



Performance comparison of latent heat storage systems comprising plate fins with different shell and tube configurations



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HIGHLIGHTS

- Comprehensive thermal performance comparison of latent heat storage systems.
- Higher rate of natural convection and more uniform process in vertical fin plate.
- Better thermal performance in charging and discharging with fin plate system.
- Lower entropy generation in fin plate design, reducing system size and cost.
- New knowledge for design of a latent heat storage system for high working pressure.

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ABSTRACT

For design and optimization purposes, understanding the performance characteristics of different configurations of PCM systems during charging and discharging processes is crucial, particularly for thermal storage in CSP. A numerical study using FLUENT has been performed to explore and compare the characteristics and behavior of PCM in different shell and tube configurations; namely counter flow and parallel flow in vertical and horizontal orientations. These designs have been compared with that of an alternative design using plate fins. The main practical advantage of the alternative design is decoupling the PCM location from the path of flow of the heat transfer fluid that reduces the constraints on the materials. Confined heating/cooling pipes in a channel at the bottom of the PCM enclosure makes it more flexible to match the required working pressures, and simplifies the design and material (PCM/plate) selection. This is a significant issue as higher temperatures and pressures are being required for improving the overall solar thermal system performance. Based on the same heat transfer area, amount of PCM and input energy, a performance comparison was determined based on exergy maximization. Using sodium nitrate as the PCM, the results show a higher heat transfer rate for the vertical arrangement of plate fins compared to the counter flow shell and tube configurations, as well as a more uniform heat transfer rate compared to all shell and tube arrangements for both the charging and discharging processes. The proposed design leads to less redundant PCM, as well as a smaller and more cost effective PCM system as a heat storage unit. Overall, the vertical plate fin configuration maximizes the useful heat that can be extracted for a given amount of heat and PCM, which has direct applicability to thermal storage solutions for CSP and other applications. Moreover, its modular design facilitates the selection and optimisation for different scales and applications e.g. as a heat storage for electricity production or as a protection system for a receiver from high thermal stresses in a CSP plant.

1. Introduction

In a latent heat thermal energy storage (LHTES) system, heat is stored through a charging process by melting a phase change material (PCM), and heat is released by solidifying the PCM to meet a thermal demand such as the power block in a CSP plant. The design criteria for a

LHTES system for CSP is dictated by both the upstream (solar field) and downstream (power block) requirements. Regarding the selection of an appropriate PCM, the melting temperature, latent heat of fusion, specific heat capacity and thermal conductivity are important properties for consideration in the design procedure.

A PCM system should provide optimal performance for both the

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Nomenclature

A_{mush}	mushy zone constant
C	specific heat, J/kg K
E	exergy, J/s
g	gravitation acceleration, m/s ²
h	heat transfer coefficient, W/m ² K
H	specific enthalpy, J/kg
k	thermal conductivity, W/m K
L	latent heat of fusion, J/kg
\dot{m}	mass flow rate, kg/s
Nu	Nusselt number, h r/k
P	pressure, Pa
Pr	Pr number, ν/α
q''	heat flux, W/m ²
r	width of enclosure, m
Ra	Rayleigh number, $g\beta z^3(T_h - T_m)/\nu\alpha$
s	entropy generation, J/K
So	source term in momentum equation
Ste	Stefan number, $c_l(T_h - T_m)/L$
t	time, s
T	temperature, °C
v	velocity, m/s
W	work, J
X, Y	coordinates
z	height of enclosure, m

Greek letters

α	thermal diffusivity, m ² /s
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β	thermal expansion coefficient, K ⁻¹
δ_T	thermal boundary layer, m
δ_l	liquid fraction
δ_s	solid fraction
ε	small number (0.001)
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m ² /s
ρ	density, kg/m ³

Subscript

b	base of the enclosure
h	hot wall or hot HTF
l	liquid
m	melt
o	reference
p	pressure

Abbreviations

CF	counter flow
PF	parallel flow
CFV	counter flow vertical
CFH	counter flow horizontal
PFV	parallel flow vertical
PFH	parallel flow horizontal
FPV	fin plate vertical
LHTES	latent heat thermal energy storage

charging and discharging processes. There are limitations such as the available temperature of heat transfer fluid (HTF) in a charging process while in a discharging process, it is crucial to provide the required amount of heat transfer at the necessary temperature. For the melting processes, the temperature difference between the HTF and melting front lasts longer, however this difference diminishes faster during the discharging processes due to a solid layer formation on the heat transfer surfaces such as the tubes and/or plates [1]. As a result, part of the PCM becomes redundant and incapable to provide the required heat transfer rate to support the demand side in the later stages of the discharging processes [2–3]. Analysing a LHTES system based on the first law of thermodynamics, an optimum design should decrease or eliminate the redundant PCM to achieve a smaller size and cost effective system. On the other hand, considering the second law, an optimum design should minimize entropy generation and recover the highest exergy or the highest available work/power as the ultimate goal of a storage system [4].

Investigation of different design configurations of LHTES systems to understand the evolution of temperature profiles and heat transfer between the solid and liquid at the phase front provides the required knowledge to determine the optimum design from the first law analysis and highest effectiveness for each application. In order to get a full insight, a comparative analysis of the entropy generation during the phase change process for different design arrangements should also be included. Both categories of shell and tube and flat plate heat exchangers have been studied for fluid-to-fluid heat transfer applications providing extensive knowledge in designing a conventional heat exchanger. However, the design and optimization of a LHTES system for different applications is still at the early stages and more studies are required. Although different configurations of shell and tube arrangements as a LHTES have been the focus of research, little can be found for plate or rectangular types in the literature. As improved thermal performance of concentrated solar thermal energy systems has been the

focus of research programs for reducing the cost of electricity generation, such as the Sunshot initiative in USA [5] and the Australian Solar Thermal Research Initiative in Australia [6], higher temperatures and pressures are being proposed with limitations imposed by material mechanical properties. This calls for searching for alternative design solutions that involve materials in contact with either the heat transfer fluid or the storage medium which is often a eutectic salt.

In a previous study [7] by the authors, the literature in the area of shell and tube heat exchangers as LHTES systems has been thoroughly reviewed. The focus of that study was to compare the performance of different shell and tube configurations as LHTES systems. As an alternative, rectangular plate heat exchangers have been considered and studied as LHTES [1,8,9]. Both categories of shell and tube and rectangular plate heat exchangers involve materials surrounded by the heat transfer fluid on one side and the PCM on the other. A promising variation of the second category is the use of flat plates as fins to be in contact with the PCM and connecting to the path of the heat transfer fluid outside the PCM zone [10–14] as shown in Fig. 2a and b. This study aims to compare the performance of this geometry involving plate fins with the four shell and tube configurations analyzed in the previous study [7]. To ensure a realistic comparison, the total heat transfer surface, PCM volume and the average heat input or output are equal in all compared cases. This comparison will clearly identify which configuration delivers the maximum exergy.

Using a rectangular geometry, PCM can occupy rectangular enclosures while HTF flows through narrow rectangular passages between the PCM containers. Depending on the plate orientation or HTF flow direction, the system can be considered horizontal or vertical. Furthermore, in this configuration, there has been efforts to model slab-based systems where thin slabs of PCM (e.g. 25 mm) with narrow gaps (e.g. 5 mm) for HTF is introduced for the highest heat transfer [15]. Belusko et al. [15] provided a literature review and proposed an effectiveness-NTU method to characterise slab-based PCM systems. Using

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