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Research Paper

Experimental analysis of the effective thermal conductivity enhancement of PCM using finned tubes in high temperature bulk tanks

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HIGHLIGHTS

- Experimental study at pilot plant scale of addition of fins in LTES systems.
- Comparison of two LTES tanks, with and without fins, during a charging process.
- Hydroquinone was selected as PCM.
- Effective thermal conductivity was compared at different thermal power ratios.
- Increase in measured thermal effective conductivity was 4.11–25.83%

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ABSTRACT

Solar cooling is a promising solution to overcome the high energy demand of buildings. Nevertheless, the time dependent nature of the solar source leads to the need of storage systems in order to better match the energy demand and supply. For this purpose, thermal energy storage was considered during last decades as the optimal solution at commercial scale. Latent thermal energy storage offers higher energy densities together with more constant outlet temperature than sensible heat storage, but the low thermal conductivities of PCMs represents the main drawback which limits its applicability. Several studies based on heat transfer enhancement techniques applied in latent thermal energy storage have already been performed. Specifically, the technique of adding fins in storage tanks, which is the most known and studied. However, there are few experimental studies at pilot plant scale focused on this technique and less on the analysis of the heat transfer enhancement through the parameter effective thermal conductivity. This paper presents an experimental study where this parameter is determined and compared using of two identical latent storage tanks, one with 196 transversal squared fins and another one without fins. In this case, hydroquinone was selected as PCM. A set of six experiments was performed at pilot plant of the University of Lleida (Spain), combining three different HTF flow rates and two temperature gradients between HTF inlet temperature and initial PCM temperature. Experimental results showed that the addition of fins can increase the effective thermal conductivity between 4.11% and 25.83% comparing the experiment with highest and lowest thermal power supplied to the PCM, respectively.

1. Introduction

Buildings represent one of the dominating energy-consumption sectors in the world. During the last decades the energy consumption for air-conditioning in the residential sector increased dramatically in these countries leading to a high demand on the available electric power based on the exploitation of fossil fuels, which causes greenhouse gases emissions. Solar cooling is a sustainable alternative to provide a source of industrial and residential cooling [1–3]. A wide variety of cooling techniques powered by solar collector-based thermally driven cycles have been developed and applied in the last decades [4].

Since solar energy is time dependent, the successful utilization of all these systems is a very degree dependent on the thermal energy storage (TES) systems used: integrating TES systems to solar cooling applications contributes to consumption reduction from the grid on demand

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Nomenclature

A	surface, m^2
D	diameter, m
e	distance between fins, m
h	specific enthalpy, J/kg·K
HTF	heat transfer fluid, –
k	thermal conductivity, W/m·K
L	average pipe length, m
LTES	latent thermal energy storage, –
m	mass, kg
N	number of fins, –
PCM	phase change material
$\dot{Q}$	heat transfer rate, W
S	shape factor, m
T	temperature, °C
TCES	thermochemical energy storage
TES	thermal energy storage
U	global heat transfer coefficient, $W/m^2 \cdot K$
W	distance between pipes, m
WF	with fins, –
WOF	without fins, –

Greek symbols

η	efficiency, –
θ	Mel fraction, –

Subscripts

cond	conduction heat transfer
eff	effective
eq	equivalent
ext	external
f	final
fin	fins
i	initial
in	inlet
L	liquid
out	outlet
Tube	tube
S	solid

peaks and hence, economic savings. A study about TES potential in buildings sector presented by Arce et al. [5] demonstrated that just in Spain TES systems may potentially help to save 140,883 GWh_{th} in domestic cooling applications.

Three types of TES systems may be basically applied in solar cooling applications: sensible heat (STES), latent heat (LTES), and thermochemical (TCES) [6,7]. Concerning to the LTES systems, these are based on phase change materials (PCM), which allow storing larger quantity of energy per volume in comparison with STES systems. Moreover, PCM are already well known for constant working temperature for thermal storage applications. Nevertheless, PCM show generally low thermal conductivity even in the liquid phase (usually lower than 1 W/m·K) limiting the power during charging/discharging processes and definitely LTES systems applicability. For this reason, a research effort on heat transfer enhancement techniques in LTES has been done [8]. One the one hand, the heat transfer enhancement techniques are focused on enhancing the PCM by its combination with highly thermal conductive materials (graphite composites, metal foams composites, and nanomaterials). One of the studies focused on this topic was presented by Marin et al. [9], who studied experimentally and numerically the melting and solidification processes of pure paraffin (used as cold storage material) encapsulated in plate and a porous graphite matrix. This paper demonstrated that the graphite matrix with embedded PCM presented better results in terms of thermal conductivity improvement. Regarding on the use of metal foams, Zhang et al. [10] experimentally and numerically investigated the thermal enhancement of a eutectic mixture, $KNO_3/NaNO_3$, by combining it with copper and nickel metal foams. They observed an improvement during the discharging process in 28.8% and 19.3%, respectively. As mentioned previously, another technique focused on enhancing the thermal conductivity of PCM is the addition of highly conductive nanoparticles within a TES material. Shi et al. [11] and Yuan et al. [12,13] showed an enhancement up to 60% in thermophysical properties in cementitious TES materials with SiO_2, MgO, and Cu nanoparticles in comparison with pure material.

One the other hand, the most known heat transfer technique is focused on enhancing the heat transfer between heat transfer fluid (HTF) and PCM by the addition of extended surfaces. A theoretical study was carried out by Tamme et al. [14] where the addition of fins of graphite was proposed in order to optimize the steam accumulators operating with salts as PCM. The results show a reduction of the number of pipes. Other numerical studies were carried out by Zhang and Faghri [15], Seeniraj et al. [16], Guo and Zhang [17], and Tiari et al. [18]. All these studies show significant improvements in the heat transfer rates between HTF and PCM depending on the geometry of the fins, their spacing, the tube diameter, the boundary conditions, and the thermal conductivity of the PCM selected. Tao et al. [19] numerically studied three geometrically different fins enhancement techniques (dimpled, cone-fined and helically-fined) in a LTES system. They show a reduction on the melting time of 19.9%, 26.9%, and 30.7%, respectively. This idea led other researchers to study the use secondary fins. For example Khaled [20] compared hairy fins to the more known rectangular fins.

Table 1
Average value of thermophysical properties of hydroquinone within its melting range [27–29].

Properties	Units	Values
Melting temperature range	[°C]	168–173
Melting enthalpy	[kJ/kg]K]	205.8
Density	[kg/m^3]	1180.1
Thermal conductivity	[W/m·K]	0.1
Dynamic viscosity	[mPa·s]	0.97

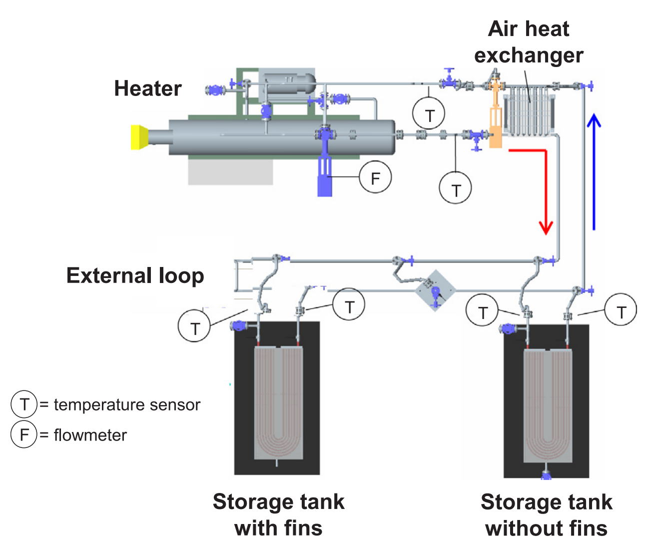

Fig. 1. Scheme of the pilot plant available at the University of Lleida during the charging process.