows the daily maximum temperature difference between the right and left cabins during the study period.



(a) (b)

Figure 4. Comparison of the hourly perceived heat index in both cabins during March 2023 (a) and the daily maximum indoor temperature difference between the right (control) and left (PCM) cabins.

Daily variations in the heat index highlight how environmental conditions change over a short period. Smaller variations suggest a more stable environment, while larger fluctuations may require more adaptive strategies to mitigate potential adverse effects. Figure 5 plots the average daily head index variations for both cabins. Overall, the left cabin (PCM) demonstrates lower daily variation in the heat index, contributing to an increased comfort factor and reduced energy expenditure typically arising from abrupt changes in the indoor temperature profile.

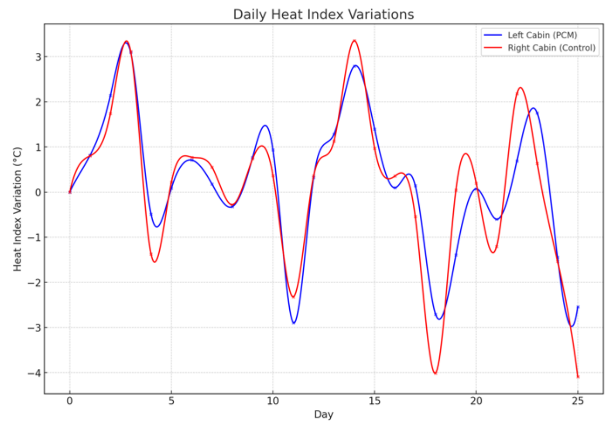


Figure 5. Comparison of daily heat index variations in both cabins

5.2 Humidity

Humidity variation can have significant implications for both environmental conditions and human comfort and health. In Figure 6, the indoor humidity profile for both cabins vs. time is plotted. Similar to the heat index profiles, the left cabin humidity profile demonstrates less variation over time, Figure 6. (b), which can lead to an overall improved indoor climate quality and improved occupants' comfort.

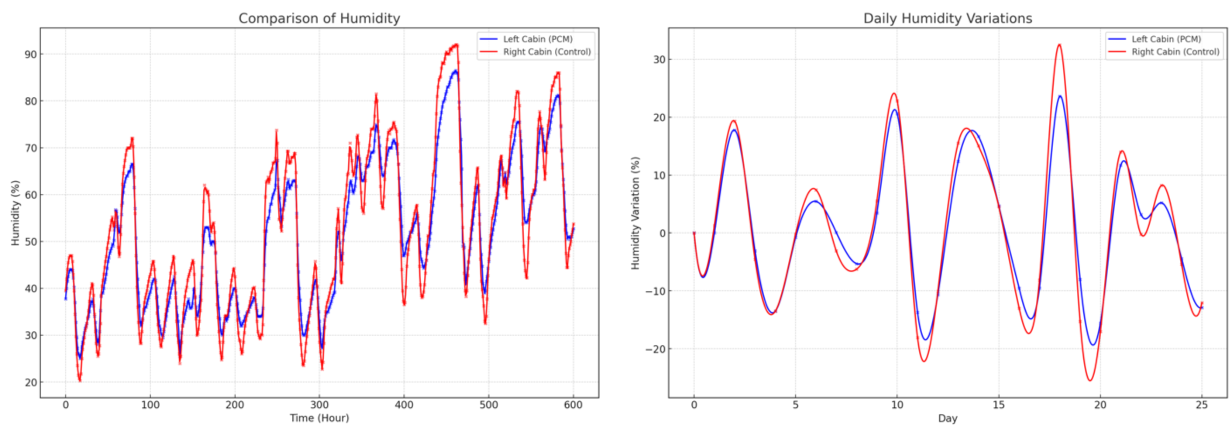
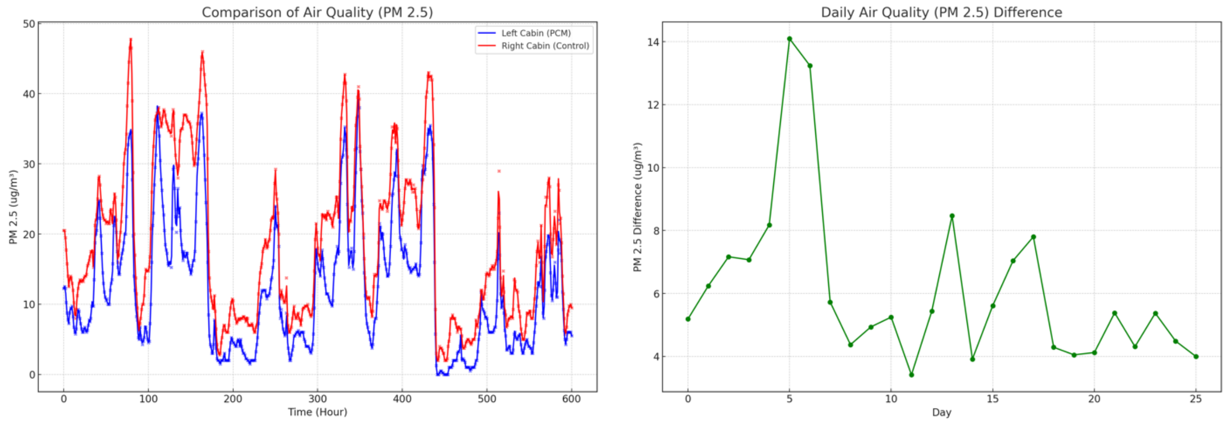


Figure 6. Comparison of the hourly humidity in both cabins during March 2023 (a) and the daily humidity variations in both cabins

5.3 Air Quality

Indoor air quality, particularly particulate matter with a diameter of less than 2.5 micrometers (PM 2.5) has significant implications on health and comfort (Cincinelli & Martellini, 2017). PM 2.5 particles can penetrate the lungs and even cross into the bloodstream, potentially leading to serious health issues such as respiratory infections, chronic bronchitis, and aggravated asthma. For individuals spending extended periods of time indoors, such as in homes, offices, or educational institutions, sustained exposure to elevated levels of PM 2.5 can compromise lung and heart health, exacerbating pre-existing conditions and reducing overall life quality. Therefore, managing indoor air quality to maintain low PM 2.5 levels is crucial for safeguarding health, enhancing comfort, and promoting a productive living and working environment.

Hourly PM 2.5 levels for both cabins are plotted in Figure 7. (a). As observed in Figure 7. (b), the left cabin has markedly lower levels of this pollutant, which can be attributed to the temperature-stabilizing effects of the PCM material in this cabin. On average, the daily PM 2.5 level was higher by approximately 6.12 $\mu g/m^3$ in the right cabin (control). This indicates better air quality in the Left Cabin, which can significantly impact respiratory health and comfort. Lower levels of indoor pollutants can also contribute to energy savings as this would require less frequent use of active air filtration and ventilation systems.



(a) (b)

Figure 7. Comparison of the hourly PM 2.5 levels in both cabins during March 2023 (a) and the difference between average daily levels of PM 2.5 in the right (control) vs. left (PCM) cabin

5.4 Implications

The results of this study demonstrate the potential of PCMs not only in enhancing thermal comfort and air quality but also in providing a sustainable solution to reduce energy consumption in hot climates like Kuwait. These findings have significant implications for urban planning, residential building designs, and energy policies in regions with extreme temperatures. PCM systems can be integrated into new constructions as well as retrofitted into existing buildings, potentially reducing reliance on active cooling systems like air conditioning. This would lead to lower electricity demand during peak summer months, reduced carbon emissions, and long-term cost savings for both residents and governments. The proposed solution can be applied to other nations facing similar energy challenges making it particularly suitable for regions with high energy demands for cooling.

5.5 Limitations and Future Studies

Despite promising results, this study faces limitations to be addressed in the future. To extend these results, further studies should quantify the exact energy savings resulting from reduced active air conditioning load due to PCM integration and evaluate the cost-benefit ratio of such installations on larger scales. To this end, scaling up the use of PCM-based passive cooling systems requires several considerations. These include the initial cost of materials, the availability of government incentives, and logistical concerns like integration with existing infrastructure. It also involves evaluating the efficiency of PCM materials for different regional climates. Furthermore, this study is based on short-term data, and longer-term studies would be required, particularly during the warmer seasons to fully understand seasonal variations and their impact.

6. Conclusion

This comparative study highlights the promising potential of PCM in improving the indoor comfort levels of residential areas in hot and arid climates such as Kuwait. These experimental results show that a cabin equipped with PCM (left cabin) provides a more controlled and comfortable indoor environment compared to a control cabin (right cabin). More particularly, utilizing PCM in the left cabin mitigated extreme temperature fluctuations effectively, contributing to lower peak temperatures (a reduction of 3.31°C on average) enhancing both human comfort and energy efficiency. The air quality analysis further supports the superiority of the left cabin's environment, making it preferable for prolonged occupancy and sensitive activities. These findings highlight the broader potential of PCMs for creating more sustainable and comfortable indoor environments, with future studies needed to explore their long-term energy-saving benefits and applications in diverse climatic conditions.

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Biographies

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Ahmad Sedaghat is a professor at the Australian University in Kuwait with over 30 years of experience in the field of Mechanical Engineering. He also serves as an adjunct research professor at Central Queensland University (CQU), Australia. Prof. Sedaghat has a distinguished academic and research background, focusing on renewable energy, aerodynamics, and nanofluids. He has played a pivotal role as a course coordinator in project-based learning (PBL) and is a key member of the curriculum committee at the Australian University in Kuwait. Prof. Sedaghat has been awarded multiple international research grants, including three projects funded by the Engineering and Physical Sciences Research Council (EPSRC) in the UK, as well as several grants from the Kuwait Foundation for the Advancement of Sciences (KFAS). His research has made substantial contributions to energy efficiency, fluid mechanics, and renewable energy systems. With more than 145 refereed journal publications and over 4,700 citations, his work has earned him global recognition, including the Research Achievement Award at Australian University in 2018/2019. As a Fellow of Engineers Australia and a chartered aerospace and mechanical engineer, Prof. Sedaghat is actively involved in academia and industry. He frequently reviews for prestigious journals and serves on editorial boards, having received multiple awards for his contributions as a reviewer in the fields of Energy and Renewable Energy.

Sayed Mohamad Soleimani is currently serving as a professor of engineering practice at the Lyles School of Civil and Construction Engineering at Purdue University. He boasts over 15 years of rich industrial experience, specializing in bridge engineering, concrete and steel design and construction, and project management. His professional credentials include licensure as a professional engineer in California, British Columbia, Ontario, and Australia. Furthermore, he has been honored as a Fellow of the Institution of Engineers Australia Fellow. His research interests focus on energy management in buildings, the development of sustainable, high-quality construction materials, and the repair and retrofit of civil infrastructures. He is also interested in transferring his knowledge to the next generation of engineers and this fuels his passion for research in engineering education.