Evaluating cascaded and tunable phase change materials for enhanced thermal energy storage utilization and effectiveness in building envelopes

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Abstract

The incorporation of phase change materials (PCMs) in envelopes is considered an effective thermal energy storage (TES) method for energy savings and load flexibility in buildings. However, an important limitation of PCMs is their fixed and narrow transition temperature range. Because the interior temperature setpoints are typically different in summer versus winter, and the exterior temperature varies substantially above and below the setpoints during the year, PCMs with a fixed transition temperature are utilized only during part of the year. In this study, we provide an extensive numerical analysis of the performance of a lightweight building envelope containing three different types of PCMs: traditional single-layer PCM with a fixed transition temperature, novel cascaded two-layer PCM with different transition temperatures, and a "futuristic" tunable PCM whose transition temperature can be varied in-situ using external excitation. We compare their performances by evaluating the relationship between the PCM utilization and parameters such as latent heat, transition temperature range, PCM thickness, and PCM location. While traditional PCMs are mostly active during one season, properly designed cascaded and tunable PCMs can be active much longer, thereby allowing load shift and energy savings in both heating and cooling seasons. Under the operating conditions considered in this study, tunable PCMs performed best, providing the highest utilization (about 2 times the traditional PCMs) and enhanced effectiveness (up to 99% peak load reduction in cooling season and 34% peak load reduction in heating season) with the same amount of material as the traditional PCMs; however, cascaded PCMs can be a good alternative while tunable PCMs are unavailable.

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1. Introduction

Thermal energy storage (TES) using phase change material (PCM) in building components is an effective method to reduce energy use and shift peak load to achieve load flexibility [1, 2]. PCMs are particularly effective in modulating heat flow through lightweight building envelopes, thereby reducing indoor temperature fluctuations and enhancing occupants' thermal comfort [3]. However, they have one important limitation: PCMs are effective only when they change phase, which is directly dependent on the phase transition temperature [4, 5]. PCMs have a narrow transition temperature range, which limits their utilization under a fixed temperature bound, affecting their overall performance and levelized cost of energy storage. This is particularly relevant for buildings that experience large temperature fluctuations during the year. For instance, the ambient air temperature in some locations can range from -10°C in winter to +35°C in summer. Additionally, the interior setpoint temperature is typically around 24°C in summer and 20°C in winter, meaning that PCMs have largely variable temperature conditions during the year. Therefore, PCMs can only be effective during either cooling or heating, remaining either solid or liquid the rest of the year. A field study by Miller et al. [6] showed that PCMs used in south- and east-facing building envelopes were fully active only 0–8% of days per year and partially active 36–38% days per year.

In recent years, researchers have attempted to dynamically vary the transition temperature of PCMs. Cao et al. [7] suggested to vary the hydration level in calcium chloride hydrates to control their phase transition temperature for cooling applications in the power plants. This paper reported that by removing moisture with dry airflow, the low melting point $CaCl_2{\cdot}6H_2O$ (transition temperature ~ 29°C) can be tuned to a high melting point $CaCl_2{\cdot}4H_2O$ (transition temperature ~ 39°C). The process was then reversed by adding liquid water. The melting point tunability feature of this PCM was found to improve energy savings by up to 1.6% when year-round usage was considered. Khomein et al. [8] demonstrated a copolymerization strategy to tune transition temperature of a solid-solid PCM, called polymeric polyethylene glycol methyl ether methacrylate, between 18°C and 35°C by varying the copolymer content. Han et al. [9] recommended a more advanced technique for tuning the phase transition of organic PCMs by controlling the intermolecular interactions between PCM molecules and photochromic dopants using optical switching. They introduced azobenzene dopants into conventional organic PCMs to provide stability to the phase storing thermal energy. Reversible heat storage and release in the PCM composite was obtained by photoisomerization of azobenzene dopants using ultraviolet and visible-light illuminations. Researchers have also attempted to control the phase transition by applying external excitation through pressure [10-12], light irradiation [13, 14], and electric current [15, 16]. Tokoro et al. [17] proposed a solid-solid phase transition ceramic that exhibits phase change by application of heat and external pressure. This paper reported that lambda titanium pentoxide (λ-Ti_3O_5) undergoes a solid-solid phase transition to beta titanium pentoxide (β-Ti_3O_5) on application of external pressure, and releases latent heat of 230 kJ/L. Conversely, β-Ti_3O_5 was found to transform back to λ-Ti_3O_5 by application of heat, light, or electric current. Using external pressure of 15–530 MPa, tunable ceramics were shown to provide the flexibility to utilize the stored energy between 300 K and 510 K. These materials were later used to develop a low-pressure-responsive heat storage system for automobiles [18] and a long-term energy storage system from hot water for thermal and nuclear power plants [19].

While dynamically tunable PCMs are still under development and unavailable, an alternative to enhance energy storage benefits in building envelopes is to employ multiple PCM layers with different transition temperatures, in a cascade or composite manner, technically called cascaded latent thermal energy storage (CLTES). While CLTES systems are popular in concentrating solar power plants to enhance charging and discharging rates and increase exergy efficiency [20, 21], we could not identify prior attempts in the literature to use it in buildings.

The objective of this study is to examine three different PCM configurations in building envelopes: a conventional single-layer PCM, a cascaded design containing two different PCMs with different transition temperatures, and a theoretical tunable PCM whose transition temperature can be varied in-situ using external excitation. We simultaneously optimize PCM utilization (degree of phase change) and effectiveness (ability to shift and reduce the loads) and compare configuration performance to provide load flexibility in buildings. We evaluate the relationship between PCM utilization and effectiveness in shifting peak demand and reducing total energy use. The parameters that affect the utilization and effectiveness of the PCM-integrated building envelopes can be divided into two categories: material properties such as thermal conductivity and heat capacity, and system parameters such as thermal resistance of the building assembly, PCM location, and PCM quantity. While some of these parameters have been studied previously [22], in this study we focus on PCM energy density, thickness, location, and transition temperature range to evaluate each configuration's combined impact on utilization and effectiveness in the building walls.

2. Methodology

2.1. Wall assembly and PCM integration

We focus on lightweight wood-framed construction, typically used for residential buildings in the United States. To compare the thermal performance of different PCMs, we consider three kinds of assemblies (Figure 1). Figure 1(A) shows the traditional PCM-integrated building wall that contains a single layer of a static PCM with a fixed transition temperature of either 23°C or 19°C (not shown). Figure 1(B) shows the cascaded design with two layers of PCM with transition temperatures of 19°C and 23°C, respectively. Based on the preliminary analysis, the order of the two PCMs was found insignificant when the PCM thickness is small (<0.5 in. or 1.27 cm). Lastly, Figure 1(C) shows the tunable PCM with variable transition temperature, which is calculated based on the outdoor and indoor temperature conditions.

The transition temperature of the single PCMs was calculated based on the temperature of the PCM in the wall under heating or cooling seasons. During preliminary analysis, it was noted that the PCM temperature varies nearly from 21 °C to 25 °C in the cooling season and from nearly 16 °C to 21 °C in the heating season. Therefore, we selected the PCM transition temperature of 23 ±2 °C for the cooling season and 19 ±2 °C for the heating season. Note that the transition range of the PCM for the heating season can be slightly larger, but in this study, we have considered it to be 4 °C for both the seasons to maintain consistency. For tunable PCM, transition temperature was calculated based on the indoor and outdoor conditions. For the given climate, we first obtained the varying temperature of a static PCM in the wall for the whole year. The transition temperature of the tunable PCM for a given day was then calculated by averaging the temperature of the static PCM for 24 hours of the day. In all three cases, the PCM layer is added behind the drywall to maximize its influence on the thermal load of the building.

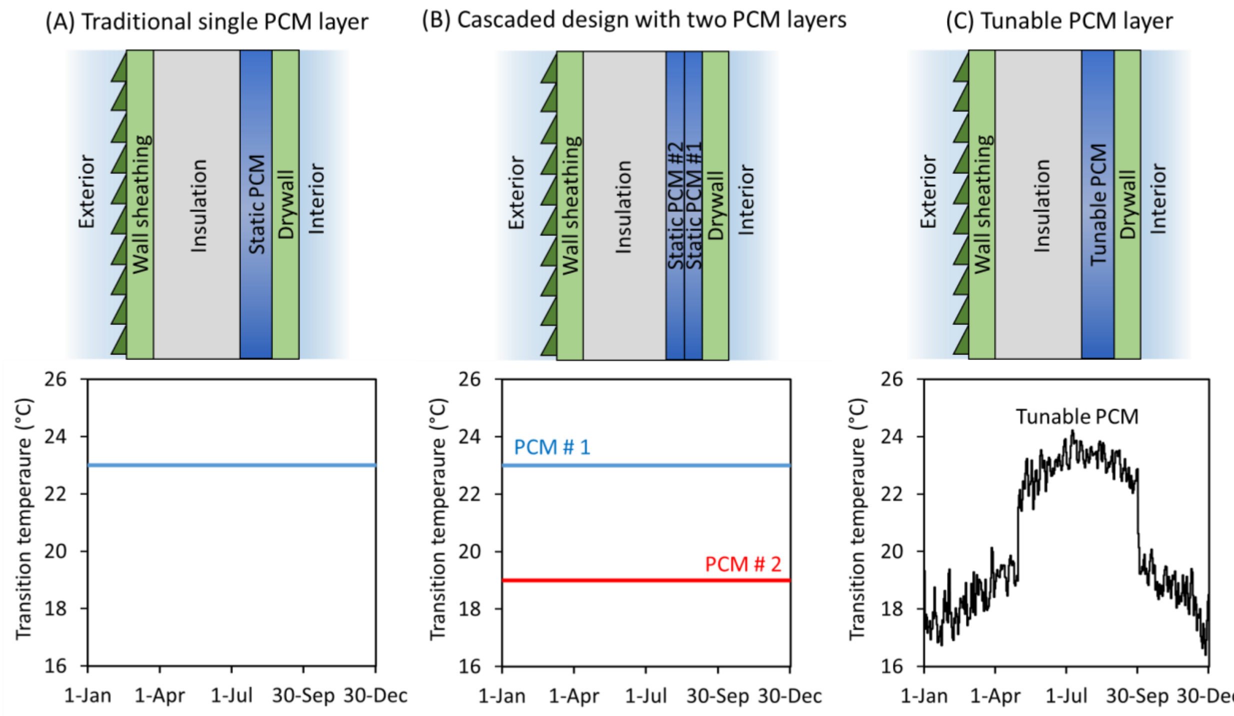

Figure 1. Schematic of the PCM-integrated walls and transition temperatures studied: (A) traditional single-layer static PCM with a fixed transition temperature, (B) cascaded design containing two layers of PCM with different transition temperatures, and (C) tunable PCM with variable transition temperature.

2.2. PCM utilization versus PCM effectiveness

We define the year-round utilization (μ) of the PCM as the average phase change over the entire year. Mathematically, it can be expressed as:

$$\mu = \frac{1}{365}\sum_{d=1}^{d=365}[x_{\max}(d) - x_{\min}(d)] \quad (1)$$

where $x_{\max}$ and $x_{\min}$ represent the maximum and minimum melt fraction of the PCM on a certain day "d" of a year.

The effectiveness of the PCM can be defined in two different ways, depending on the objective of the PCM integration in a building envelope. The first criteria can be based on the ability to reduce the total energy use in the building (i.e., energy savings), whereas the second measure can be focused on the capacity to shift the thermal loads in the buildings from peak hours to off-peak hours (i.e., load shifting). Mathematically, these factors can be expressed as:

$$\eta_{\text{save}} = \left[\frac{Q_{\text{Baseline}} - Q_{\text{PCM}}}{Q_{\text{Baseline}}}\right]_{\text{Total}} \tag{2}$$

$$\eta_{\text{shift}} = \left[\frac{Q_{\text{Baseline}} - Q_{\text{PCM}}}{Q_{\text{Baseline}}}\right]_{\text{peak hours}} \tag{3}$$

where Q_{Baseline} is the thermal load in the reference building with no PCM, and Q_{PCM} denotes the modulated thermal load in the PCM-integrated building. Subscript "Total" denotes the total thermal load over the entire day, while "peak hours" denotes thermal load during the peak hours. In other words, η_{save} is the reduction in the total thermal load from a PCM-integrated wall, and η_{shift} denotes its peak load shifting capacity.

2.3. Numerical model

To minimize the computational expenses and due to symmetry, only a portion of the wall has been considered for numerical modeling. As shown in Figure 2, the building walls are comprised of 2×6 wood studs, resulting in stud thickness of 1.5 in. (~3.8 cm) and wall cavity depth of 5.5 in. (~14 cm). Thickness of the exterior sheathing and interior drywall is 0.5 in. (~1.3 cm). We apply the symmetry boundary conditions (shown as the lines of symmetry) at the middle of studs and cavity to ensure that this simplified geometry physically captures a full-size building wall, as suggested in previous studies [23-25].

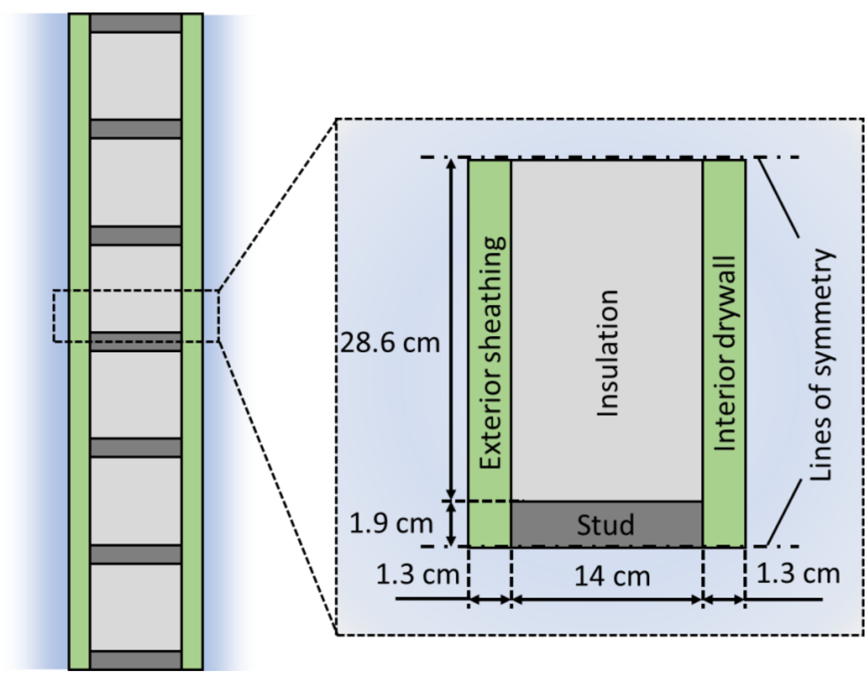

Figure 2. Two-dimensional geometry representing cross-sectional area of the wood-framed wall and the key geometric dimensions considered for the numerical simulations.

Various components of the assembly and their material properties are listed in Table 1. Table 2 shows the range of PCM parameters as well as their default values used for the parametric analysis. These values were selected based on our previous study that indicates that out of numerous PCM parameters, the most important ones are latent heat, thickness, transition temperature, and location [22]. While the total thickness of all three PCMs is the same, the individual layers of cascaded PCMs are half as thick as traditional and tunable PCMs. This is intentional to ensure the same amount of PCM material in the building walls.

Table 1. Material properties of different components in the wall assembly [26]

Component	Material	Density (kg/m^3)	Thermal conductivity (W/m-K)	Specific heat (kJ/kg-K)
Insulation	Expanded polystyrene	24	0.037	1.214
Stud	Wood	577	0.144	1.633
Exterior wallboard	Oriented strand board	640	0.130	1.410
Interior wallboard	Gypsum	550	0.153	1.089
PCM (solid)	---	887	0.300	2.750
PCM (liquid)	---	898	0.100	1.848

Table 2. PCM parameters and their values used for parametric analysis

PCM parameters	Default value	Range
Latent heat (kJ/kg)	50	25–200
PCM thickness (cm)	0.63	0.31–2.50
Transition range (°C)	4	2–16
PCM location (X*)	0	0–L

* X denotes distance from the drywall, and L is thickness of the wall cavity.

2.4. Governing equations

We solve the transient heat transfer equation using the method described in our previous studies [22, 27, 28]. The modified governing equation describing the transient heat flow in a PCM-integrated wall is given as [29]:

$$\rho_{eff} C_{eff} \frac{\partial T}{\partial t} + \nabla \cdot \left(-k_{eff} \nabla T\right) = 0 \tag{4}$$

where the effective density (ρ_{eff}) and the effective thermal conductivity (k_{eff}) of the PCM are given as [29]:

$$\rho_{eff} = \theta_s \rho_s + \theta_l \rho_l \tag{5}$$

$$k_{eff} = \theta_s k_s + \theta_l k_l \tag{6}$$

where θ is volume fraction of the solid and liquid phases of the PCM, which are denoted by subscripts "*s*" and "*l*". θ_l is typically defined as melt fraction of the PCM.

The effective heat capacity of the PCM is calculated as [29]:

$$C_{eff} = \frac{1}{\rho_{eff}} (\theta_s \rho_s C_s + \theta_l \rho_l C_l) + L_{s \to l} \frac{\partial \alpha_{s \to l}}{\partial T} \tag{7}$$

$$\alpha_{s \to l} = \frac{1}{2} \frac{\theta_l \rho_l - \theta_s \rho_s}{\theta_s \rho_s + \theta_l \rho_l} \tag{8}$$

where C_s and C_l are the specific heat capacity of the pure solid and liquid states of the PCM, $L_{s \to l}$ denotes the latent heat capacity of the PCM, and $\alpha_{s \to l}$ represents the fractional change in the PCM composition during the phase change. The value of $\alpha_{s \to l}$ changes from $-{}^{1}\!/_{2}$ to ${}^{1}\!/_{2}$ when PCM changes its state from pure solid to pure liquid.

2.5. Boundary and initial conditions

Equations (3)-(7) were solved using the following boundary and initial conditions:

- The initial condition of the building components and PCMs was assumed to be 23°C in all simulations.
- The exterior surface of the wall experiences a heat flux boundary condition (q''_{ext}) comprising solar irradiance, convection losses, and long-wave radiation [23-25]:

$$q''_{ext} = \alpha q''_{solar} + h_{ext}\left(T_{out} - T_{e,wall}\right) + q''_{LWR} \tag{9}$$

  where α is the solar absorptance of the exterior surface, q''_{solar} is the solar irradiance on the exterior surface, h_{ext} is the convection coefficient due to ambient air, T_{out} is the outside air temperature, $T_{e,wall}$ is temperature of the exterior surface, and q''_{LWR} is the heat transfer due to long-wave radiation.

- The long-wave radiation includes the radiation exchange between the exterior surface and the outside environment, ground, and sky. With the assumption that outside environment and ground are at nearly the same temperature, q''_{LWR} is expressed as [23]

$$q''_{LWR} = \varepsilon\sigma\left[\left(1 - F_{sky}\right)\left(T_{out}^{4} - T_{e,wall}^{4}\right) + F_{sky}\left(T_{sky}^{4} - T_{e,wall}^{4}\right)\right] \tag{10}$$

  where σ is the Stefan-Boltzmann constant, ε is the infrared emittance of the exterior surface, T_{grnd} is temperature of the ground, T_{sky} is the sky temperature, and F_{sky} is the radiation view factor between the exterior surface and the sky.

- On the interior, we assume that the HVAC system could exactly match the instantaneous interior loads of the building, so that the desired interior temperature (T_{int}) is maintained. At the interior surface of the wall, we assign a convection boundary condition that is expressed as:

$$q''_{in} = h_{int}\left(T_{i,wall} - T_{int}\right) \tag{11}$$

  where h_{int} denotes the equivalent heat transfer coefficient (incorporating convection as well as radiation effects) and $T_{i,wall}$ is the temperature of the interior surface of the wall.

- A symmetry boundary condition was applied at the centerline of the wall cavity and the stud. The symmetry boundary condition ensures no normal heat flux across a boundary and is represented as [30]:

$$q''_{\perp} = 0 \quad (12)$$

where $q''_{\perp}$ denotes the heat flux component normal to the boundary.

The average temperature setpoints were 23°C during the summer (May to September) and 20°C during the winter (October to April). However, as shown in Figure 3, to facilitate the load shift during the cooling season, we increased the interior temperature by 1°C during the peak hours (15:00 to 21:00) and decreased the setpoint temperature by 1°C during off-peak hours (0:00 to 6:00). Likewise, during the heating season, we decreased the interior temperature by 1°C during the peak hours (6:00 to 9:00 and 18:00 to 21:00 pm) and increased the interior temperature by 1°C during off-peak hours (0:00 to 6:00). This technique, referred to as precooling or preheating, allows the PCM to controllably charge during off-peak hours and discharge during peak hours, thereby reducing the overall energy usage cost in the buildings. The heat transfer coefficients (h_{int} and h_{out}) of 2.5 and 33.4 W/m^2-K were assumed for the interior and exterior surfaces [31, 32], respectively. For a vertical wall, the sky view factor can be calculated to be 0.353 [33]. The solar absorptance and the infrared emittance of the exterior surface were 0.6 and 0.8, respectively [23-25].

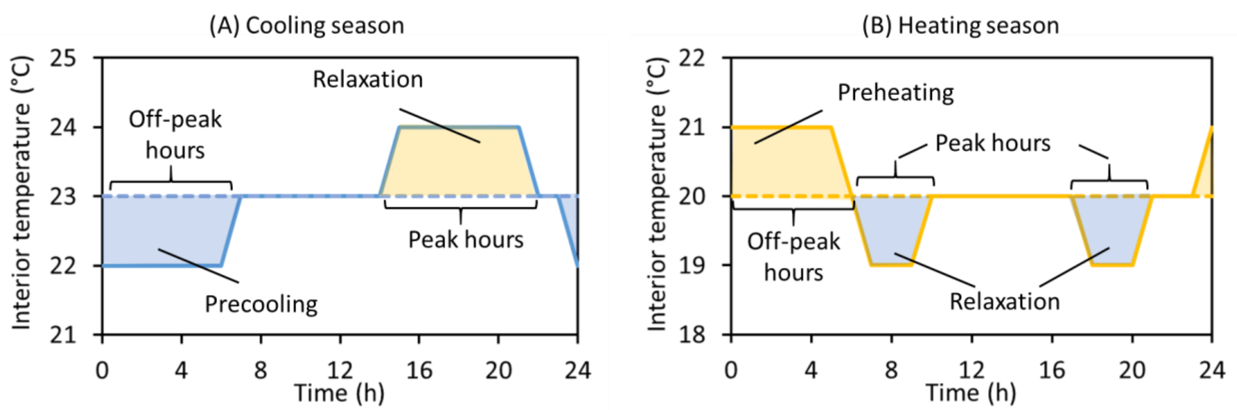

Figure 3. Modulation in interior temperature to controllably charge and discharge the PCM during off-peak and peak periods in (A) cooling and (B) heating seasons.

2.6. Solution strategy

All the simulations are performed using the commercial code COMSOL Multiphysics version 5.6. We employed the structural quadrilateral mesh to discretize the wall assemblies. To ensure minimal variation in numerical results with change in the mesh density, we performed the mesh independence tests where the element count was varied between 500 and 4,200. Increasing the number of elements from 1,800 to 4,200 resulted in less than 1.0% relative change in total heat gains; therefore, the element count of 1,800 was selected for all simulations in this study. We also validated the numerical model using experimental data available in the published literature and noted a root mean square error of less than 1°C, as described in our prior publications [26, 27].

3. Results and discussion

We arbitrarily selected Baltimore as the outdoor climate and used the same exterior conditions for the entire analysis. We have divided our discussion of the results into the following subsections:

- Section 3.1 is focused on understanding the performance of conventional, cascaded, and tunable PCMs. We compare the utilization and effectiveness of different PCMs and investigate the impact of cascading and tunability on enhancing the PCM performance.
- In section 3.2, we study the effect of the PCM latent heat on its utilization and, consequently, its impact on the building's thermal load and its load shifting capacity.
- Section 3.3 describes the effect of the PCM thickness on its utilization, as well its effectiveness in shifting the peak load and reducing the total thermal load.
- In section 3.4, we study the effect of the PCM transition temperature range on the annual utilization and effectiveness of different PCMs.
- Lastly, section 3.5 highlights the influence of the PCM location in the assembly, which affects its interaction with the interior and exterior environments.

3.1. Utilization versus effectiveness of the PCMs

Figure 4(A) shows the melt fraction of a single-layer PCM with a transition temperature of 23°C. Because its transition temperature is close to the cooling setpoint, it is active mostly during the cooling season. In the heating season, because the setpoint temperature and outdoor temperature are lower than the transition temperature of the PCM, the PCM remains mostly solid. Figure 4(B) shows the melt fraction of another traditional single-layer PCM with a transition temperature of 19 °C. Because its transition temperature is lower than the cooling setpoint and exterior temperature in the cooling months, it is active mostly in the heating season, but remains in liquid state during summer months.

Table ***3*** shows the annual utilization and effectiveness of the two PCMs in reducing the heat flow through the walls during peak hours. The PCM with fixed transition temperature of 23°C has annual utilization of 14%, whereas the PCM with fixed transition temperature of 19°C has annual utilization of 11%. Despite having similar annual utilizations, the PCM with transition temperature of 23°C is much more effective (94%) in shifting the peak heat gain than the PCM with transition temperature of 19°C is in shifting the peak heat loss (28%). This happens because of the higher temperature difference between indoor and outdoor during heating compared to cooling season, resulting in larger thermal load through the walls during the heating season. It will be discussed in the subsequent sections that PCM effectiveness in heating seasons can be enhanced by increasing its heat capacity, which is restricted by the availability of high energy density PCM materials. Another way to increase the PCM utilization and effectiveness is by increasing the preheating/precooling. This method, however, can affect the thermal comfort of the occupants. Figure 4(C) shows the melt fraction of the cascaded PCMs, with transition temperatures of 23°C and 19°C, respectively. While the cascaded PCMs are active most of the year, only one PCM is active at a time: PCM 1 is active in cooling season and PCM 2 is active in heating season. Consequently, the maximum melt fraction of the cascaded PCMs can be only up to 50%, since at least half of the PCM remains always inactive. As shown in

Table ***3***, cascaded PCMs exhibit average annual utilization of 9%, which is lower than the single-layer PCMs. Additionally, their effectiveness (83%) in cooling season is also lower than the single-layer PCM and nearly the same as the single-layer PCM in heating season. Figure 4(D) shows the melt fraction of the tunable PCM. It is active throughout the year because of its variable transition temperature, tuned for continuous phase change.

Table ***3*** shows that the annual utilization of the tunable PCM is 27%, which is almost 2 times higher than that of the traditional single-layer PCMs, and 3 times higher than that of the cascaded PCMs. The effectiveness of the tunable PCM is 99% in cooling season and 34% in heating season, which is 1.1–1.3 times higher than the single-layer PCMs or two-layer cascaded PCMs. We will further note in the subsequent sections that utilization and effectiveness of PCMs can be independently varied by controlling different operating parameters.

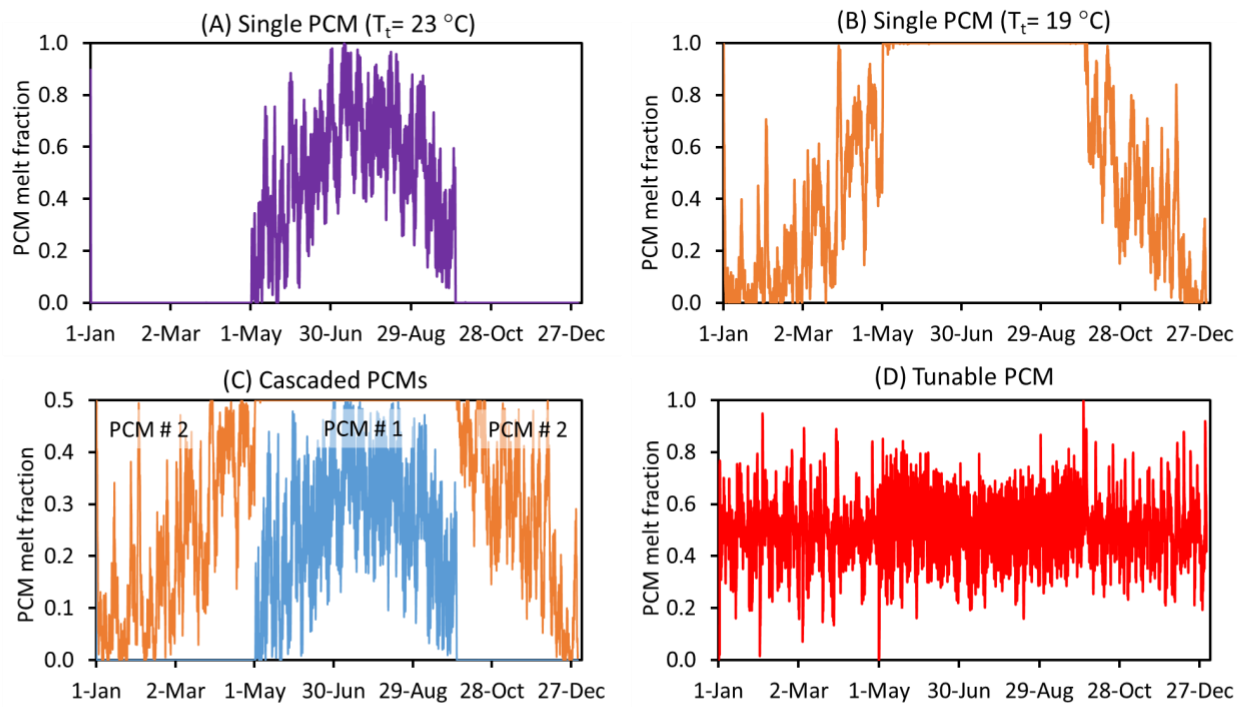

Figure 4. Melt fraction and annual utilization of different PCMs: (A) traditional single-layer PCM with transition temperature of 23°C, (B) traditional single-layer PCM with transition temperature of 19°C, (C) two-layered cascaded design comprising PCMs at transition temperatures of 23°C and 19°C, respectively, and (D) tunable PCM.

Table 3. Annual utilization and effectiveness of different PCMs in minimizing peak thermal load through building walls.

PCMs	Annual utilization (%)	Peak hours heat gain reduction (%)	Peak hours heat loss reduction (%)
Static PCM (T_t=23°C)	14%	93%	---
Static PCM (T_t=19°C)	11%	---	28%
Cascaded PCMs	9%	83%	30%
Tunable PCM	27%	99%	34%

3.2. Effect of latent heat on PCM utilization and effectiveness

Changes in latent heat of the PCM are expected to have a significant effect on the utilization and effectiveness of the TES system. Figure 5 shows the melt fraction of different PCMs considered in this study and compares their annual utilization. Increasing the PCM latent heat does not alter the period of activity: the traditional single-layer PCM at T_t=23°C remains active in the cooling season whereas the two cascaded PCMs remain active in heating and cooling seasons. Likewise, the tunable PCM is active throughout the year, irrespective of the value of latent heat. However, an increase in latent heat reduces the daily fluctuation in the melt fraction, which is important because it indicates that the daily utilization of the PCM lowers with an increase in latent heat (Figure 5(D)). Increasing latent heat from 25 kJ/kg to 200 kJ/kg reduces the annual utilization of a single-layer PCM at T_t=23°C by 78%, a single-layer PCM at T_t=19°C by 74%, cascaded PCMs by 67%, and tunable PCM by 79%. Notably, at a fixed value of latent heat, the annual utilization of the tunable PCM is about twice the utilization of the single-layer PCMs. Comparing to cascaded PCMs, the tunable PCM is 4 times more utilized when the latent heat is 25 kJ/kg; however, this ratio reduces to nearly 2 times when the latent heat is 200 kJ/kg. This indicates that, compared with the cascaded PCMs, the impact of the tunable PCM diminishes with increasing latent heat.

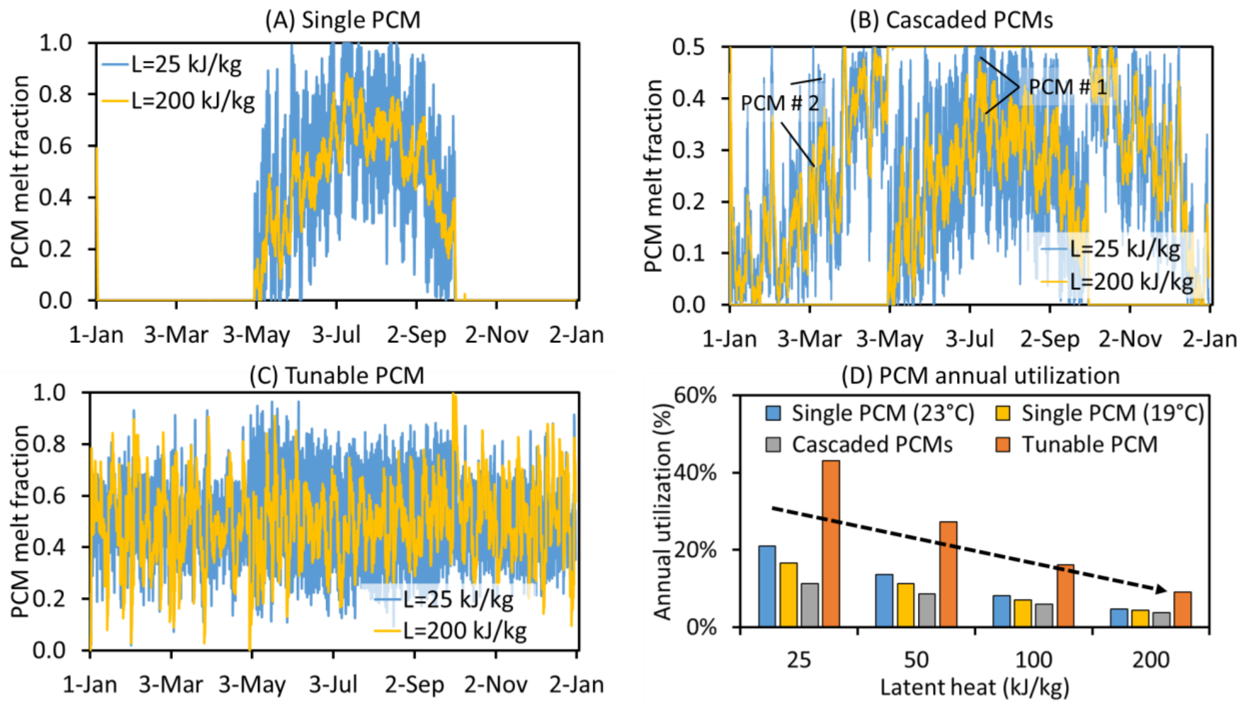

Figure 5. Effect of latent heat on melt fraction of different PCMs: (A) traditional single-layer PCM, (B) two cascaded PCMs, and (C) tunable PCM; (D) annual utilization of different PCMs at various latent heat capacity.

It is expected that a decrease in annual utilization of PCMs should have a negative consequence on their effectiveness on load shifting capacity. Figure 6, however, shows an opposite trend. The peak heat gain is smaller with higher latent heat in both cooling and heating seasons. As shown in Figure 6(A), during cooling season the peak load shifting capacity of the tunable PCM is highest, followed by the single-layer PCM (T_t=23 °C) and cascaded PCMs. The difference, however, is more prominent for smaller latent heat, and it saturates beyond 200 kJ/kg. Figure 6(B) shows the effect of latent heat on the peak load shifting capacity in the heating season. At lower values of latent heat, the cascaded PCMs perform better than the traditional single-layer PCM (T_t=19°C) but worse than the tunable PCM. However, when the latent heat is above 100 kJ/kg, the cascaded and single-layer PCMs perform similarly. Overall, the load shifting capacity of the PCMs increases monotonically with the increase in latent heat. Note that load shifting capacity is lower in heating season than in cooling season. This is because Baltimore, the climate considered in this study, experiences a larger temperature difference between indoor and outdoor during winter months than in summer months, leading to much larger thermal load in the heating season compared to the cooling season. The peak load shift is typically not free as it leads to an increase in the total thermal load [34, 35]. Figure 6(C) and (D) shows the energy penalty associated with load shifting in cooling and heating seasons. In the cooling season, because there is not much change in load shifting capacity beyond 50 kJ/kg, the increase in the total heat gain remains nearly the same with an increase in latent heat. In the heating season, however, the total heat losses seem to reduce with an increase in latent heat, though the change in not substantial. This further emphasizes that the need for higher latent heat PCMs is much more critical in heating season than in cooling season.

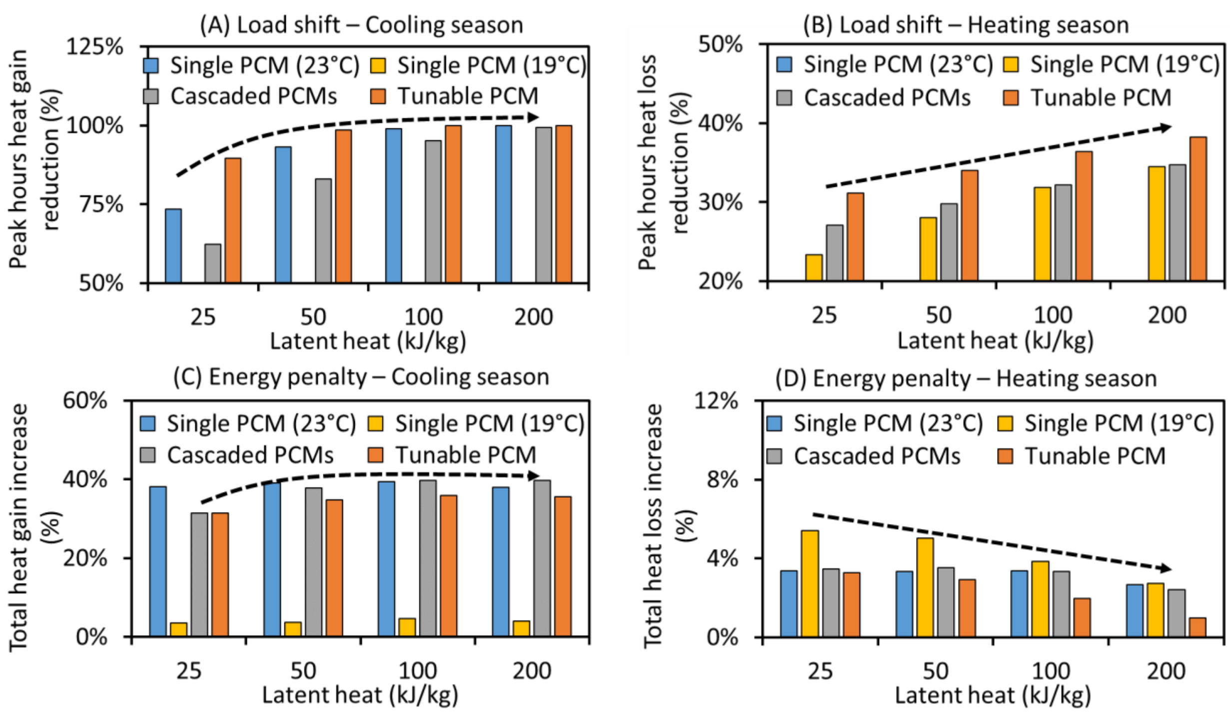

Figure 6. Effect of latent heat on peak load shifting capacity of different PCMs in (A) cooling and (B) heating seasons; effect of latent heat on energy penalty for load shifting by different PCMs in (C) cooling and (D) heating seasons.

3.3. Effect of PCM thickness on PCM utilization and effectiveness

The energy storage capacity of a PCM-integrated envelope can also be increased by adding more PCM mass. Figure 7 shows the effect of PCM thickness on the melt fraction of different PCMs and compares their annual utilization. Like latent heat, increasing thickness does not alter the period when the PCMs are active. That is, the traditional single-layer PCM is active during either cooling or heating season, whereas cascaded and tunable PCMs are active throughout the year. However, an increase in PCM thickness reduces the daily fluctuations in the melt fraction due to increased heat storage capacity, which remains unutilized. Figure 7(D) depicts the annual utilization of different PCMs with increasing thickness. The annual utilization of all PCMs decreases almost linearly with increases in their thickness. Importantly, at a fixed PCM thickness, utilization of the tunable PCM is highest and nearly twice that of the single-layer PCMs. The effect is most prominent when the PCM thickness is small.

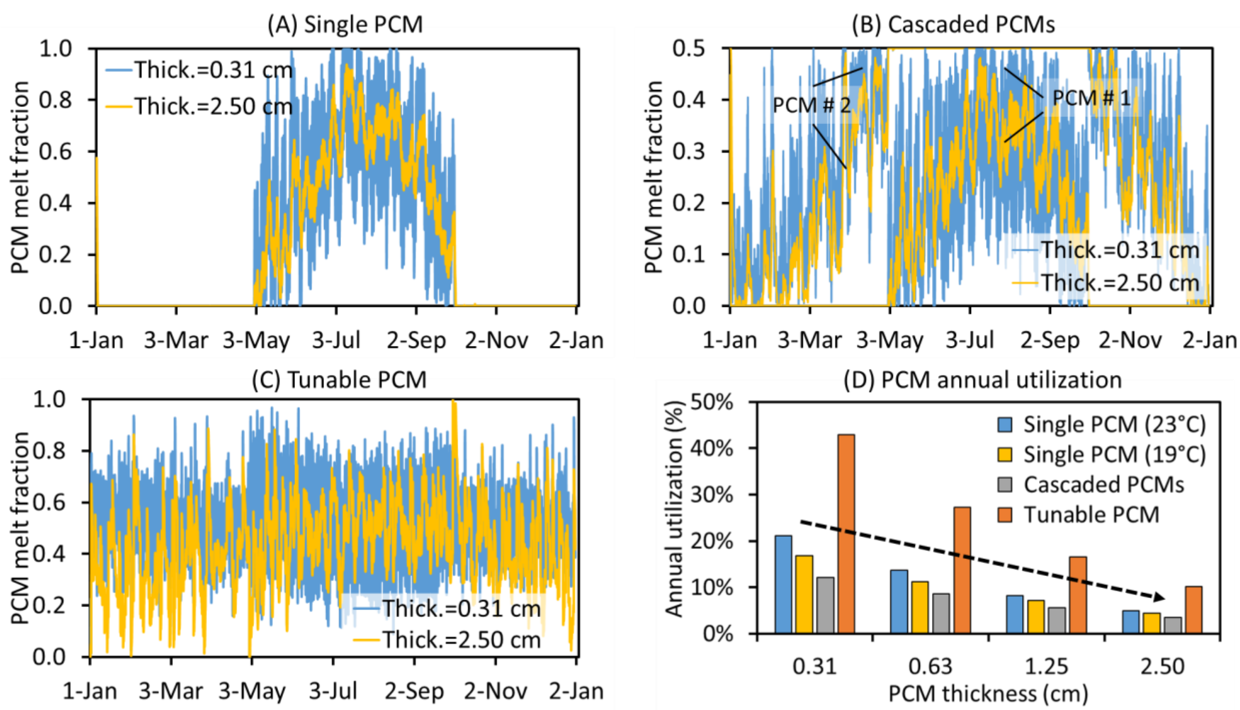

Figure 7. Effect of thickness on melt fraction of different PCMs: (A) traditional single-layer PCM, (B) two cascaded PCMs, and (C) tunable PCM; (D) annual utilization of different PCMs at various thicknesses.

As with latent heat, reduced utilization due to increased PCM thickness does not necessarily mean a reduction in PCM effectiveness. As shown in Figure 8(A), the peak load shifting capacity of the PCMs in cooling season increases with PCM thickness. However, the load shifting capacity saturates beyond a PCM thickness of 0.5 in. (1.27 cm). At a fixed PCM thickness, the tunable PCM performs the best, and cascaded PCMs perform the worst, when PCM thickness is small (<0.63 cm). At higher PCM thicknesses (>1.25 cm), performance of all three PCMs saturates to a constant value, indicating that thicker PCM is desirable. In the heating season, however, the trend appears different (Figure 8(B)). At a given PCM thickness, the tunable PCM performs the best, followed by cascaded PCMs and traditional single-layer PCM (T_t=19°C). Notably, the load shifting capacity shows a small change when the PCM thickness is increased from 0.125 in. (0.31 cm) to 0.25 in. (0.63 cm), but then starts to decrease with further increases in PCM thickness. This seems unusual because, as we noted for latent heat, an increase in heat capacity is expected to enhance PCM effectiveness. In this case, however, because we reduced the amount of insulation to accommodate additional PCM, the envelope thermal resistance decreased. The two counteracting effects—positive influence on heat capacity by increasing PCM thickness and negative influence of lower thermal resistance—seem to be balanced in cooling season due to the smaller thermal gradient across the wall. However, in heating season, the reduction in thermal insulation dominates and offsets any positive influence of additional PCM, especially when its thickness is large. Figure 8(C) and (D) depict the effect of PCM thickness on energy penalty for load shifting. Again, in cooling season there is not a substantial change, but in heating season there is a dramatic increase in heat loss due to increased PCM thickness. The effect is least prominent in the case of the tunable PCM, followed by cascaded PCMs. Additionally, we observe a dramatic increase in heat losses when the PCM thickness is greater than 0.5 in. (1.25 cm). Importantly, a single-layer PCM at T_t=23°C provides benefits toward shifting the peak load in the heating season, but it also leads to an increase in total heat losses. This happens because of the reduction in wall insulation from addition of PCM, irrespective of whether it is active or not. This infers that inappropriate selection of PCM not only provides no benefit but also causes harm by increasing the heat losses.

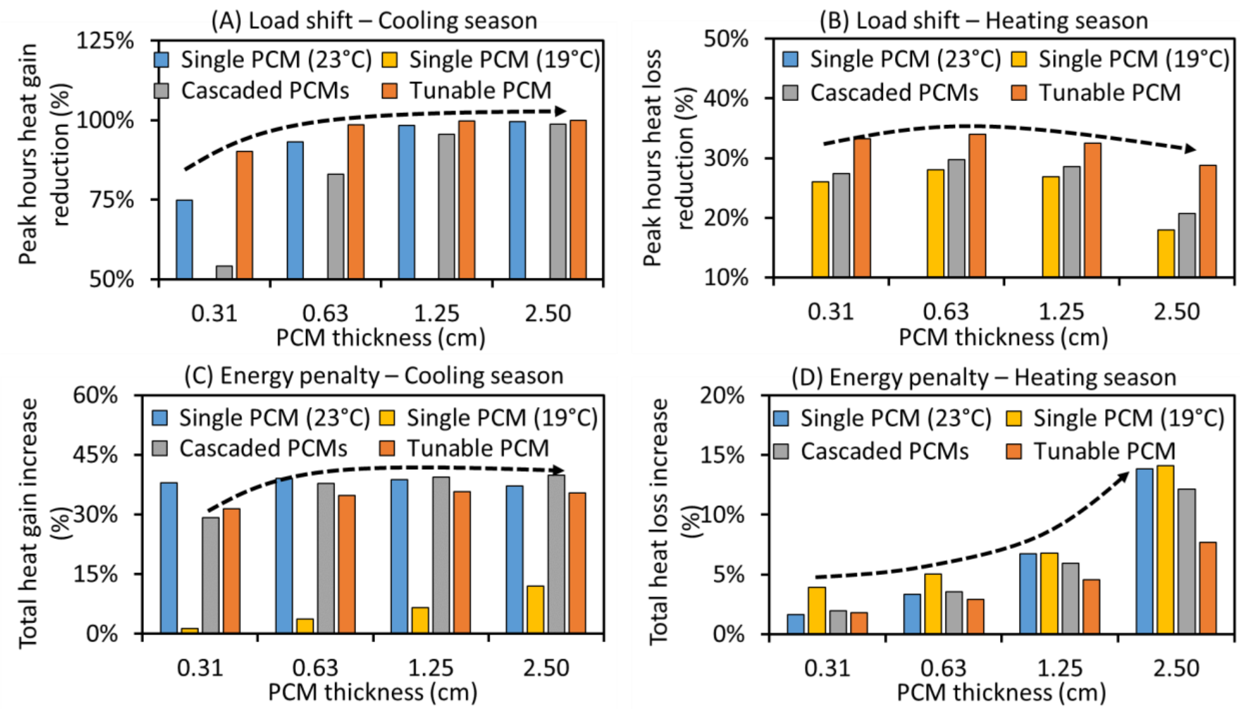

Figure 8. Effect of thickness on peak load shifting capacity of different PCMs in (A) cooling and (B) heating seasons; effect of PCM thickness on energy penalty for load shifting by different PCMs in (C) cooling and (D) heating seasons.

3.4. Effect of transition range on PCM utilization and effectiveness

One of the key material parameters that affects PCM phase change is transition temperature. Previous studies have shown that the mean PCM transition temperature should be close to the temperature setpoints [36, 37]; however, it is not clear how the transition range (ΔT) affects the utilization and effectiveness of the PCM in the wall. While narrow ΔT provides higher energy density per unit change in temperature, it limits the annual utilization of the PCMs due to smaller operating temperature band. In contrast, a wider ΔT is expected to provide a larger year-round utilization, but it reduces the energy storage capacity for a unit temperature change.

Figure 9 shows the melt fraction and utilization of different PCMs under two different transition range scenarios (2°C and 16°C). As shown in Figure 9(A) and (B), in the case of single and cascaded PCMs, there is a trade-off between day-wise utilization and year-wise utilization. Compared to the narrow transition range (2°C), the large transition range (16°C) makes the PCM active for a longer duration in a year, thereby enabling it to be effective in both heating and cooling seasons. However, the daily fluctuations when ΔT=16°C are much smaller than when ΔT=2°C, thereby reducing the influence of the PCM on its heat storage capacity. For this reason, as shown in Figure 9(D), the annual utilization of the traditional single-layer and cascaded PCMs do not change substantially with increases in ΔT. However, the tunable PCM experiences a substantial drop in utilization when ΔT is increased from 2°C to 16°C. This can be explained by Figure 9(C). The tunable PCM is always utilized over the entire year, irrespective of the transition range. Therefore, increasing transition range reduces its daily fluctuation, leading to reductions in its annual utilization.

It is also interesting to note the abrupt change of the PCM melt fraction near the transition period from cooling to heating season and vice-versa. This is due to change in the interior temperature condition, which is driven the operating mode (cooling or heating) of the HVAC system. In the cooling season, the interior temperature is close to the cooling set-point temperature of 23 °C, whereas in the heating season, the interior temperature is close to the heating set-point temperature of 20 °C. Since in this study, we have not considered the set-point temperature in the shoulder seasons, the change in the interior condition causes the abrupt change in the PCM melt fraction. In practice, however, we expect a gradual change in melt-fraction because the transition in interior temperature from heating to cooling set-points typically happens more steadily.

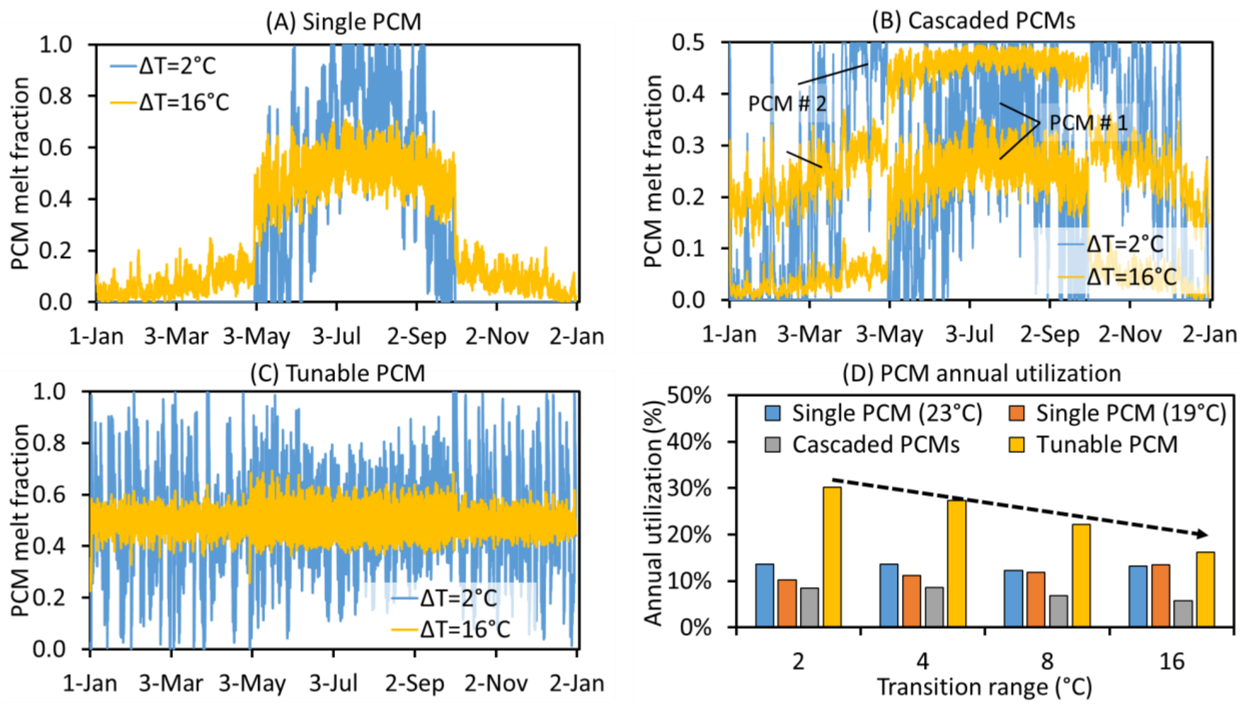

Figure 9. Effect of transition range on melt fraction of different PCMs: (A) traditional single-layer PCM, (B) two cascaded PCMs, and (C) tunable PCM; (D) annual utilization of different PCMs at various transition range values.

Figure 10(A) depicts the effect of PCM phase transition range on its load shifting capacity in cooling season. For a single-layer PCM (T_t=23°C) and cascaded PCMs, the peak heat gain reduction first increases from ΔT=2°C to ΔT=4°C, and then decreases with further increases in ΔT. This happens because of the trade-off between day-wise utilization versus year-wise utilization of the PCM. When ΔT is small (<2°C), daily utilization is large but year-wise utilization is relatively small. In contrast, when ΔT becomes larger than 4°C, PCM year-wise utilization increases, but daily fluctuations decrease. This logic, however, does not hold true for the tunable PCM, which is always active throughout the year. Increases in ΔT for tunable PCM continuously reduce its daily utilization, leading to reductions in its load shifting capacity. As shown in Figure 10(B), the single-layer PCM (T_t=23°C) is not active during heating season, except when ΔT is large (>16°C). The peak load shifting capacity of the single-layer PCM (T_t=19°C) and the cascaded PCMs show small changes, with best performance near 4°C. As expected, the performance of the tunable PCM lowers with increases in transition range. As shown in Figure 10(C) and (D), there is no definite trend for total heat gain/loss reduction with variations in ΔT. In the cooling season, the total heat gain appears to decrease with an increase in ΔT, except for the single-layer PCM at Tt=19°C, which shows an increasing trend in the total heat gain. However, in the heating season, we observe no substantial change in total heat loss. In summary, we can conclude that for traditional and cascaded PCMs, there exists an optimal transition range (~4°C) where PCMs are most effective. For tunable PCM, however, a smaller transition range is advantageous.

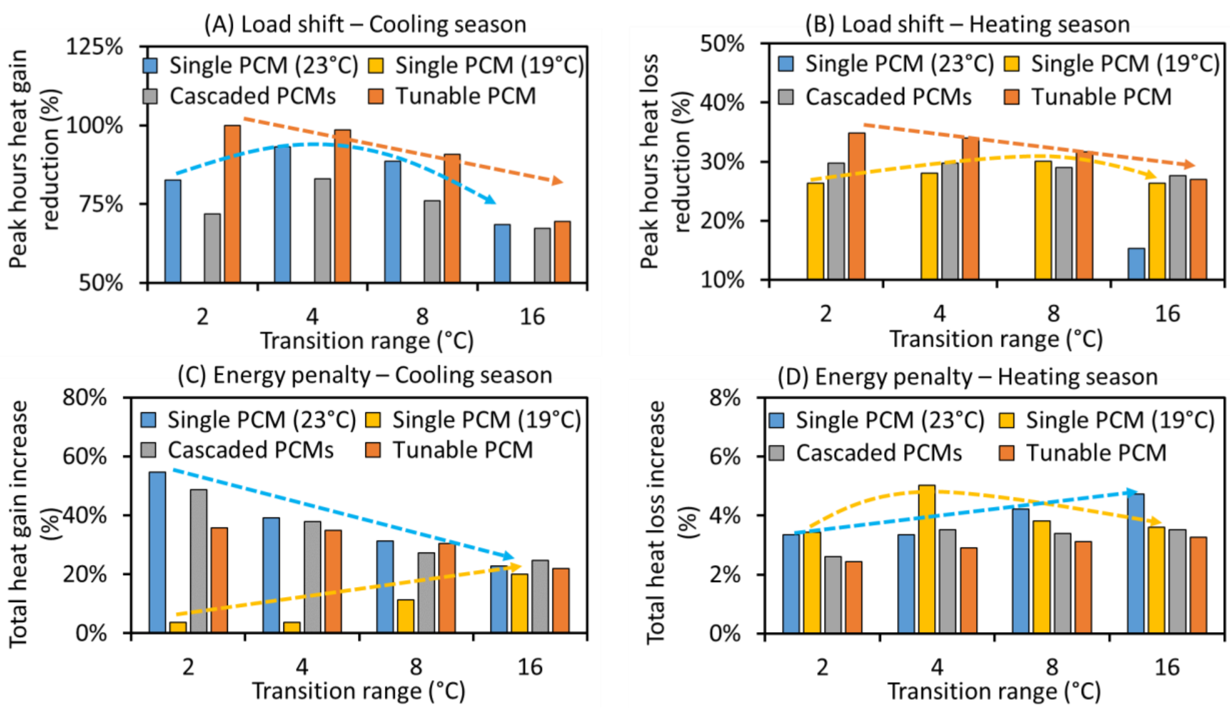

Figure 10. Effect of transition temperature range on peak load shifting capacity of different PCMs in (A) cooling and (B) heating seasons; effect of transition temperature range on energy penalty for load shifting by different PCMs in (C) cooling and (D) heating seasons.

3.5. Effect of PCM location on PCM utilization and effectiveness

An important system factor that affects PCM utilization as well as its effect on building energy use is its location in the wall. Figure 11 shows the effect of the PCM location in the wall thickness on its melt fraction and annual utilization. “X” denotes the PCM distance from the drywall, and “L” represents the width of the wall cavity. It can be noted that increasing the PCM distance from the interior substantially changes its utilization. When the PCM is located near the interior space, temperature variations are limited, leading to small fluctuations in its melt fraction. However, when the PCM moves closer to the exterior surface, it experiences large temperature swings due to variations in outdoor temperatures, leading to large fluctuations in its melt fraction. This observation is consistent for all three PCMs. As shown in Figure 11(D), the annual utilization of all three PCMs reaches a minimum when they are located 0.5L from the drywall. The annual utilization increases by a small percentage when the PCM is moved toward the interior; however, the PCM utilization increases dramatically as the PCM is moved closer to the exterior. In fact, the tunable PCM is nearly 100% utilized when it is located near the exterior.

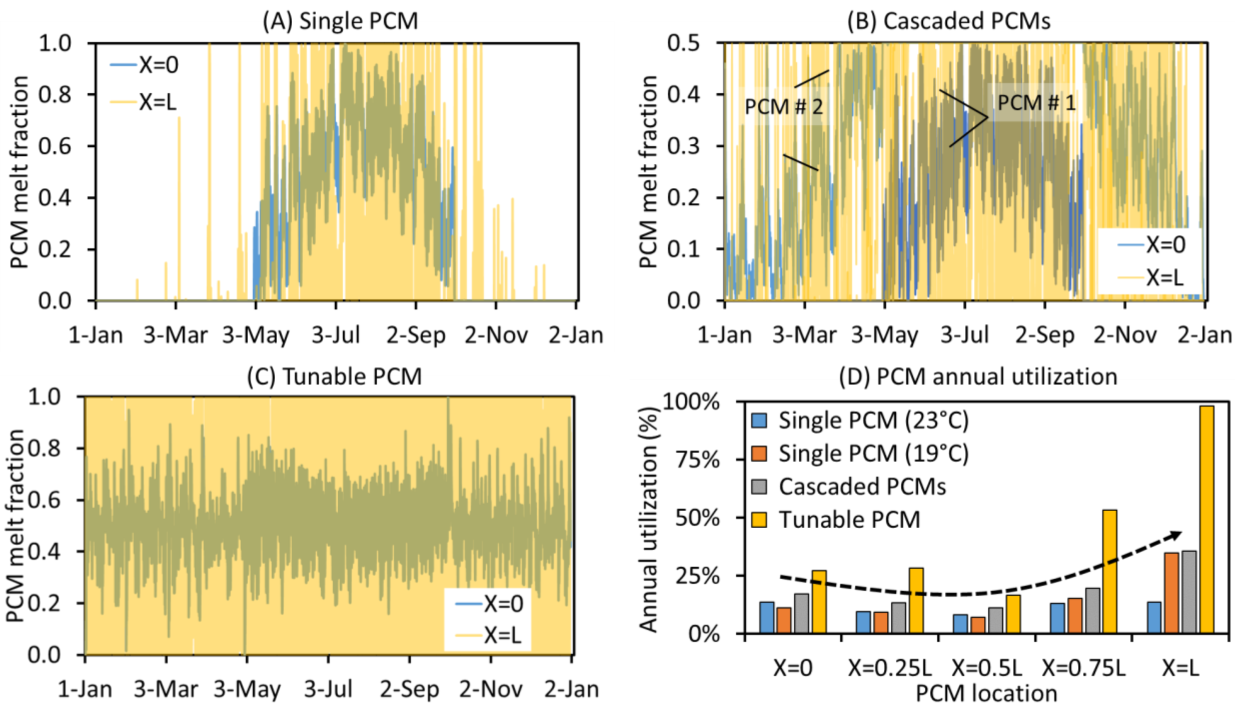

Figure 11. Effect of PCM location on its melt fraction: (A) traditional single-layer PCM, (B) two cascaded PCMs, and (C) tunable PCM; (D) annual utilization of different PCMs at various PCM locations in the wall. X is the distance of PCM from the drywall, and L is the total width of the wall cavity.

While PCM utilization is at its maximum when it is located close to the exterior, this does not mean that this configuration is most effective. As shown in Figure 12(A) and (B), in both cooling and heating seasons, the load shifting capacity of the PCM greatly lowers as its distance from the interior increases. This happens because of the increase in thermal resistance between the PCM and the interior, leading to a reduced effect of preheating/precooling on the PCMs. Figure 12(C) and (D) show the effect of the PCM location on the total heat gain/loss. During cooling season, the energy penalty is negative when the PCM is located near the center of the wall. In other words, this configuration results in energy savings by reducing the total heat gain. During heating, the energy penalty remains positive. This observation is consistent with previous research that demonstrated that, when saving energy is the goal, the optimal PCM location is near the center of the cavity [26, 27, 38, 39].

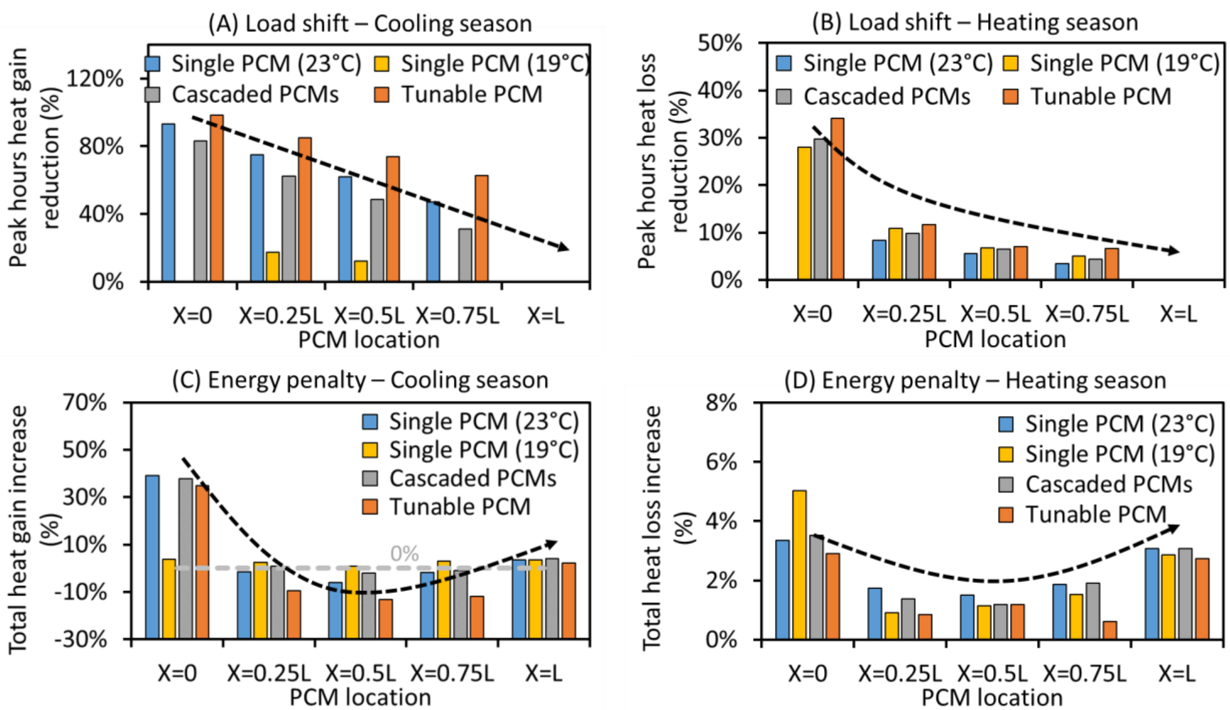

Figure 12. Effect of PCM location on peak load shifting capacity of different PCMs in (A) cooling and (B) heating seasons; effect of PCM location on energy penalty for load shifting by different PCMs in (C) cooling and (D) heating seasons.

4. Practical considerations and limitations

The results presented in the previous sections clearly highlight the limitations of single-layer PCMs in terms of annual utilization and load shifting capacity. The tunable and cascaded PCMs provide the possibility of enhancing PCM utilization during the entire year, and thus increase its load shifting capacity to both heating and cooling seasons. However, there are several practical aspects, which have not been considered in this study, but they must be considered before making the changes in a building and integrating PCMs in the walls.

- **Additional investment/material cost**: While PCMs provide benefits, their integration in a building requires additional investments, including material cost. Because tunable PCMs are not yet available, their cost and operational requirements are unknown. Cascaded PCMs appear to be a temporary solution; however, because only half of the PCMs are active at a time, they can never be utilized to their full capacity. Additionally, with increases in renewable energy penetration in total energy mix, energy storage needs are becoming more frequent, leading to changes in conventional peak and off-peak periods. It is possible that in the future when renewable energy contributions are large, a cascaded design would require more than two PCM layers to account for load flexibility at different time scales.

- **Loss of insulation**: When the total wall thickness is limited, PCM integration may require a reduction in the wall insulation. We noted that there is a PCM thickness limit, up to which its benefit overweighs the heat losses due to reductions in thermal resistance. This needs to be calculated and tested, including the expected changes in the future TES needs.

- **Energy penalty:** We noted that the load shift is not free as it typically results in an increase in total heat gain/loss through the walls. The higher the load shift requirement, the higher the total energy penalty. Reductions in wall insulation because of PCMs and energy storage related losses during charging and discharging of PCMs are the reason. Thus, a thorough cost-analysis is required.

- **Effect of climatic conditions and occupants' thermal comfort:** The selection of PCMs depends greatly on indoor and outdoor conditions. The effects of PCMs can dramatically change based on the interior temperature as well as preheating and precooling magnitude and duration, which are also related to the thermal comfort of the occupants. Likewise, the effect of climate can change the PCM selection, especially its transition temperature and latent heat requirements. We selected Baltimore for this study because of its mixed requirement for heating and cooling loads. However, some climates can be highly dominated by cooling or heating, making cascaded or tunable PCMs less necessary.

5. Conclusions

PCMs have been extensively studied in the past for their energy savings and load shifting benefits in buildings. PCMs, however, are effective only when they undergo phase change. Because PCMs typically have a fixed narrow transition temperature, their benefits are restricted to a particular season of the year. In this study, we examined three different kinds/configurations of PCMs—traditional single-layer PCM, cascaded two-layer PCMs, and a tunable PCM—for their application in a lightweight building wall and compared their annual utilization and effectiveness in managing the thermal loads in buildings.

Our key observations are:

- Traditional PCMs are utilized only during a part of the year when temperature changes lie within the transition range. Cascaded and tunable PCMs are active throughout the year, providing benefits in both heating as well as cooling seasons.
- We observed no direct correlation between utilization and effectiveness of the PCMs. A PCM can be less utilized but still more effective than another PCM that is more utilized. For energy saving benefits, effectiveness of the PCMs is a more important parameter to consider; however, the cost of the technology is expected to be high when utilization is less. Therefore, for practical deployment, both the parameters are equally important.
- Increases in latent heat and PCM thickness cause a decrease in annual utilization of the PCMs due to increases in their total heat capacity. However, PCM effectiveness and load shifting capacity improve with increases in latent heat. A tunable PCM with latent heat more than 100 kJ/kg can provide up to 99% peak load reduction in cooling season and 37% peak load reduction in heating season.
- Increases in PCM thickness beyond a certain amount are not always advantageous because of reductions in insulation. Loss in total thermal resistance of the wall exceeds the TES benefits of the PCM when its thickness is more than 0.5 in. (1.3 cm).
- Increases in the transition temperature range of the traditional PCMs lead to lower daily utilization but higher year-wise utilization because of increases in operating temperature band. Therefore, there exists an optimal transition temperature range (~4°C), where traditional and cascaded PCMs provide the highest utilization and effectiveness. Tunable PCMs, however, work best when the transition temperature range is small.
- The location of the PCM in the wall is important. When the PCM is located near the interior, it is moderately utilized but most effective in managing peak loads. PCM location near the center of the wall provides the highest reduction in total heat gain/loss. PCM

placement near the exterior sheathing leads to the highest utilization but lowest effectiveness.

- A limitation of the study is that the shoulder seasons were not specifically considered. However, since the thermal load in the buildings during shoulder seasons is typically small, this limitation is expected to have a small impact on the observations of the study.

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