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Performance comparison of a group of thermal conductivity enhancement methodology in phase change material for thermal storage application

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ABSTRACT

Phase change materials (PCM) are able to store thermal energy when becoming liquids and to release it when freezing. Recently the use of PCM materials for thermal energy storage (TES) at high temperature for Concentrated Solar Power (CSP) technology has been widely studied. One of the main investigated problems is the improvement of their low thermal conductivity. This paper looks at the current state of research in the particular field of thermal conductivity enhancement (TCE) mechanisms of PCM to be used as TES. This work considers a numerical approach to evaluate the performance of a group of TCE solutions composed by particular configurations of two of the principal TCE systems found on the literature: finned pipes and conductive foams. The cases are compared against a single PCM case, used as reference. Three different grades of graphite foams have been studied, presenting a charge time 100 times lower than the reference case for the same capacity. For fins two materials are analyzed: carbon steel and aluminum. The charge times of fin cases are from 3 to 15 times faster, depending on the amount and type of material employed. The internal mechanisms are analyzed to understand the results and locate possible improvement.

1. Introduction

1.1. Thermal energy storage (TES)

Low-carbon economy policies are every year more strict and demanding. By 2050 the low-carbon economy roadmap presented by the EU intends to reduce emissions to 80% below 1990 levels, which implies progressive cuts of 25%, 40% and 60% in 2020, 2030 and 2040 respectively [1]. The main actors in this reduction are the power and the industrial sectors. As the energy demand is expected to increase in the incoming years, the pressure to reach a renewable energy driven power system increases as well [2–4].

In response to this request the number several Concentrated Solar Power plants (CSP) have been built, like PS10 and PS20 in Spain or more recently Khi Solar One in South Africa. These commercial plants are based on Direct Steam Generation (DSG) where the boiler of conventional Rankine cycles is replaced with a solar receiver. CSP is unique among renewable energy generation sources because it can easily be coupled with thermal energy storage (TES) making it highly dispatchable [5–9]. Although the mentioned plants have installed TES based on steam accumulators, currently it is not feasible to manage the large capacities required for long time operation using this storage technology. As more hours of production and a better coupling of the demand curve add valuable capabilities to this technology, lots of efforts have been made over the last decades to achieve an efficient large scale thermal storage for high temperature processes.

Among the options analyzed, latent heat based systems have emerged as great potential storage systems [10,11]. This technology relies on the energy contained in a material changing its phase, capable of concentrating high energy ratios on narrow temperature ranges. Thanks to these effects ultra-compact units can store big amounts of energy, which can be absorbed or released at an almost constant temperature. The latent-latent heat transference allows a better matching in the boiler, maximizing the exergy efficiency in the evaporator as the temperature difference can be maintained constant, with the consequent benefit to the entire power plant.

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Nomenclature

A_{fin}	area occupied by the fins
A_{PCM}	area occupied by the PCM
A_{tot}	total area occupied by the system
f	volume fraction occupied by fins
D_{PCM}	diameter of the PCM region
D_{pipe}	external diameter of the process pipe
ε	accesible porosity of the foam
ρ	material density
H	material energy per unit mass
k	material thermal conductivity
T	temperatrure
h	sensible energy stored per unit mass
h_{ref}	reference energy level per unit mass
c_p	material specific heat
β	volume liquid fraction of the PCM
L	latent heat of the PCM
$T_{solidus}$	solidus temperature of PCM
$T_{liquidus}$	liquidus temperature of PCM

1.2. Phase change material (PCM) selection

The most common studied phase change transformations [12–15,35] have been the solid-liquid and liquid-gas, although some other transformation are under investigation, such as solid-solid for the development of structural materials capable of storing energy. However, the latter transformation stores small energy quantities compared with the formers and its phase transition temperature is not generally suitable for the industrial application here considered. Liquid-gas transformation has, as a general rule, the highest energy density, but this attractive property is linked with the important drawback of a high volume variation, that makes it difficult to store the gas phase in conventional containers. In contrast, solid-liquid transformation has still a high energy conversion and relatively small volume variation, making it suitable to solve the demanding storage requirements.

Related to the DSG technology, working steam pressures between 100 and 150 bar have been reported as the most interesting conditions for the power block operation [16]. For an optimum TES the PCM melting point has to be close to the boiling temperature of the steam, between 310 °C and 342 °C for the pressures here considered. It is important to consider that, for the discharge process, the boiling temperature has to be reduced below the PCM melting point with the correspondent impact on the power block.

The chosen PCM media must present other properties as high energy density and chemical stability. Of course, reduced cost, high conductivity and safety issues such as low corrosion, non-toxicity and non-flammability are properties desired for the optimal storage material. None of the materials tested fulfills completely the list of requirements here exposed. Organic materials are discarded by their low operation temperature. Within the inorganic materials, pure metals and alloys have great conductivity but in general the energy density found does not pay off the high costs of the material. In contrast, inorganic salts have shown a good ratio of energy density and material cost, but they have generally low thermal conductivity, making difficult to design a proper heat transference system.

$NaNO_3$ presents a suitable melting temperature, reduced cost and great thermal stability with the extra that it is a very well-known and studied salt as heat transfer fluid for the CSP molten salt tower technology. With the aid of the correct TCE system the material could offer a feasible solution for CSP Industry. For these reasons it will be the storage media employed for this analysis.

1.3. Thermal conductivity enhancement systems

As already seen, further developments are required to successfully implementing the PCM on a commercial storage units. Within the group of inorganic salts the main research efforts have been focused in the development of thermal conductivity enhancement systems (TCE).

One first option to reach this goal is to increase the transfer area between both mediums (storage and heat transfer fluid medium). This possibility has been specifically and deeply analyzed for the design of PCM cascade [17], where the storage unit is composed by different encapsulated PCM materials stages with sequentially increasing melting points. The encapsulation of the PCM can achieve this purpose, allowing a direct contact with the process fluid. However during the process some energy density is lost due to the shell thickness and the requirement of an interior empty space for the volume expansion management. Shell material must be carefully selected [18] to handle the operation conditions, either from the chemical degradation, mechanical stresses and high pressures and temperatures.

A second option is to extend the surface area using fins attached to the process pipe. This solution is commonly employed in the industry as a mechanism for improving the heat transference on heat exchangers; the transient nature of the PCM exchange implies additional challenges to achieve an optimal design. The shape and position of the fin is crucial to achieve good heat transference. Most of the studies are focused on simple geometries, being longitudinal straight fins [19,20,21] and circular fins [22] the most studied geometries. Some studies had shown a better performance from longitudinal fins [23] rather than circular. In the work proposed by Doerte et al. [24] a complex longitudinal fin pattern is suggested for increasing the heat transfer ratio.

A third option to increase the heat transference is to mix the PCM with a high conductivity carrier material. Due to its high thermal conductivity, graphite foams with high porosity have been employed to improve the heat transference of PCM [25,26]. This composite material has to be infiltrated with the PCM to ensure a proper distribution in the foam structure. The infiltration must maximize the amount of filled PCM, ensuring the evacuation of the contained gas.

An alternative proposed methodology was the use particles of expanded natural graphite (ENG) mixed with the PCM to improve the system conductivity [27]. This solution pretends to mix the ENG particles with the PCM in liquid or solid state, ensuring the resultant composite is compact enough to maintain the properties, avoiding PCM leakage in the container element.

Besides the extensive amount of literature material published on different TCE systems for PCM, consistent comparative between these systems are scarce on the literature. The work developed in this paper is intended to partially cover this lack of comprehensive analysis, providing a general comparative between two of the most popular TCE, longitudinal fins and graphite foams, and their improvement over a single PCM system.

1.4. Objectives and scope

The aim of this work is to find the optimal TCE system for a given TES configuration. The scope of the analysis is not only to find which system shown the better performance but to find which specific configuration works better within the cases analyzed. The study will be focused in two TCE systems, longitudinal fins and