Energy Conversion and Management 150 (2017) 48–61

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermal performance and economic evaluation of a newly developed phase change material for effective building encapsulation

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ARTICLE INFO

Keywords:
PCM
Heat flux
Economy
Thermal performance

ABSTRACT

Ever-growing construction industries worldwide require energy saving, environmental friendly, inexpensive, and thermally efficient materials. Driven by this demand, we evaluated the thermal performance and economy of a newly developed PCM called local paraffin. These PCMs as potential thermal energy storage (TES) systems were extracted from Iraqi crude petroleum waste product and encapsulated in the building construction. Two identical test rooms were constructed by incorporating such paraffin (40% oil + 60% wax) on the roof and walls for determining its effect on the heat transfer over the temperature range of 40–44 °C. Experiments were conducted for achieving the controlled comfort temperature of 24 °C (below the PCM melting temperature). Room without PCM encapsulation was demonstrated to consume higher energy at 24 °C than the one with PCM. The energy economy of the PCM incorporated room was assessed by comparing the estimated electricity cost with the building that contains the traditional air conditioning system. Analytical calculation was performed to validate the experimental results. These paraffin based TES systems were established to be suitable alternative for efficient and green energy implementation in the building design for hot climate nations.

1. Introduction

Most of the countries worldwide with extended winter and summer seasons show rapid fluctuations in the day and night temperatures. It is needless to mention that load demand in the nations with prolonged summer and winter seasons being so high frequent power failure and high electricity bills is quite common. Consequently, the electricity consumption over the day and night time varies considerably during such periods [1]. The power cost depends on the load demand arise from various activities in the residential, commercial, and industrial sectors. Thu, the cost of energy consumption also varies during off peak and peak season. In this regard, an ideal thermal energy management is required to conserve the energy during such peak demanding period. Recently, it is realized that thermally efficient and energy saving building construction materials is the only option to cope up with the ever-growing power demand. Therefore, the phase change materials (PCM) as potential thermal energy storage (TES) systems emerged in its own right [2–5].

A phase change material called PCM appears versatile for enhancing the heat energy saving when encapsulated in the building ceiling, floor, roof, and walls. The PCM containing surface allows the absorption of solar thermal radiation and maintains the internal temperature of the building at the comfort point for extended time period. Presently, the surface area of most of the commercially available PCM incorporated products is not sufficient to heat the building efficiently [6]. Conversely, the ceiling and walls of the room in building covers the major surface region for passive thermal transfer in every setting [7]. Thus, the proficient implementation of PCM in the construction of building can be accomplished via different modes such as: (i) in conservation components for cooling and heating; (ii) in the floor and ceiling; (iii) in the walls. For PCM encapsulated floor, ceiling and wall (classified as passive systems) the heat accumulation or discharge in the PCM can be programmed depending on the ambient/atmospheric temperature. In opposition, the first type being considered as an active system releases stored heat based on actual demand [8].

The applicability of gypsum wallboard and concrete block impregnated PCMs have already been realized towards building construction [9,10]. In wallboard construction, although the PCM is positioned in the other building structures, gypsum board, or plaster but the

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http://dx.doi.org/10.1016/j.enconman.2017.07.043
Received 14 March 2017; Received in revised form 14 July 2017; Accepted 20 July 2017
0196-8904/

Nomenclature

Cp	specific capacity of heat (kJ/kg K)	T_m	melting temperature
Cp_L	specific heat of liquid PCM (kJ/kg K)	k_L	thermal conductivity of PCM at liquid state
Cp_s	specific heat of solid PCM (kJ/kg K)	ρ_S	density of PCM at solid state (kg/m^3)
T	temperature (°C)	ρ_L	density of PCM at liquid state (kg/m^3)
T_∞	ambient temperature (°C)	α_S	thermal diffusivity of PCM at solid state
U	heat transfer coefficient	α_L	thermal diffusivity of PCM at liquid state
h	enthalpy (kj/kg)	h_0	room outside heat transfer coefficient
k	thermal conductivity of aluminium	h_i	room inside heat transfer coefficient
TC	thermo cable	q_s	heat flux in W/m^2
		T_{Roof}	roof temperature
		T_{amb}	ambient temperature

principle of latent heat storage (LHS) can be employed on any appropriate structure. The procedure of PCM integration process into the plasterboard may differ. First, it can be either through the procedure of post-production siphoning of liquid PCM within the pore spaces of plasterboard. Second, it can be via the incorporation within the plasterboard construction wet stage. Traditionally, the heat comfort inside the light-weight building is enhanced by integrating the PCMs into the building structure. Majority of the processes that use macro-capsules or direct immersion suffers from various limitations. Due to these drawbacks most of the commercially available PCM based products are not able to penetrate the expansive market successfully.

The highest diurnal energy storage is found to present at the encapsulated PCM melting temperature value closest to the moderate comfort room temperature under various situations. Furthermore, the diurnal energy storage is reduced during the phase transformation over a temperature range. According to Stovall and Tomlinson [11] research, 30% of PCM in a normal wallboard acts as an ideal energy saver in the passive solar systems with a payback period of 5 years.

The physio-mechanical properties of this manufactured heat storage wallboard are found to consistent with the attributes of standard gypsum board. Turnpenny et al. [12] suggested an insulation system by developing a latent thermal storage unit integrated with embedded thermal pipes in PCMs. A model simulation (one dimension) on the heat transfer from air towards PCM revealed an enhancement of the test unit sizing. Besides, it is observed that the proposed system can preserve the coolness at the night time by releasing the heat during the day time. It is demonstrated that such systems can recover 17–36% of the heat lost on the first gain [13] by installing a fan at 30 cm above the floor. Within the spherical PCM disc, the small-sized aluminium tubes enclosing the inlet from the water tank and an outlet towards the surroundings are configured. This is considered as reference for comparing with the numerical outcomes of the PCM cold storage simulation model in buildings. The modified ceiling fan is discerned to be a prospective solution for effective cooling.

Kondo and Ibamoto [14] used PCM for an office building ceiling boards to determine the influences of air conditioning systems on the peak energy shaving. Micro-capsulate PCM, with melting point of ≈25 °C is used to enhance heat storage of rock wool PCM ceiling board. In this arrangement, PCM ceiling board replaced the rock wool one. It is shown that during night time the stored heat allowed the cold air to enclose the chamber space of the ceiling and cooled the PCM ceiling board thereby preserved the cool heat energy. [15] analyzed experimentally the cooling of a building using paraffin (melting point of 22 °C) impregnated ceiling board. The PCM cooling during the night time is monitored for a whole week. It is observed that the external temperature remained stable during the entire week. The amount of PCM generated cool air is computed for 0–300 min and the system provided an ideal cooling condition inside the building. In addition, the floor heating played a vital role to provide comfortable internal condition than the convective heating arrangements.

Athienitis and Chen [16] examined the transient thermal transfer for floor heating systems. They determined the influence of solar radiation and floor cover layer temperature distribution on the energy consumption. The effect of full and partial (area) carpets as well as the hardwood cover layers on gypcrete (a mixture of gypsum and concrete) or concrete heat storage is studied. Numerical simulation results for an external test room revealed that the solar radiation generate a local floor surface temperature within the area under illumination which is 8 °C higher than the one within the shadowed region. Likewise, the partial carpet is found to enhance the floor surface temperature by 15 °C due to solar radiation absorption. This observation is attributed to the preservation of solar radiation inside the floor thermal mass which in turn reduced the heating energy consumption by 30% or more. Enhancement of the thermal mass thickness from 5 to 10 cm did not produce significant energy storage in the presence of traditional proportional-integral control.

Lin et al. [17] studied the thermal performance of under-floor electric heating system using shape-stabilized phase conversion material composed of 75% paraffin wax and 25% polyethylene. Using the supplied electrical power during the night this system is recharged and then discharged automatically during the day. Although the variation of temperature during day and night time of 12 °C but the average indoor temperature remained constant at 31 °C. Thus, an optimum indoor temperature is achieved without any major alteration in the temperature during the experiment. Nagano et al. [18] proposed a floor conditioning system by blending paraffin mixture with foamed waste glass beads. The PCM packed bed of 3 cm thick is installed below the floorboard that contained several tiny openings. The amount of stored heat and alteration of the room temperature is estimated. A cooling load revealed a shifting tendency in the presence of packed granulated PCM.

Earlier great researchers dealt with commercially available paraffin and melting temperature achieved in commercially obtained paraffin is just 29 °C [19–28]. Herein, in practical situation especially in hot climate countries the temperature variation over the year is too large and the maximum summer temperature can reach up to 55 °C. Thus, the suitability of these extracted materials requires a testing around this temperature which is performed by making roof and wall structures with the implementation of locally extracted paraffin. Yet, the heat flux inside the room at temperature higher than 30 °C is not investigated. It is expected that the use of the newly extracted local paraffin as PCM may bring more thermal comfort in terms of reduced temperature fluctuation inside the test room. This would be advantageous to minimizing the electricity consumption and saving economy.

2. Materials and methods

2.1. Materials

Experiments are performed in collaboration with the Ministry of Petroleum (Iraq) as a provider of indigenously extracted paraffin (PCMs as by-products of oil) which is proven to be non-flammable and safe material for building construction. Paraffin of three different compositions including PCM1 (60% oil + 40% wax), PCM2 (50% oil + 50% wax) and PCM3 (40% oil + 60% wax) are tried to determine best one