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High density polyethylene spheres with PCM for domestic hot water applications: Water tank and laboratory scale study

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ABSTRACT

Renewable energy is a potential alternative energy provider with fewer CO_2 emissions. However, the mismatch between energy supply and demand is the main disadvantage. Therefore, thermal energy storage becomes an essential technology for enhancing renewable energy efficiency and providing energy supply to the end user. In solar thermal energy systems, hot water tanks are widely used as sensible heat storage technology. Moreover, water storage usually requires large volumes and their improvement has been studied in terms of shape and arrangement. Latent heat storage materials are a potential technology for implementation in water storage tanks in order to reduce their volume and to enhance their efficiency. In this paper, the incorporation of shape high density polyethylene spheres with PCM into domestic hot water tanks is studied. Undesired results obtained in the water tank set-up lead the authors to analyse the PCM leakage in the laboratory. Laboratory analysis pointed out that the PCM-spheres must be thermally cycled and cleaned before their implementation in real application of domestic hot water in order to stabilize the PCM content inside the PCM- spheres.

1. Introduction

Renewable energy systems are characterized as providing energy with fewer CO_2 emissions than conventional systems [1]. However, the main drawback of renewable energy is the gap between supply and consumption [2]. Therefore, energy storage technologies are an important part of the system to ensure the energy supply available to the end user. Thus, the energy storage system plays a very important role to define the energy efficiency of the system [3].

In the case of solar energy, the sun as an energy source can be guaranteed only for few hours a day and it has variable intensity during daytime [1]. These facts require a storage system capable of providing heat during periods of reduced solar radiation [4]. Moreover, the use of thermal energy storage (TES) technologies has high potential to shift or smooth the peak power demand, as it is demonstrated by [5]. Nowadays, heat storage in a hot water tank is the most widely used system, where the sensible heat is stored in a liquid medium. Many studies have focused on improving these tanks in terms of shape [6], material [7], envelope [8] and the tank arrangement [9].

A promising energy storage technology is the use and implementation of phase change materials (PCM) [10]. In this case, the latent heat absorbed and released during the phase change from solid to liquid is used. With these materials a larger amount of thermal energy can be stored compared to the sensible heat absorbed by the water [11]. In addition, the PCM works within a specific temperature range (phase change temperature), between 55 °C and 70 °C in the case of domestic hot water tanks, which allows the design of the system to be related to the desired application for obtaining the maximum amount of energy [12].

The inclusion of PCM to improve the performance of the TES systems have been studied by improving heat transfer through the application of fins, enhancing thermal conductivity, application of tube-in-shell TES, and using microencapsulation [13]. In a study done by Cabeza et al. [14], the authors concluded that it is a very promising technology, because it provides hot water for a longer period of time. Moreover, Nkwetta et al. [15] used a numerical investigation to study the performance of a domestic hot water tank with integrated PCM. The impact of different PCM, its amount and location inside the water tank were the principal aspects analysed. The authors concluded that for practical application, the

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PCM should be placed at the top of the tank to promote stratification and take advantage of it in order to achieve high energy storage performance. Moreover, Farid et al. [16] in their review provided a vision on PCM encapsulation, concluding that macro-encapsulation offered more benefits in solar thermal energy storage applications.

In a domestic heating solar-aided system, Esen et al. [17] studied two different designs for a latent heat storage tank. A tank with PCM encapsulated in cylinders, studied in detail by Esen [18] in a later article, and a tank filled with PCM which contained pipes were the HTF flows through. Authors concluded that the PCM melting time depends not only on the thermo-physical properties of the PCM, but also on the geometric parameters.

The geometrical configuration of the PCM encapsulation is an issue that Barba and Spiga [19] took into account. The performance of three different cases (slab, cylinder and sphere) was analysed during the discharging process of a domestic hot water tank. The authors concluded that the best configuration was represented by small spherical capsules if a rapid discharge mode was desired. The same conclusion drew Wei et al. [20] where different geometric properties of the macro-encapsulation were also studied.

The encapsulation methods most used in domestic hot water systems or solar thermal energy storage applications are the macro-encapsulation (also called core-shell) and shape-stabilized PCM [21]. Different materials have been used to contain the PCM such as acrylics, urea, formaldehyde and silica based polymers, metals and carbon based composites as graphene and graphite, among others [21]. Shape stabilized PCM presents some interesting advantages such as high amount of PCM content can be integrated into the material matrix and thermal reliability over a long time period [22]. In this context authors found a commercial product, where the PCM is impregnated in a high-density polyethylene in spherical form. Therefore, the inclusion study of a new spherical product containing phase change materials in a domestic hot water tank solar-assisted is presented in this paper. Different amounts of PCM inclusion were studied in order to determine the most appropriate implementation according to their thermal behaviour. Moreover, a laboratory analysis of the spherical product was carried out to evaluate its thermal stability.

2. Pilot plant scale

2.1. Experimental set-up

An experimental set-up was prepared to analyse the effect of adding phase change materials (PCM) in the top part of a water tank. The experimental set-up consisted of a transparent acrylic plastic water tank of 600 × 400 × 500 mm supplied by an external power source that simulated a solar collector. The tank was instrumented with 15 thermocouples type-T prepared in the laboratory according to the EN-60584-1:2013 [23], related to the applicable accuracy to this type of sensors, with a standard deviation of 0.16 °C. The sensors were placed inside a PVC pipe as shown in Fig. 1 in order to measure the temperature of the water at different levels of the tank.

A commercial product (Ball-ICE® marketed by PCM Products [25]) of polyethylene spheres impregnated with a paraffin mixture that has a melting point of 58 °C (Fig. 2), were tested. The spheres were analysed with the differential scanning calorimetry (DSC) in order to obtain their thermal properties and the results are shown in Table 1 together with the ones provided by the manufacturer.

2.2. Methodology

The experiments consisted of heating the water tank up to 62 °C. Once the water reached the maximum temperature these conditions were maintained during 1 h and afterwards the tank was cooled down naturally to 32 °C. This experiment was carried out with the water tank without PCM and with different amounts of PCM spheres, thus increasing the energy storage capacity of the water tanks by 17% and 33%, respectively (Table 2). Each experiment was duplicated to have repeatability.

The storage density provided in Table 2 is calculated through the addition of the energy provided by the amount of PCM spheres (Q_{pcm}) to the energy provided by the water in the tank (Q_{water}). The following equations were used:

$$Q_{pcm} = m_{pcm} \cdot L_{pcm} \quad (1)$$

where, m_{pcm} is the total PCM spheres mass incorporated in the system and L_{pcm} is the latent heat of fusion.

$$Q_{water} = m_{water} \cdot Cp_{water} \cdot \Delta T_{\mathrm{exp}} \quad (2)$$

where, m_{water} is total water mass, Cp_{water} is the water specific heat capacity, ΔT_{exp} is the temperature difference performed in the water tank during the experiment (62 °C to 32 °C).

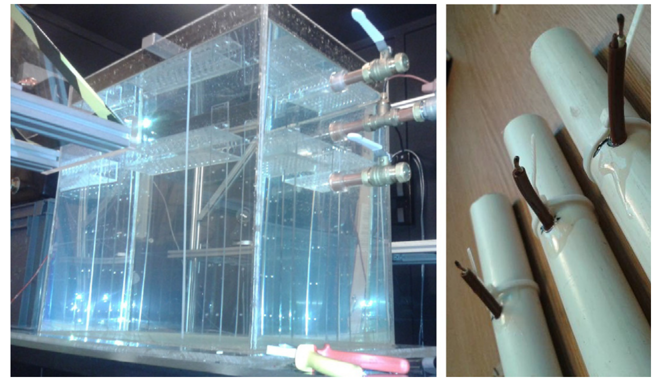

Fig. 1. Left, water tank installation; right, thermocouples type T.

Fig. 2. PCM spheres (Ball-ICE®).

Table 1
PCM spheres physical properties.

PCM spheres A58	Manufacturer	DSC	
Phase change temperature	58	T_m 55–T_s 45	(°C)
Density	910	–	(kg/m^3)
Latent heat capacity	132	135	(kJ/kg)
Volumetric heat capacity	120	–	(MJ/m^3)
Specific heat capacity	2.2	–	(kJ/kg·K)
Thermal conductivity	0.22	–	(W/m·K)

T_m: melting temperature; T_s: solidification temperature.