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Experimental investigation of a latent heat storage for solar cooling applications

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HIGHLIGHTS

- Testing of a latent heat storage for solar cooling applications is proposed.
- The storage is made of a finned heat exchanger and a paraffinic blend.
- The effect of operating parameter and incomplete phase change have been evaluated.
- Thermal conduction is the dominant heat transfer process in the storage system.

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ABSTRACT

The paper presents the realization and experimental characterization of a lab-scale latent heat storage, specifically developed for solar cooling applications. The latent heat storage is based on a compact fin-and-tube stainless steel heat exchanger (HEX) and a commercial paraffin blend, having a nominal melting temperature of 82 °C, suitable for solar cooling plants employing non-concentrating solar collectors technology. The realised heat storage has been experimentally characterised in lab, by means of a test rig able to simulate the working boundary conditions of a solar cooling plant. Charging and discharging tests have been performed both simulating a completed charge phase followed by a complete discharge phase, to analyse system efficiency and achievable energy storage density. Furthermore, dynamic tests, simulating short consecutive charge/discharge phases (with incomplete phase change), have been accomplished, to analyse the heat transfer efficiency inside the reactor. Main results confirmed that the heat storage density increases of about 50%, compared to sensible water storages. Satisfactory discharge efficiency, ranging between 45% and 60% has been obtained under analysed working conditions. Average discharging power between 0.7 and 1.2 kW has been measured, which confirms the necessity to further optimize the HEX efficiency as well as the thermal conductivity of the employed PCM.

1. Introduction

Solar cooling technology has recently gained a growing interest in many countries. Accordingly, different technologies for the exploitation of solar thermal energy for HVAC applications are the focus of an intense research activity [1]. Indeed, solar energy is widely available throughout the world and presents a great potential for the reduction of fossil fuels consumption. However, its availability is strongly dependent on time, since mismatches exist between energy accessibility and energy demand. In such applications, a thermal energy storage system (TES) is therefore necessary in order to increase the exploitability of such a resource, resulting in consistent energy savings. Indeed, considering solar thermal systems in all Europe, the achievable energy savings have been estimated close to 10% [2]. Great effort has been put, during the last years, in the search for thermal storage technologies able to guarantee high energy density and efficiency. Particularly, both thermochemical and latent heat storage systems have been deeply analysed [3]. Phase change materials (PCMs) are considered among the most promising solutions, for the possibility of tailoring the temperature of the material to the chosen field of application and for their storage density that can be up to 300% higher than those of sensible heat systems [4]. Extensive information on the available PCMs, their classification and properties can be found in [5–7], where possible applications are highlighted.

The studies in literature regarding the application of phase change materials in solar systems comprise several fields of

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Nomenclature

A	area (m^2)
c_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
E	energy (MJ)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	power (kW)
T	temperature (°C)
u	uncertainty (–)
U	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
V	volume (m^{-3})
x	linear dimension (m)

Subscripts

ave	average
ch	charge
disch	discharge
eff	effective
fin	final
in	inlet
out	outlet
th	theoretical
0	initial

Greek letters

ε	efficiency (–)
τ	time (s)

Abbreviations

CSP	Concentrating Solar Power
DSC	Differential Scanning Calorimeter
HEX	heat exchanger
HTF	heat transfer fluid
HVAC	Heating Ventilation and Air Conditioning
PCM	phase change material
TES	thermal energy storage

application: systems for domestic hot water (DHW) production, with the storage embedded either in the solar collector [8,9] or as a stand-alone component [10,11]; systems based on air solar collectors and PCM-based thermal storage for building heating applications [12]; Concentrating Solar Power (CSP) plants with high temperature (i.e. higher than 250 °C) thermal storage [13]. More recently, some analysis on application of PCMs in solar cooling thermal storage applications have been issued. In [14] Helm et al. reported the energetic analysis of a solar cooling plant employing a latent thermal storage on the medium temperature loop to support the heat rejection of the absorption cooling machine to the ambient. This application proved to be particularly efficient in shifting the electrical energy needed to drive the cooling tower from the main hours of the day to the off-peak hours during night, thus reducing the operating cost of the whole system. Belmonte et al. [15] numerically investigated similar application, by comparing a standard open wet tower to a PCM storage inserted in the heat rejection loop of a solar cooling plant. The analysis was conducted through system simulation in different areas in Spain. The obtained results, in terms of total cooling energy produced and system efficiency demonstrated the possibility to get a beneficial effect especially in locations with temperate and humid summers, where the cooling tower needs high electrical energy to be efficiently operated. More recently, the experimental and theoretical analysis of the integration of a packed bed cold storage employing encapsulate PCM in a solar cooling plant has been reported by Cheng et al. [16]. The study aimed at analysing the effect of temperature and flow rate of the heat transfer fluid on the achievable energetic and exergetic efficiency. The results confirmed the possibility of enhancing the performance of the system since its operating stability is increased thanks to the inclusion of the cold storage. Nevertheless, so far, only a few activities have been reported on the analysis of high temperature PCM-based heat storage, employed to store solar thermal energy to drive the sorption chiller, thus extending the operating range of the system also when the solar radiation is not sufficient to operate the system. Most of them are based on modelling activities, focusing on energy, exergy and economic analysis [17,18]. The experimental works carried out on materials and components for high temperature thermal storage in solar cooling plants have been mainly focused on systems employing concentrating solar collectors (e.g. parabolic through, Fresnel collectors) as the main heat source [19–21]. This implies that such activities are restricted to temperature levels higher than 150 °C, which are not compatible with most typical solar cooling systems based on non-concentrating solar thermal collectors (e.g. flat plate, evacuated tubes). More recently, Brancato et al. [22] have reported about the investigation of different promising PCMs for application in solar cooling systems driven by non-concentrating solar thermal collectors. The investigated PCMs are primarily meant to store heat at a temperature level compatible with the driving temperature of commercial sorption chillers (i.e. 80–100 °C). The work investigated both achievable thermodynamic performance as well as cycling stability issues. Main results confirmed the possibility to increase significantly the energy storage density of the system (i.e. up to seven times the heat storage density of water), by selecting the proper PCM. Nevertheless, it was clearly highlighted that most of the non-commercial materials still need to be investigated and optimized, in order to increase their long-term stability.

Despite the promising features of PCMs, their practical utilization and exploitation is still limited by their low thermal conductivity [3,5]. To increase heat transfer inside the material, and therefore charging/discharging efficiency, several methods have been proposed: the addition or dispersion of highly conductive particles inside the material, microencapsulation, impregnation of highly conductive porous materials or metal foams or the addition of fins to the heat exchanger (HEX) containing the material. An extensive overview of the proposed techniques for heat transfer enhancement is given in [3]. The application of fins to a latent heat storage using erythritol has been studied in [23], where a 20% increase in discharge efficiency was obtained through the use of longitudinal or circular fins. In [24], a comparative analysis of different HEXs (finned-tube, plate, double pipe) has been performed, with the finned HEX resulting in the higher power output and a good heat storage capacity.

Furthermore, in the literature there is still a lack of experimental activities dedicated to the characterization of heat storages for non-concentrating solar cooling applications. Indeed, as recently reported by Wang et al. [25], typical temperature difference between inlet and outlet of the hot water stream is between 10 °C and 15 °C (e.g. 90 °C inlet and 75–80 °C outlet). This confirms the need to experimentally investigate the storage behaviour under controlled boundaries able to replicate typical working conditions of a non-concentrating solar cooling plant, allowing the