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Author/s:

Mousavi, S;Rismanchi, B;Brey, S;Aye, L

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Lessons Learned from PCM Embedded Radiant Chilled Ceiling Experiments in Melbourne

Syedmostafa Mousavi¹, **B. Rismanchi**¹, S. Brey², L. Aye¹

¹ RE&EE group, Department of Infrastructure Engineering, Faculty of Engineering and Information Technology (FEIT), The University of Melbourne, VIC 3010, Australia

² InvAus Pty Ltd, Melbourne, VIC 3000, Australia

ABSTRACT

Buildings are responsible for over a third of energy consumption worldwide, particularly for the increasing demand of air-conditioners in response to the more extreme heat around the globe. It is imperative to move towards more energy-efficient space cooling alternatives. The integration of phase change material (PCM) with a radiant chilled ceiling (RCC) is a promising technology due to its benefits regarding energy efficiency and indoor environmental quality. This article presents a field study conducted on a newly-developed PCM embedded radiant chilled ceiling (PCM-RCC) installed in a stand-alone cabin located in Melbourne. The study evaluates the thermal and energy performance of the system through investigation of the transient thermal behaviour of PCM panels in charging-discharging cycles, the indoor comfort conditions, and the electricity peak demand. It was observed that the proposed PCM-RCC can provide satisfactory comfort conditions and contribute to load shifting if a refined operating strategy is applied. The efficiency of PCM recharge overnight depends on several factors that need to be carefully considered in design. The challenges related to the implementation of optimal operating dynamic schedules in response to the thermal behaviour of PCM-RCC, and accurate weather forecasting should be addressed to realise the full potential of this technology.

Keywords: Chilled Ceiling; Energy Efficiency; Experiment; Phase Change Material (PCM); Radiant Cooling; Thermal Comfort

1. INTRODUCTION

2020 was recently ranked as the world's second-hottest year on record, closely behind 2016 [1]. The global climate continues to warm due to the extra heat-trapping greenhouse gas emissions caused by human activities and the upsurge in global energy consumption [2]. As the world keeps getting warmer, a range of changes on the human's routine life is come through. Focusing on the IAQ-related impacts, the more extreme heat affects the occupants' comfort level and stimulates unprecedented demand for space cooling. As the data indicate, buildings account for more than a third of final energy consumption worldwide, particularly due to the increasing demand for air-conditioners (ACs). 1.6 billion ACs are already installed worldwide and it could jump to around 5 billion units by 2050, becoming one of the main drivers of global energy demand [3]. To put this "cold crunch" on a sustainable path, more energy-efficient cooling technologies together with energy demand flexibility strategies are greatly appreciated. The PCM embedded radiant chilled ceiling (PCM-RCC), owing to its potentials in energy savings, peak load shifting, and thermal comfort establishment, has been introduced as a sustainable cooling technology [4,5].

In this study, the operation and thermal-energy performance of a newly-developed PCM-RCC system were experimentally evaluated in a real-scale condition. The research aimed to figure out 1) the transient thermal behaviour of PCM panels and the heat transfer rates in both charge and discharge cycles, 2) the indoor comfort level provided by the system, and 3) the amount of energy consumed for PCM recharge overnight.

2. MATERIALS AND METHODS

In PCM-RCC, PCM absorbs the indoor sensible heat during the daytime and starts melting. Overnight, the chilled water circulating through the panels rejects the PCM heat and force it to solidify.

Here, the experiments were performed on a stand-alone test cabin equipped with a PCM-RCC system (Fig. 1, left), in which shape-stabilised organic PCM boards with the phase change range of 15–20 °C and latent heat capacity of 900 kJ/m² were utilised (Fig. 1, right). The cabin was also equipped with multiple sensors to measure various parameters required for PCM-RCC performance evaluation. All measured data were then imported to the developed data portal for visualisation and further analyses.



Fig. 1 The test cabin at the University of Melbourne (left), and PCM ceiling panels with capillary tubes (right)

3. RESULTS AND DISCUSSION

Based on the measured data, after a 6-hour night-time recharge cycle on the first day, the panel temperature reached about 15 °C. The positive values of heat flux during the daytime confirms that the ceiling panels gradually absorbed the indoor heat while PCM was melting. Closely before 17:00, the melting phase of PCM in panels located near the façade was almost ended. For panels along the south wall, PCM remained active until around 20:00. The heat transfer rate was then decreased with a steeper slope.

Due to this accumulated heat in the cabin at the end of the first day, it was predicted that with the same night-time schedule, the fully-recharged panels cannot be achieved the next morning. Hence, a longer recharge cycle was set for the second and third days. An operating strategy for peak design conditions was also defined to preserve more cooling capacity for the peak demand period.

According to ISO 7730:2005 and also assuming the occupancy hours of 9:00–17:00, it was observed that the installed PCM-RCC can maintain indoor comfort mostly within Class C (24.5 ± 2.5 °C). The measured relative humidity during the occupancy hours was $54 \pm 5\%$ for all three days, which is in the range of what ASHRAE 62-2001 recommends for a comfortable range. Also, the vertical temperature between 0.1 m and 1.7 m was always found lower than 2°C, as ISO 7730 defines within Class A.

Regarding the total energy consumption, the system utilised about 70% of the daily energy usage outside of the peak period (15:00–21:00 weekdays in Victoria). PCM-RCC ability in peak load shifting can be further improved if a more refined, flexible control strategy is employed.

4. CONCLUSION

The system showed satisfactory performance in terms of thermal energy storage to meet the peak cooling demand during the daytime. Typically, 6–8 hours of recharge cycle seems to be sufficient if no over-heating occurs before midnight. The low heat transfer rate of water capillary tubes and the lack of full thermal contact between PCM and the tubes are identified as the main issues of the current panel design. Overall, an optimal operating and control strategy in response to the transient thermal behaviour of PCM, the indoor environment, and the weather condition should be implemented to realise the full potential of this technology.

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