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Using phase change materials for residential air conditioning peak demand reduction and energy conservation in coastal and transitional climates in the State of California

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A B S T R A C T

The recent rapid economic and population growth in the State of California have led to a significant increase in air conditioning use, especially in areas of the State with coastal and transitional climates. This fact makes the electric peak demand to be dominated by air conditioning use in buildings during the summer time. However, this extra peak demand caused by the use of air conditioning equipment lasts only a few days out of the year. As a result, avoidable power outages occur when power utilities do not keep up with such demand. This paper proposes a possible solution to this problem by using building thermal mass via phase change materials to reduce peak air conditioning demand loads. This proposed solution was tested using a wall herein referred to as phase change frame wall (PCFW). The PCFW is a typical residential frame wall in which Phase Change Materials (PCMs) were integrated to add thermal mass. The thermal performance of PCFWs using a hydrated salt PCM was evaluated via computer simulations of residential buildings located in coastal and transitional climates in California. Simulated results indicated that the PCFWs would reduce the space cooling load by an average of 10.4%.

1. Introduction

The ongoing California electricity crisis (i.e., large-scale brownouts, shortages of electricity, and trans-state pipeline shutdowns), coupled with the rapid growth in the use of summer air conditioning, especially in the coastal and transitional climates of the State has prompted the adoption of technologies and programs aimed at maximizing electric energy efficiency in all sectors affected by these climates, especially the building sector. Coastal climates refer to climates in marine-dominated coastal locations and transitional climates refer to intermediate climates in locations between coastal areas and inland areas of the Central Valley or semi-deserts.

There are two important factors influencing electricity use in California. One is economics and population growth and the other is hot weather. As expected, electricity use increased as economic activity and population, both increased. Hot weather also increases electricity demand for air conditioning. California electricity peak demand generally fluctuates with summer temperature variations, where the air conditioning load contributes a large portion [1].

Electricity use in California is divided into residential, commercial, and industrial sectors. The electric demands by the residential, commercial, and industrial sectors were 43.8%, 34.6%, and 12.0% in 2012, respectively. The remaining demand of 9.6% was contributed by other sectors, such as the agricultural and “other” [2]. Air conditioning use has become a common practice in residential buildings in coastal and transitional climates where air conditioning is typically required only a few days out of the year. Because of the mild nature of the climate in this part of the country, the air conditioning load during those few days has nearly as much impact (percentage wise) on peak demand as the air conditioning load in hotter climates. As a result, residential air conditioning is characterized by sharp peaks [3].

State of California utilities make efforts so that power systems can have enough capacity to serve the entire demand. However, it is costly to build an electric generation and transmission system to supply a peak demand that lasts only a few days each year. Instead, the power system is operated to accept some risks of outages which end up affecting State industries (e.g., tourism, investing), as well as residents’ comfort [1,3].

For this reason, the research presented in this paper was focused on a method to mitigate peak electric demand by reducing the residential air conditioning load in coastal and transitional climates. This method relies on increasing thermal mass in residential

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buildings by adding phase change materials (PCM) to their exterior walls.

In buildings, enclosure thermal storage is an important aspect of energy management and conservation. It is related to building thermal mass. In general, thermal storage is achieved by constructing massive structures, which is expensive and old-fashioned. The principle of thermal storage can be significantly assisted by the incorporation of latent heat storage in building components. This can be achieved by the use phase change materials (PCMs), which absorb and release heat much more effectively than conventional building materials. This is the case because conventional building materials store heat energy in a sensible rather than latent manner. Many experimental and simulation studies on the application of PCMs in building components appear in the technical literature [4–15].

The technology proposed and evaluated in this paper is referred to as phase change frame wall (PCFW). A PCFW is a typical wall in which phase change materials (PCMs) have been incorporated via macroencapsulation to enhance the energy storage capabilities of building walls via the high latent heats of fusion of the PCMs. Macroencapsulation is the technology whereby PCMs are encapsulated in containers larger than 1 mm. Examples of containers include tubes and spheres.

The concept of the phase-change frame walls is an improvement from previous attempts made to integrate PCMs into frame walls. In the past, the attempts to enhance the energy efficiency of walls and ceilings by the application of thermal mass, using the heat storage available during the phase-change process, were met with mixed results [15]. Various PCMs were utilized for this purpose, which were mostly introduced via an imbibing process into gypsum wallboards. These systems demonstrated many advantages in energy savings; however, four main problems limited their potential application. These were (1) durability of PCM-impregnated gypsum wallboards, (2) low water permeability of the walls, (3) low fire rating, and (4) issues of contact between PCM and people and/or PCM and wall coatings and/or wallpapers [14].

The use of PCFWs is proposed to reduce the elevated on-peak demand from air conditioning. The results of the research presented in this paper set in motion a new technology, which if refined, adopted, and implemented, could significantly reduce electricity outages, improve power plant summer load factors, and make residential air conditioning a more cost-effective load to serve. Also, should this technology be adopted, it would represent another step in the United States' efforts to develop energy-efficient home designs that will help lower or eliminate compressor-based space conditioning and that would allow space comfort systems to achieve their intended efficiencies and operation life by reducing their current short-cycle operation.

The main goal of this research was to determine the feasibility of using phase change frame walls (PCFWs) for peak air conditioning demand reduction and energy conservation in California's coastal and transitional climates. Therefore, the results are expected to apply to buildings located in these climate zones, which subject the power utilities to high electric demands and usage for short periods of time in the summer.

2. Numerical model

A model was developed to predict heat transfer across residential walls outfitted with PCMs. The model was validated against experimental data to assess its accuracy. The purpose for this was that a validated model could be used to translate experimental results to full-scale buildings located in basically all climates.

A typical residential wood frame wall was used to develop the model. The section of the wall is shown in Fig. 1. Among other reasons, the construction type of the PCFW was selected based on the fact that this construction type could be used to validate the model presented in this paper. This model was used for extrapolation purposes. To simplify the numerical model, the effects of the studs in the walls were neglected. Including the studs into the model would have required a much complex model, which is out of the scope of the current work. The exterior of the wall was considered to be 1.1 cm plywood sheathing. The insulation was assumed to be fiberglass, 8.9 cm thick, with a thermal resistance of 1.94 m^2 °C/W, which was assumed to fill the cavity between the studs. A 1.3 cm gypsum board was assumed for the inside sheathing. A set of 2.5 cm diameter, type 'M' copper pipes, was used to encapsulate the PCM. The model positioned the pipes within the insulation section very similarly to the actual conditions. For simplicity and as a first step toward developing a PCM model, the interior convective heat transfer coefficient was assumed to have a constant value of 8.29 W/m^2 °C. The exterior walls' convective heat transfer coefficient was assumed to be 22.71 W/m^2 °C. These values were obtained from ASHRAE's Surface Conductances and Resistances for Air [16]. The 8.29 W/m^2 °C was selected based on a vertical wall exposed to the inside of a dwelling where the direction of the heat flow was horizontal and the surface emittance was non-reflective. The 22.71 W/m^2 °C was selected based on a vertical wall exposed to the elements during summer for an average wind speed of 12 km/h and the surface emittance being non-reflective.

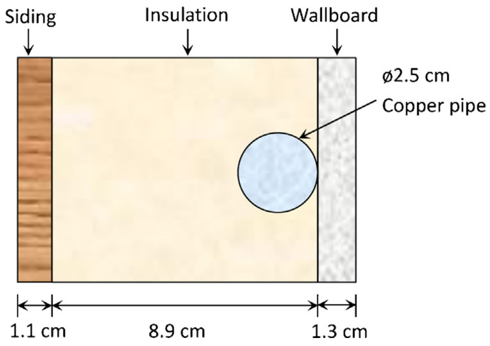

Fig. 1. Section of simulated wall.

The effective heat capacity method (EHCM) was selected, but was modified according to several observations. For example, it is inherent in the EHCM that the latent heat, Q_{lat}, is released during phase change as a function of temperature. However, instead of using the original specific heat, c_p, for either solid or liquid state of the PCM during the phase change, an additional value was added, which resulted in a larger effective c_p. This was done to simulate the slow temperature change during the phase change process. Similarly, several relationships between c_p and phase change temperature could have been assumed. However, in the present case, a simple linear relationship proved to give the best results. Therefore, the value of c_p was simulated as a linear function of temperature over a two degree range. This is shown in Fig. 2. A more robust model, which builds upon what was learned in this research is the topic of a follow up paper. The follow up model will present further research aimed at improving the current model and at minimizing the simple assumptions used in the present model.

Because phase change over a temperature range and the temperature of PCM may not reach a high enough value to complete the melting or solidification process, some portion of the PCM was left "untouched" during melting or solidification. This, when it happens, greatly affected the performance of the PCFW during the next phase change cycle. To consider this situation, it was assumed that the PCM that melted at the higher temperature would solidify at a higher temperature.