Improving building energy performance with phase change materials: a case study in Alberta for energy-savings

Jie Ren, Lexuan Zhong

Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

Abstract

Phase Change Materials (PCMs) show great promise for use in building envelopes to mitigate indoor temperature fluctuations and reduce energy demands through their Thermal Energy Storage (TES) properties. A crucial aspect of utilizing PCMs is quantifying their energy savings based on the climate regions and buildings, especially when considering year-based benchmarks and typical day energy-saving features. This research aims to provide PCM application analysis in a residential building in Alberta using typical micro-encapsulated PCM integrated walls. The goal is to estimate potential energy savings, analyze the load features, and provide PCM selection guides. In a focused case study, the performances of various hypothetical PCMs were evaluated by year-round building load simulation using EnergyPlus software. Key PCM application settings, encompassing 9 kinds of melting temperature (enthalpy curve) and 2 kinds of installation position (interior and exterior), are evaluated. Additional factors, such as building operation schedules and indoor temperature settings, are also considered to provide a more realistic analysis of PCM performance. The result shows that the interior installation position is better, and the best melting temperature is 21℃ for winter and 24℃ for summer. For heating-dominated climate regions, the performance of adding PCM may not be as good as adding insulation directly. This work offers valuable references for PCM selections and understanding its work mechanisms in cold climate regions based on the energy-saving feature analysis.

Keywords

Phase Change Material (PCM), Building Loads with PCM, Energy-saving Features, Cold Climate

Introduction

Phase Change Materials (PCMs) show promising potential for application in energy efficiency and sustainable building design (Baylis & Cruickshank, 2023). Taking advantage of the thermal energy storage property, PCMs can be well incorporated into building wallboards to reduce building loads in both heating and cooling (Saffari, Roe, & Finn, 2022). The working mechanism of PCMs is the absorption and release of latent heat in the phase transitions at a specific temperature range, typically from solid to liquid and vice versa, thus influencing the heat flux between indoor and outdoor environments. In order to promote the application of PCMs, quantifying their energy savings and understanding more of their working mechanisms under specific situations can be highly useful in both the building design and retrofit stages.

A large number of variables can influence PCMs' building energy performance, such as (1) installation position in the building; (2) phase-change temperature; (3) latent heat and heat conductivity; (4) climate zones of the site; (5) feature of internal gains; (6) encapsulation method and thickness; (7) thermostat of the indoor environment and so on (Soares, Gaspar, Santos, & Costa, 2014). Many works have been done in numerical (Ji, Zou, Chen, Zheng, & Qu, 2019) or experimental (Berardi & Soudian, 2019) to assess the performance of PCMs. The selection of desired PCMs is highly dependent on cases; many works have proven an acceptable performance of PCMs in hot climate regions (Chernousov & Chan, 2016; Ji et al., 2019), while research in cold climate zones is relatively scarce.

This case study aims to evaluate the performance of PCMs in heating and cooling load reductions in Alberta by selecting the best installation position and phase change temperature under two kinds of building operation schedules. Both long-term and short-term energy savings will be investigated. The best combination of parameters will be selected by comparing the long-term performance. In addition, short-term analysis, covering a consecutive 72 hours, will be done in summer, winter, and transit seasons. The PCMs' energy-saving features will be explored by analyzing the heat transfer procedure during selected time durations. Further, EnergyPlus software (v23.1, USDOE) is used to simulate the ideal building loads, and the phase change property is realized by defining the enthalpy curve of several hypothetical PCMs.

Methods

Work description

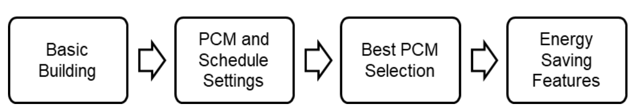

Figure 1 Workflow description

The current case study workflow comprises four primary steps, as shown in Figure 1. Firstly, it involves the foundation of the reference building model, encompassing tasks such as establishing building geometry, configuring basic envelope settings, and accounting for internal gains from people, lighting, and equipment. The results of basic cases will serve as benchmarks for further evaluation. Subsequently, attention shifts to schedule settings and PCM settings respectively. On the one hand, both normal and night schedules are defined, standing for two typical operation modes of residential buildings. The thermostat will be different when the building is unoccupied under the night schedule type. On the other hand, various PCM options, including 9 kinds of enthalpy curves and 2 kinds of installation positions, are defined under both schedules. The third step is selecting the most suitable PCM based on simulation results of building loads, further optimizing PCM choices for both normal and night schedules. Lastly, the work addresses long-term and short-term energy-saving features by examining yearly, daily, and hourly load profiles with detailed analyses.

EnergyPlus simulation

EnergyPlus v23.1 is used for the evaluation of PCMs by building load simulation. The phase change feature is realized by the CondFD (Conduction Finite Difference) model proposed by Pederson, which has been incorporated into the software (Pedersen, 2007). This model employs an implicit finite difference scheme integrated with an enthalpy-temperature curve to precisely capture phase-change energy phenomena. Several wallboard internal nodes are established for the one-dimensional discretization procedure to calculate the temperature distribution between indoors and outdoors. Since it is an unsteady state simulation, the time steps are required. Based on some guidelines (Tabares-Velasco, 2012) for the use of the EnergyPlus PCM model, time steps equal to or less than three minutes are recommended. In the current work, the CondFD model with 30 time-steps per hour (2 minutes) is used for the heating and cooling energy demands analysis.

Additional considerations are needed for PCM materials in the simulation, when simulating some hysteresis PCMs (Zastawna-Rumin, Kisilewicz, & Berardi, 2020), also known as the 'subcooling' feature, refers to PCMs with lower solidifying temperature points than their melting points; accuracy issues cannot be ignored. Hence, in this work, the hysteresis in PCMs is not considered. Another issue is the encapsulation method of PCMs, as the heat transfer caused by convection is not considered in this pure heat conduction model, it is not accurate enough to simulate PCMs with air gaps, which are macro-encapsulated PCMs that it common to see in the market. Some researchers simulated this kind of material without enough consideration of its thermal resistance caused by air gaps (Muruganantham, 2010), while some works calculated the equal total thermal resistance ('R' value) of air and PCMs (Wijesuriya & Tabares-Velasco, 2021), which can be a reasonable correction on this model. In the current work, we assume an isotropic feature on the PCMs layer and only consider micro-encapsulated PCMs to improve the simulation accuracy, which is more compatible with the 1-D CondFD heat transfer model in EnergyPlus.

For the demand calculation method, the ideal HVAC system model 'idealLoadAirSystem' in EnergyPlus is used to calculate the building loads. That means no specific kind of heating or cooling equipment is defined, which makes the results more general for reference.

Reference building and Case settings

The case study is done under the weather of Edmonton in Canada, which belongs to climate zone 7 based on ASHRAE's standard. In this cold climate, the main load for buildings is heating rather than cooling. That is to test the functions of PCMs in cold regions, and also to compare their performance with simply using more insulations.

The reference building is selected as a common residential building as shown in Figure 2. It is a one-story residential building with 127 m^2 (11.58m×10.97m) and 3.05 m of indoor height, and the roof pitch is set to 4:12. The building is perfectly south-oriented with a total of 10 windows (1.83m×1.52m), resulting in the window to wall ratios of around 25% in south and west and 15% in north and east, which is designed to obtain more solar radiations during summer time. No blind is considered in the current building model, and the space is considered as a single big room without internal walls for simplicity. All areas except the attics are considered air-conditioned spaces. Ventilation is not considered in the setting, its influences on the PCM-enhanced building can be found in literature (Tunçbilek, Arıcı, Krajčík, Nižetić, & Karabay, 2020).

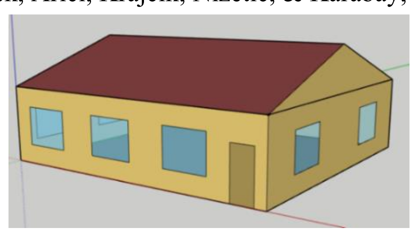

Figure 2 Reference building model facade

For the internal heat gains, a total number of 4 people is considered as the maximum occupancy, with an equal of 1.2 met (126 W/person) constant metabolic rate. The maximum total heat gains from lighting and equipment are defined as 400 W and 1250 W respectively. That equals a power density of around 3.2 W/m^2 and 9.9 W/m^2.

Internal heat gains, thermostat, and schedule settings

Figure 3 shows the internal gains (people, lighting & equipment) intensity schedule considered in the model. 2 types of schedules, namely (a) normal schedule and (b) night schedule are defined. The 2 types of schedules have the same distribution during nighttime, from 6:00 p.m. to 09:00 a.m. the next day. During this time duration, the building is fully occupied with four people in the room, and the light and equipment are turned lower after midnight. The time before midnight comes with the highest internal heat gains. The main difference lies in the daytime duration. In the normal schedule, the room is still occupied with a relatively lower people density, and the use intensity of equipment and lighting are also maintained at a relatively high level. In the night schedule, the building is set to be unoccupied during the daytime, thus resulting in relatively lower lighting and equipment usage intensity. These two schedules can be very typical and common to see in residential buildings, some buildings with people away for work during the daytime can fall into the night schedule, while some households have elders or kids or have people working from home can fall into the normal schedule.

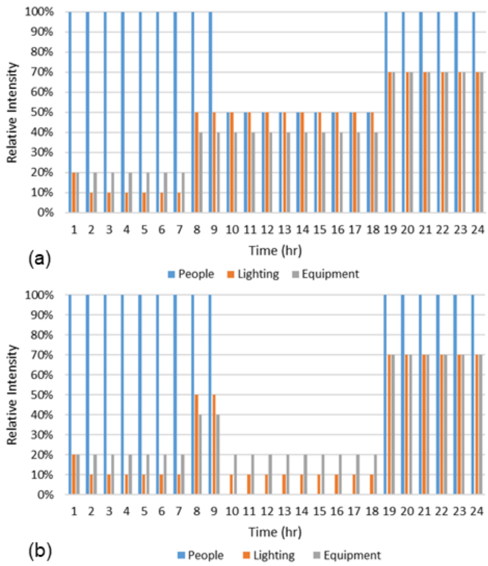

Figure 3 Internal gains (people, lighting & equipment) intensity settings. (a) normal schedule; (b) night schedule

Additionally, not only does the internal gains intensity change as the occupancy status changes but so does the thermostat. Table 1 shows the thermostat settings under normal type and night type schedules. In the normal type schedule, the room is maintained between 20℃ to 25℃ for 24h for the whole year. The set for different design temperatures is because the clothes worn during different seasons can be different, thus the comfortable temperature can be a range considering all-year-around. For the night type schedule, during the unoccupied daytime, the temperature setpoint is changed to 15℃ for heating and is closed for cooling based on the climate feature of Alberta. That is to balance the energy cost and thermal comfort. For extremely cold weather, we need to ensure the room can be recovered to 20℃ quickly when people come back home. As for the cooling, there is no extremely hot condition in Edmonton, thus the cooling is closed during the unoccupied time slot.

Table 1 Schedule and Thermostat settings

Schedule	Mode	Setpoint	Time
Normal Type	Cooling	25℃	24h
	Heating	20℃	24h
Night Type	Cooling	closed	Unoccupied 09:00-18:00
	Heating	15℃	
	Cooling	25℃	Occupied Other time
	Heating	20℃	

The changes in internal heat gains and thermostat settings are combined in the normal type and night type schedule. The energy demands will be different under these two basic cases and the PCM-enhanced cases, which are simulated and analyzed respectively.

Envelope and PCM material settings

Table 2 shows the material properties used in the basic wall. Other envelope settings (roofs and windows) satisfy ASHRAE 189.1-2009 climate zone 7 and are maintained the same in all the simulation cases. Only the exterior wall is considered to be PCMs-enhanced (the attic part is not included). The given ‘U’ values and ‘R’ values show the thermal performance of the basic wallboards. The insulation layer has the most thermal resistance and thus has the most temperature drops when considering the wall's heat transfer performance. The ‘R’ value portion of the insulation layer over the whole basic wall is 91.2%, further simplifying the PCM position settings in the wall construction. We will only consider the relative position of the insulation layer and the PCMs layer to evaluate the influence of the PCMs layer’s position. Figure 4 gives the construction of the basic wall used in the simulation, and the additional PCM layer is added in two different positions, one is in the interior of the insulation layers, making the PCM closer to the indoor environment, and the other is the exterior position, making the PCM closer to the outdoor environment.

Table 2 Wall material properties used in the basic wall and additional PCM layer

Material	Thickness	Conductivity	Density	Specific heat	"U" value	"R" value	"R" value portion
	m	W/m·K	kg/m^3	J/kg·K	W/m^2·K	m^2·K/W	
Stucco	0.0253	0.692	1858	837	27.35	0.04	1.3%
Concrete HW	0.2033	1.73	2243	837	8.51	0.12	4.2%
Insulation	0.1104	0.043	91	837	0.39	2.57	91.2%
Gypsum	0.0127	0.16	785	830	12.60	0.08	2.8%
				Total	**0.36**	**2.80**	**100%**
Added PCM layer	0.04	0.18	855	2500	4.50	0.22	7.9%

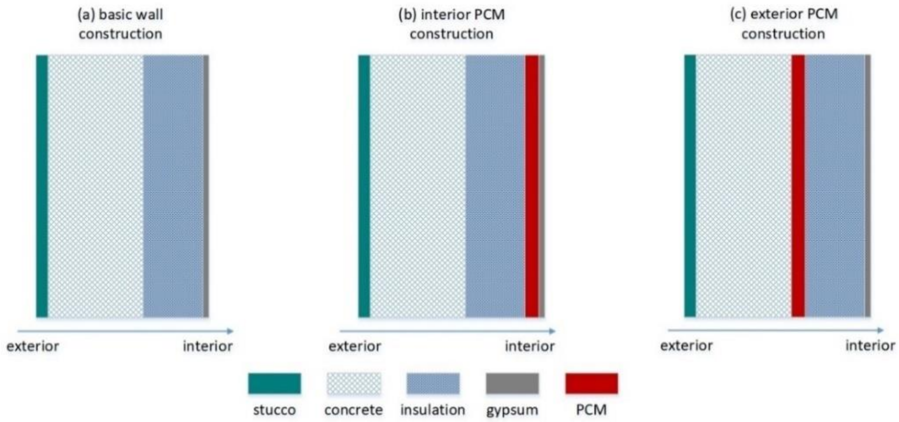

Figure 4 Basic wall and PCM position construction settings, (a) basic wall construction used in the benchmark cases; (b) interior PCM position construction; (c) exterior PCM position construction.

The position of the PCM plays an important role in the heat transfer procedure, especially when there is an insulation layer that blocks the most heat flux. The temperature gradient will change as the position changes, so we set the PCM position inside or outside the insulation layer.

The added PCM layers property is also given in Table 2. As mentioned before, micro-encapsulated PCM is preferred in the current simulation. The DuPont™ Energain® micro-encapsulated PCM product from reference experiment test (Cao et al., 2010) is selected as the prototype of the current PCM layer. This material comes with a nonlinear enthalpy-temperature relationship, and its melting temperature range is around 6℃, centered at 21.7℃; the total latent heat is 70 kJ/kg, and its density is 855kg/m^3, with a specific heat of 2.5 kJ/kg·K. The tested thermal conductivity is changed between 0.14 to 0.18 W/m·K. Based on this micro-encapsulated PCM product, we made some simplifications in the simulation. The nonlinear enthalpy-temperature relationship is represented by 4 points; constant gradient is applied before, during, and after the phase change, respectively.

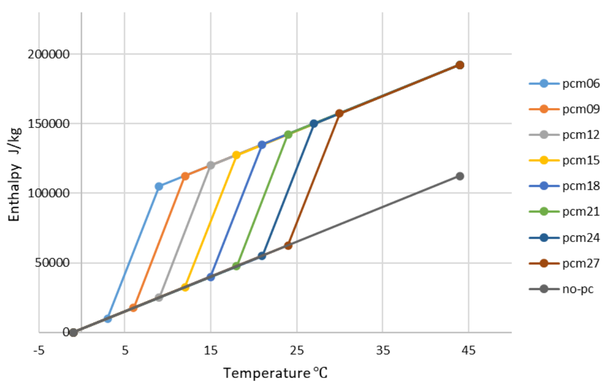

Figure 5 Temperature-Enthalpy curve of 9 hypothetical PCMs (pcm06 to pcm27, no-pc (no phase change) 'solid'

According to the work (Tabares-Velasco, 2012), the energy-saving results are not very sensitive to the linearization procedure. A total number of 9 kinds of enthalpy-temperature curves is presented in Figure 5, they are all hypothetical PCMs. 8 kinds of PCMs from them are materials with phase change features, with their melting temperature centered at 6, 9, 12, 15, 18, 21, 24, and 27℃ respectively. These assumptions of different melting temperatures are reasonable as PCMs can be produced for almost all temperatures between -10℃ to 90℃ (Rubitherm®Technologies, 2024). For comparison, one kind of no-pc (no phase change) 'solid' material is also given in the figure and simulated. In addition, the thermal conductivity is considered a constant value equal to 0.18 W/m·K, and the thickness is 4 cm for all PCMs.

Table 3 Overview of parameter settings for cases

	Schedule & thermostat	**PCM layer position**	**PCM enthalpy curve**
Types	Normal Type & Night Type	Interior & Exterior of insulation	9 (8 typical PCM & 1 'solid' PCM)
Variable Numbers	2	2	9

To sum up, Table 3 shows the described variables in this section: they are 2 kinds of schedules and thermostats, 2 kinds of PCM layer positions, and 9 kinds of enthalpy curves. The total number of cases is 38 (36 plus 2 basic benchmark cases).

Energy-saving definition

In the current work, we are mainly concerned with the energy savings for comparing and selecting PCMs. The energy-saving rate is defined in this work:

$$X, Savings = \left(1 - \frac{E_{X,PCM}}{E_{X,Basic}}\right) \times 100\% \qquad (1)$$

Where X can be H, C, or T, which stands for Heating, Cooling, or Total in the results, respectively. The energy demand results with PCMs are presented as $E_{X,\,PCM}$, and the corresponding benchmark results without the use of PCM are presented as $E_{X,\,Basic}$.

Results & Discussion

Year-round performance

In this part, the annual assessment results for all the cases are presented. Figure 6 shows the energy-saving percentage of all the cases under two types of schedules for heating and cooling. Table 4 gives the details of the results of load calculation and energy savings.

For the heating energy savings, pcm21 shows the best results of 4.7% and 3.8% under normal and night schedules with interior installation respectively. Interior PCM proved to be more effective than exterior PCM in achieving heating energy savings. The addition of a single 'solid' PCM yielded the most significant improvements in energy conservation with 3.6% and 2.9% respectively for the two schedules. In other words, the extra 'phase change' function under the best selection of pcm21 only improves around 1% annual energy savings in the current case. While for the exterior PCM position, almost no fluctuations in the result are found in the heating energy-savings, all the cases with exterior position show very close performances, which means that they work similarly to the 'solid' case, the PCMs basically don't work in these cases. The reason can be the insulation layer isolated the most portion of the heat release from indoors, making it difficult for the PCMs to modulate the room temperature. This also indicates that under the climate in Alberta, to make use of the PCM in building energy efficiency, the heat to activate the PCMs comes from indoors, and a melting temperature close to the room temperature can be better in reducing the fluctuation and achieving savings.

For the cooling performance, pcm24 shows the best results of 22.1% and 28.1% for normal and night schedules respectively, still with the interior installation position. Once again, interior PCM outperformed exterior PCM configurations. Similarly, the inclusion of a single solid PCM resulted in the most substantial enhancements in energy efficiency. The 'no-pc' case shows 12.5% and 11.8% savings in cooling. Both cases show greater improvements than in the heating mode. The best case reaches close to 30 percent energy savings, which is a great value for energy savings. A notable deviation from the heating results is observed in the impact of scheduling. Specifically, under the 'night' schedule, there were more significant relative energy savings in cooling compared to the 'normal' schedule. This can be the result of changing the thermostat during the unoccupied time duration, giving more chances for PCM to absorb heat for storage and release it during the night. This facilitates the reduction of cooling energy needed during the daytime, and promisingly, if the temperature fluctuation is relatively high (with lower night temperature), extra savings can happen in the form of heating load reduction.

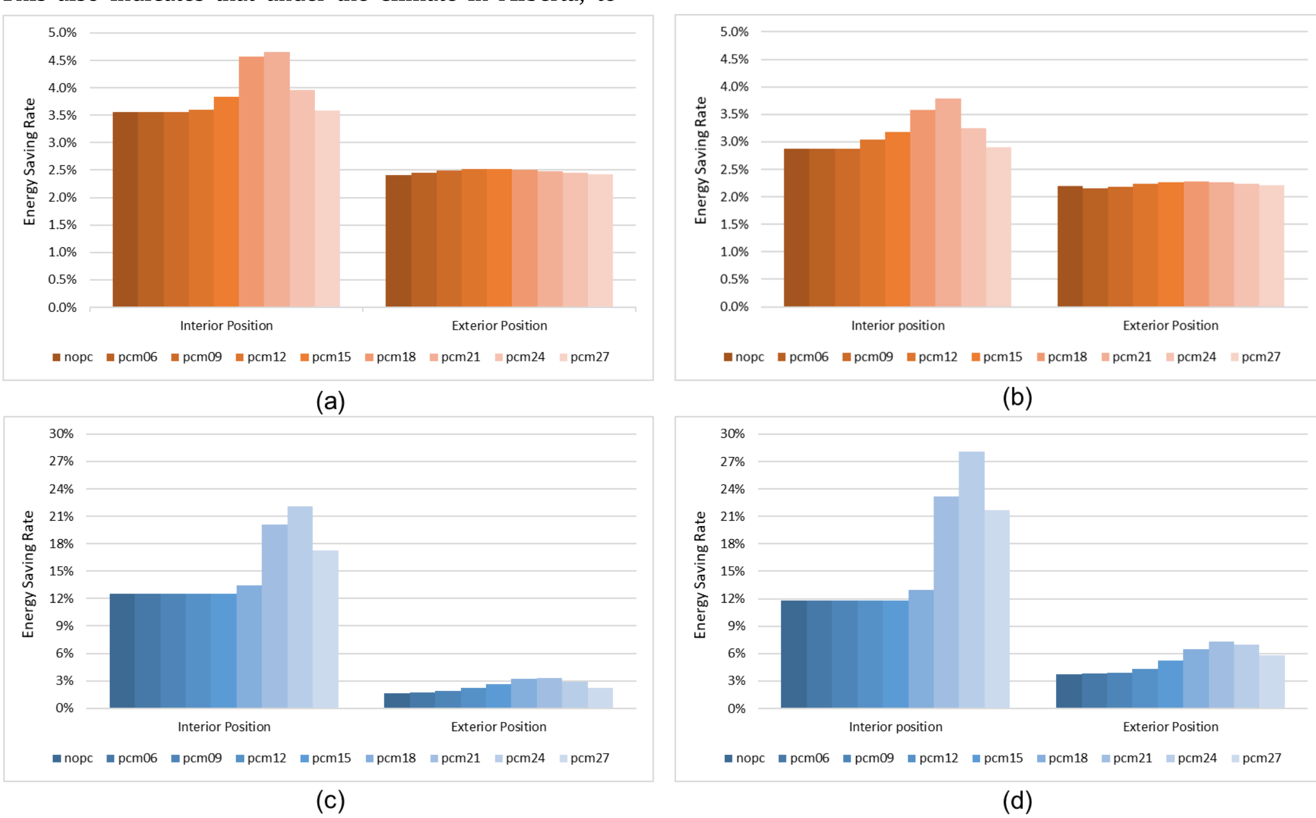

Figure 6 Energy saving rate of (a) heating of normal schedule; (b) heating of night schedule; (c) cooling of normal schedule; (d) cooling of night schedule

Table 4 Results of loads calculation and energy savings

Sche-dule	PCM Layer Position	Usage/Cases	basic wall	no-pc	pcm06	pcm09	pcm12	pcm15	pcm18	pcm21	pcm24	pcm27
Nor-mal	Interior	Heating kWh	8478	8176	8176	8176	8173	8153	8091	8083	8142	8174
		H, Saving %	/	3.6	3.6	3.6	3.6	3.8	4.6	4.7	4.0	3.6
		Cooling kWh	1204	1054	1054	1054	1054	1054	1042	963	939	997
		C, Saving %	/	12.5	12.5	12.5	12.5	12.5	13.5	20.1	22.1	17.3
		Total kWh	9683	9230	9230	9230	9227	9207	9133	9046	9081	9171
		T, Saving %	/	4.7	4.7	4.7	4.7	4.9	5.7	6.6	6.2	5.3
	Exterior	Heating kWh	8478	8273	8270	8267	8264	8265	8266	8268	8271	8273
		H, Saving %	/	2.4	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.4
		Cooling kWh	1204	1184	1184	1182	1178	1172	1166	1164	1169	1178
		C, Saving %	/	1.7	1.7	1.9	2.2	2.7	3.2	3.3	2.9	2.2
		Total kWh	9683	9458	9454	9449	9442	9437	9432	9432	9440	9450
		T, Saving %	/	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.5	2.4
Night	Interior	Heating kWh	8045	7814	7814	7814	7800	7789	7757	7741	7783	7811
		H, Saving %	/	2.9	2.9	2.9	3.0	3.2	3.6	3.8	3.3	2.9
		Cooling kWh	558	492	492	492	492	492	485	429	401	437
		C, Saving %	/	11.8	11.8	11.8	11.8	11.8	13.0	23.2	28.1	21.7
		Total kWh	8603	8306	8306	8306	8292	8281	8242	8169	8185	8248
		T, Saving %	/	3.5	3.5	3.5	3.6	3.7	4.2	5.0	4.9	4.1
	Exterior	Heating kWh	8045	7868	7872	7869	7865	7862	7862	7862	7865	7867
		H, Saving %	/	2.2	2.2	2.2	2.2	2.3	2.3	2.3	2.2	2.2
		Cooling kWh	558	537	537	536	534	529	522	517	519	525
		C, Saving %	/	3.8	3.8	3.9	4.3	5.2	6.5	7.3	7.0	5.8
		Total kWh	8603	8405	8408	8405	8399	8391	8383	8379	8384	8392
		T, Saving %	/	2.3	2.3	2.3	2.4	2.5	2.5	2.6	2.5	2.4

Daily saving features

Based on the long-term analysis, the best position of PCM is interior, and the optimal PCM selection for heating is pcm21, while pcm24 proves most effective for cooling across both scheduling types. To investigate its performance further, the daily energy savings amount is given in Figure 7 for both schedules. Both load reduction results are calculated from their best performance cases.

Results pcm21 for heating and pcm24 for cooling exhibited similar daily load reduction profiles in both scheduling types, albeit with varying energy savings. The cooling load in the benchmark case under the night schedule is almost half the normal schedule, corresponding with the cooling load reduction in the daily results. The heating load reduction shows nearly the same results. This finding underscores a strong correlation between outdoor temperature and energy conservation.

For the heating results, the relatively large saving value happens during the transit season, while during the winter, the absolute heating load is vast, but the savings are minimal. This indicates the importance of the phase change cycle of PCMs in applications. Case pcm21 is favored as the optimal choice for winter conditions due to its exceptional performance during transitional seasons. Specifically, it can release daytime-absorbed-heat effectively when outdoor temperature drops, particularly at night. For the cooling results, the energy saving happens when PCM absorbs the heat during the daytime, on the premise that its release is not converted into the cooling load, which depends on the outdoor temperature at night.

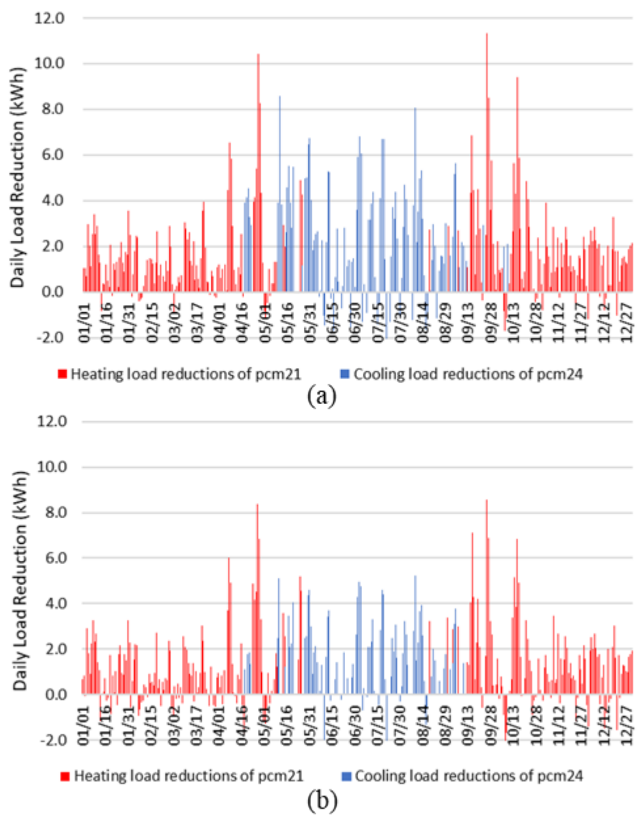

Figure 7 Daily load reduction in kWh of (a) normal schedule; (b) night schedule with best PCM selection

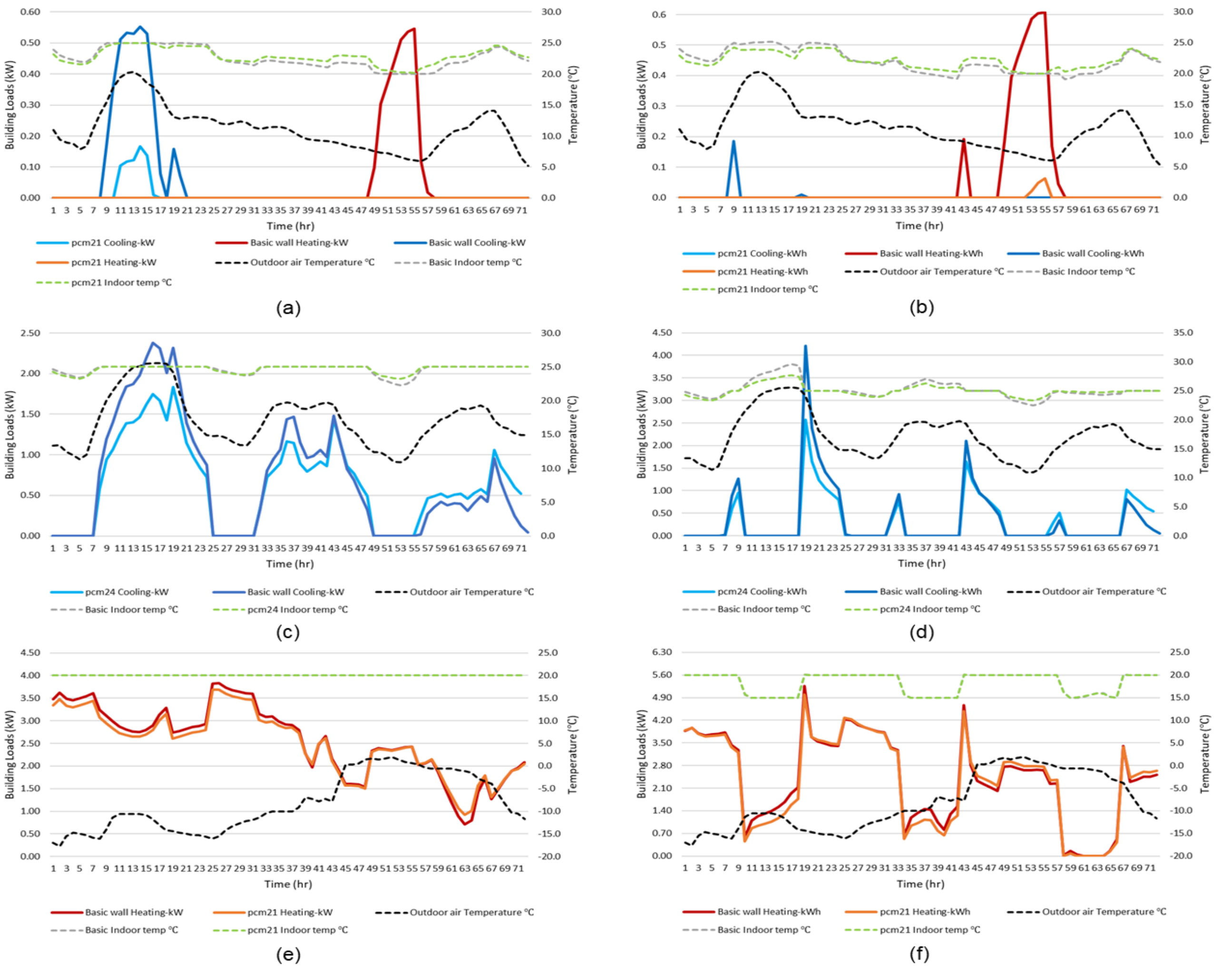

Figure 8 Building loads and temperature features of 72hrs in typical seasons. (a)&(b) heating and cooling load profile for the transition season (0512-0514) of the normal schedule and night schedule, respectively; (c)&(d) cooling load profile for the summer season (0719-0721) of the normal schedule and night schedule, respectively; (e)&(f) heating load profile for the winter season (1219-1221) of the normal schedule and night schedule, respectively.

Hourly saving feature analysis of typical periods

Figure 8 shows the results of building loads and temperature of a typical 3-day analysis for transit, summer, and winter seasons under both schedules.

For the transit season shown in Figure 8 (a)&(b), pcm21 demonstrates the most optimal performance year-round, making it the preferred choice for transition season load analysis. During this period, a notable reduction in peak cooling load by 75% and a complete elimination of heating load are observed on the normal schedule. The charging (melt) and release (solidification) of pcm21 form a robust cycle during the transition season. Initially, internal heat gains are efficiently stored in the PCM, reducing the cooling load. Subsequently, this stored heat is released when the outdoor air temperature drops, effectively reducing the heating load. This combination exemplifies best practices in PCM applications and has the largest energy savings ratios.

For the summer season, shown in Figure 8 (c)&(d), pcm24 is chosen for summer season load analysis. On a typical day, there is a reduction in peak cooling load ranging from 25% to 40%. It's worth noting that PCM solidification heat can sometimes contribute to an additional cooling load, particularly when the outdoor air temperature remains above 15°C at night (between 67 to 72 hours). Interestingly, the energy required for PCM melting primarily originates from internal gains rather than outside air, even during summer. These observations are based on the current case study conducted in Edmonton, and it is also found that in some hot regions, the melting heat for PCM can mainly come from exterior heat gains like sunlight or outdoor air (Ji et al., 2019).

For the winter season, shown in Figure 8 (e)&(f), pcm21 is designated for winter season load analysis. The load reduction performance is primarily due to its role in thermal resistance rather than exhibiting phase change functionality. It should also be noted that under the night schedule, when the thermostat changes at 9 a.m., a fraction of heat is released, thus reducing the heating load. Still, extra heating is needed to recharge the PCMs when increasing the room temperature again at 6 p.m. These two energies cancel out each other and thus result in trivial total savings.

Conclusion

In the current work, we executed a case study in Alberta to investigate the performance of PCMs in building energy savings in cold climate regions. The main findings can be categorized as below:

1. Installing PCM in the interior layer of insulation yields superior performance than the exterior in Alberta.
2. Case pcm21 is optimal for winter, while pcm24 is ideal for summer. But we need to point out that the optimal selection may change as the indoor thermostat and outdoor climate change.
3. Night schedules demonstrate higher energy-saving cooling rates than normal schedules.
4. PCM proves effective during transition seasons, particularly on days with significant temperature fluctuations.
5. Increasing insulation proves to be more economical in saving heating energy than using PCM in cold climate cities like Edmonton.
6. The melting energy primarily originates from internal heat gains rather than the outside air in cold regions.
7. Outdoor temperatures and internal gains can have a vital influence on the energy-saving performance.

There are some limitations in the current work, like the case settings in the reference building and PCMs, and the lack of optimization algorithms, as currently, we are using the grid search method to find the optimal case. We would like to improve it in our future works, including the expansion of the case study across various climate zones, and the application of single- or multi-objective optimization algorithms for the parametric design and selection of PCMs.

Acknowledgement

This research was supported by funding from the Canada First Research Excellence Fund as part of the University of Alberta's Future Energy Systems research initiative (CFREF-2015-00001).

References

Baylis, C., & Cruickshank, C. A. (2023). Review of bio-based phase change materials as passive thermal storage in buildings. *Renewable and Sustainable Energy Reviews, 186*, 113690.

Berardi, U., & Soudian, S. (2019). Experimental investigation of latent heat thermal energy storage using PCMs with different melting temperatures for building retrofit. *Energy and buildings, 185*, 180-195.

Cao, S., Gustavsen, A., Uvsløkk, S., Jelle, B. P., Gilbert, J., & Maunuksela, J. (2010). *The effect of wall-integrated phase change material panels on the indoor air and wall temperature-Hot box experiments.* Paper presented at the Renewable Energy Conference.

Chernousov, A. A., & Chan, B. Y. (2016). Numerical simulation of thermal mass enhanced envelopes for office buildings in subtropical climate zones. *Energy and buildings, 118*, 214-225.

Ji, R., Zou, Z., Chen, M., Zheng, Y., & Qu, S. (2019). Numerical assessing energy performance for building envelopes with phase change material. *International Journal of Energy Research, 43*(12), 6222-6232.

Muruganantham, K. (2010). *Application of phase change material in buildings: field data vs. EnergyPlus simulation*: Arizona State University.

Pedersen, C. O. (2007). Advanced zone simulation in EnergyPlus: incorporation of variable properties and phase change material (PCM) capability.

Rubitherm®Technologies. (2024). PCM RT-LINE. Retrieved from https://www.rubitherm.eu/en/productcategory/organische-pcm-rt

Saffari, M., Roe, C., & Finn, D. P. (2022). Improving the building energy flexibility using PCM-enhanced envelopes. *Applied Thermal Engineering, 217*, 119092.

Soares, N., Gaspar, A., Santos, P., & Costa, J. (2014). Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. *Energy and buildings, 70*, 411-421.

Tabares-Velasco, P. C. (2012). *Energy impacts of nonlinear behavior of PCM when applied into building envelope* (Vol. 44816): American Society of Mechanical Engineers.

Tunçbilek, E., Arıcı, M., Krajčík, M., Nižetić, S., & Karabay, H. (2020). Thermal performance based optimization of an office wall containing PCM under intermittent cooling operation. *Applied Thermal Engineering, 179*, 115750.

Wijesuriya, S., & Tabares-Velasco, P. C. (2021). Empirical validation and comparison of methodologies to simulate micro and macro-encapsulated PCMs in the building envelope. *Applied Thermal Engineering, 188*, 116646.

Zastawna-Rumin, A., Kisilewicz, T., & Berardi, U. (2020). Novel simulation algorithm for modeling the hysteresis of phase change materials. *Energies, 13*(5), 1200.