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Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system

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HIGHLIGHTS

- PCM wallboards were used in combination with PCM underfloor heating system.
- Price-based method were experimentally used to perform peak load shifting.
- Solar irradiation was used to minimize energy consumption.
- A cost and energy saving up to 35% and 44.4% respectively were achieved.

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ABSTRACT

Phase change materials are used with various building materials in order to increase their thermal mass. This research is on the application of phase change material in the form of DuPont Energain® wallboards in combination with an underfloor heating system incorporating phase change materials. An experimental study was carried out using two identical test huts at the Tamaki Campus, University of Auckland. Results using a price-based method showed electricity savings in both consumption and cost of up to 35% and 44.4% respectively.

1. Introduction

High energy demand, and excessive consumption of natural resources, have become one of the most critical global challenges. Energy consumption in buildings is responsible for 40% of global energy in the European Union, contributing to production of up to 35% of greenhouse gases [1]. It is expected that, between 2008 and 2030, the world energy demand will increase by about 50% [2]. More than 30% of this energy consumption is caused by heating, cooling and ventilation systems demonstrating the huge potential for improving energy efficiency of buildings [3]. This can be done through modifying the construction systems and using new technologies such as thermal energy storage (TES) for more efficient energy usage in buildings. Latent heat thermal energy storage (LHTES) is preferred for its high energy storage density [4]. Many researchers have suggested the use of phase change materials (PCMs) in buildings to improve their performance [5].

Active and passive storage systems are two types of TES systems that can be used in buildings. Active systems, such as ice storage [6], require an additional fluid loop to charge and discharge the storage tank and to deliver cooling to the existing chilled water loop. PCM also can be used in a storage tank and uses an additional liquid to charge and discharge the PCM. In one example, Martin et Al. [7], used direct contact PCM water storage and managed to obtain between 30 and 80 kW/m^3 of storage. Solar-assisted PCM storage tanks are also another example of active storage systems which can be used for heating application, as demonstrated through modeling and experimental study [8–10] (Similar works can be found in [11–13]). Passive systems, however, do not require any additional heat exchanger to extract heat or cold from the storage [14,15]. Passive TES systems may use the thermal mass of the building to store energy in the form of sensible heat [16,17] or may use PCM in building envelopes to store energy in the form of latent heat, with the objective of shifting and reducing peak cooling loads

Abbreviations: PCM, phase change materials; TES, thermal energy storage; LHTES, latent heat thermal energy storage; DSC, differential scanning calorimetry; RT, room temperature; OP, online price; PC, price constraint; AC, air conditioner.

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[18]. PCM can be incorporated into various building components such as walls [19], floors [20] and window glazing [21].

Impregnation of PCM into construction materials has become a popular area of research in recent decades. This is mainly because walls and floors offer large heat transfer areas within the building, enabling a high heat transfer rate [22]. PCM wallboard [23–25], bricks [26], concrete [27–29] and PCM-impregnated gypsum boards [30,31] are among the common construction elements used for passive storage of energy.

In 2005, a German research group used microencapsulated PCM (peak melting point of 25 °C) in two similar rooms of a full-size building. Results showed that PCM had very little effect on the room temperature because of the high melting point of the PCM chosen. The study also suggested that an adequate ventilations system was required for the solidification of the PCM during the night [32]. Voelker et al. 2008 used micro-encapsulated PCM (melting range between 25 °C and 28 °C) in gypsum boards. The boards were used in two identical lightweight chambers. PCM-modified gypsum board reduced the temperature fluctuation in the chamber by 3 °C. However, because of the high melting point of the PCM, the room temperature increased to 35 °C, well above the comfort level [33]. Numerous experimental studies using microencapsulation or gypsum board impregnated with PCM have shown similar results [34].

In [35], the ENERGAIN PCM board (DuPont) was used, which contained 60 wt% PCM compared to 25–30% in the case of gypsum boards. Results showed that using ENERGAIN PCM boards reduced the room temperatures by up to 4.2 °C compared to a room with normal gypsum board. Further studies focusing mainly on characterization of ENERGAIN boards can be found in [36,37].

The main focus in all these studies has been to increase the thermal mass of lightweight buildings. There has been very little work published on the application of PCM wallboards for peak load shifting application. Qureshi et al. [38], used the same facilities built by [34] consisting of office-size construction containing gypsum board impregnated by RT21 as PCM to facilitate peak load shifting. PCM gypsum wallboards (RT21 used as the PCM) were used to store heat and use it for peak load shifting. The results obtained showed a significant reduction in electricity consumption during peak periods and allowed a total of 31% less energy consumption during a period of 12 days [38].

Unlike the application of PCM in walls, there is limited literature regarding the application of PCM in underfloor heating systems. More than a decade ago, Farid and Kong used a salt hydrate PCM (peak melting point about 28 °C) in concrete slabs to reduce temperature fluctuations of the slab surface. The application of PCM was shown to significantly reduce temperature fluctuations of the slab surface, indicating potential future use of this method for peak load shifting applications. However, the study was done on a small concrete slab and did not explore what the effect of the proposed method would be in a real building. Later in 2005, a Chinese research group used a high melting point PCM in an underfloor heating system (with phase transition temperature of 52 °C). The results showed that enough energy can be stored in the PCM for the following day. However, the reported floor temperature in the study was above 40 °C, which is too high for human comfort. According to the European standard, floor temperature should not exceed 35 °C [39].

Despite a large number of reported studies on the application of PCM in building materials, very little work has been reported on the use of PCM (passively) for price-based peak load shifting. This paper presents the application of PCM wallboards in combination with a PCM underfloor heating system to perform a successful peak load shifting. The research uses a price-based peak load shifting scheme to demonstrate how application of phase change material can significantly improve both energy and cost savings.

2. Methodology

2.1. Price-based control

In the proposed price-based method, the electricity provider monitors electricity load and, as soon as the electricity consumption peaks, the electricity provider increases the unit price. Then users who are using the price-based control system make a decision whether to continue using electricity and pay the higher price, or turn it off. A program was developed using LabVIEW software [40] to read the electricity price from a website when the website address is provided. In this study, wholesale electricity prices for the Auckland city region (obtained from http://www.electricityinfo.co.nz) were used as the electricity price variable.

In order to mimic the real situation, both price and price constraints were fed directly to the control system remotely from the University of Auckland city campus, 12 km away from the experimental huts located at Tamaki Campus of the University.

2.2. Experimental setup

The proposed method for space heating applications was tested using two identical test huts, Hut 1 and Hut 2, situated at the University of Auckland Tamaki Campus. Both huts were constructed using standard lightweight materials, were elevated above the ground, and had a north-facing window (Fig. 1). Hut 1 was used as the reference in this study. Its interior walls and ceiling were finished with ordinary 13 mm thick gypsum board. It is referred to as Hut 1 or the "reference hut" and is used as the base-case in this study. These experimental Huts are similar to those used by [34,38], with the exception of the way PCM and the heating is done and controlled, as described in the following section.

2.2.1. Underfloor heating system

In the first part of this study, Hut 2's interior walls and ceiling were finished with gypsum wallboards, similar to Hut 1. However, the floor was covered with 10 mm PCM-impregnated

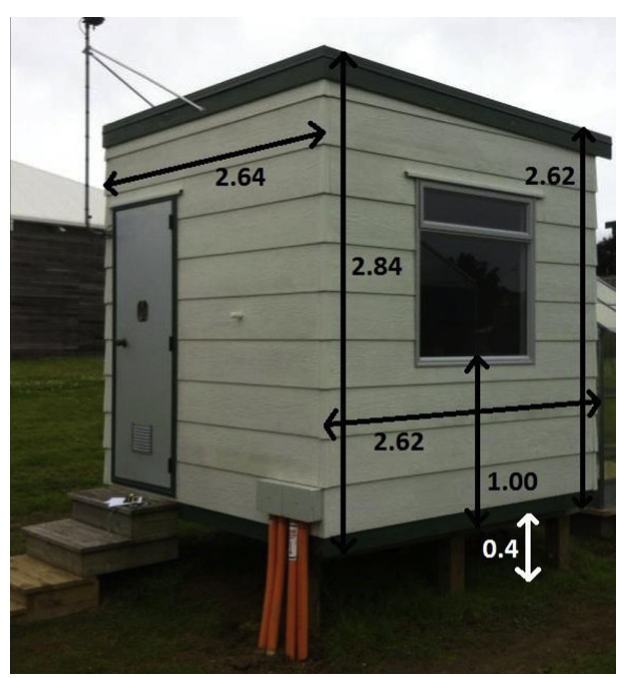

Fig. 1. Experimental hut at Tamaki Campus, University of Auckland.