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Research Paper

# Effect of the insulation level on the thermal response of a PCM-modified envelope of a dwelling in Chile

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## HIGHLIGHTS

- Temperature-dependent thermal properties of hexadecane (PCM) were measured.
- PCM-modified walls of a dwelling in two thermal zones of Chile were simulated.
- The effect of the insulation level on the heating and cooling demands was studied.
- If the insulation level is increased, the cooling demand is augmented in Santiago.
- When the insulation level is increased, the cooling demand is augmented.

## ARTICLE INFO

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## ABSTRACT

Chile exhibits a continuous growth of energy demand, and for this reason energy saving approaches in the commercial, public, and residential sectors, which share 21% of the final energy consumption in Chile, have been encouraged. One of the solutions to increase energy savings in buildings and dwellings is to increase the thermal performance of their envelope. The use of phase change materials (PCMs) has gained attention during recent years, especially in northern climates, since they can be used to enhance the thermal inertia of light building materials. Usually, the thermal envelope of a dwelling in Chile is made of brick or wood together with light building materials such like fiber-cement, plasterboard, and thermal insulating materials as polystyrene foam. The experimental part of this work deals with the thermal characterization of an organic PCM (hexadecane), which has a relatively low phase transition temperature. The characterization involves the measurement of density, thermal conductivity, and heat capacity as a function of temperature, and the determination of phase change temperature and latent heat. The thermophysical properties were implemented in a set of thermal simulations of an actual project dwelling located in Santiago and Puerto Montt. The numerical results in terms of heat storage and temperature profiles in the envelope, and heating and cooling demands are shown for different insulation levels.

## 1. Introduction

In Chile, the commercial, public and residential sectors share 21% of the total of energy consumption, with electric energy as the most important energy source (34%), followed by biomass (32%), LPG (18%), and NG (11%) [1]. Specifically, the residential sector use 16% of the total electric energy use in Chile [2]. The average Chilean home has an annual total energy consumption of 10,232 kWh/year, which is considered high mainly because of the use of wood as an energy source in the south of the country, mainly due to its low price and availability compared to other sources. In southern Chilean cities like Puerto Montt, wood is used mainly to maintain thermal comfort conditions in houses [3]. Due to its geographical position with respect to high pressure zones, the presence of a polar front, and the influence of the Pacific Ocean and the Andes mountains, Chile has a broad variety of climates. In 2006 the Ministry of Housing and Urban Development of Chile set down act 192, which establishes that *all housing must meet the requirements of thermal conditioning*. The details of this act were shown and discussed in a previous paper [4].

Phase change materials (PCMs) have high latent heat values, therefore they store large quantities of thermal energy per unit volume. The heat storage of PCMs as latent heat is three to four times higher than heat storage as sensible heat [5]. One of the main characteristics of these materials is that during phase change processes, the temperature

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varies within a narrow range while the material absorbs or releases thermal energy. PCMs are classified as inorganic, organic and eutectic mixtures [6]. Among organic PCMs (O-PCMs), three different groups of substances may be found: paraffins, fatty acids, and organic mixtures [7]. These materials have melting temperature close to indoor temperature, thus could be potentially used in residential buildings. O-PCMs are chemically stable, melt and solidify conveniently, without adding nucleating agents, and therefore they are less prone to subcooling [8]. One of the possible applications of the thermal storage capacity of O-PCMs is the increase of the thermal inertia of the envelope materials, the shifting of thermal loads, and the regulation of temperature, helping to decrease temperature variations in a building during a period of time.

Some authors have studied the inclusion of PCMs in the envelope of buildings or in additional building components. Omari et al. [9] made numerical simulations of a one-dimensional heat transfer problem of a modified insulation material with paraffin PCM particles (100 $\mu$m), and optimized the thickness of the insulation material and the PCM load. The effect of melting and solidification of the PCM particles and of the environmental conditions on the temperature and heat transfer across the modified material were studied. The authors found that the thermal conductivity of the insulation material is increased by the addition of PCM and that the melting temperature is a relevant parameter in the optimization of the performance of the modified material according to the season. Moreover, the authors found that the optimal conditions for summer are not suitable for winter. Hichem et al. [10] performed an experimental validation of 2D numerical simulations of heat flux through bricks modified with four different organic PCMs and an inorganic PCM using ANSYS/FLUENT®. The authors analyzed the effect of the position of the PCM inclusion on the modified bricks and the type of PCM on heat flux. Using the inorganic PCM, an 82.1% reduction was found in the heat flux through the brick. However, only 28% of the liquid fraction of the PCM was reached. Kuznik et al. [11] developed a numerical code to simulate a wall containing a commercially available PCM-enhanced material. The authors analyzed different levels of thermal insulation in the wall and the thickness of the PCM-enhanced layer. The results showed that the thickness of the insulation layer does not affect the optimal PCM layer thickness. Bastani et al. [12] performed a one-dimensional numerical study about the effect of a PCM wallboard on shifting cooling energy demands. The boundary conditions of the PCM wallboard corresponds to an adiabatic surface and a time dependent interior set-point temperature. The authors analyzed ten cases in which the thickness and thermal properties of the PCM were varied. The study focused on the analysis of the loading cycle of the PCM wallboard in terms of the thermophysical properties, which allows the optimization of both PCM and building materials properties to generate the desired displacement of the peak cooling load and to reduce the costs of energy consumption.

Other authors have focused on the effects of including PCMs in building materials on thermal comfort. Kusama et al. [13] prepared and thermally characterized modified plaster boards with PCM, which were evaluated in box-shaped test samples and two dwellings with different heating systems during winter. The authors observed that by including PCMs, room temperature fluctuation rate is reduced by up to 40%. Rodriguez-Urbinas et al. [14] studied the effect of the use of micro-encapsulated PCM (30 wt% and melting temperature of 26 °C) in drywall panels. The authors performed numerical simulations in five cities with different weather conditions in Spain, analyzing the effect of window to wall ratio and different shading factors. The results show an increase of up to 31% of hours within the comfort range by using PCM materials, compared to reference cases without PCM.

The effect of the inclusion of PCM on the thermal envelope of buildings on thermal comfort and energy consumption has also been studied using commercially available building performance simulation software, which includes modules specifically designed for the simulation of PCM applications. Saffari et al. [15] performed a review of the studies that evaluate the possibilities of using PCM to reduce cooling energy and to increase the number of hours inside the thermal comfort range in passively cooled buildings. The authors observed that warm temperature weathers were studied more often due to the potential of PCM to reduce cooling energy. Soares et al. [16] reviewed studies regarding PCM applications in buildings, showing that EnergyPlus, TRNSYS, and ESP-r are the most widely used software for numerical simulations of PCM in buildings. EnergyPlus is a commonly used Building Performance Simulation. By having an incorporated validated PCM model, EnergyPlus includes the analysis of PCM alongside different energy saving approaches, during the building design stage. Tabares-Velasco et al. [17] performed a validation of the PCM model implemented in EnergyPlus following the ASHRAE Standard 140, which requires an analytic verification, comparative testing, and empirical validation of the numerical results. Panayiotou et al. [18] analyzed the effect of using PCM enhanced bricks in a dwelling under the weather conditions of Cyprus on energy consumption and free-floating temperature during a whole year. The authors performed numerical simulations using TRNSYS, in which they analyzed different cases with thermal insulation and PCM element implementation and position. The results showed that the lower energy consumption was observed in the case with PCM elements on the exterior surface of the bricks. Moreover, the case with thermal insulation and PCM elements presented a slightly higher energy consumption than in the case with only thermal insulation, but a lower free floating temperature during the summer was observed in the former case. Ramakrishnan [19] performed numerical simulations of dwellings to evaluate the effect of inner linings of PCM materials in walls and ceilings for reducing heat stress during heat waves. The simulations were performed using the CondFD object of EnergyPlus. The simulations consider a night forced ventilation strategy. The authors studied a commercially available PCM (Bio-PCM) and a fictitious PCM with melting temperatures between 25 °C and 31 °C. The authors found that during a heat wave in Melbourne (Australia), the use of Bio-PCM along with night ventilation reduced the hours during which the interior temperature is out of the comfort range by 32% and up to 62% for the best performing fictitious PCM. Marin et al. [20] performed numerical studies with EnergyPlus implementing plaster boards with PCM with a melting temperature of 25 °C in air-conditioned (packaged terminal heat pumps) containers placed in several locations. The authors found that the energy savings in air conditioning depends on the weather conditions. Of the assessed locations, the highest reductions in cooling and heating loads were observed in Calama (Chile). Furthermore, the authors evaluated the free floating temperatures in the containers at the same locations, and found that the use of PCM increases the number of hours within the thermal comfort range, except in tropical locations. Chernousov et al. [21] studied numerically with EnergyPlus the effect of implementing PCM elements in an office building envelope located in a subtropical climate to reduce cooling energy during the summer morning hours. The study considered two stages. The first one consisted in simulations to determine the effects of PCM position within the envelope, the amount of solar radiation received and PCM layer thickness. After these analyses, the authors studied the PCM enhanced PCM building including the chiller of the cooling plant, to evaluate the effect of the PCM on cooling energy consumption. The results showed that using the PCM on the interior surfaces of the building reduces the energy consumption by 1% to 4%, and that increasing the thickness of the PCM layer increases cooling energy consumption.

The present work is focused first on the thermal characterization of hexadecane as a phase change material of a relative low phase transition point (18 °C), near to the transition point of some fatty acids [22], which may be of interest in near to room temperature applications mainly thanks to their condition of no oil-derived product. Thermal conductivity, heat capacity, and density were measured as a function of temperature, in both the liquid and the solid phase. These properties are required in the second part of the paper that deals with the thermal