Improvement of thermal comfort in naturally ventilated classrooms by phase change material roofs in Taiwan

S F Chang¹, R L Hwang¹,∗ and K T Huang²

¹ Department of Industry Technology Education, National Kaohsiung Normal University, Taiwan
² Department of Bioenvironmental Systems Engineering, National Taiwan University, Taiwan
∗ rueylung@nknu.edu.tw

Abstract. This paper researched the effects of different types of insulated roofs, PCM roofs, and composite roofs on the overheating risk (Ihot) in the naturally ventilated classroom in Kaohsiung, Taiwan. The EnergyPlus was applied to simulate the hourly operative temperatures in the classroom. The optimal melting temperature (tmp) and thickness of the PCM roof, as determined from design day, were 36°C and 26mm, respectively, which are consistent with the results from year-round simulations. The design PCM roof could decrease the Ihot by up to 64%, leading to an effect equivalent to the decrease by 25mm insulation. However, with thickness of PCM>26mm or insulation>25mm, their effect on the Ihot was not significant. The changes of Ihot was insignificant while tmp of PCM roof in the range of 34-40°C, and Ihot increased rapidly when tmp>40°C. The effect of tmp of composite roof on the Ihot was not significant.

1. Introduction

As classrooms are the main place for study, in their daily life, students spent most of their time in classrooms, and the environment within classrooms could directly affect students’ physical and mental health and learning efficiency. In Taiwan, as it is hot and wet in summer, has increasingly severe global warming, urban heat island effect, and densely-occupied classrooms, the environment within classrooms is prone to the risk of overheating. Educational authorities, parents of students, and scholars have attached great importance to this issue, in particular, the classrooms on the top floor, which are exposed to the scorching sunshine all day.

As roof is a key factor for obstructing heat conduction between indoor and outdoor environments, its thermal properties are of great importance to thermal comfort in naturally ventilated classrooms. In addition, the heat shift property of PCMs to release the heat stored in the daytime into the air during the night can be fully realized only in an environment with significant diurnal temperature variations. In Taiwan, the outside surface temperature of a roof can reach 40-60°C due to absorption of solar radiant heat in the daytime, and can lower to 20-30°C at night. In light of this, this paper aims to analyze the effect of a PCM roof with different melting temperatures (tmp) on the risk of overheating naturally ventilated classrooms, and to identify the optimal design of a PCM roof suitable for classrooms in Taiwan.

2. Method and materials

2.1. Investigated classroom

The investigated room was a common south-north classroom, as located on the top floor in middle and primary schools in Taiwan, with two interior walls, two exterior walls, and a 2.0m-depth corridor in the south, as shown in figure 1(a). The dimensions of the classroom are: width: 9.0m; length: 8.0 m; height: 3.6 m. Two windows were installed on both exterior walls, and two doors were installed on the exterior wall closest to the corridor. The base roof was set as the common 150mm concrete structure; the
structure from the exterior to the interior: PCMs + insulation + reinforced concrete, as shown in figure 1(b). The thickness of the insulation, the thickness and $t_{mp}$ of PCMs for different types of roof structures are as shown in table 1. This paper selects common PCMs and physical properties of the materials are as shown in table 2. The classroom was used from 8:00-16:00. The load of the appliance and lights in the classroom was assumed at 1,400W, and the number of students was assumed at 29. The thermal environmental conditions in the classroom during the hottest season from May to October were simulated by applying EnergyPlus. Kaohsiung, Taiwan was selected as the location for simulation, and TMY3 in Kaohsiung was used as the meteorological data required for simulation.

![Figure 1. Schematic diagram of investigated (a) classroom and (b) roof structure.](image)

### Table 1. The combination of insulations and PCMs for different types of roof structures.

| Classification         | Insulations | PCM Thickness (mm) | Insulations Thickness (mm) | PCM Thickness (mm) | $t_{mp}$ ($^\circ$C) |
|------------------------|-------------|--------------------|-----------------------------|--------------------|---------------------|
| Base roof              | no insulations and PCMs | 0                  | NA                          | NA                 | NA                  |
| Insulated roof         | only insulations   | 25-100             | NA                          | NA                 | NA                  |
| PCM roof               | only PCMs       | 0                  | 26-34                       | 34-45              |                     |
| Composite roof         | insulations + PCMs | 25                 | 26-34                       | 34-45              |                     |

### Table 2. Physical properties of the construction materials.

| Physical property         | PCMs | Insulations |
|---------------------------|------|-------------|
| Thermal conductivity      | 0.35 | 0.03        |
| - liquid (W/m K)          | 0.15 | 0.03        |
| - solid (W/m K)           | 814  | 43          |
| Density (kg/m3)           | 2150 | 1210        |
| Specific heat capacity (J/kg K) | 296 | /           |
| Latent heat of fusion (kJ/kg) |     |             |

### 2.2. Overheating risk assessment

Liang et al. [1] established a thermal comfort model for primary and middle school students in Taiwan, and their results showed that the thermal perceptions of Taiwan’s students are different from the model proposed by ASHRAE 55 [2]. Therefore, the thermal comfort model proposed by Liang et al. was applied. The optimal comfortable temperature ($t_n$) and the proportion of thermal dissatisfaction due to overheating ($P_{hot}$) is shown in Eqs. (1)-(3).

$$t_n = 12.1 + 0.62 \times t_{om}$$  \hspace{1cm} (1)
where $t_{om}$ is monthly average air temperature, and $t_{op}$ is the indoor operative temperature.

The method proposed by ISO 7730\[3\] for evaluating the long-term overheating severity of indoor environments was applied. In that method, the overheating severity was quantified with a weighting factor when the actual thermal condition exceeds the upper limit of thermal comfort. Calculation of the weighting factor ($wf$) is shown in Eq. (4). Aggregate overheating severity ($I_{hot}$) throughout the year, shown in Eq. (5), can be used as an indicator for evaluating the risk of overheating in a classroom installed with various types of roof. The $PPD_{lim}$ suitable for school classrooms, as proposed by ISO 7730, is 15%.

$$P_{hot} = \frac{\exp(0.6802 \times \Delta t - 3.7690)}{1 + \exp(0.6802 \times \Delta t - 3.7690)} \quad (2)$$

$$\Delta t = t_{op} - t_n \quad (3)$$

$$wf = 1 + \frac{PPD_{act}}{PPD_{lim}} = 1 + \frac{P_{hot}(t_{op})}{0.15} \quad \text{for} \ PPD_{act} > PPD_{lim} \quad (4)$$

$$I_{hot} = \sum_{year} wf \times t \quad (5)$$

3. Results and discussion

3.1. Determination of design thickness and $t_{mp}$ of PCMs

As PCMs were installed on the outside surface of roof in this paper, Eq. (6) and Eq. (7) were used to estimate the heat stored in PCMs in the daytime($Q_d$), as well as the heat released from PCMs during the night ($Q_n$). The design thickness ($L$) of PCM can be determined by the minimum value of $Q_d$ and $Q_n$, as shown in Eq. (8). Table 3 summarized the design thickness of PCM at different $t_{mp}$. As expected, table 3 shows that $Q_d$ decreases and $Q_n$ increases with the rise in $t_{mp}$, when $t_{mp} = 36^\circ C$, $Q_d$ and $Q_n$ are closest, while min ($Q_d$, $Q_n$) reaches its maximum value. This indicates that a PCM with $t_{mp} = 36^\circ C$ would lead to the maximum heat shift effect in Kaohsiung.

$$Q_d = \int_0^{24} h_o \times (t_{sol-air} - t_{mp}) \, dt \quad \text{if} \ t_{sol-air} > t_{mp} \quad (6)$$

$$Q_n = \int_0^{24} h_o \times (t_{mp} - t_{sol-air}) \, dt \quad \text{if} \ t_{sol-air} < t_{mp} \quad (7)$$

$$L = \frac{\min(Q_d, Q_n)}{c_p \times \rho} \quad (8)$$

| Melting temperature ($^\circ C$) | 34  | 35  | 36  | 37  | 38  | 39  | 40  |
|-------------------------------|-----|-----|-----|-----|-----|-----|-----|
| $Q_d$ (MJ/m$^2$)              | 14.55 | 13.81 | 13.07 | 12.34 | 11.69 | 11.03 | 10.38 |
| $Q_n$ (MJ/m$^2$)              | 10.56 | 11.70 | 12.84 | 13.99 | 15.22 | 16.44 | 17.67 |
| min ($Q_d$, $Q_n$)            | 10.56 | 11.70 | 13.07 | 12.34 | 11.69 | 11.03 | 10.38 |
| $L$ (mm)                      | 21  | 24  | 26  | 25  | 24  | 22  | 21  |

Where $t_{sol-air}$ is the fictitious temperature of the outdoor air which, in the absence of radiative exchanges on the outer surface of the roof, would give the same rate of heat transfer through the roof as the actual combined heat transfer mechanism between the sun, the surface of the roof, the outdoor air and the surroundings. $h_o$ is the surface heat transfer coefficient for radiation and convection.

3.2. Simulation results

Figure 2 shows the comparison of the hourly operative temperatures in the classroom among the base roof, the 25mm insulation roof, the $t_{mp}=36^\circ C$, $L=26\text{mm}$ PCM roof, and the composite roof (25mm insulation + $t_{mp}=36^\circ C$, $L=26\text{mm}$ PCM), during the hottest days from July 2 to July 4. It can be seen from figure 3 that the insulation roof, PCM roof, and composite roof can significantly decrease the operative temperature in the classroom. The $I_{hot}$ distributions for all types of roof structures in table 1 are shown in figure 3. Through calculation of the differences ($\Delta I_{hot}$) of $I_{hot}$ between a base roof and other types of
roof, the decrease of the overheating risks in the classroom attributable to the insulation roof, PCM roof, and composite roof can be understood. The $\Delta I_{hot}$ of an insulation roof ranges from 1,610 to 1,802 hour, which is equivalent to a decrease of 70%-78%; the $\Delta I_{hot}$ of a PCM roof and composite roof range from 1,568-1,220 (53%-69%) and 1,807-1,767 (76%-79%) hour, respectively. Therefore, it can be seen that the application of insulation, PCM, or both, in the roof could alleviate the impact of external air temperature and solar insolation, and thus, improve comfort in the classroom.

![Figure 2](image)

**Figure 2.** The operative temperatures in classrooms with different roofs (July 2 - July 4).

3.3. Impact of the insulation thickness

Figure 4 shows the impact of the insulation thickness on $I_{hot}$. As seen in figure 5, when 25mm insulations are installed, the $I_{hot}$ decreases from 2,287 to 667 hour, representing a decrease of 70%. On the other hand, when the insulation thickness increases from 25mm to 100mm, $I_{hot}$ seems not to decrease more with the increase of insulation thickness. As compared with the 25mm insulation, $I_{hot}$ for 100mm insulation decreases only from 667 to 514 hour. Although the thickness is tripled, $\Delta I_{hot}$ only increases from 1,620 to 1,773 hour, which represents a mere decrease of 9%.

3.4. Impact of the thickness of PCM

Figure 5 shows the changes of $I_{hot}$ and $\Delta I_{hot}$ for PCM roof with the PCM thickness when $t_{mp}=36$ °C. The $I_{hot}$ decreases from 2,287 to 821 after the installation of 26mm PCM on the base roof, representing a decrease of 64%. The decrease in $I_{hot}$ tends to be flat with the increased thickness of PCM;
for example, as compared with the PCM thickness of 26mm, the heat storage capacity of the 34mm thick PCM increases by 30%, while the $\Delta I_{hot}$ only increases by 3.5%, which is mainly attributable to the restriction of the potential maximum heat shift between daytime and night. As shown in table 1, the potential maximum heat shift is observed for the combination of 36°C and 26mm thick PCM under the climate in Kaohsiung.

3.5. Impact of PCM $t_{tmp}$

Figure 6 demonstrates the $I_{hot}$ for 26mm PCM roof against $t_{tmp}$. In figure 6, it was found that the impact of $t_{tmp}$ on $I_{hot}$ is insignificant when $t_{tmp} < 40^\circ C$; $I_{hot}$ increases rapidly when $t_{tmp} > 40^\circ C$. While the rise in $t_{tmp}$ can increase the heat released from PCM during the night, it will also reduce the heat stored in the daytime, and hence, reduce the heat shift. Whereas, a decrease in $t_{tmp}$ will increase the heat stored in PCM during the daytime, but will also reduce the heat released during the night, and hence, reduce the heat shift. As shown in figure 6, the optimal $t_{tmp}$ occurred at 37°C, which corresponds to the minimum $I_{hot}$, and is 1°C higher than the optimal $t_{tmp}$, as shown in table 3. Figure 6 also shows the change of $I_{hot}$ for composite roof with $t_{tmp}$ of PCM. It can be seen that $t_{tmp}$ has slight impact on $I_{hot}$ in composite roof.
4. Conclusions

In this paper, based on a classroom on the top floor of a school in Kaohsiung City, Taiwan, we researched the effect of different types of insulation roofs, PCM roofs, and composite roofs on the risk of overheating in the naturally ventilated classroom. The findings are summarized as follows:

- The optimal $t_{mp}$ and thickness of PCM can be calculated by using the sol-air temperature on the design day.

- The insulation roof can effectively reduce the risk of overheating in naturally ventilated classrooms. In Kaohsiung, Taiwan, a 25mm insulation could reduce the $I_{hot}$ by up to 70%; however, improvement will be limited if the insulation thickness is further increased.

- In Kaohsiung City, Taiwan, the optimal PCM roof design could decrease the $I_{hot}$ by up to 64%. The decrease in $I_{hot}$ tends to be flat with the increased PCM thickness. The effect $t_{mp}$ of PCM on $I_{hot}$ was insignificant for $t_{mp}$ varied within 34-40°C, but significant when $t_{mp} > 40°C$.

- The impact of $t_{mp}$ on $I_{hot}$ for composite roof was not significant.

![Figure 6. Impact of $t_{mp}$ on the different types of phase change materials roofs.](image)

References

[1] HH Liang, TP Lin and RL Hwang, Linking occupants’ thermal perception and building thermal performance in naturally ventilated school buildings, *Applied Energy* **94** (2012) 355–363

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[3] ISO 7730. Moderate thermal environments—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort; 2005.