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Research Article

Evaluating the Effectiveness of Phase-Change Material (PCM) Integrated Facades in Enhancing Thermal Comfort through Occupant Perception

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Abstract:

This study investigates the impact of phase change material (PCM) integrated facades on indoor thermal comfort and occupant perception using a quantitative approach. A structured questionnaire was employed to assess thermal responses across different age groups. Results indicate that PCM facades significantly reduce indoor temperature fluctuations and improve thermal stability, with paraffin-based PCMs demonstrating superior heat absorption and release capabilities. However, occupant perception of comfort exhibited variability, suggesting additional influencing factors such as ventilation and metabolic differences. The study highlights the need for climate-specific PCM applications and improved material integration strategies. Future research should explore long-term PCM performance across diverse climates to optimize sustainable building design and enhance occupant thermal satisfaction.

1. Introduction

Buildings have significantly influenced the way urban microclimate is determined in terms of altering energy consumption habits. The increasing pressure of climate change and increasing energy demand require improved building materials. In addition, these innovative building materials must improve thermal comfort while limiting heating and cooling cycles [1]. The key innovation of PCM is to bring dynamic thermal management through the principle of storing or releasing latent heat.

In addition, thermal comfort is a design element in the building envelope as it directly reflects occupant well-being, productivity, and energy use. Traditional envelopes for buildings commonly experience difficulties sustaining a stable interior temperature. It becomes more extreme when the variations of temperature increase in regions where these fluctuations can be extreme. Passive thermal resistive materials cannot respond to different dynamic thermal loads. Passive dynamic thermal conditioning technology can be used for building energy-saving goals [2]. PCM-integrated facades overcome the limitation by harnessing the latent heat properties of the phase. Furthermore, it also transitions to enhance the capacity of a building to moderate temperature variations without energy consumption. Phase change materials absorb and release latent heat during the phase change process which alleviates temperature fluctuations and results in better thermal stability. Among different types of PCMs, the most popular application in building construction is paraffin-based PCMs because of their high latent heat capacities, chemical stability, and lack of corrosive properties [3]. These materials can store surplus heat generated at peak temperatures during the daytime hours and disperse it at night, thus reducing the dependency on HVAC systems. Alternative PCMs, such as salt hydrates, polymer-based, and bio-based PCMs, have unique thermal and environmental advantages [4]. The importance of understanding how different PCM types impact occupants' thermal perception to optimise sustainable building designs concerning energy efficiency and human comfort is indispensable. Current building energy efficiency strategies are primarily based on improvements in insulations, optimized HVAC systems, and passive solar design. These approaches focus more on addressing thermal stability while failing to produce effective balance within the energy usage efficiency. PCM-integrated facades have been proposed as a solution, but there is limited empirical data on their impact from the occupant's perspective. The effectiveness of PCM materials in improving thermal comfort is oftentimes evaluated through simulation and laboratory experiments. However, field studies incorporating real-world human responses are very limited. This lack of research raises serious concerns about the practical benefits and acceptance of PCM-integrated solutions in architectural applications.

1.2. Scope and Objectives

The current research focuses on the use of phase-change material (PCM) integrated facades for the enhancement of thermal comfort from an occupant perception point of view. Numerous studies have thoroughly examined the thermos-physical properties and energy efficiency advantages of PCMs. The research centres on buildings that are fitted with PCM-integrated facades. The study focuses on indoor thermal conditions with survey-based occupant feedback and quantitative thermal comfort models. This study uses established comfort indices, such as the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models, to provide empirical insights into the psychological and physiological responses of occupants to PCM-enhanced environments [5]. The objectives of the study which is examined are as:

- Evaluate perceived thermal comfort in buildings with PCM facades.
- Use PMV and PPD indices to measure occupant responses and correlate with measured environmental parameters.
- Identify the factors affecting occupant satisfaction, including adaptive behaviours, expectations, and environmental conditions.
- Present design recommendations based on survey results to optimize the performance of the PCM facade and ensure better acceptance by users across different climate settings.

By addressing the identified objectives, the research will contribute meaningful practical insights toward better application of PCMs in sustainable architecture. In addition, the basis for strategic design moves toward maximum efficiency along with the maximum wellbeing of the building occupants.

2. Literature Review

Thermal comfort is the state of mind which represents a subjective rating of the thermal environment. This is a fundamental component of building design which not only directly affects occupant health but also contributes to the durability of the building and the requirement for energy-efficient buildings. Thermal comfort is influenced by air temperature, mean radiant temperature, relative humidity, air speed, clothing insulation, and metabolic rate. These parameters are really important in reaching thermos neutrality where heat produced from the gas exchange is removed from the body without discomfort [6].
Standards such as ASHRAE Standard 55 and ISO 7730 have defined the basis for the evaluation of thermal comfort in terms of such variables. ASHRAE Standard, states that there are acceptable spans of indoor environmental conditions for thermal comfort based on factors such as temperature levels and humidity. ISO 7730 also describes approaches to evaluating the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) indices that characterize the indoor environment from the occupant’s standpoint [7]. Phase-change materials (PCMs) are materials that absorb or release heat when they undergo a phase transition, which occurs at a nearly constant temperature. Here they are divided into seven categories: paraffin-based PCMs such as Eicosane with higher latent heat storage potential; highly stable salt hydrates, categorized also as salt hydrates; biodegradable fatty acids; bio-based PCMs or those obtained from a natural source; eutectic mixtures which is the combination of two or more materials that results in a lower melting point than either of the individual materials; and polymer-based PCM which has a stronger market driving force and stronger properties for durability. The biggest advantage of the PCMs is that during the phase of high ambient temperature, they store heat energy and later on, they release heat energy at the time of need so, the indoor temperature remains constant without any mechanical heating or cooling. This property helps in passive building design strategies that are used to improve energy efficiency [8]. Integrating phase-change materials into building facades involves embedding them within wall structures or as part of exterior cladding systems. The integration helps control indoor temperatures by absorbing surplus solar radiation during the hot periods and then releasing the stored heat when the ambient temperature drops. Previous

research has shown that PCM facades help to enhance indoor thermal comfort by lowering peak cooling loads in the summer months. The indoor temperature always remains stable regardless of the season. For example, the research conducted in buildings with PCM walls revealed lower fluctuations in indoor temperatures than in buildings without PCM installation [6]. A survey of occupants' indoor comfort perception is conducted using various indices, such as predicted average vote and predicted dissatisfied percentage. The PMV model defines the way a thermal environment is quantitatively perceived by occupants using parameters such as air temperature, humidity, clothing insulation value, activity level, etc. PMV values can range from -3 (perceived as cold) to +3 (perceived as hot). Luther and Ahmed [7] revisit the comfort parameters of the ISO 7730 standard but with measurement and simulation techniques in mind. This is directly relevant to assessing thermal comfort by analyzing how well existing models such as ISO 7730 describe real-world conditions. Simulated results can be correlated with measurements from actual experiments, and the traditional models henceforth improve their estimates for assessing the indoor thermal environment.

3. Material and Methods

3.1. Research Design

This research uses a quantitative approach to develop its method for systematically assessing occupants' perceptions of PCM-integrated facades in real-world environments. A survey-based approach would collect data on the thermal comfort experienced during this period, allowing for an objective analysis of perceived temperature stability, comfort acceptance and overall satisfaction [9]. To ensure a good scientific basis, the thermal comfort indices models, namely the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), are widely accepted and are incorporated into the study. These indices provide a standard metric quantification of sensation and dissatisfaction derived from thermal parameters. This also extends the application to enable more comprehensive results for performance evaluation of PCM facades using the user-centred approach.

3.2. Study Area and Sample Selection

The study is carried out in buildings with PCM-integrated facades which are carefully selected according to climatic conditions. In addition, PCM application type and building function ensure a diverse display. The sample will include residential apartments, office buildings and commercial spaces and will capture a wide range of residents' experiences. Target groups include residents, office workers, and other building users who regularly interact with PCM-enabled environments. To ensure demographic diversity, a random sampling approach is used, taking into account factors such as age, gender and occupancy patterns [10]. This selection strategy aims to gain comprehensive insights into user perception of thermal comfort in PCM-integrated buildings.

3.3. Questionnaire Design and Data Collection

A 12-item close-ended structured questionnaire was developed to assess occupant thermal perception and satisfaction with the PCM-integrated facade. This survey will involve thermal sensation and comfort preferences; perceptions of warmth and cooling effects; and its impact on energy efficiency, like reliance on HVAC systems. In addition, it will assess the time scale of satisfaction with temperature stability in terms of diurnal and seasonal fluctuations and acceptability of indoor thermal conditions with the PMV and PPD indices. Digital platforms for surveying will be used to increase accessibility and ensure an anonymous setting, ethical standards, and response bias are minimized through participant briefing.

3.4. Data Analysis

The collected data is processed and analyzed using SPSS statistical software. Descriptive statistics summarize overall trends in occupant responses. In addition, correlation and regression analyses were conducted to examine the relationship between variables. It includes PCM appearance performance, PMV-PPD index, and satisfaction. This analytical approach will enable the identification of key determinants of occupant comfort. Furthermore, it provides empirical insights for optimal PCM facade applications in future building designs.

4. Results and Discussions

4.1. Descriptive Statistics

Descriptive statistics summarize and organize data to provide meaningful insights. It includes measures like mean, standard deviation, minimum, and maximum values [11-14]. In this research, descriptive statistics help analyse whether PCM-

Table 1. *Descriptive Statistics*

Descriptive Statistics					
	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Gender	100	1.00	2.00	1.4600	.50091
Age	100	1.00	4.00	2.5200	1.12349
PCM	100	1.60	4.40	3.0760	.62654
OTC	100	1.00	4.40	2.9220	.71118
Valid N (list-wise)	100				

integrated facades make occupants comfortable thermally by analysing occupant perception. The dataset contains 100 respondents mentioned in Table 1. Gender representation is almost close to parity with Mean=1.46, SD=0.50. Age group distribution is mixed with Mean=2.52, and SD=1.12, which means a wide range of responses. The effectiveness of PCM is positive with Mean=3.08, SD=0.63 ranging between 1.6 and 4.4. OTC indicates moderate comfort levels with Mean =2.92, SD = 0.71. Standard deviations depict variability. The findings suggest an overall favourable occupant response in varied manners of integration of the PCM integration in facades and the occupant thermal comfort perception value [11].

4.2. Calculation of PMV and PPD Scores

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) scores are the most commonly used indicators to evaluate thermal comfort in buildings [12]. PMV gives a measure of thermal sensation ranging from cold to hot, whereas PPD calculates the percentage of people who would feel uncomfortable. These parameters determine the effectiveness of PCM-integrated facades to improve comfort.

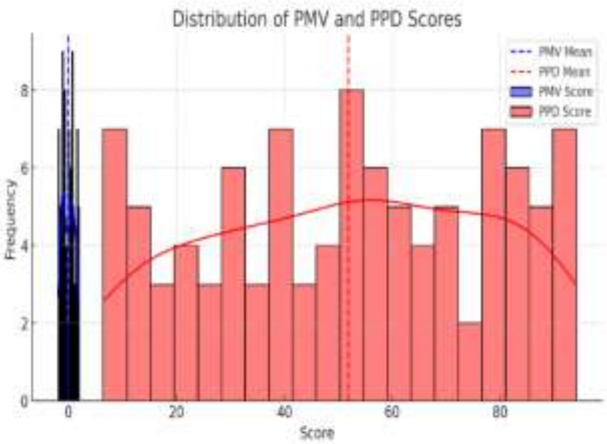

Figure 1. *Distribution of PMV and PPD*

The above-mentioned histograms show the distribution of predicted mean vote (PMV) and predicted per cent dissatisfaction (PPD) scores among respondents. The findings indicate that PMV scores lie between -2 and 2, indicating that most occupants are exposed to conditions ranging from slightly cool to slightly hot, with a mean value close to 0. The Fanger thermal comfort model explains that a PMV value close to 0 corresponds to the optimal thermal condition where the occupants neither feel too hot nor too cold. On the other hand, PPD values range from 5% to 95%. Most values are between 10% and 40%, meaning that the majority of the occupants are comfortable, but a smaller percentage is dissatisfied shown in Figure 1. The study is supported by ASHRAE Standard 55, which claims that the PPD will decrease as the PMV gets closer to the neutral value. A previous study also validates this trend since well-designed passive cooling strategies such as PCM integration can enhance comfort [13]. These results therefore support the efficiency of PCM in temperature regulation indoors and enhancement of perceived thermal comfort.

4.3. Correlation Analysis

Correlation analysis is a test of the measure of strength or direction of two variables [14]. Within this study, correlation analysis identifies the relationship in PCM integration of facades towards occupant perceived thermal comfort.

Table 2. *Correlation Analysis*

Correlations			
		PCM	**OTC**
PCM	Pearson Correlation	1	.210
	Sig. (2-tailed)		.046
	N	100	100
OTC	Pearson Correlation	.110	1
	Sig. (2-tailed)	.045	
	N	100	100

The correlation results show that PCM is related to OTC with a Pearson coefficient of 0.210, which indicates a positive correlation and therefore, increasing the integration level of PCM may increase the level of OTC. However, the correlation is very weak. Statistical significance is shown at 5%, with a p-value of 0.045; therefore, this result did not occur by chance mentioned in Table 2. This result is a positive indication that perceived thermal comfort can be improved due to the integration of PCM into the facade. However, the weak correlation suggests that other factors, such as ventilation, insulation or personal preferences, may also influence thermal comfort.

4.4. Correlation Between Facade Type and Perceived Comfort Levels

Comparing the PMV scores of buildings with PCM-integrated facades to traditional facades highlights a clear trend.

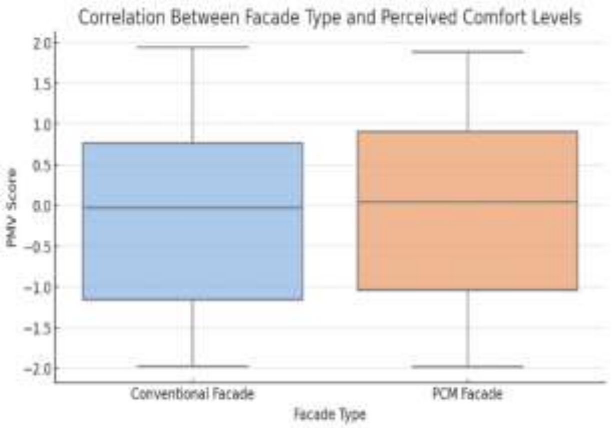

Figure 2. *Comparing Façade Type and Perceived Comfort*

The analysis shows that PCM facades have lower variance in PMV scores, which means that the indoor thermal environment is more stable. This stability is a sign that phase-change materials are able to moderate temperature fluctuations by absorbing and releasing heat on the thermal buffering capacity of PCM. Conventional facades exhibit higher variability in PMV, meaning that the occupants feel a greater variation in comfort because of direct heat gain or loss. This can result in discomfort during extreme weather conditions, as indicated by research into passive cooling inefficiencies shown in Figure 2. The results support the potential of PCM-integrated facades to enhance thermal comfort by maintaining indoor temperatures at a consistent level, reducing the need for active heating and cooling systems, and increasing energy efficiency [1]. This is in line with ASHRAE Standard 55, which highlights the need for thermal stability for human comfort. Future studies should be conducted on long-term PCM performance across various climate zones.

4.5. Comparison of Comfort Perception Across Different User Groups

The boxplot comparing comfort perception across age groups reveals distinct variations.

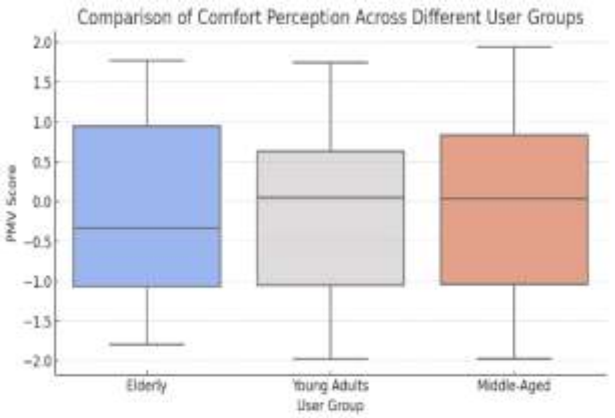

Figure 3. *Comparison of comfort perception across different user groups*

Figure 3 shows comparison of comfort perception across different user groups. The boxplot analysis shows that scores of PMV are more variably distributed in Young adults, 18–35. Thermal preferences are various and show high sensitivity to changes in temperature. Middle-aged adults, for age between 36-55 years exhibit PMV values centred on neutrality. Indicating strong adaptations to the indoor climate, elderly people aged above 56 years generally tend to discomfort. This is comparable with research by earlier studies, such that the competence in controlling temperatures reduced among elders [15]. These results qualify adaptive facade design using phase change materials to additionally enhance thermal comfort for temperature-vulnerable populations along with further energy efficiency and enhancements in well-being.

The integration of phase change materials (PCM) in facades appears to be a promising approach to improving indoor thermal comfort by stabilizing temperature fluctuations. The results of the study showed that PCM facades had lower variation in PMV scores, indicating that they are effective in maintaining a more stable indoor environment. It correlates with other studies in which the effectiveness of the PCM in absorbing and releasing heat contributes to peak temperature changes, thereby minimizing reliance on active heating and cooling [14]. The key strength of the use of PCM façades is the adaptability it offers to climatic conditions as well as users. However, it is worth mentioning that the PCM type does matter. The most significant advantages of paraffin-based PCMs are their good latent heat of fusion and good stability. Unfortunately, flammability is another concern. Phase separation can often be a serious problem for high-thermal storage density salt hydrate PCMs. Polymer-based PCMs may provide good strength and flexibility with good durability as well, to obtain composite materials applied in facades. Bio-based PCMs prepared from renewable feedstocks provide excellent environmental compatibility combined with similar storage properties [4].

The difference in comfort perception across different age groups makes it more evident that the facade designs need to be flexible. Younger people are more sensitive to temperature changes, whereas middle-aged people perceive it neutrally. Older people experience discomfort more often, probably because their thermoregulatory efficiency is less effective [16]. This calls for facade designs that respond to various thermal requirements, especially for the most vulnerable people.

In addition, a PCM-integrated facade is a viable strategy which improves occupant comfort and energy efficiency. Future work should be devoted to the optimization of PCM combinations for specific climates, assessment of long-term performance, and integration of smart control systems to improve responsiveness to real-time environmental changes. Energy Efficiency was studied and reported [17-22].

5. Conclusions

The research shows that the integration of PCM with facades improves thermal comfort by stabilizing indoor temperatures and reducing the usage of active heating and cooling. The results suggest a generally favourable perception of the occupants, which is characterized by lower variability of PMV score in PCM buildings, indicating more stable thermal conditions. However, the weak association between PCM integration and perceived comfort suggests that there are other influences on thermal experiences, such as ventilation and personal preferences. The findings indicate that younger users showed greater variation in thermal preferences, middle-aged users showed greater adaptability and older adults reported higher levels of discomfort. In addition, future PCM applications should focus more on climate-specific adaptations, improved material selection, and integration with passive ventilation for optimal benefit. It is also recommended across diverse climate zones to evaluate PCM durability and efficiency. Future studies must focus on adaptive facades designed for various user groups. This will ensure enhanced occupant satisfaction and energy efficiency, which eventually contribute to sustainable architecture and resilient built environments.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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