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Optimization of a ceiling ventilation system with integrated photovoltaic thermal collectors and phase change materials

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Keywords

ventilation, materials, ceiling, change, optimization, phase, collectors, thermal, photovoltaic, integrated, system

Disciplines

Engineering | Science and Technology Studies

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Abstract

This paper presents the performance evaluation and design optimization of a ceiling ventilation system with integrated solar photovoltaic thermal (PVT) collectors and phase change materials (PCMs) by using a hybrid Particle Swarm Optimization and Hooke-Jeeves Pattern search (PSO-HJ) algorithm. In this novel ceiling ventilation system, the PVT collectors are used to generate electricity and provide the low-grade heating energy for buildings by using the winter daytime solar radiation, while the PCM is integrated into the building ceiling as part of the ceiling insulation and at the same time, as a centralized thermal energy storage unit to temporally store the low-grade thermal energy collected from the PVT collectors and use it later when needed. The benefit of using this proposed PVT-PCM integrated ceiling ventilation system in active buildings with air-conditioning systems was evaluated in terms of the total power consumption of the house for space heating. Further optimization was performed in order to identify the optimal values of the key design parameters. In the hybrid PSO-HJ algorithm used in the design optimization, the PSO is first used to identify the optimal region of the design variables while the HJ algorithm is then used to perform a local search to identify the “global” optimal values. The results showed that the integration of PVT collectors and PCMs with the ceiling ventilation can greatly reduce the power consumption of the house for space heating in winter. By employing the optimal design identified using PSO-HJ algorithm, the power consumption of the house can be further reduced.

Keywords: Design optimization; Phase change materials; Photovoltaic thermal; Particle Swarm Optimization; Hooke-Jeeves Pattern search; Ceiling ventilation

1. Introduction

As one of the major energy consumers, buildings worldwide account for as much as 45% of global energy consumption with a similar share of greenhouse gas emissions [1]. Promoting building energy efficiency is therefore essential to reduce global energy usage and carbon footprint. Many efforts have been made in the development and deployment of various cost-effective solutions and low energy technologies in buildings [2 ,3].

Photovoltaic thermal (PVT) collectors and phase change materials (PCMs) are among the promising methods that have attracted increasing attention over the recent decades. PCMs with high energy storage densities can store a large amount of thermal energy and release it for later use at a relatively constant temperature [4]. Air-based PVT collectors can generate electricity and the low-grade thermal energy simultaneously, and the thermal energy carried by the hot air can be used for direct space heating or used as an additional heat source for building services systems [5]. The integration of solar PVT collectors with PCMs in building envelopes provides an alternative solution to greatly reduce building energy consumption while maintaining the satisfied indoor thermal comfort.

Over the last decades, simulation-based optimization has become an efficient measure to satisfy several stringent requirements of high performance buildings [6] in terms of low-energy demand. A variety of optimization methods have been used to optimize buildings and building service systems. For instance, Hooke-Jeeves (HJ) Pattern search algorithm was used by Bojic *et al.* [7] to optimize the thermal insulation of a low energy house for energy savings. A hybrid Particle Swarm Optimization and Hooke-Jeeves (PSO-HJ) algorithm was used by Lee *et al.* [8] to optimize a chilled water system. A Genetic Algorithm (GA) algorithm was employed to optimize the performance of a solar absorption chiller-PCM system [9]. Simplex algorithm of Nelder and Mead with extension of O'Neill (SA), HJ, PSO using Inertia Weight (PSOIW) and a hybrid PSO-HJ were used and compared by Futrell *et al.* [10] to minimize lighting loads. HJ and PSO algorithms were also used by the same authors [11] for bi-objective optimization of building thermal performance and lighting performance. A mutual information hybrid Evolutionary Algorithm (EA) enhanced by pseudo-differential gradients as a mutation operator and a hill-climbing algorithm was proposed and applied by Bucking *et al.* [12] to optimize the design of a net-zero energy house, which achieved better optimal designs than that using traditional EA algorithm and PSO.

This paper presents the performance evaluation and design optimization of a ceiling ventilation system with integrated air-based PVT collectors and PCMs. A hybrid Particle Swarm Optimization and Hooke-Jeeves Pattern search (PSO-HJ) algorithm implemented in Generic Optimization Program (GenOpt) [13] was used as the optimization technique to search for optimal solutions to the optimization problem. The optimization was carried out based on a typical Australian house through TRNSYS [14] simulation.

2. Building system description and modelling

The case building concerned in this study is a simplified typical Australian house with a floor area of 200 m^2. The air-based PVT collectors were assumed to be installed on the whole north roof of the house, while two PCM layers with an air channel between them were integrated into the ceiling, as illustrated in Figure 1. Apart from increasing the local thermal mass, the two PCM layers also serve as a thermal energy storage unit to temporally store the low-grade thermal energy generated from the PVT collectors, and use it later for space heating. During the daytime, the heated air from the PVT collectors can be directed through the PCM thermal storage unit for heat charging. The air can then be exhausted, or further directed into the room for space heating when there is a need for space heating. Space heating can also be achieved by circulating the indoor air through the PCM thermal storage unit to extract the heat stored in the PCM layers to maintain the satisfied indoor air temperature. An air source heat pump was installed in the house as an auxiliary heating system in case the heating provided by the PVT-PCM integrated ceiling ventilation system cannot satisfy the indoor heating demand.

The house was modelled as two thermally separated zones (*i.e.* roof space and room space) using TRNSYS Type 56 Multi-zone building component model. The room space of the house was further modelled as 6 coupled air nodes. One of the air nodes represented the room space with occupants' activity, while the other five air nodes were used to couple the PCM layer 2 with the ceiling. The hysteresis phenomenon during the phase change process was modelled by employing two *h-T* curves [15], as shown in Figure 2. The PVT model used was a dynamic model developed in a previous study [16]. The air conditioner used is a split-type heat pump system, assumed to operate at a fixed air flow rate of 1500 kg/h. During the daytime, the heated air from the PVT collectors will be used to charge the PCM thermal storage unit. The outlet air from the PCM will be directed into the room for space heating if the air is still warm enough. If the PVT-PCM integrated ceiling ventilation system cannot provide the sufficient heat, a fraction of the indoor air will be used to mix with the air from the PCM thermal storage unit, and the mixed air is then further processed by the heat pump unit.

The system can operate with different modes on the basis of the weather conditions, thermal energy stored in the PCM and the indoor heating demand through ON/OFF control of the isolation valves (*i.e.* V_1-V_5) and fans (*i.e.* PVT fan and PCM fan) (see Figure 1).

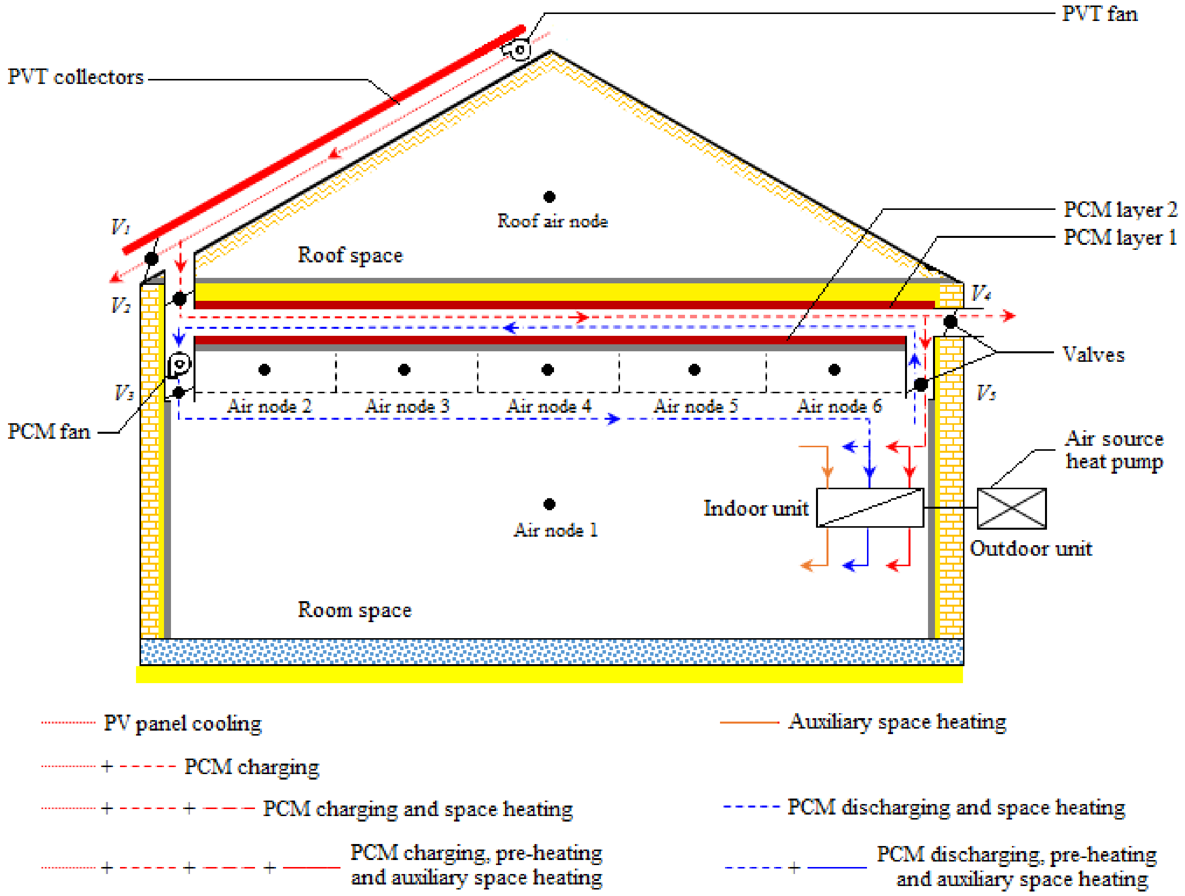

Figure 1: Illustration of the PCM-enhanced house with PVT collectors on the roof.

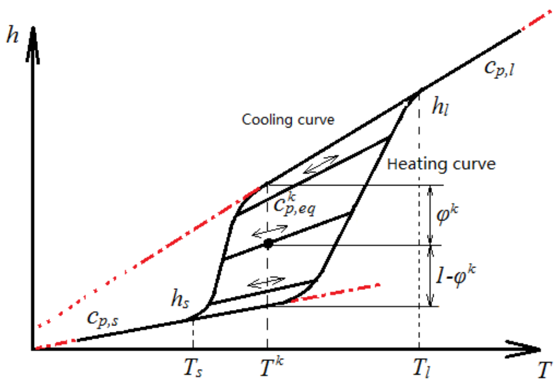

Figure 2: Enthalpy-temperature relationship considering hysteresis during the phase change process, where h is the enthalpy, T is the temperature, c_p is the specific heat capacity, φ is a weighting factor, $c_{p,eq}$ is the equivalent PCM specific heat capacity within the hysteresis region, and subscripts s and l represent the solid and liquid states, respectively.

3. Formulation of the optimization problem

The objective of the optimization problem is to minimize the total power consumption of the PVT-PCM integrated ceiling ventilation system together with the air source heat pump in winter for space heating, as described in Eq. (1). The power consumption of the PVT and PCM fans was calculated according to the air flow rate and the pressure drop estimated in the PVT-PCM integrated ceiling ventilation system, and the power consumption of the heat pump was calculated based on the catalogue data provided by the manufacturer. It is noteworthy that the electricity generation from the PVT collectors was not considered.

$$\min P_{total} = P_{HP} + P_{PVT\ fan} + P_{PCM\ fan} + f_p\left(\dot{Q}_{m,PCM}, \delta_{air}\right) \quad (1)$$

where *P* is the total power consumption over the time period of concern, the subscript *HP* indicates the heat pump, $f_p(\dot{Q}_{m,PCM}, \delta_{air})$ is a penalty function to ensure that the air velocity in the air channel between the PCM layers is less than 1.0 m/s [17].

In this study, the PCM charging air flow rate, the PCM discharging air flow rate, the thickness of the two PCM layers and the size of air channel between the two PCM layers were considered as the optimization variables. The major constraints used for these variables are summarized in Table 1.

Optimization variables	**Description**	**Constraints**	
		Lower limit	**Upper limit**
$\dot{Q}_{m,charging}$	PCM charging air flow rate, (kg/h)	1000	3000
$\dot{Q}_{m,dis\ charging}$	PCM discharging air flow rate, (kg/h)	500	1500
δ_{PCM}	Total thickness of the two PCM layers, (mm)	10	30
δ_{air}	Size of the air channel between the PCM layers, (mm)	10	50

Table 1: Optimization variables and their corresponding constraints used in the optimization.

In this study, a hybrid optimization algorithm with Particle Swarm Optimization and Hooke-Jeeves Pattern search implemented in GenOpt [13] is used as the optimization tool to determine the optimal solutions of the optimization problem. In PSO-HJ algorithm, PSO was first used as a “global” search tool to identify a near optimal region. Hooke-Jeeves Pattern search was then initialized and used to search for optimal solutions locally based on the near optimal region identified by PSO.

A Particle Swarm Optimization [18] is a primary population-based search approach which has been commonly used in building optimization studies [13]. It was originally developed to model the social behaviours of birds in flock or swarm [13]. In PSO, the velocity of every particle (*i.e.* individuals in the swarm) is updated by its current position relative to the positions of its personal best and neighbourhood best solutions such that the individual accelerates towards both potential optimal positions from generation to generation [11]. The detailed implementation steps of PSO can be found in [18, 19].

Hooke-Jeeves algorithm [20] is one of the generalized pattern search methods. In Hooke-Jeeves Pattern search method, there are two search types: exploratory search and pattern search [21]. The exploratory search is employed to identify the direction of the objective optimization, while the pattern search uses the identified optimization direction to accelerate the search process [22]. The step size of the exploratory search is slowly reduced until the predefined minimal step size is reached when a better solution cannot be found during the optimization process. The general steps of using the Hooke-Jeeves pattern search algorithm to determine the optimal solutions can be found in [20].

4. Results and discussions

The performance evaluation and optimization of the integrated PVT-PCM ceiling ventilation system were conducted over a typical winter week under Sydney weather conditions, as shown in Figure 3. In this study, a commercial PCM product SP24E from Rubitherm [23] was used.

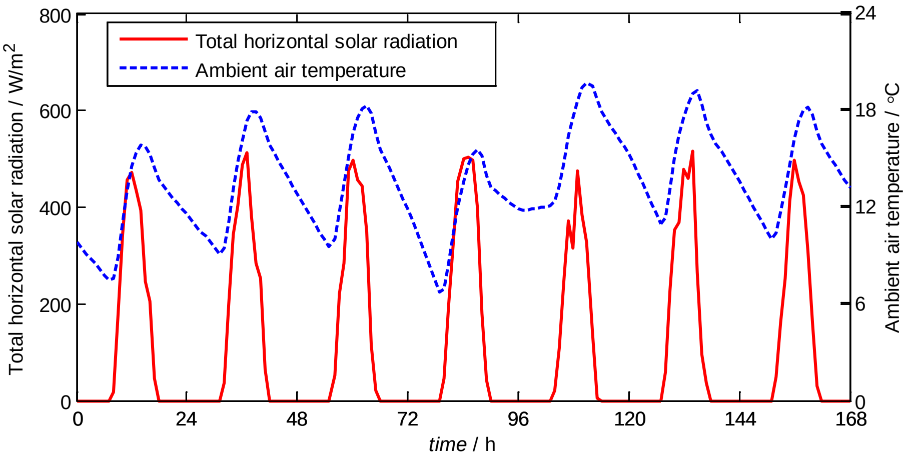

Figure 3: Solar radiation and ambient air temperature during the typical winter week selected.

4.1 Performance evaluation

The performance of the PVT-PCM integrated ceiling ventilation system was first evaluated based on a no-optimization design (*i.e.* no-optimization *case*) with the PCM charging air flow rate of 2000 kg/h, the PCM discharging air flow rate of 1500 kg/h, the total thickness of the two PCM layers of 20 mm and the air channel size of 30 mm. The total power consumption in the no-optimization *case* was compared with a *baseline case* in which only the air source heat pump was used for space heating and there was no PCM and PVT collectors used.

Figure 4 shows the accumulated power consumption of the house for space heating over the selected week under the *baseline case* and no-optimization *case*. It can be seen that the total power consumption of the house under the no-optimization *case* using the PVT-PCM integrated ceiling ventilation system was much lower than of the *baseline case.* Compared to the *baseline case*, the total power consumption of the house reduced from 87120 to 34673 kJ.

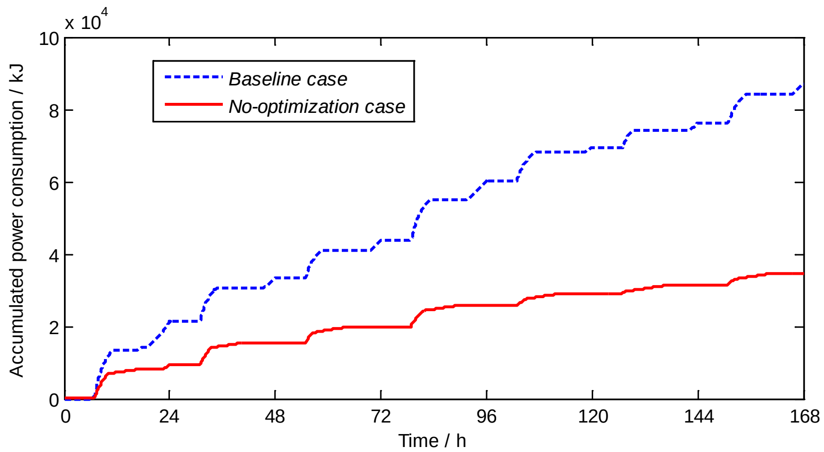

Figure 4: Accumulated power consumption over the selected week under the baseline case and on-optimization case.

4.2 Optimization

Optimization was conducted to further reduce the power consumption of the house by using the PVT-PCM integrated ceiling ventilation system and the auxiliary heat pump. The optimization process by using the PSO-HJ algorithm is shown in Figure 5. It can be seen that PSO was first executed to identify the near optimal region and HJ was then used to search for “global” optimal solutions in the near optimal region identified by PSO. The significant fluctuation at the beginning of the optimization was due to the influence of the penalty function used in the objective function. The optimal PCM charging air flow rate, the optimal PCM discharging air flow rate, the optimal total thickness of the two PCM layers and the optimal air channel size identified were 1300 kg/h, 1500 kg/h, 14 mm and 32 mm, respectively. It is worthwhile to note that the sensible heat storage capacity in the two PCM layers was considered to be useful for space heating in this study. As a consequence, the charging process continues even the two PCM layers are fully liquefied.

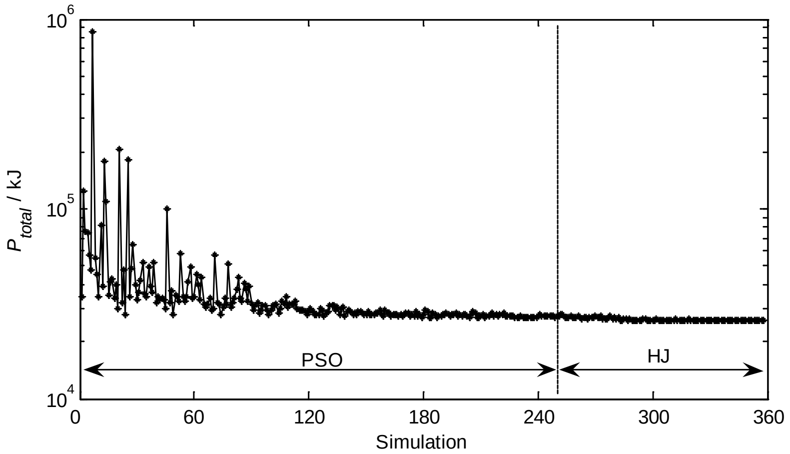

Figure 5: Optimization process by using PSO-HJ algorithm.

By employing the optimal design, a decrease in the total power consumption of the house for space heating can be achieved (see Figure 6). Table 2 summarises the power consumption of the house under three different cases. The total power consumption of the house in the selected week reduced from 34673 to 25828 kJ through the implementation of the PSO-HJ optimization, as compared to the no-optimization case. Compared to the baseline case, 70.4% and 60.2% of power savings can be achieved by using the PVT-PCM integrated ceiling ventilation system with the PSO-HJ optimization and no-optimization, respectively.

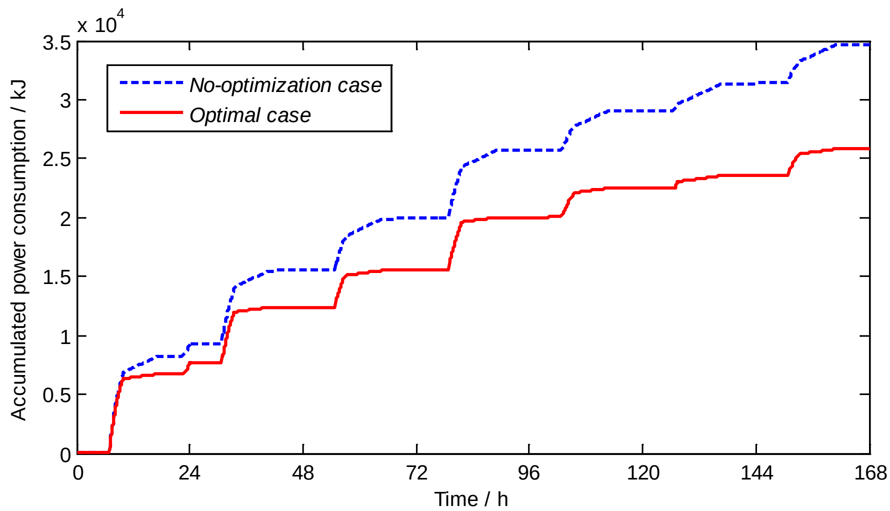

Figure 6: Accumulated power consumption of the house over the selected week with and without using optimization.

Case	Key design parameters				P_{total} (kJ)	Power savings (%)
	$\dot{Q}_{m,charging}$ (kg/h)	$\dot{Q}_{m,dis\ charging}$ (kg/h)	δ_{PCM} (mm)	δ_{air} (mm)		
Baseline case	-	-	-	-	87119.9	-
No-optimization case	2000	1500	20	30	34672.5	60.2
Optimal case	1300	1500	14	32	25828.1	70.4

Table 2: Comparison of the power consumption of the house among three different cases.

5. Conclusions

This paper presented the performance evaluation and design optimization of a PVT-PCM integrated ceiling ventilation system in active buildings using an air source heat pump system. To minimize the power consumption of the house for space heating, a hybrid Particle Swarm Optimization and Hooke-Jeeves Pattern search algorithm was employed as the optimization tool to identify the optimal values for the key design variables of the system, including the PCM charging air flow rate, the PCM discharging air flow rate, the total thickness of the PCM layers and the size of the air channel between the two PCM layers.

It was found that the use of the PVT-PCM integrated ceiling ventilation system can significantly reduce the power consumption of the house for space heating. 60.2% of power consumption of the house can be saved over a typical winter week in Sydney weather condition, as compared to that only using the air source heat pump for space heating. The optimal PCM charging air flow rate, the optimal PCM discharging air flow rate, the optimal total thickness of the two PCM layers and the optimal size of the air channel between the two PCM layers identified by using PSO-HJ algorithm were 1300 kg/h, 1500 kg/h, 14 mm and 32 mm, respectively. Compared to the use of PVT-PCM ceiling ventilation system without optimization, the power consumption of the house for space heating can be further reduced from 34673 to 25828 kJ through the implementation of the optimization.

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