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Abstract

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Keywords

performance, thermal, pattern, evaluation, optimal, design, buildings, integrated, jeeves, air, hooke, photovoltaic, collectors, phase, change, materials, method, search

Disciplines

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Thermal Performance Evaluation and Optimal Design of Buildings with Integrated Air-Based Photovoltaic Thermal Collectors and Phase Change Materials Using the Hooke-Jeeves Pattern Search Method

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Abstract:

Over the last several decades, many low energy technologies have been developed and deployed to reduce building energy consumption. Among various solutions, solar photovoltaic thermal (PVT) collectors and phase change materials (PCMs) are among the most promising methods receiving increasing attention. This paper presents a thermal performance evaluation and optimal design of buildings integrated with air-based solar PVT collectors and PCMs embedded in the building envelope by using The Hooke-Jeeves pattern search method. The Hooke-Jeeves generalized pattern search is used to search for optimal solutions of the optimization problem. The variables optimized include the PVT air flow rate, additional wall insulation and PCM layer thickness. The optimal values identified by using the Hooke-Jeeves pattern search method for the PVT air flow rate, additional wall insulation and PCM layer thickness were 1359.4 kg/h, 3.0 $m^2 \cdot K/W$ and 0.03 m, respectively. The Coefficient of Thermal Performance Enhancement (CTPE) of the house reached 72.6% when the optimal design values identified were used.

Keywords - Hooke-Jeeves pattern search; Photovoltaic-thermal; Phase change materials; Optimal design; Performance evaluation

1. Introduction

As one of the major energy consumers, buildings account for as much as 45% of global energy consumption [1], resulting in increasing awareness on energy supply difficulty, exhaustion of energy resources and global environmental impacts [2]. Many efforts have been made in the development and deployment of various cost-effective solutions and low energy technologies to promote building energy efficiency and mitigate global warming [3, 4].

Among a wide range of technologies, phase change material (PCM) thermal energy storage and solar photovoltaic thermal (PVT) collectors have attracted wide attention. 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 [5]. Air-based PVT collectors can generate electricity and 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 [6. 7]. The integration of both technologies might provide a promising solution to effectively use solar energy and thereby enhance building thermal/energy performance [8].

Appropriate design and optimization plays an essential role in ensuring good building performance. Numerous studies have been focused on optimization of buildings and building service systems by using different methods [9]. For instance, Genetic Algorithm (GA) was employed to optimize the performance of a solar absorption chiller-PCM system [10]. A chilled water system was optimized by using particle swarm optimization and the Hooke-Jeeves (PSO-HJ) algorithm [11]. The Hooke-Jeeves (HJ) and particle swarm optimization (PSO) algorithms were also used by Futrell *et al.* [12] for bi-objective optimization of building thermal performance and lighting performance. The optimization results by using HJ and PSO were further compared with that of using simplex algorithm (SA) of Nelder and Mead with extension of O'Neill and PSO-HJ by the same authors [13]. Taguchi method [14] was used by Sivasakthivel and Murugesan [15] to optimize solar assisted ground source heat pump systems. As Taguchi method can only handle limited number of discrete variables, a Taguchi-Fibonacci search method was developed to solve the building optimization problems with both discrete and continuous variables [16].

This paper presents the optimal design of buildings with integrated air-based solar PVT collectors and PCMs in building envelopes by using the Hooke-Jeeves pattern search method integrated in Generic Optimization Program (GenOpt). The optimization was carried out based on a typical Australian house through TRNSYS [17] simulations.

2. Description of the system and formulation of the optimization problem

2.1 Description of the modelling system

The case building concerned in this study is one of the 'typical' Australian dwelling designs [18]. The air-based PVT collectors were assumed to be installed on the whole north roof of the house while the PCM layers were assumed to be laminated onto the walls and the ceiling of the house, as illustrated in Fig. 1. During the winter daytime, the heated air from the PVT collectors is directed into the house for space heating, if the air temperature is higher than the indoor temperature. The PVT system is switched off if there is no solar radiation during night-time.

To simplify the simulation, the house was modified and modelled as two thermally separated zones (*i.e.* roof space and room space) using TRNSYS Type 56 Multi-zone building component model.

The PVT model used was a dynamic model developed in a previous study [19]. The key governing equations used are presented in Eqs. (1) - (3). By using the PVT model, the outlet air temperature, electrical power generation and thermal efficiency of the PVT collectors can be easily determined.

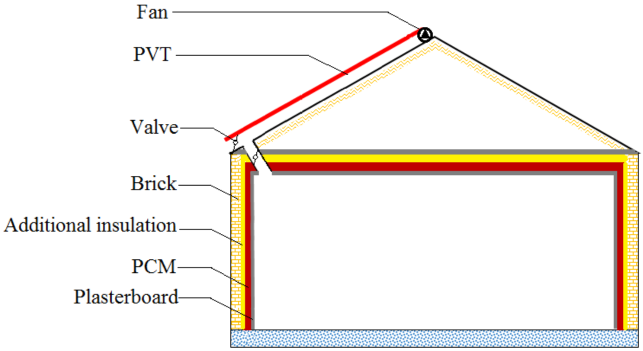


Fig. 1 Illustration of the PCM-enhanced house with PVT collectors on the roof.

$$\dot{Q}_m c_{p,f} \frac{dT_f}{dx} = W_p \left(\dot{q}_{p-f} - \dot{q}_{f-r} \right) \quad (1)$$

$$m_p c_{p,p} \frac{dT_p}{dt} = \left(1 - \rho_{ref}\right) \cdot IAM \cdot \left(1 - \eta_p\right) \cdot A \cdot Gt - \dot{Q}_L - \dot{Q}_{p-f} - \dot{Q}_{p-r} \quad (2)$$

$$m_r c_{p,r} \frac{dT_r}{dt} = \dot{Q}_{p-r} + \dot{Q}_{f-r} - \dot{Q}_{r-rs} \quad (3)$$

where, $\dot{Q}_m$ is the air mass flow rate, c_p is the specific heat capacity, m is the mass, T is the temperature, x is the coordinate direction along the PVT length, W is the width of PVT collectors, A is heat transfer area, ρ_{ref} is the reflectance of PV panel, *IAM* is the incident angle modifier, *Gt* is the total solar radiation on the PV panel, η_p is the electrical efficiency, $\dot{q}$ is the heat flux, $\dot{Q}$ is the heat flow rate, subscripts *f, p, r, L and rs* indicate the working fluid, PV panel, roof insulation, heat losses and roof space, and subscripts *p-f*, *p-r*, *f-r*, *r-rs* indicate the heat transfer directions from the PV panels to the working fluid, from the PV panels to the roof insulation, from the working fluid to the roof insulation, and from the roof insulation to the roof space, respectively.

The building envelope-integrated PCM model developed in a previous study [20] was used to simulate the dynamic response and heat transfer of the building envelopes. The hysteresis phenomenon during the phase change process was considered in the model by employing two different heating *h*-*T* curves and the relationship between the enthalpy and temperature of PCMs is determined by Eq. (4).

$$h^{k+1}=\begin{cases} h_{heating}\left(T^{k+1}\right), & \begin{cases} if\ h^k=h_{heating}\left(T^k\right), & T^{k+1}\geq T^k, \quad T_s<T^k<T_l \\ or \quad if \quad T^k\geq T_l \end{cases} \\ c^k_{p,eq}\left(T^{k+1}-T^k\right)+h^k, & \begin{cases} if\ h^k=h_{heating}\left(T^k\right), & T^{k+1}<T^k, \quad T_s<T^k<T_l \\ or \quad if \quad h_{heating}(T^k)<h^k<h_{cooling}(T^k), & T_s<T^k<T_l \\ or \quad if \quad h^k=h_{cooling}\left(T^k\right), & T^{k+1}>T^k, \quad T_s<T^k<T_l \end{cases} \\ h_{cooling}\left(T^{k+1}\right), & \begin{cases} if\ h^k=h_{cooling}\left(T^k\right), & T^{k+1}\leq T^k, \quad T_s<T^k<T_l \\ or \quad if \quad T^k\leq T_s \end{cases} \end{cases} \tag{4}$$

where, h is the specific enthalpy, $h_{heating}$ and $h_{cooling}$ represent the heating curve and cooling curve respectively, $c_{p,eq}$ is the equivalent specific heat capacity within the hysteresis region, T_s and T_l are the lower and upper temperature limits of the hysteresis region respectively, the superscript k represents the time step, and the subscripts s and l indicate the solid and liquid, respectively.

2.2 Performance indicator and optimization objective

In this study, the building thermal performance enhancement due to the use of the PCMs in the building envelopes and PVT collectors was focused on the winter heating conditions. A performance indicator, named as Coefficient of Thermal Performance Enhancement (*CTPE*) and described in Eq. (5), was used to evaluate the thermal performance of the PCM-enhanced house with integrated air-based PVT collectors [20]. This performance indicator was also used as the optimization objective of the optimization problem.

$$CTPE=1-\frac{\int_0^{tot}\left\{-\min\left[0,(T_{indoor}-T_{setting,low})\right]\right\}dt}{\int_0^{tot}\left\{-\min\left[0,(T_{indoor}-T_{setting,low})\right]\right\}dt\Big|_{baseline}} \tag{5}$$

where, tot is the total time of concern, T_{indoor} is the indoor temperature, and the subscript *baseline* indicates the baseline condition of the house without using PVT collectors and PCMs for building thermal management, $T_{setting,low}$ is the lowest temperature settings for the living and sleeping spaces regulated by NatHERS [21]. Accordingly, the *CTPE* will be varied from 0 to 100%, in which the *CTPE* of the baseline house without using PVT collectors and PCMs was set as 0.

In the design optimization, the air flow rate from the PVT collectors, the additional wall insulation, and the thickness of the PCM layer were considered as the continuous optimization variables. The constraints used for these variables are as follows. It is noteworthy that the effect of the air velocity on human thermal comfort was not considered in this study.

$$\dot{Q}_m \in [1000,4000]\,\text{kg/h};\ R_{wall} \in [1,3]\,\text{m}^2\text{K/W};\ \delta_{PCM} \in [0.01,0.03]\,\text{m}$$

where, $\dot{Q}_m$ is the PVT air flow rate, R_{wall} is R-value of the additional wall insulation, and δ_{PCM} is the PCM layer thickness.

3. Hooke-Jeeves pattern search method

The Hooke-Jeeves algorithm [22] is one of the generalized pattern search methods. In this study, the Hooke-Jeeves algorithm implemented in GenOpt [23] is used as the optimization tool to determine the optimal solutions of the optimization problem. In this method, there are two search types: exploratory search and pattern search [24]. 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 [25]. 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 are as follows [24, 25]:

- Initialization step: determine the starting point, and choose a termination parameter, an initial step size, and an acceleration factor;
- Conduct exploratory search and perform exploratory move at each coordinate;
- Conduct pattern search and replace the starting point; and
- Reduce the step size, and then conduct exploratory search and pattern search until the step size is smaller than the termination parameter defined.

4. Results of performance evaluation and optimization

The performance evaluation and optimization of the PCM-enhanced house with the PVT collectors was conducted over a total of 14 consecutive winter days under Sydney weather conditions, as shown in Fig. 2.

In this study, a commercial PCM product SP21E from Rubitherm [26] was considered and assumed to be integrated into the building envelope.

4.1 Thermal performance evaluation

To evaluate the thermal performance of the PCM-enhanced house with integrated air-based PVT collectors, a design case (named as the PVT-PCM baseline case hereafter) with a PVT air flow rate of 2000 kg/h, additional wall insulation of 1.0 m^2K/W, and the thickness of the PCM layer of 0.01 m were first simulated and compared with that of the house without using PVT collectors and PCMs for building thermal management (named as baseline case). The indoor air temperatures of the house under the two baseline cases are presented in Fig. 4. It can be seen that the indoor air temperature of the house was improved greatly when air-based PVT collectors and PCMs were used. As a consequence, the *CTPE* of the house under the PVT-PCM baseline case reached 42.2%, indicating a significant enhancement of building thermal performance.

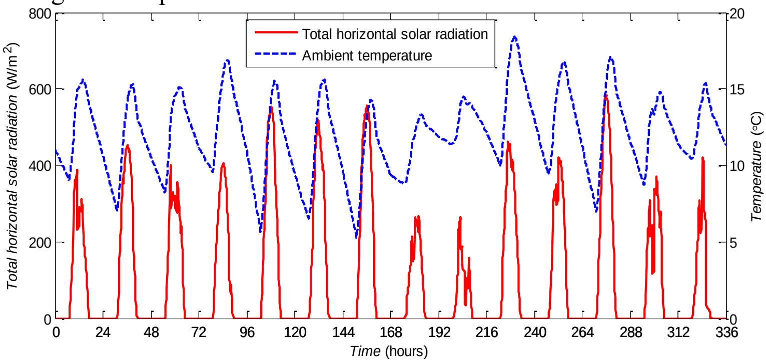


Fig. 2 Solar radiation and ambient air temperatures during the 14 winter test days.

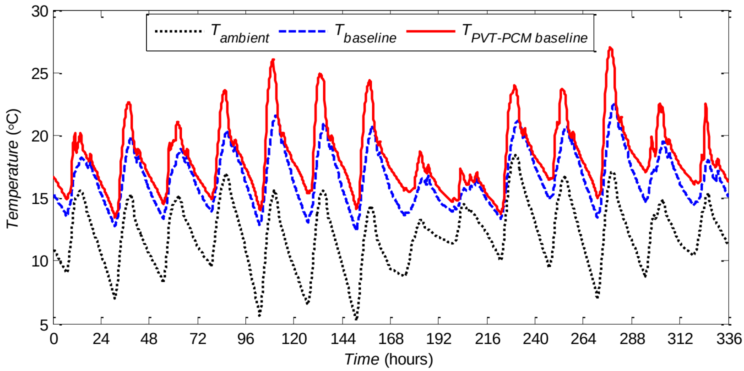
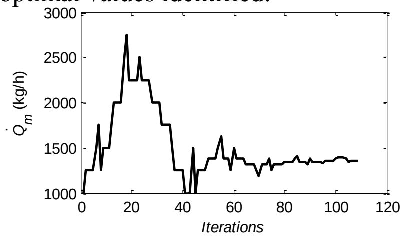


Fig. 3 Indoor temperature of the house under the PVT-PCM baseline case and baseline case without using PVT collectors and PCMs for building thermal management.

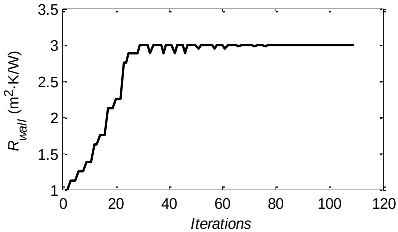
4.2 Design optimization using Hooke-Jeeves pattern search

Further optimization was conducted based on the thermal performance evaluation of the PCM-enhanced house with integrated air-based PVT collectors.

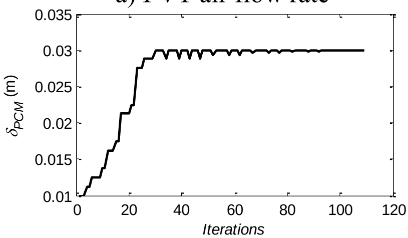
The optimization process using the Hooke-Jeeves pattern search method is shown in Fig. 4, which shows the convergence process against the iteration numbers. It can be seen that, during the optimization process, the PVT air flow rate first increased and then decreased and reached to a relatively stable range (see Fig. 4 a). The identified optimal PVT air flow rate was 1359.4 kg/h. The searched additional wall insulation and PCM layer thickness increased rapidly at the beginning of optimization process and then converged to 3 $m^2 \cdot K/W$ and 0.03m, respectively (see Fig. 4 b and Fig. 4 c). The optimal *CTPE* of the house was 72.6% when using the optimal values identified.



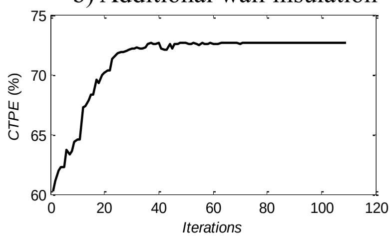
a) PVT air flow rate



b) Additional wall insulation



c) PCM layer thickness



d) *CTPE*

Fig. 4 Optimization process when using the Hooke-Jeeves pattern search method.

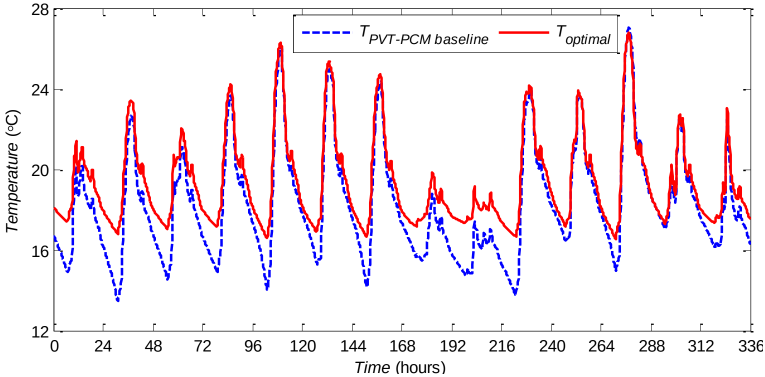


Fig. 5 Indoor temperatures of the PCM-enhanced house with integrated air-based PVT collectors by using the optimal design, and the house under the PVT-PCM baseline case without optimization.

The indoor temperature profile of the PCM-enhanced house with integrated air-based PVT collectors by using the optimal design values identified was compared with that of the house under the PVT-PCM baseline case without optimization and the results are presented in Fig. 5. Compared to that of the house under the PVT-PCM baseline case without optimization, the indoor temperature of the house by using the optimized design was improved significantly during night-time, while it was slightly improved during the daytime in general. This is because more thermal energy was stored in the PCM layer when using the optimal design, which was effectively used during the nigh-time for space heating. During the daytime, the thermal energy collected from PVT collectors was the main contributor to the building thermal performance enhancement. The resulted *CTPE* of the PCM-enhanced house with integrated air-based PVT collectors was enhanced significantly to 72.6% by employing the optimal design values identified by the Hooke-Jeeves pattern search method, which was higher than that of the PVT-PCM baseline case of 42.2%. It is worthwhile to mention that the optimization results will be influenced by the indoor lower temperature settings selected.

5. Conclusions

This paper presents a thermal performance evaluation and design optimization of a PCM-enhanced house with integrated PVT collectors. The Hooke-Jeeves pattern search method was employed as the optimization tool to identify the optimal values of the key design variables, including the PVT air flow rate, additional wall insulation and PCM layer thickness.

The results showed that the simultaneous use of PVT collectors and

PCM in the house can greatly improve the building thermal performance under winter heating conditions. The Coefficient of Thermal Performance Enhancement (*CTPE*) of the house can reach 42.2%, as compared to that without using PVT collectors and PCMs. The *CTPE* of the house can be further increased to 72.6% when using the optimal design values identified by the Hooke-Jeeves pattern search method. The identified optimal values for the PVT air flow rate, additional wall insulation and PCM layer thickness were 1359.4 kg/h, 3.0 m^2K/W, and 0.03 m, respectively.

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