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Influence of design on performance of a latent heat storage system at high temperatures

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HIGHLIGHTS

- Simple model for the design of a latent heat storage was developed and validated.
- The influence of various design parameters on the efficiency is investigated.
- Higher efficiency values obtained for lower number of capsules.
- Higher efficiency values obtained by operating the system with lower flow rates.
- The close packing of the capsules is another way of achieving high efficiency.

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ABSTRACT

This work focuses on the design of a low cost utility scale thermal storage, consisted of vertically placed cylindrical phase change material capsules, for next-generation power plants. In this paper a simple model for the design of a storage unit is presented. This model includes both latent and sensible heat stored in phase change material. The exergetic efficiency and the operation time of the storage is considered as the design criterion in this model and the influence of various design parameters on the exergetic efficiency and operation time is investigated. Results show that under study conditions exergetic efficiency varies between 98.991% and 98.692% and operation time changes between $4h$ and $21h$. Higher efficiency values obtained for lower number of capsules, lower heat transfer fluid flow rates and lower distance between capsules. Decreasing number of capsules and the distance between capsules also decreases the operation time. However, the decrease in the flow rate increases the operation time.

1. Introduction

Thermal energy storage (TES) has been a main focus of research in renewable energy to overcome inherent intermittency, such as that of solar energy. Storing heat in phase change materials (PCM) is one of the most effective ways of storing thermal energy. Latent heat thermal energy storage (LHTES) takes advantage of the phase change of the material, allowing the material to store and release a large amount of heat at a relatively constant temperature as opposed to sensible heat storage. In LHTES systems, PCMs may be encapsulated in spheres, cylinders or other geometrical shapes and placed in a heat exchanger unit. Each LHTES system must be designed and optimized for efficient heat transfer [1–5].

Even though the feasibility of PCMs for high temperature storage applications has been analyzed in the past, most experimental studies have focused on low temperature (below 500 °C) LHTES applications. Zalba et al. [1] reviewed numerous phase change materials based on their properties, stability, and their potential for commercial applications. Sharma et al. [2] reviewed LHTES systems and applications. Khan et al. [6] reviewed various materials with melting points up to 135 °C including eutectics, metallics, salt hydrates, paraffins, and fatty acids. Kenisarin [7] examined change materials, from 120 °C to 1000 °C, and discussed the practicality of PCMs with encapsulation materials. The importance of finding a suitable encapsulation technique is paramount in high temperature range systems as it depends on parameters like reactivity and structural stability at elevated temperatures, formability and manufacturability of the encapsulating material. Ceramics as encapsulation materials provide high corrosive resistance but are not

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Nomenclature

A	heat transfer area, m^2
b	total number of partitions, –
c	specific heat, J/kg K
D	capsule diameter, m
D_h	hydraulic diameter of the annular region, m
Ex	exergy, W
h	convection heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
l	length of a single tank/capsule, m
L	total flow path length, m
LF	loss factor, %
ΔL	thickness of a partition, m
$\mathbb{L}$	latent heat, J/kg
m	mass, kg
M	number of tanks, –
$\dot{m}$	mass flow rate, kg/s
n	total number of grids in a partition, –
N	number of capsules in a tank, –
Nu	Nusselt number, –
p	distance between tube centers, m
Pr	Prandtl number, –
$\dot{Q}$	heat transfer rate, W
r	radius, m
Δr	distance between cell centers, m
R	capsule radius, m
Re	Reynolds number, –
t	time, sec
T	temperature, °C
U	overall heat transfer coefficient, W/m^2 K
X	liquid fraction, %

Subscript

amb	ambient
cap	capsule
Ch	charging
Dch	discharging
htf	heat transfer fluid
i	partition index
in	in/inner
j	cell index
l	liquid
$loss$	heat loss
L	left
m	melting
out	out/outer
pcm	phase change material
r	recovered
R	right
s	supplied/solid
S	stored
T	total

Superscript

t	time index

Greek symbols

μ	viscosity, Pa s
ε	exergetic efficiency, %

economical compared to metals [8–10]. For a temperature range of 500–600 °C, with certain preventive measures to control the surface oxidation, metallic encapsulation was found to be stable and economical [11]. Metallic encapsulation in the shape of cylinders is very practical considering the availability of steel tubes [12].

Numerous studies have been conducted in the past to understand the energy exchange process between the heat transfer fluid and the PCM capsules during charging and discharging processes. The main factor of heat transfer in an LHTES unit is the geometry and layout of the LHTES unit, which is a large factor in the cost of the system. The LHTES system can be arranged like a shell and tube heat exchanger where the heat transfer fluid passes through or around the PCM, or encapsulated PCM is arranged in a packed bed configuration. Regin et al. [13] reviewed various geometry of capsules that have been studied in numerical models and experiments. Agyenim et al. [14] reviewed materials and heat transfer formulation for LHTES systems. Niyas et al. [15] modeled and experimented on a system where the heat transfer fluid passed through tubes. It was found that the charging was a convection dominant process while the discharging was a conduction dominant process. A lab-scale TES system, with polymer-based macroencapsulated spherical capsules, was developed and tested by Alam et al. [16–18]. However, this system used capsules wrapped in polymer for medium-low temperature applications of 286–326 °C.

Many studies have explored the use of cylindrical and rectangular capsules in thermal storage as the ideal geometry for large scale systems. Liu et al. [19] reviewed different system configurations including ones using cylindrical pellets arranged randomly in a tank and shell and cylindrical tubes of PCM. In a system of horizontally arranged cylindrical capsules, Chen et al. [20] experimentally and numerically analyzed a LHTES system for low temperature storage. Jones et al. [21] experimentally and numerically examined melting in a cylinder. Shokouhmand et al. [22] experimentally investigated melting in a LHTES unit where the melting front and heat transfer was analyzed in a rectangular unit. Papanicolaou et al. [23] examined transient natural convection in a LHTES at high Rayleigh numbers. Zivkovic et al. [24] examined isothermal phase change of PCMs within rectangular and cylindrical containers. Paraffin wax was used as the PCM in a study on melting behavior by Regin et al. [25]. In this study, the phase change was observed through a temperature range rather than at a constant temperature and a model describing the experimental data was developed. In a separate study, the use of multiple phase change materials in a cylindrical capsule was studied for the purpose of improving the charging rate [26]. Saitoh et al. [27] performed experimental work to examine the heat transfer characteristics in the liquid region in a horizontal cylindrical capsule. Shmueli et al. [28] numerically modeled the PCM melting process in a vertical cylindrical tube. Bareiss et al. [29] studied a LHTES system with cylindrical capsules of different aspect ratios filled with wax. The heat transfer between the tube wall and PCM was determined as functions of non-dimensional numbers. Pointner et al. [30] investigated various numerical models with various software for a LHTES consisting of eutectic mixture $NaNO_3(46\,wt\%)–KNO_3(54\,wt\%)$ which melts at 220 °C. Between MATLAB, C, and ANSYS CFX, ANSYS had the highest computational time. MATLAB performed the best for large time steps while C performed better with small time steps.

There are numerous techniques that can be used to improve the heat transfer of LHTES. Khan et al. [6] reviewed a number of these. Additives, such as graphite, aluminum, and carbon fiber have been tested on their ability to improve heat transfer by conduction in PCMs. Other techniques include the addition of heat pipes, fins in the PCM and the use of microencapsulation. Goswami et al. [31] used a numerical model to assess the use of a metal matrix embedded in a cylindrical PCM