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Experimental analysis of hydroquinone used as phase change material (PCM) to be applied in solar cooling refrigeration

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ABSTRACT

This present paper is focused on the study of high temperature thermal energy storage (TES) using phase change materials (PCM) to be applied on cooling and refrigeration systems by solar cooling. Thus, a pilot plant with a working temperature range between 150 and 200 °C was designed and built at the University of Lleida (Spain). Hydroquinone was selected for the specific application from different PCM candidates as the most suitable material after a literature review and a differential scanning calorimetry (DSC) analysis. This PCM has a phase change temperature range between 166 °C and 173 °C and a melting enthalpy of 225 kJ kg^{-1}. Two storage configurations were evaluated using the same PCM to have preliminary results before the final storage tank design. From the pilot plant results and experience, a 5 Tn PCM storage tank was designed and built to work in a real solar cooling installation in Seville (Spain).

Analyse expérimentale de l'hydroquinone utilisée comme matériau à changement de phase dans les applications de refroidissement solaire

Mots clés : énergie solaire ; refroidissement ; accumulation thermique ; changement de phase ; transfert de chaleur ; ailette

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1. Introduction

Nowadays, the use of solar energy in solar cooling applications or concentrated power plants may play an important role in the energy savings and CO_2 reduction EU commitments (Gil et al. (2010)). A wide variety of cooling techniques powered by solar collector-based thermally driven cycles have been developed and applied in the last decades. Tsoutsos et al. (2003) studied the potential for market penetration for each solar cooling technology, and have stated that absorption has the highest one. On the other hand, Kim and Infante Ferreira (2008) listed a wide variety of possibilities to use solar energy for refrigeration.

Thermal energy storage (TES) is a widely studied and used topic due to its potential load reduction and energy savings since solar energy is time dependent and therefore a mismatch between the energy supply and the energy demand may occur. TES systems may potentially help to save around 7.5% of the total energy consumed in the European Union each year. In particular, a study about TES potential in buildings and industrial sectors presented by Arce et al. (2011) demonstrated that only in Spain TES systems may potentially help to save 140,883 GWh_{th} in domestic cooling applications.

Different high temperature TES systems and materials were studied by many researchers such as Zalba (2003) and Sharma and Sagara (2005) during last years. Storage systems could be based on sensible, latent or thermo-chemical heat. Here, a TES system based on phase change materials (PCM) which absorb or release heat when the PCM undergoes a phase change is considered. The key issue of TES systems is the selection of the best storage material (phase change temperature and latent heat) for each application. Many researchers have been working on the analysis of the thermal performance of different materials using both sensible and latent heat materials. Trp et al. (2006) analysed numerically and experimentally the transient phenomenon during both charging and discharging processes of the shell-and-tube latent energy storage system using paraffin as PCM. The authors concluded a general statement saying that the selection of the operating conditions and geometric dimensions depends on the required heat transfer rate and the time in which the energy has to be stored or delivered. Schweigler et al. (2007) studied the application of water/lithium bromide (LiBr) as PCM in a solar cooling installation. Similarly, Adine and Qarnia (2009) presented a numerical analysis of the thermal behaviour of a shell-and-tube PCM system comparing the utilization between one and two PCM.

The objective of this study is to test different storage systems using hydroquinone as PCM in an adequate temperature for solar cooling applications to be applied to a real installation using an absorption chiller and a field of Fresnel collectors as Fig. 1 shows. To achieve this objective, a high temperature pilot plant with two similar storage tanks (one with and the other without fins) were designed and built at the University of Lleida. In addition, from the results got at the pilot plant scale and the experience with working with such systems (Gil et al., 2013a and Gil et al., 2013b), a bigger storage tank using the same material as PCM was designed and built to be placed on the roof of the Engineering School of Sevilla building for solar cooling purposes (Gallego et al., 2013).

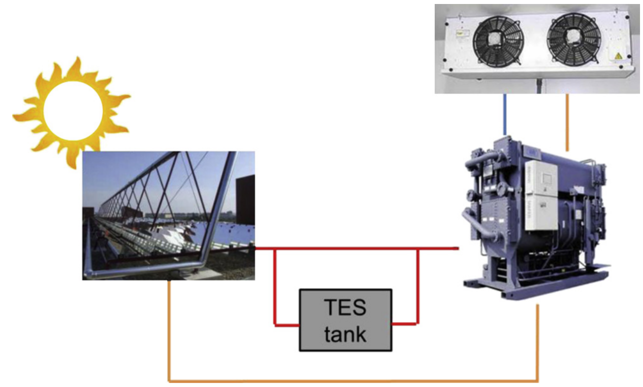

Fig. 1 – Location of the thermal energy storage tank in the solar cooling application.

2. Materials and methodology

2.1. Phase change material selection

The main requirement in terms of PCM selection was a melting temperature range between 140 °C and 200 °C, where 140 °C represents the minimum inlet temperature in the absorption chiller and 200 °C the maximum temperature leaving the solar collectors. Another requirement was a latent heat higher than 150 kJ kg^{-1}. Moreover, mechanical, chemical, economic, and environmental properties of the candidates such as volumetric variation between solid and liquid state, chemical stability, vapour pressure, toxicity, compatibility with the container material, price and availability were taken into account in the selection process.

Table 1 shows all the possible PCM candidates in the temperature range of solar cooling applications from both literature review and experimental data by Differential Scanning Calorimetry (DSC) presented in the previous work carried out by Gil et al. (2013a). The equipment used to perform this analysis was a DSC-822e commercialized by Mettler Toledo. The analysis was performed using a dynamic method from 150 to 180 °C and a heating rate of 1 °C min^{-1}. The amount of sample studied was around 15 mg in an aluminium crucible under N_2 atmosphere. Hydroquinone was selected as the most suitable material for this application because its melting temperature range is within the range defined, the phase change enthalpy is higher than the minimum value required and presented almost no subcooling.

2.2. Experimental set-up

The University of Lleida pilot plant has been constructed to test accurately different TES systems working with latent or sensible heat storage materials. This facility is compound by an electrical boiler of 24 kW_e to heat up the heat transfer fluid (HTF) acting as energy source during the charging process, different storage tanks containing PCM materials and an air heat exchanger of 20 kW_e to cool down the HTF in order to simulate the real energy consumption which in this application would be the absorption chiller. All the tubes connecting