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Using solar photovoltaic thermal collectors in phase change materials enhanced buildings for thermal performance management

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Abstract

This paper presents the investigation of using air-based solar photovoltaic thermal (PVT) collectors in phase change materials (PCMs) enhanced buildings for effective thermal management. PVT collectors are used to generate electricity and provide low grade heating energy to buildings for winter space heating. PCMs are either integrated into building walls to increase the local thermal mass or used as a temporary centralized thermal storage to store the low grade thermal energy derived from the PVT collectors. The thermal performance of buildings due to the integration of the PVT collectors and PCMs is tested and evaluated through computer simulations. It is found that appropriate use of PCMs in buildings can smooth the indoor temperature fluctuations. Using heated thermal energy generated from the PVT collectors in PCM enhanced buildings can significantly improve the indoor thermal comfort in winter heating conditions and appropriate integration of PVT collectors and PCMs can avoid undesirable overheating problems.

Keywords

photovoltaic, thermal, performance, collectors, management, phase, change, materials, enhanced, buildings, solar

Disciplines

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Using Solar Photovoltaic Thermal Collectors in Phase Change Materials Enhanced Buildings for Thermal Performance Management

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Abstract: This paper presents the investigation of using air-based solar photovoltaic thermal (PVT) collectors in phase change materials (PCMs) enhanced buildings for effective thermal management. PVT collectors are used to generate electricity and provide low grade heating energy to buildings for winter space heating. PCMs are either integrated into building walls to increase the local thermal mass or used as a temporary centralized thermal storage to store the low grade thermal energy derived from the PVT collectors. The thermal performance of buildings due to the integration of the PVT collectors and PCMs is tested and evaluated through computer simulations. It is found that appropriate use of PCMs in buildings can smooth the indoor temperature fluctuations. Using heated thermal energy generated from the PVT collectors in PCM enhanced buildings can significantly improve the indoor thermal comfort in winter heating conditions and appropriate integration of PVT collectors and PCMs can avoid undesirable overheating problems.

Keywords: Photovoltaic thermal (PVT) collectors; Phase change materials (PCMs); Thermal management; Thermal storage

1. Introduction

The growing energy demand in the building sector has resulted in the problems such as the shortage of energy supply and global warming [1]. In many International Energy Agency (IEA) member countries, building energy consumption represents over 40% of primary energy usage [2]. One of the main reasons for this growing trend is the ever growing demand for better indoor thermal comfort [3]. Due to the rapid increase in the living standard together with climate changes and economic development, energy use in buildings will continuously increase in forthcoming years. Improving energy efficiency in buildings is therefore essential to reduce global energy use, improve the security of national energy supply and promote environmental sustainability.

Over the last two decades, many low energy technologies and eco-friendly solutions have been proposed to improve building energy performance [4,5]. Among different technologies and solutions, solar photovoltaic-thermal (PVT) collectors and thermal energy storage using phase change materials (PCMs) have attracted increasing attention for developing energy efficient buildings. Solar PVT collector is a combination of photovoltaic and solar thermal systems which can produce both electricity and thermal energy simultaneously from one integrated component [6]. The low grade thermal energy generated by the PVT collectors can be used for space heating, cooling and other functional proposes such as hot water supply required in buildings. Due to the intermittence of solar energy, the use of PVT collectors alone cannot continuously meet building demand [7].

The integration of phase change materials (PCMs) with PVT collectors may provide an alternative approach to overcoming the intermittence of solar energy to maximise the utilisation of solar energy. PCMs are substances that can absorb, store and release a large amount of thermal energy at a relatively constant temperature and are well suited to building cooling and heating applications [8]. PCMs can be embedded into building materials such as concrete, gypsum wallboard and plaster, as part of building structure for lightweight or even heavyweight buildings to increase building thermal mass to reduce the indoor temperature fluctuations. PCMs can also be incorporated into building air conditioning systems as centralized and distributed thermal energy storage systems to reduce the mismatch between energy supply and demand through load shifting. It is becoming clear that the use of PCMs in buildings can play a significant role in decreasing the energy consumption and greenhouse gas emissions from buildings [9]. The need for air-conditioning can also be minimized.

However, only very limited studies to date reported the integration of PVT collectors with PCMs for building performance enhancement. Fiorentini *et al.* [10], for instance, recently developed a novel HVAC system integrated with an air-based PVT collector and a PCM thermal storage in a net-zero energy building. A water-based PVT system incorporating a PCM layer underneath the PV cells was studied in Ref. [11]. The results showed that, by including an appropriate PCM, the PV output can be increased by typically 9% with an average water temperature rise of 20^{o}C. A ceiling ventilation system integrated with PVT collectors and PCMs was presented in Ref. [12]. The use of night radiative cooling effect of water-based PVT collectors to regenerate the PCM ceiling of a Solar Decathlon house was reported in Ref. [13]. This paper presents and summarises our recent studies on the use of air-based solar PVT collectors in phase change materials (PCMs) enhanced buildings for effective thermal management. Three different scenarios are presented for integration of PCMs into buildings.

2. Scenario I: Experimental testing of a centralised PCM thermal storage integrated with PVT collectors

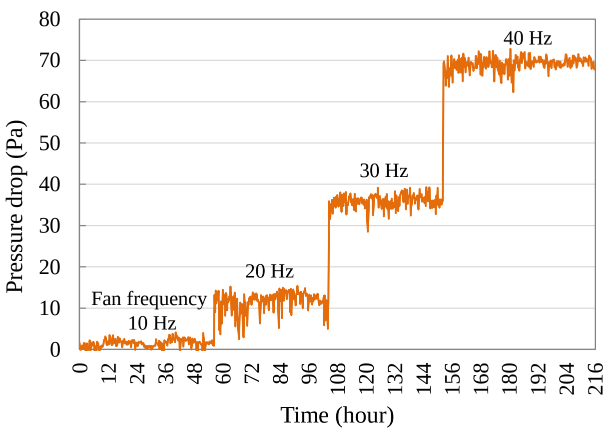
PCMs can be used as a centralised thermal storage to temporarily store the low grade thermal energy derived from the PVT collectors and use it later for direct space heating and cooling or preconditioning the ventilation air entering the air handling units. A centralised PCM thermal storage was designed and integrated with a lab-scale PVT-PCM test rig, as illustrated in Figure 1, to investigate the potential benefits of integrating PCMs with PVT collectors. The PCM storage tested consists of a total of 12 PCM bricks (see Figure 1) that were inserted into a metal duct, creating 3 air channels separated by the two arrays of the PCM bricks. The PCM tested is a commercial product, named as PlusICE PCM S21 [14]. The thermo-physical properties of S21 are summarised in Table 1. T-type thermocouples were installed near the inlet and outlet of the PCM storage to measure the air temperature profiles. A differential pressure transmitter was used to measure the pressure loss across the PCM thermal storage.

The test results under the autumn weather conditions in Sydney area from 09 May 2015 to 17 May 2015 are presented in Figure 2. During the test, the fan operating frequencies used were 10 Hz, 20 Hz, 30 Hz and 40 Hz, respectively. It can be found that the pressure drop significantly increased when a larger fan operating frequency was used. Under the same fan operating frequency, there was a fluctuation in the pressure drop across the PCM thermal storage. During the daytime, the outlet air temperatures from the PCM thermal storage were lower than that of the inlet, indicating that the heat in the heated air was charged into the PCM bricks. However, higher outlet air temperatures from the PCM thermal storage than that of the inlet were observed during the nigh-time, demonstrating that the heat stored in the PCM was released to the air flowing through the storage. During the first four test days, there was a relatively large temperature difference between the inlet air and outlet air of the PCM thermal storage. However, the difference was very small during the rest test days due to the increased fan operating frequency. This illustrates that air flow rate flowing through the PCM is a critical variable that should be optimised. The decision to charge or discharge the PCM thermal storage is important when considering integration of centralised PCM thermal storage systems with PVT collectors.

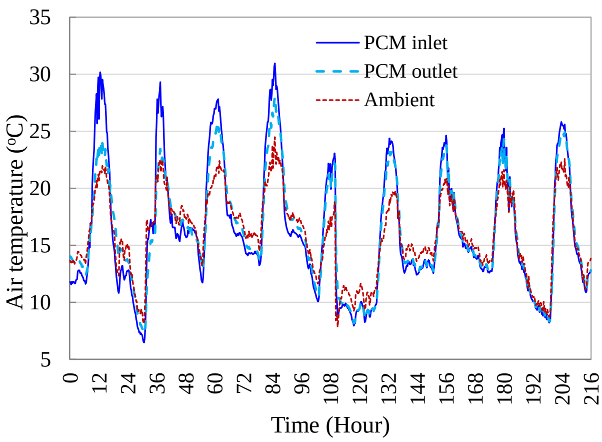
Figure 1: Illustration of the PVT-PCM test rig and PCM brick tested [14].

Table 1: Thermo-physical properties of PCM S21 tested [14]

Phase change temperature [°C]	Density [kg/m^3]	Latent heat capacity [kJ/kg]	Specific heat capacity [kJ/(kg.K)]	Thermal conductivity [W/(m.K)]
22	1530	170	2.2	0.54



(a) Pressure drop across the PCM storage



(b) PCM storage Inlet and outlet air temperatures

Figure 2: Test results under the autumn test conditions

3. Scenario II: Simulation study of a PVT-PCM integrated ceiling ventilation system

In this case, two PCM layers with an air channel between them were assumed to be installed in the pitched ceiling of the living room of a Solar Decathlon (SD) house (see Figure 3). The PCM layers were used to increase the local thermal mass and, at the same time to serve as a centralized thermal storage unit. The whole north roof of the SD house was assumed to be covered by the PVT collectors with a total area of 40 m^2. The low grade energy generated by the PVT collectors can be directly used for space heating/cooling, or can be directed into the air channel between the PCM layers to charge the PCM thermal storage, or can be first used for PCM charging and then for space heating. During the winter night-time, the indoor air can circulate through the PCM air channel to discharge the heat stored in the PCM storage for space heating. The PCM used in this scenario is SP24E, a commercial inorganic PCM from Rubitherm PCM [15] and the thermo-physical properties of SP24E are summarized in Table 2.

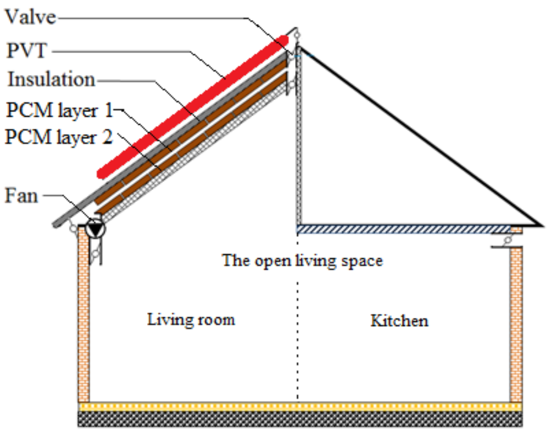


Figure 3: PVT-PCM ceiling ventilation system in a Solar Decathlon house.

Table 2: Thermo-physical properties of SP24E [15]

Melting temperature range [°C]	Solidification temperature range [°C]	Density: solid/liquid [kg/m^3]	Latent heat capacity [kJ/kg]	Specific heat capacity [kJ/(kg.K)]	Thermal conductivity [W/(m.K)]
24-25	23-21	1500/1400	190	2	0.6

The indoor air temperatures of the living space (including living room, kitchen and dining room) of the house by using the PVT-PCM ceiling ventilation system, by using PCM only and that of the original house without using the PVT collectors and PCMs are illustrated in Figure 4. The data presented was tested in three consecutive winter days under Sydney weather conditions. Compared to that of the original house, the indoor air temperature of the house using the PCM only reduced during the daytime while it slightly increased during the night-time. The limited increase in indoor air temperature during the night-time was because the PCM layers were only installed in the pitched ceiling of the living room of the house. When the PVT collectors were used, more heat can be stored in the PCM thermal storage during the daytime and this amount of heat can be used for night-time space heating. Therefore, the indoor air temperature of the house increased obviously during both the daytime and night-time. However, necessary optimization strategies are required to maximise the utilisation of the storage capacity of the PCM layers.

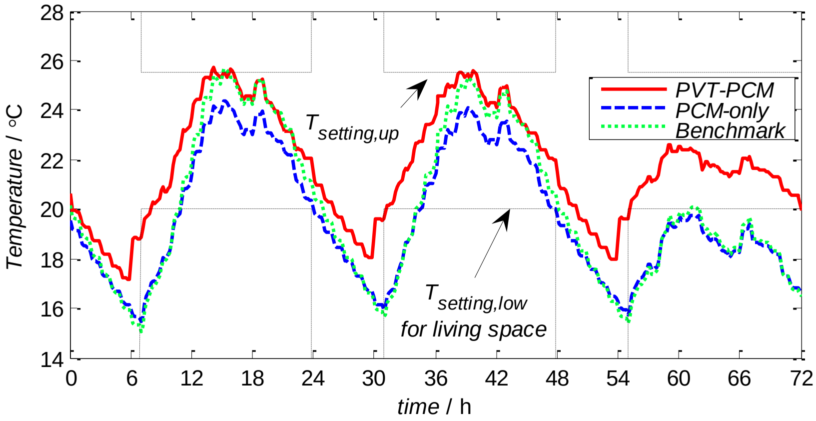


Figure 4: Indoor air temperatures of the house - *Scenario II*.

4. Scenario III: Simulation study of thermal performance of buildings with integrated PVT collectors and PCMs in building walls

In this case, PCMs were integrated into building walls to increase the local thermal mass. The heated air from the PVT collectors was directed into the building for space heating. The simulation study was performed based on a typical Australian house [16], as illustrated in Figure 5. The PVT collectors with an air mass flow rate of 2000 kg/h were assumed to be installed on the whole north roof of the house. The PCM used in this scenario is SP21E, a commercial inorganic PCM product from Rubitherm [15]. The thermo-physical properties of SP21E are summarized in Table 3.

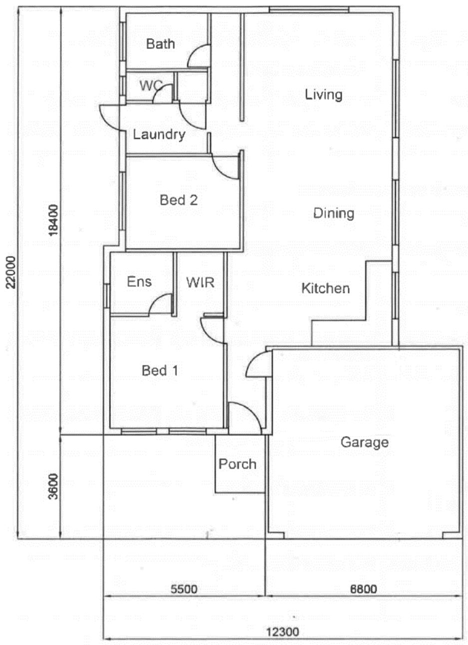


Figure 5: Floor plan of a typical Australian house.

Table 3: Thermo-physical properties of SP21E [15]

Melting temperature range [°C]	Solidification temperature range [°C]	Density: solid/liquid [kg/m^3]	Latent heat capacity [kJ/kg]	Specific heat capacity [kJ/(kg.K)]	Thermal conductivity [W/(m.K)]
22-23	21-19	1500/1400	160	2	0.6

The indoor air temperature of the house by using the PVT ventilation and PCM in the building walls was compared with that of the house with the PCM in building walls and the original house without using the PVT collectors and PCM under the same three winter test days as that in *Scenario II*, and the results are presented in Figure 6. Compared to the original house, the indoor air temperature fluctuation of the house by using the PCM only reduced substantially. The use of PVT ventilation and PCM in building walls simultaneously can further improve the indoor air temperature of the house. The indoor air temperature of the house significantly increased during the daytime and also slightly increased during the night-time as the PCM layer laminated onto the building walls stored more heat during the daytime. However, the amount of heat generated from the PVT collectors directed into the house should be optimized. Otherwise, overheating of the house may be resulted, as illustrated in Figure 6.

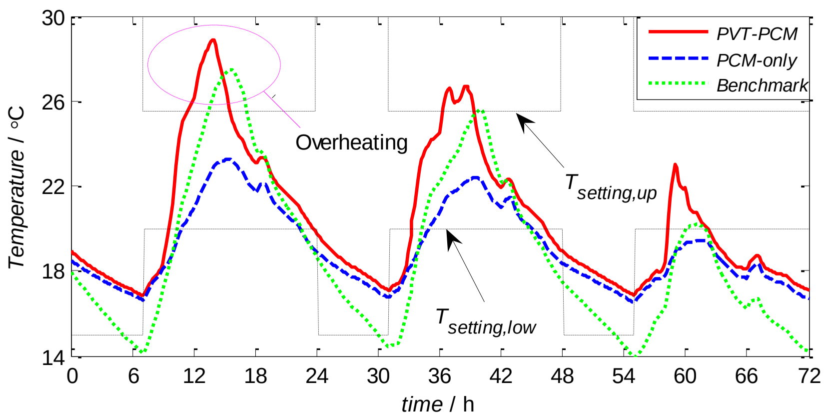


Figure 6: Indoor air temperatures of the house - *Scenario III*.

5. Conclusions

This paper presented the investigation of using air-based solar photovoltaic thermal (PVT) collectors in phase change materials (PCMs) enhanced buildings for effective thermal management. Three different scenarios, including the integration of PVT collectors with a centralized PCM thermal storage (*Scenario I*), a PVT-PCM ceiling ventilation system (*Scenario II*), and the using of PVT ventilation in buildings with walls enhanced by PCMs (*Scenario III*), were presented to understand how building thermal performance can be improved through appropriately using PVT collectors and PCMs. The results showed that appropriate use of PCMs in passive buildings can smooth the indoor temperature fluctuations. Using PVT collectors and PCMs simultaneously can significantly improve building indoor thermal comfort under winter weather conditions. However, necessary optimisation is required to maximise the utilization of the storage capacity of the PCMs used.

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