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Development of radiant floor cooling system using phase change material in the hot and humid climate of Indonesia

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SUMMARY
This study aims to develop a radiant floor cooling system for medium-high rise apartments in the hot-humid climate. In the proposed system, phase change material (PCM) is attached under the concrete floor slab and its cooling effect is enhanced by the forced ventilation using louvers and exhaust fans at the inlets and outlets of the ceiling void respectively. Field measurement in an experimental building and parametric study using computational fluid dynamic (CFD) simulation were conducted to clarify the key parameters to optimize the cooling effect of the proposed system. The results show that the cooling effect of the proposed system is apparent mainly near the floor surface. Moreover, the forced ventilation under the floor at night also enhances the cooling effect. Furthermore, the result reveals that the dominant key parameter is the phase change temperature.

KEYWORDS
Radiant cooling, Phase change materials, Passive cooling, Natural ventilation, Tropics

1 INTRODUCTION
In the tropics, the daily maximum temperature usually exceeds 30 °C with a high humidity of about 70-90%. This condition would force building occupants to use mechanical ventilation, such as air conditioner (AC) to meet their thermal comfort. Nevertheless, it has become necessary to explore and develop new materials and construction system to promote the energy conservation to face the global warming challenges. Passive design strategies, in particular the application of natural ventilation is considered to be efficient to achieve thermal comfort while reducing the energy consumption. The night ventilation is effective to cool the indoor through the structural cooling. Nevertheless, the thermal comfort during the daytime cannot be satisfied by the night-ventilation alone. On the other hand, the daytime ventilation would increase the indoor temperature, although daytime comfort ventilation is a common practice in the tropics (Mori et al., 2018). These imply that additional cooling strategies are required to be used in combination with the daytime comfort ventilation, such as: the use of appropriate materials, building orientation, solar shading, etc.

One cooling strategy is to utilize the thermal storage capacity of building materials. Because of the high thermal storage capacity, phase change material (PCM) in active and passive cooling/heating mode is one of efficient ways to store thermal energy. The PCM application in buildings can be a very useful way to keep the indoor temperature within the comfort range by reducing the temperature fluctuations.

This study aims to develop a new radiant floor cooling system using PCM for medium-high rise apartments in Indonesia. The main idea is to utilize the radiant cooling of the floor by attaching PCM to the concrete floor slab and employing forced ventilation in the interstitial space between floor slab and ceiling (hereafter referred as ceiling void). In the proposed system, louver windows are designed at the inlets of the ceiling void, whereas exhaust fans are installed at the outlets (Figure 1). Moreover, a preliminary CFD simulation suggested to use the wind fin to increase the wind speed and distribute the wind near PCMs. The wind fin creates a narrow space of 60 mm between PCM and the fin which could enhance the solidification of PCM, thus enhance its cooling effect. The optimisation of PCM's cooling effect was investigated by adjusting the combination of operation between the louver and exhaust fans. Field measurement in the experimental building and parametric study using CFD simulation were conducted to clarify the key parameters.

2 METHODS

2.1. Field measurement in the experimental building

Field measurement aims to verify the effects of the proposed radiant cooling system as well as to collect actual measurement data for computational fluid dynamic (CFD) model validation. Measurement was conducted in an experimental building located in Tangerang Regency, Indonesia (6.221°S 106.579°E). Figures 2 and 3 show the layout, dimension, and features of the experimental buildings. Room-A was set as the experimental unit where the PCM is installed while Room-B was used as control room (i.e. without PCM).

To create the ceiling void space, concrete floor panels were laid 500 mm above the original floor and supported by the wooden platforms. Moreover, to install PCM under the floor, firstly, the PCM is packed into a single aluminium foil packaging (21x21 mm/pack). Then,

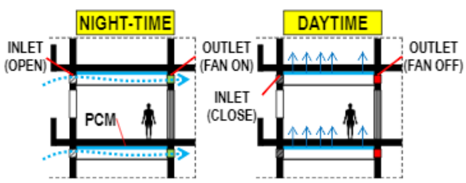

Figure 1. Concept of the proposed radiant cooling using PCM for apartment.

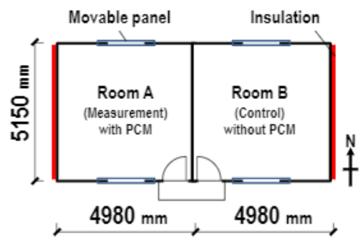

Figure 2. Layout of the experimental building.

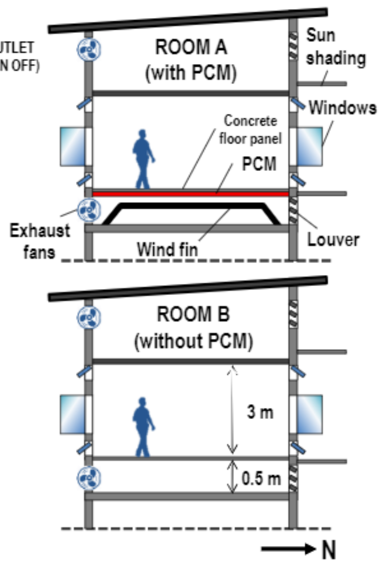

Figure 3. Sections of Room A and B.

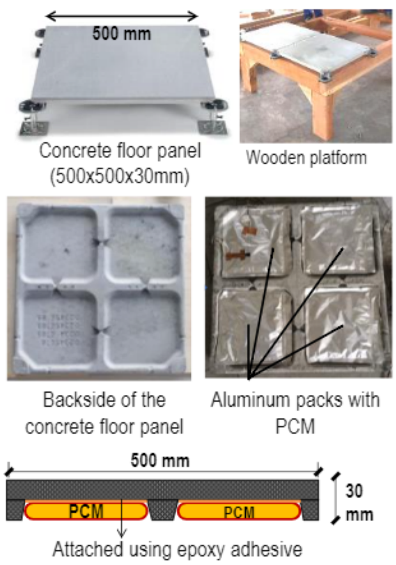

Figure 4. Details of concrete floor panel and PCM packs.

Table 1. PCM properties

Item	Description
Phase change temperature	29 °C
Latent heat	220 kJ/kg
Specific heat	2.0 kJ/kg.K
Conductivity	0.2 W/(m.K)
Installed amount	2.54 kg/m^2
Thermal storage	558.8 kJ/m^2

Table 2. Measured variables

Measured variables	Sensor
Air temperature and humidity	T&D TR-72nw-S
Air and surface temperature	Thermocouple type-T, ⌀0.35 mm
Wind speed	Kanomax 6332D with Probe 9065-3
Heat Flux	Prede HF-100

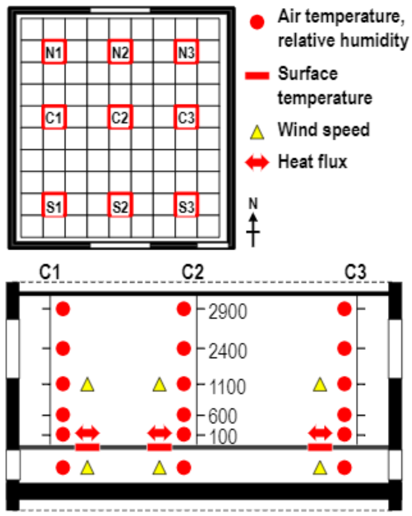

Figure 5. Distribution of measurement points (simplified).

four PCM packs are glued on the back side of the floor panel (see Figure 4). The properties of PCM are listed in Table 1. Table 2 summarizes the measured variables and sensor setting, while the measurement points are depicted in Figure 5.

2.2. Case design of the field measurement

Measurement was conducted in dry season (March 6th to May 24th, 2019). There are four scenarios of operation schedule as listed in Table 3. Room-B is set to represent the actual condition of apartment unit (i.e. without louvers and exhaust fans) so that the operation schedule is only applied for Room A.

2.3. Parametric study using CFD simulation

The CFD simulations employed a commercial software, i.e. scSTREAM version 14. It is a thermal fluid analysis software that has been used for environmental assessment in architectural industries. As for the turbulent model, the standard k-ε model was used in this simulation. The simulation was conducted in two steps. Firstly, the phase change temperature of 25, 27, 28, 29, and 31 °C were tested respectively. Meanwhile, amount of PCM were tested by changing thickness of PCM package. The tested values of thickness are 2, 4 and 8 mm. In the second step, the investigation is focused on the ceiling void space. The height of the space

Table 3. Case design of the field measurement

Scenario name	Opening devices	Room A		Room B	Description
		Day	Night	Day & Night	
Case 1	Windows Louvers Ex. Fans	Closed Open Off	Closed Open Off	Closed Closed Off	• No ventilation • Ex. Fans are always off
Case 2	Windows Louvers Ex. Fans	Closed Open Off	Closed Open ON	Closed Closed Off	• No ventilation • Ex. Fans are turned on only at night
Case 3	Windows Louvers Ex. Fans	Open Open Off	Open Open Off	Open Closed Off	• Full-day ventilation • Ex. Fans are always off
Case 4	Windows Louvers Ex. Fans	Open Open Off	Open Open ON	Open Closed Off	• Full-day ventilation • Ex. Fans are turned on only at night

**Day: 8:00-18:00; Night: 18:00-8:00*

between PCM and wind fin; and number of fans were set as the parameters. The tested heights were 60, 150 and 300 mm, while the number of exhaust fans was 1 unit and 3 units. The experimental building in Tangerang was used as a base model. The weather data measured from 9 to 11 April 2019 was used as the input weather conditions. The model validation results show a good agreement between the simulation and the measurement data and satisfy the criteria of ASHRAE Guideline 14 (ASHRAE, 2014).

3 RESULTS

3.1 Results from the field measurement

Figure 6 shows the temporal change of air temperature differences between Room A and B for each case. The negative value indicates the temperatures in Room B are higher than in Room A. In overall, the temperature difference between Room A and B is larger on the floor surface than at 0.1 m and 1.1 m. Comparing between Cases 1 and 3, the surface and air temperatures differences were diminished when the full-day ventilation was adopted (Figures 6a, 6c). Nevertheless, regardless the ventilation modes, large temperature reductions were observed when the exhaust fans were turned on at night (Figures 6b, 6d). The reductions of daytime temperatures in Case 2 (no ventilation), in average, are slightly larger (0.2-1.1 °C) than those in Case 4 (0.4-0.8 °C) (full-day ventilation), while those at night are almost the same.

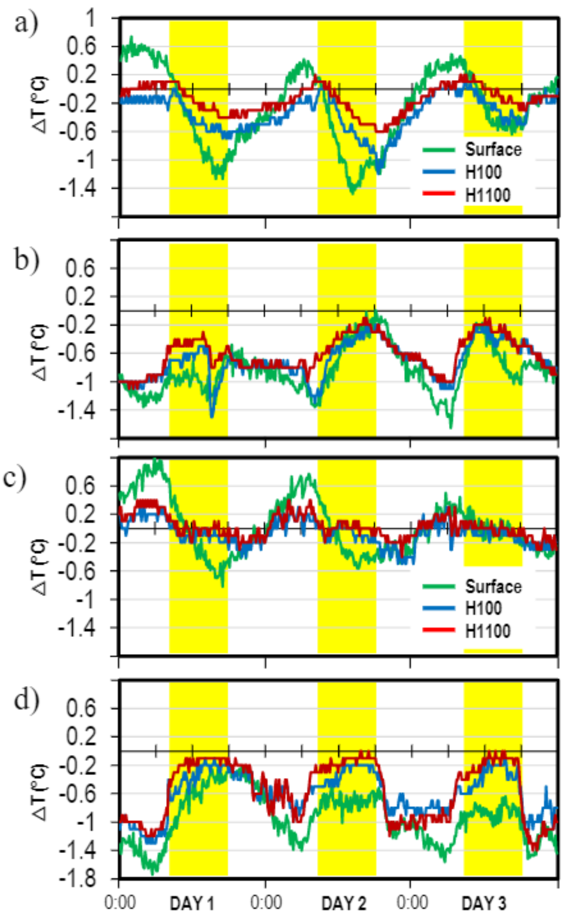

Figure 6. Daily variations of air temperature differences at floor surface, 0.1 m, and 1.1 m between Room A and B for (a) Case-1, (b) Case-2, (c) Case-3 and (d) Case-4. Negative value indicates Room B's temperatures are higher than Room A. Yellow color indicates daytime.

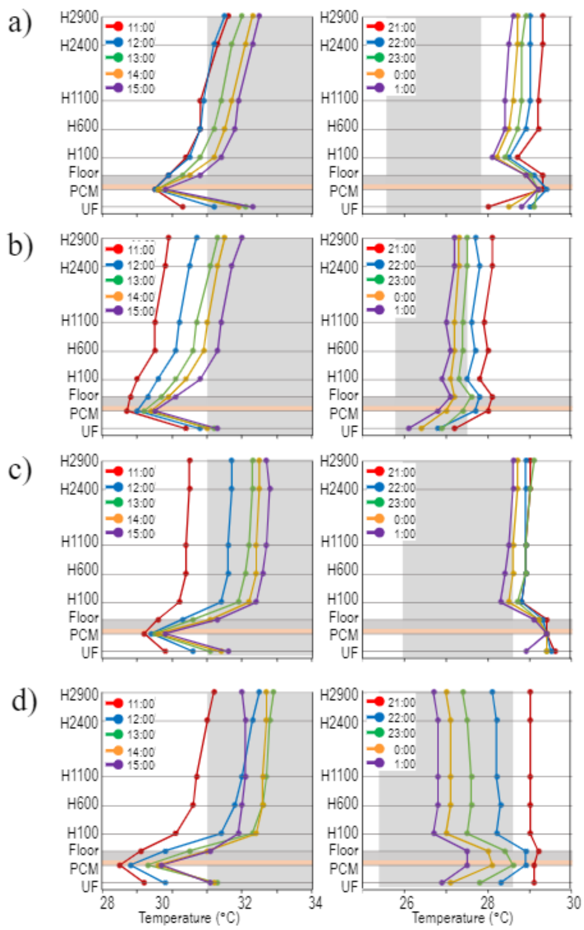

Figure 7. Vertical distributions of temperatures in Room A during daytime (left side) and night-time (right-side) for (a) Case-1, (b) Case-2, (c) Case-3 and (d) Case-4. The grey zone indicates the outdoor temperature range.

Figure 7 shows the vertical distribution of temperatures at the centre of Room A for each case respectively. As shown, the temperature ranges of the floor surface, PCM and ceiling void space (i.e. UF) at night in Cases 1 and 3 (without forced ventilation) are within a close range of the phase change temperature (i.e. 28-29 °C), while those with forced ventilation (i.e. Cases 2 and 4) measure lower temperature ranges than Cases 1 and 3. This shows that ventilating the ceiling void space using the exhaust fans help to improve the cooling effect of the proposed system. The use of louver window alone is not sufficient to provide ventilative cooling at the ceiling void space, especially when the nocturnal outdoor wind speed is very slow.

3.2 Results from CFD simulation

Figure 8 shows the effects of the several phase change temperatures on the floor surface temperatures, mean radiant temperatures (MRT), and air temperatures at 1.1 m, respectively. As shown in Figure 8a, during the daytime, floor surface temperatures in Room A are lower than that in Room B in all cases. In the cases of phase change temperature of 25 °C and 31°C, the floor surface temperatures increase immediately after sunrise because these phase change temperatures are simply out of the ambient air temperature range in the morning (i.e. around 26-29 °C). As a result, the average temperatures during daytime in those cases also become high. Meanwhile, the phase change temperature of 27°C, 28°C, and 29°C allows the solidification of PCM during the night-time. Therefore, floor surface temperatures were relatively stable in the morning and increase after exceeding the phase change temperature of the PCMs. In the daytime, the cooling effects are significantly different, depending on its phase change temperature. Large cooling effects of more than 1°C can be observed when the phase change temperature is 28 °C, 29 °C and 31°C. The maximum reduction of 2.2°C is obtained when the phase change temperature is 29 °C. This also reduces the MRT and air temperature at 1.1 m by up to 0.86 °C and 0.36 °C during the daytime, respectively. The above results indicate that the phase change temperature of 29 °C is the most appropriate for daytime under the given conditions with the outdoor temperature of approximately 30-35 °C in the proposed cooling system.

Figure 9 show the simulation results of the effects of amount of PCM, which is represented by

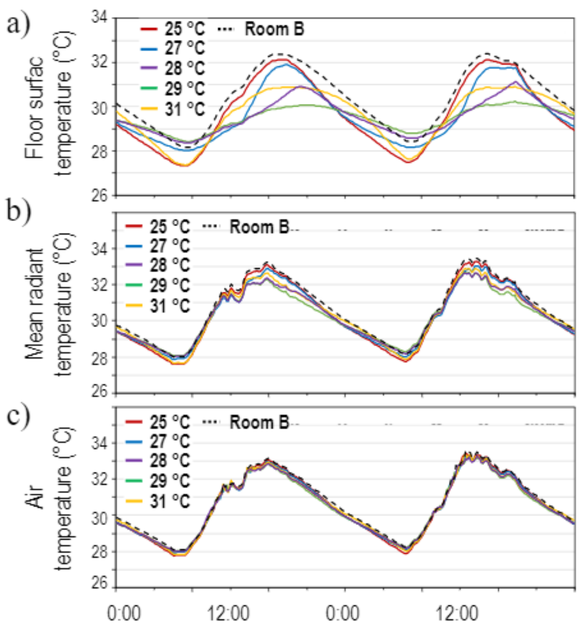

Figure 8. Effects of phase change temperatures on (a) surface temperature, (b) MRT, (c) air temperature at 1100 mm.

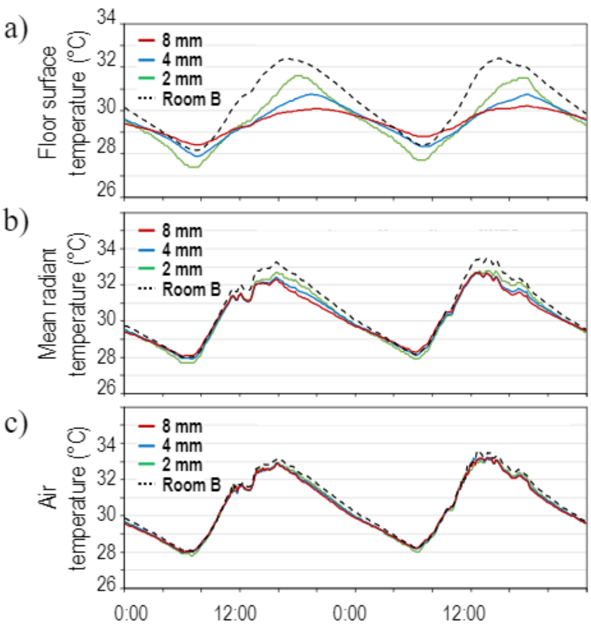

Figure 9. Effects of PCM thicknesses on (a) surface temperature, (b) MRT, (c) air temperature at 1100 mm.

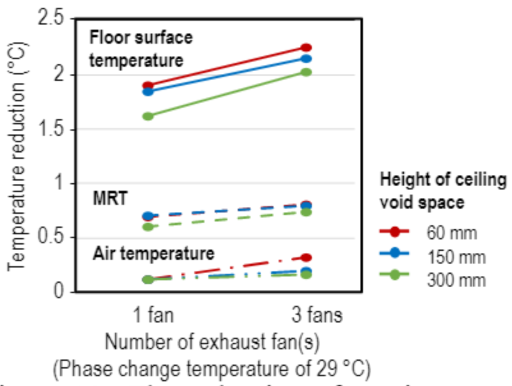

Figure 10. The reduction of maximum temperatures by the effects of ceiling void space and number of exhaust fans.

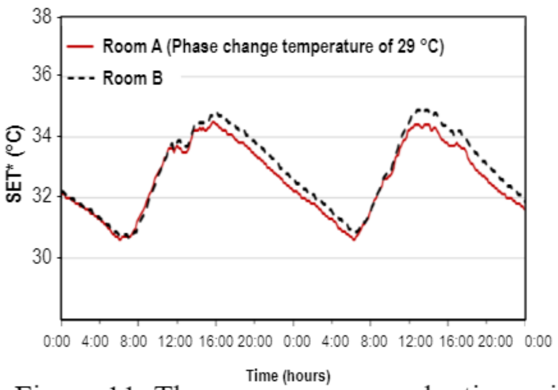

Figure 11. Thermal comfort evaluation using SET* at 1.1 m above the floor in Room A and Room B under no-ventilation condition.

the thickness of PCM pack. It can be seen that the temperature fluctuations of the floor surface tends to be narrower as the thickness of PCM increases.

Figure 10 shows the maximum temperatures reductions with different number of exhaust fans and height of ceiling void space under the phase change temperature of 29 °C. As shown, the cooling effect increases with the increase in number of fans. Moreover, the maximum reduction of floor surface temperatures of 2.3°C was obtained under the height of attic space of 60 mm. The average air speed at the center of the ceiling void space during the night-time is approximately 0.34 and 0.21 m/s with the height of 60 and 300 mm, respectively.

Figure 11 shows the temporal variations of SET* comparisons between Room A (with optimum setting) and Room B (control unit). This simulation was conducted under no ventilation conditions and therefore the SET* is higher than the ambient temperature due to low indoor air speed. Nevertheless, the SET* in Room A is lower by approximately 1.0°C than Room B during the daytime, showing the improvement in thermal comfort of occupants.

4 CONCLUSIONS

The cooling effect was confirmed in the field measurement not only due to the PCM but also due to the nocturnal forced ventilation using exhaust fans both in the no-ventilation and full-day ventilation conditions.

Furthermore, the results of CFD simulation showed that the largest cooling effect was obtained in which the thickness of PCM was 8 mm with a phase change temperature of 29 °C, and three exhaust fans were installed in a narrow ceiling void space of 60 mm. Under this setting, the proposed cooling system was able to achieve lower SET* by up to 1 °C during the daytime under closed window conditions, mainly due to the radiant cooling effect.

Further study is necessary to determine the optimum window design to improve the indoor thermal comfort by utilizing not only radiant cooling effect but also ventilative cooling effect.

ACKNOWLEDGEMENT

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