Application of phase change materials in the solar energy greenhouse exposed to cold climate

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Abstract

Climate change continues to accelerate, causing food insecurity and rising costs. A potential solution may be found in growing food locally in highly productive greenhouses. This study presents the passive application of phase change materials (PCMs) in solar energy greenhouse located in Winnipeg to reduce its energy consumption while maintaining growing indoor conditions. Hysteresis is a crucial energy performance factor for the PCM-enhanced building envelope. Therefore, this study investigates the integration of PCMs within three external walls of the greenhouse using the hysteresis method in EnergyPlus and compares a recently developed hysteresis method against its precursor enthalpy-temperature method. The results show that PCM achieves 17 % to 99.5 % heating and 20 % to 30 % and cooling energy savings. Furthermore, compared to the enthalpy-temperature approach, the hysteresis method results in higher heating and cooling energy savings of approximately 4.11 % and 2.60 %, respectively.

Introduction

Climate change continues to accelerate, causing food insecurity and rising costs. Remote communities in cold climates are already experiencing high prices, low availability, and poor quality of fresh food. Furthermore, the production, processing, distribution, preparation, and preservation of food is energy-intensive and highly dependent on fossil fuel energy sources, thereby contributing to global warming and climate change. Canada has pledged in the Paris Agreement to cut its greenhouse emissions by 30% from 2005 levels by 2030 (NRDC 2016). Agriculture is one of the critical components to meet this goal as it is responsible for about 10 % of GHG emissions in Canada (Environment and Climate Change Canada 2017). A way to reduce net emissions from land use, agriculture, and deforestation is to grow food locally and maximize land use with highly productive, sustainable greenhouses.

Greenhouses have been used to extend growing seasons or to raise exotic, tropical plants in otherwise inhospitable climate zones since antiquity. Today, greenhouses are mainly composed of glass or plastic supported by a frame structure. Conventional greenhouses are typically heated in shoulder and winter seasons by forced-air furnaces or boilers fired by natural gas, propane, or fuel oil. Their energy consumption is often very high due to the envelope's poor insulation and low thermal mass. A new type of greenhouse, a solar energy greenhouse, is thermally insulated and equipped with different strategies and technologies to collect, store and retain solar energy in the daytime and use this energy for heating at night and during the overcast sky.

The most commonly used thermal energy storage technologies in passive solar greenhouses are sensible heat storage systems that rely on temperature change. Sensible storage systems are typically made of solid (e.g., stone, earth, concrete) or liquid (water containers), with a high density and specific heat capacity, known as thermal mass. A more efficient method for storing energy is to use phase change materials (PCMs). These innovative materials change their phase from liquid to solid at a constant temperature to store heat and have the potential to store and release significant quantities of heat per unit of mass through a phase change. Therefore, PCMs can absorb heat in the greenhouse during the daytime as they melt and release this heat back to the greenhouse during the cooler nighttime by returning to their solid phase.

Energy storage studies for heating greenhouses date back to the 1980s. Kern and Aldrich (1979) investigated the use of calcium chloride hexahydrate ($CaCl_2.6H_2O$) with a melting point of 29 °C and managed to recover between 60 % and 80 % of the stored heat. Paris (1981) maintained a minimum air temperature of 8 °C inside the greenhouse under extreme winter conditions and saved about 5000 1 of oil using a eutectic mixture of sodium hydroxide (NaOH) solution and chromium nitride. Boulard et al. (1990) studied the performance of 13.5 tons of organic PCM encapsulated into flat plastic pouches of the 500 m² area of the greenhouse. The PCM-enhanced greenhouse had 60-80 % lower space conditioning requirements than the conventional double-covered greenhouse. Guan et al. (2015) proposed a three-layer wall with phase-change materials to improve the energy performance of the greenhouse. The simulation results showed an increase in heat capacity of the wall, ranging from 12.2 % to14.0 %, along with a reduction in the cumulative heat loss of the PCM north, ranging between 4.5 % and 5.6 %. The study also concluded that the PCM-enhanced north wall could provide between 6.6 % and 21.4 % of the daily heating requirements.

Successful and cost-effective application of PCMs depends on many factors, the most important of which is selecting the appropriate melting/freezing temperatures for the specific use (Kośny et al., 2007). Furthermore, because PCMs are new materials with high costs, their optimal application typically requires customized solutions based on detailed numerical analysis (Zhou et al. 2012, Al-Janabi and Kavgic, 2019). Numerical and mathematical models can expand the experimental results beyond the limitations of an experiment, such as small scale and unrealistic design. However, there is a limited number of modeling tools capable of simulating the phase change phenomena. EnergyPlus is a few whole-building simulation tools capable of modeling the PCM with hysteresis effect since version 8.9. Several studies found that hysteresis is a crucial energy performance factor for the PCM-enhanced building envelopes (Brown et al. 2014, Dutil et al. 2012, Tabares-Velasco et al., 2012).

Moreover, there is a lack of research focused on using PCMs as latent heat storage systems in greenhouses located in cold climates. Thus, the results and recommendations from studies conducted in different environments cannot be directly transferred to greenhouses in Canada, and further research is needed to understand which PCMs would be the most appropriate for our climate.

Therefore, this study provides new knowledge and information needed for implementation and better comprehension of the recently developed hysteresis object in EnergyPlus. It also seeks to extend the existing knowledge and understanding necessary for successfully integrating PCMs into solar energy greenhouse exposed to cold climates. Consequently, the outcomes are likely to be of interest to audiences in both academia and industry. This study aimed to model a realistic integration of the PCM within the walls of a solar energy greenhouse to enable passive heating and cooling.

This paper is organized as follows. The EnergyPlus model section describes the geometry and characteristics of the greenhouse. Then it describes modelling for PCM in EnergyPlus by two different methods: enthalpy-temperature method and hysteresis method. The results and discussion section compares energy consumption and indoor air temperature predictions by the hysteresis approach, enthalpy-temperature approach, and base case (Without PCM). Finally, a conclusion section provides the main findings of this study.

EnergyPlus Model

Because EnergyPlus does not have a user interface to define the geometry, the 3D model of the greenhouse was developed in SketchUp. The geometry was distributed into different thermal zones based on their orientation, glazing area, and the HVAC system. Therefore, the greenhouse model was divided into five thermal zones, with the greenhouse portion being one thermal zone and the other four spaces defined as separate zones. Figure 2 visualizes the 3D model of the greenhouse and the applied zoning approach.

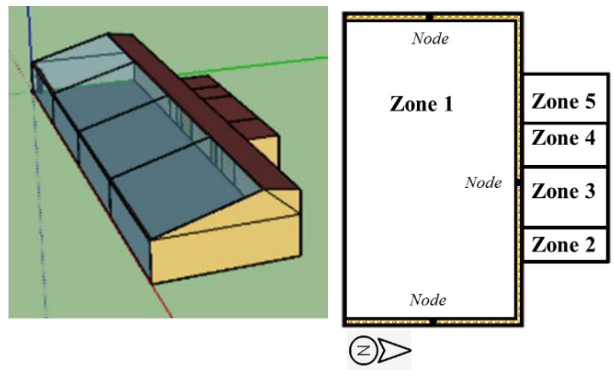

Figure 1 3D model and thermal zoning of the greenhouse

Site planning and proper orientation of the greenhouse are of prime importance to capture a large amount of solar radiation. El-Maghlany et al. (2015) developed a model for calculating the amount of solar energy that the greenhouse surface can obtain through glazing. The research results show that the aspect ratio of length and width of 4:1 achieves the highest solar energy captured per square meter of the greenhouse area. Hence, the length of the simulated greenhouse is 30 m (~100 feet), whereas the width of the greenhouse is 7.5 m (~25 feet). Additionally, the greenhouse is oriented in an east-west direction, so the long and glazed side of the greenhouse faces south for maximizing solar gains in winters (see Figure 1).

In EnergyPlus, envelop construction is defined in multiple layers starting from the outside layer to the inside layer. Each layer is composed of a specific material having specific physical properties. Table 1 provides a summary of the description of the construction of the greenhouse structure.

Table 1 Characteristics of the greenhouse model

Description	**Value**
Greenhouse Parameters	Length = 30.48 m Width = 7.31 m Top Point Height = 3.81 m Aspect ratio = 4.16 Volume (Zone 1) = 681.37 m^3 Space area (Zone 1) = 222.97 m^2 Window Glass Area (Zone 1) = 58.57 m^2
Wall Assembly	F07 25 mm stucco (Outside layer) I05 270 mm batt insulation Vapor seal - plastic film G01a 19 mm gypsum board (inner layer) U value - 0.16 $W/m^2 K$

Roof Assembly	Polycarbonate layer (Outside layer) Air gap Polycarbonate layer (Inner layer) U value - 3.03 $W/m^2 K$
Floor Assembly	150 mm concrete slab U value - 2.25 $W/m^2 K$

HVACTemplate:Thermostat, HVACTemplate:Zone:Unitary, and HVACTemplate:System:Unitary were used to define the HVAC system, where one zone should be considered a control zone for the control of heating and cooling operation in the greenhouse. The production room with the larges square meter area (thermal zone 1) was selected as the control zone. The thermostat was used to define heating and cooling setpoints of 18 °C and 25 °C, respectively. These setpoints are specified to maintain optimal growing conditions (Guan et al., 2015).

Load and energy demand are mainly affected by weather conditions. Winnipeg's winters are long and extremely cold, with average outdoor air temperatures ranging from −5 °C to −20 °C. In contrast, summers are short and warm, with average outdoor air temperatures ranging from 5 °C to 25 °C. Winnipeg also experiences relatively low evening and night temperatures with an average of approximately 15 °C during the three warmest summer months. Consequently, the greenhouse requires heating throughout the year, whereas it needs cooling during the shoulder and summer months. Because of the theoretical nature of this study, a Typical Meteorological Year (TMY) was used in the simulation. Furthermore, the use of TMY provides more reliable predictions over the lifetime of the greenhouse than the weather data of the specific year that could be too cold or too warm than the average.

PCM modeling in EnergyPlus

The growing area, thermal zone 1, is selected for the PCM integration because it has the highest solar heat gains and energy consumption due to its south orientation, the largest glazing area, and the largest floor area. To be fully active, PCM needs to change its phase in 24 hours (Kośny 2015). Therefore, as shown in Figure 1, the nodes are used to measure the surface temperatures of the walls. This approach allowed (1) the selection of adequate PCM types and (2) the estimate of whether the PCM layer undergoes a phase change cycle or not. The analysis of node temperatures showed that the year-round operation of PCM requires the use of two types of PCM with different phase-change temperatures, including PCM19 and PCM23. Furthermore, based on the analysis, PCM19 was integrated into the east wall, whereas PCM23 was incorporated into the north and west walls.

Five different PCM thicknesses, including 0.5 cm, 1 cm, 1.5 cm, 2 cm, and 2.5 cm, are investigated to enable passive cooling and heating through the interaction with the internally conditioned air.

EnergyPlus uses the conduction finite difference (CondFD) solution algorithm to simulate the PCM and materials with different thermal properties by allowing the calculation of internal nodes (U.S. Department of Energy 2018). The user must change the algorithm in the Heat Balance Algorithm class list to CondFD as the EnergyPlus uses the CTF algorithm by default. With the new releases of EnergyPlus (v8.8 and over), PCMs can be modeled using the enthalpy-temperature method and the hysteresis method. For the enthalpy-temperature object, 16 sets of enthalpy-temperature pairs used for the specific heat calculations were defined in EnergyPlus. The main limitation of this approach is that it uses only a single enthalpy-temperature curve, either a melting or freezing curve. As a result, accuracy issues can occur when simulating a PCM with a pronounced hysteresis.

The hysteresis method addresses this limitation by considering the current state and the previous state to determine the specific heat of the PCM. Additionally, the hysteresis method allows users to input PCM's thermophysical data such as thermal conductivity, specific heat capacity, and density in both solid and liquid states. The hysteresis method further requires users to provide the total latent heat during the phase change process. Figure 2 shows the different input parameters for both enthalpy-temperature and hysteresis methods for modeling PCMs.

(a)

Field	Units	Obj1
Temperature 8	C	20
Enthalpy 8	J/kg	53830
Temperature 9	C	21
Enthalpy 9	J/kg	70000
Temperature 10	C	22
Enthalpy 10	J/kg	100950
Temperature 11	C	23
Enthalpy 11	J/kg	177030
Temperature 12	C	24
Enthalpy 12	J/kg	248220
Temperature 13	C	25
Enthalpy 13	J/kg	254450
Temperature 14	C	26
Enthalpy 14	J/kg	259970
Temperature 15	C	27
Enthalpy 15	J/kg	265310

(b)

Field	Units	Obj1
Name		PCM 23
Latent Heat during the Entire Phase Change Process	J/kg	227000
Liquid State Thermal Conductivity	W/m-K	0.15
Liquid State Density	kg/m3	830
Liquid State Specific Heat	J/kg-K	1990
High Temperature Difference of Melting Curve	deltaC	1
Peak Melting Temperature	C	23
Low Temperature Difference of Melting Curve	deltaC	4
Solid State Thermal Conductivity	W/m-K	0.25
Solid State Density	kg/m3	910
Solid State Specific Heat	J/kg-K	1840
High Temperature Difference of Freezing Curve	deltaC	0.5
Peak Freezing Temperature	C	21
Low Temperature Difference of Freezing Curve	deltaC	4

Figure 2 EnergyPlus PCM models: (a) enthalpy-temperature method and (b) hysteresis method

Results and Discussion

The enthalpy temperature and hysteresis methods are analyzed using a 1 cm thick PCM layer to compare against previous studies (Al-janabi and Kavgic 2019). Table 2 summarizes total, heating, and cooling energy consumptions of enthalpy-temperature and hysteresis methods. The result shows that the hysteresis method achieves approximately 3.6 %, 4.11 %, and 2.60 % higher total heating, and cooling energy savings, respectively, compared to the enthalpy temperature.

Table 2 Total, heating, and cooling energy consumptions of the two methods

Energy Consumption (kWh)	Enthalpy-temperature	Hysteresis
Total	61598.61	59349.47
Heating	42833.26	41071.71
Cooling	18765.35	18277.76

Furthermore, a monthly comparison of the two methods presented in Figure 3 indicates that the hysteresis method predictions outperform the enthalpy-temperature method throughout the year. In particular, the hysteresis method achieves more significant heating energy savings during cold winter months, including December, January, and February, compared to the enthalpy-temperature approach. The differences in cooling energy consumption are less pronounced between the two methods, especially during the winter.

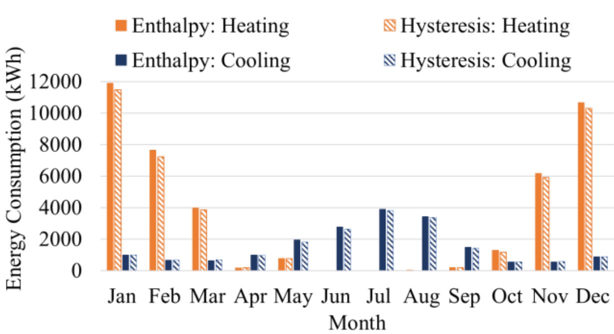

Figure 3 Monthly heating and cooling energy consumptions of the two methods

Figure 4 compares the hourly energy consumptions of the two approaches. Although the zone has demand for cooling during winter months (see Figure 3), its cooling energy consumption is not shown in Figure 4 because it is significantly smaller than the heating energy consumption, and it follows the same profile. The heating energy consumptions have almost identical patterns for both methods during the daytime. The highest discrepancy occurs during evening and night when the hysteresis method achieves higher heating energy savings than the enthalpy-temperature approach. Figure 4 also illustrates that the hysteresis method generates higher cooling energy savings during the daytime than the enthalpy temperature.

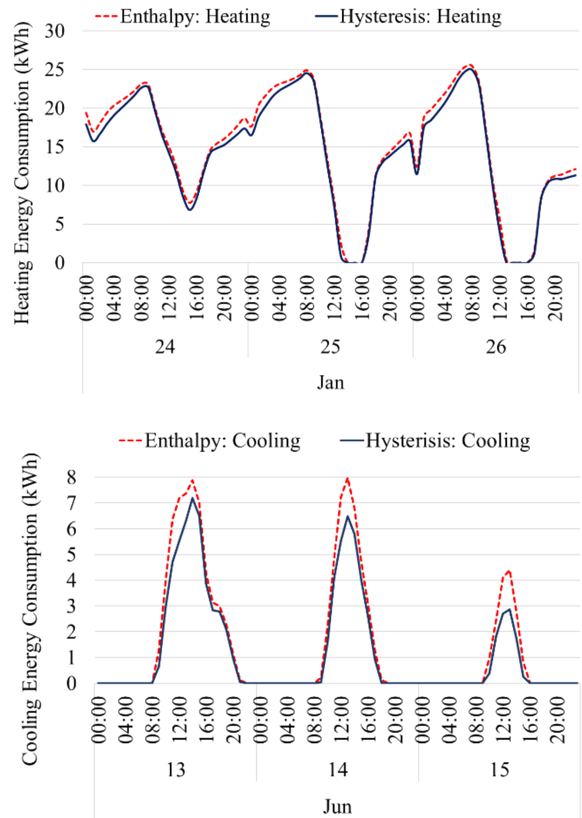

Figure 4 Hourly heating and cooling energy consumptions of the two methods from January 24th to 26th and from June 13th to 15th

The analysis of hourly indoor air temperatures of a day in March and June, presented in Figure 5, provides further explanation for the better performance of hysteresis than the enthalpy-temperature method. The hysteresis method maintains higher indoor air temperatures during the heating season in March and lower temperatures during the cooling season in June compared to the enthalpy temperature. Consequently, the HVAC system has to provide less heat to the zone to maintain the heating setpoint. Likewise, the HVAC has to remove less heat from the area to keep the cooling setpoint.

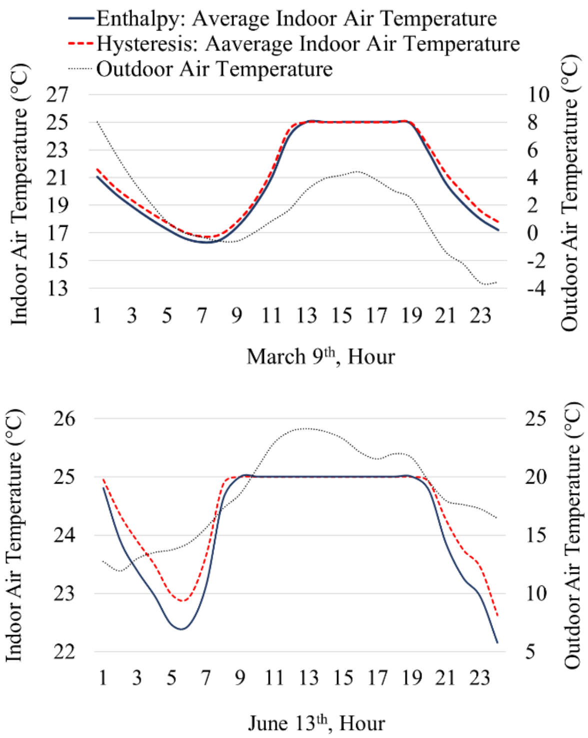

Figure 5 Hourly outdoor air temperatures and indoor air temperatures of the two methods on March 9th and June 13th

Figure 6 compares the total heating and cooling energy consumptions of five different thicknesses. The results indicate that all PCM widths achieve significantly higher heating energy savings ranging from approximately 14 % to 20 % than cooling energy savings ranging from around 1 % to 6 %.

The results also show that a 0.5 cm thick PCM layer achieves the smallest total energy savings of 9.2 %. The likely reason is its smaller heat storage capacity compared to other thicknesses. Also, only a 0.5 cm layer increases cooling energy consumption. The possible explanation is the high wall temperature of over 68 °C during hot days, damaging the plants located near the wall. The total energy savings of 1 cm, 1.5 cm, 2 cm, and 2.5 cm are 13.06 %, 14.81 %, 15.77 %, and 16.34 %, respectively. Considering the current high prices of PCMs and these results, a 1 cm thick layer is used in further analysis.

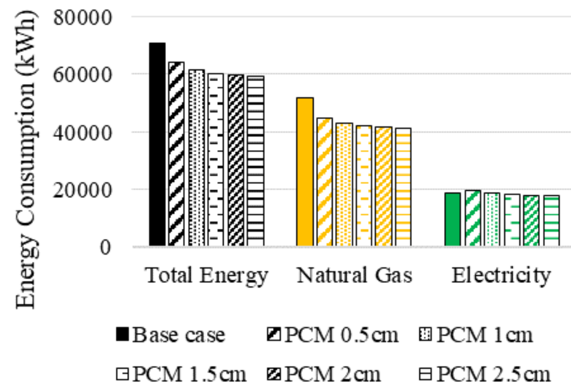

Figure 6 Energy consumptions of five PCM thicknesses

A comprehensive understanding of the energy performance of PCMs requires monthly analysis. In this regard, Figure 7 compares the monthly heating and cooling energy consumptions of the base case and PCM case. It can be observed that the PCM case achieves the most significant heating energy savings during the shoulder and summer months, ranging from 17 % to 99.5 %. In particular, during June, July, and August, the installation of PCM almost eliminates the greenhouse's heating energy requirements.

On the other hand, the PCM case achieves the smallest heating energy savings during December and January, and the possible explanations are short and cold days with low solar radiation. For example, the weather data analysis showed that the average total solar radiation in December and January is approximately 135 W/m², whereas, in February and March, it is about 229 W/m².

Furthermore, the analysis of the node temperatures indicates that only the north wall has average temperatures within the phase change temperature range of PCM23 during all four winter months (November to February). The west and east walls have adequate temperatures for phase transition of PCM23 only during a few hours in February. As a result, not all installed PCMs undergo phase transitions throughout the winter. These findings suggest that PCM's winter heating energy savings are also related to the material's insulating properties due to the low thermal conductivity ranging from 0.15 W/m K in the liquid to 0.25 W/m K in the solid region (see Figure 2).

Moreover, the PCM case achieves the most significant cooling energy savings during March, April, and October, ranging from approximately 20 % to 30 %. However, incorporating PCM into the greenhouse increases the cooling energy consumption from about 5 % to 26 % during the warm months, including May, June, July, and August. Further understanding of these findings requires analysis of hourly cooling energy consumptions and indoor air temperatures of base and PCM cases.

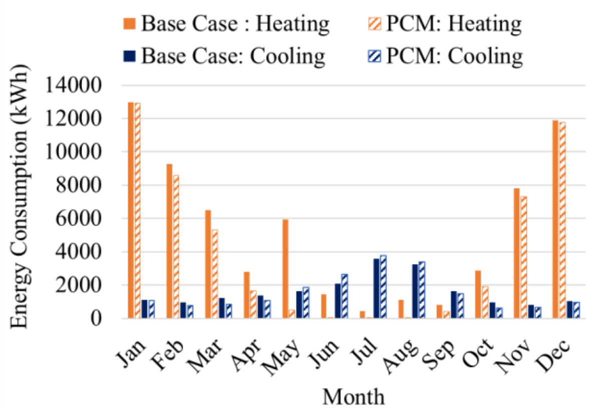

Figure 7 Monthly heating and cooling energy consumptions of base and PCM cases

Figure 8 shows that the PCM case exhibits higher cooling loads most of the day during May and June compared to the base case. On the other hand, during July and August, the PCM case has lower cooling energy consumption in the morning and early afternoon hours, whereas higher in the evening hours than the base case. Furthermore, Figure 9 illustrates that indoor air temperatures in the base case greenhouse experience more significant variations with the fluctuations of the outdoor temperatures compared to the PCM-enhanced greenhouse.

The analysis of average total solar radiation and outdoor air temperatures explains these results. As presented in Figure 8, all four summer months experience similar hourly average total solar radiation levels. In contrast, Figure 9 shows that May and June have 4 °C to 9 °C lower hourly average outdoor air temperatures than July and August. Therefore, solar energy received by the lightweight base case greenhouse (see Table 1) dissipates faster with the decline of outdoor air temperatures compared to the PCM-enhanced greenhouse. As a result, the high heat storage capacity of the PCM-enhanced greenhouse retains solar heat gains longer, leading to higher indoor air temperatures during the summer months compared to the base case.

In this regard, as presented in Figure 9, during May, June, July, and August, the PCM case, on average, 0.2 °C to 3.2 °C, higher indoor air temperatures than the base case throughout the day. The most significant temperature difference occurs in the evening, night, and morning hours, whereas from 11:00-19:00, the discrepancy between the PCM case and base case is less than 0.7 °C. These results explain, on the one hand, the reduction in the heating energy requirements and, on the other hand, an increase in the cooling energy demand of the PCM-enhanced greenhouse during the summer months shown in Figure 7.

Figure 9 also illustrates that the PCM case maintains lower indoor air temperatures in the winter months than the base case in the winter months (November to February). Hence, on average, the PCM case has 0.12 °C and 1.97 °C lower indoor air temperature from 11:00 to 15:00 than the base case. Consequently, as illustrated in Figure 7, the PCM case achieves higher cooling energy savings than the base case.

During shoulder months, the PCM case maintains, on average, 0.16 °C to 0.57 °C higher temperatures in the evening, night, and early morning hours than the base case. In contrast, from 08:00 to 17:00, it keeps, on average, 0.15 °C to 1.06 °C lower indoor air temperatures than the base case. These results explain the reduction in the greenhouse's heating and cooling energy requirements with PCM compared to the base case during March, April, September, and October presented in Figure 7.

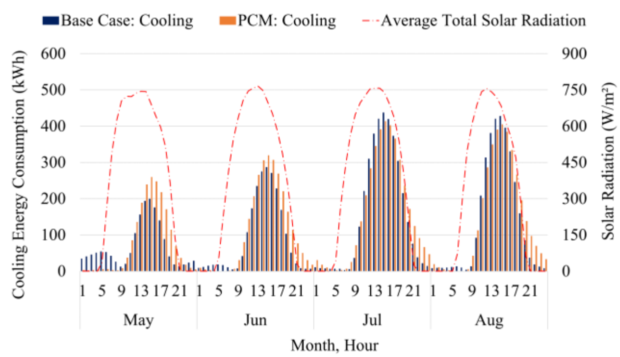

Figure 8 Hourly total solar radiation and cooling energy consumptions of the base and PCM cases

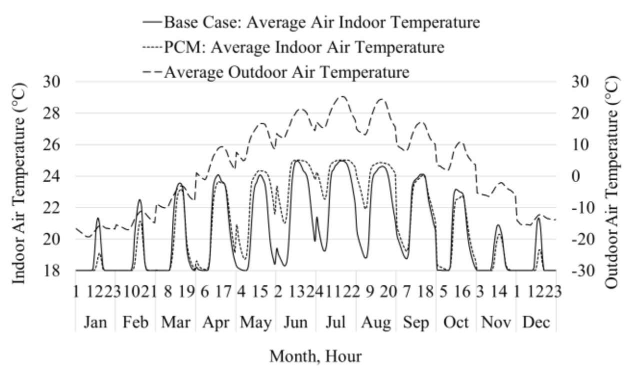

Figure 9 Hourly outdoor air temperatures and indoor air temperatures of the base and PCM cases

Furthermore, Figure 10 indicates that the base case greenhouse has lower cooling energy demand than the PCM-enhanced greenhouse during the days with average outdoor air temperature below 25 °C (i.e., June 29th and July 29th) and evening hours. However, during the hot summer days (i.e., July 6th), the base case warms up faster with the rise of the outdoor air temperature than the PCM case, thus requiring more energy to maintain a cooling setpoint of 25 °C.

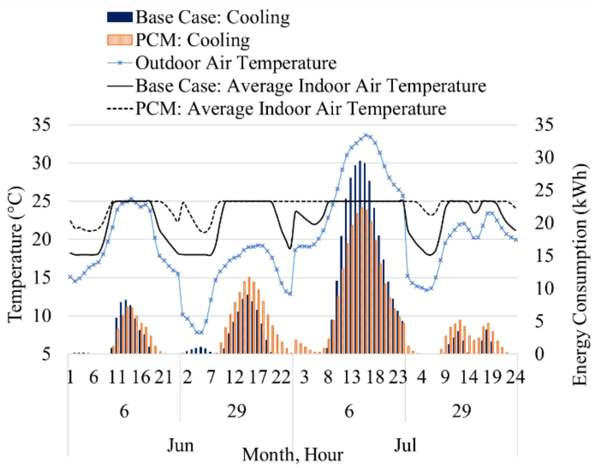

Figure 10 Hourly outdoor air temperatures, cooling energy consumptions, and indoor air temperature of the base and PCM cases

A complete understanding of the performance of the PCM-enhanced greenhouse requires an analysis of the wall temperatures. Therefore, Figure 11 compares the annual hourly averages of the node temperatures of three walls with PCM, including east, north, and west. It can be observed that all three wall assemblies of the PCM-enhanced greenhouse have lower temperatures during the day and higher temperatures during the night compared to the walls of the base case. Hence, the PCM-enhanced walls maintain approximately 0.5 °C to 4.3 °C (on average ~3.1 °C) higher temperatures than the walls of the base case in the evening, night, and early morning hours. In contrast, the PCM-enhanced walls exhibit 0.8°C to 7.7 °C (on average ~3.7 °C) lower temperatures compared to the base case walls from 09:00 to 16:00. Furthermore, there is an evident shift in the peak wall temperature between the PCM and base case.

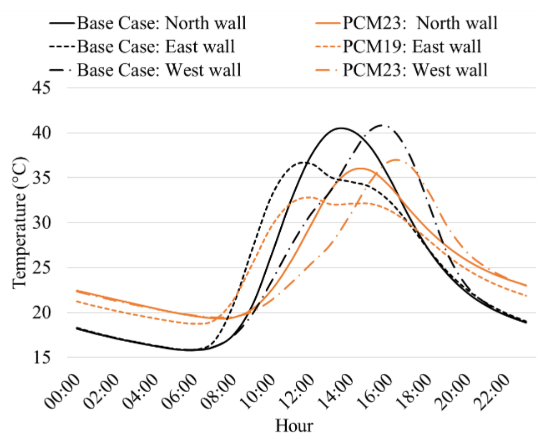

Figure 11 Annual hourly average wall temperatures

Conclusion

The comparison of the two PCM simulation methods in EnergyPlus shows approximately 4.11 % and 2.60 % higher heating and cooling energy savings, respectively, of the hysteresis compared to the enthalpy-temperature approach in solar energy greenhouse located in Winnipeg. Furthermore, heating energy savings occur during the night hours, whereas cooling energy savings typically happen during the daytime. Higher indoor air temperatures of the hysteresis than the enthalpy-temperature approach are the likely reason for more substantial heating energy savings. As a result, the heating system of the hysteresis method has to supply less energy to the zone to maintain the setback temperature of 18.0 °C than its counter, thus achieving more considerable heating energy reductions. These results support the findings of previous research studies about a discrepancy between the two methods, which depends on the intensity and duration of the solar radiation received at the PCM location (Al-janabi and Kavgic 2019). Furthermore, similar to previous findings (Ye et al. 2017, Kuznik et al. 2008), in this study, the thickness of the layer was considered to be 1 cm, as the thicker layers did not improve significantly enough the material effectiveness to justify the investment.

The findings from this study suggest the excellent potential for the application of PCMs in the solar energy greenhouse to reduce its energy consumption while maintaining growing indoor conditions of 18 °C to 25 °C. Thus, compared to the base case, the PCM-enhanced greenhouse generates 17 % to 99.5 % and 20 % to 30 % heating and cooling energy savings, respectively. The PCM achieves the most significant heating energy savings during the shoulder seasons and summer months when it almost eliminates heating requirements. The PCM case generates the most notable cooling energy savings during March, April, and October, increasing cooling energy consumption (~5-26 %) during summer months compared to the base case. Considering that the heating energy consumption participates with 70 % in the total energy consumption of the greenhouse, the absolute heating energy savings are considerably higher than the cooling energy savings. Furthermore, the heating energy reductions generate more substantial carbon savings than cooling energy reductions due to the higher carbon footprint of gas than hydroelectricity.

The study's limitations that point to the need for future work and investigation are as follows. First, future research should investigate the use of shading to reduce solar heat gains during warm days. Additionally, the use of natural ventilation, and especially during the summer evenings and nights, could also improve the performance of PCMs. Next, future research should investigate different conditioning setpoints and phase change temperatures to optimize the performance of PCM-enhanced greenhouse. In particular, there is a need for an experimental study focused on the validation of each method against the real-time energy consumption behaviour of a PCM-enhanced greenhouse.

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