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Comparative study of melting and solidification processes in different configurations of shell and tube high temperature latent heat storage system

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ABSTRACT

The performance of parallel and counter flow configurations of a shell and tube heat exchanger used as a latent heat thermal storage system was investigated. The comparative analysis of the melting and solidification processes (charging and discharging) in the vertical and horizontal orientations of counter and parallel flow was included in this study to make the results conclusive for the purpose of design of the storage system to be used in a concentrated solar power (CSP) plant. In this analyses, taking into account natural convection, numerical calculations were performed using ANSYS Fluent. The vertical parallel flow configuration shows 12% higher effectiveness compared to the counter flow for the charging and discharging processes. A higher rate of phase change occurs for both the charging and discharging processes in a parallel flow configuration, as a higher fraction of phase change material (PCM) is exposed to the heat transfer fluid inlet temperature compared to the counter flow. However, a lower temperature gradient and nearly constant effectiveness for a longer period of time are observed in the counter flow arrangement due to the higher rate of natural convection. An interesting result is the higher rate of natural convection in the horizontal orientation compared to the vertical one due to the Benard convection phenomenon, despite the fact that *Ra* is higher in the vertical orientations ($10^{10} > 10^{7}$). The horizontal counter flow and parallel flow configurations show on average 10% higher effectiveness for the charging process which is constant for a longer period during the process compared to the vertical configurations whereas the horizontal arrangement during the discharging process improves the effectiveness by about 2% due to the minor role of natural convection. The horizontal configurations provide a more uniform phase change process with the lowest peak temperatures (in the melting processes) and temperature gradient which are correlated with the highest second law efficiency and exergy recovery.

1. Introduction

The production of low cost electricity from solar thermal energy has been proved to be promising as a replacement for fossil fuels in conventional power plants. The concentrated solar power (CSP) plant is capable of producing continuous electricity on demand with the integration of a thermal energy storage system. A latent heat thermal energy storage (LHTES) system is an alternative to the commercially available sensible heat storage system. In a LHTES system, a phase change material (PCM) stores thermal energy during its melting process and releases the energy during solidification. The phase change process is near isothermal with a relatively low density change and mainly relies on the heat of fusion of PCM whereas the sensible heat storage depends on the thermal capacity of the medium (ρC_p) and the temperature difference. Research in this area shows that a LHTES system can provide higher energy density and a smaller system (Wang et al., 2012) and hence lower cost.

The design objective of a LHTES in a CSP plant is to charge and discharge heat via a heat transfer fluid (HTF) at the specifications of the plant. In the scope of high temperature PCMs (300–750 °C) relevant for the CSP plants, conduction and natural convective heat transfer are the main heat transfer modes, and depending on the process and PCM structure and thermophysical properties one mode of heat transfer can be dominant. This is important as the defining parameter of the thermal behavior of PCM and characteristics of the system. At the HTF side, the main mode of heat transfer is forced convection. The design of a LHTES for a given PCM

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Nomenclature

A_{mush}	mushy zone constant
C	specific heat, J/kg·K
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	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
X, Y	coordinates
z	height of enclosure, m
α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
δl	liquid fraction
δs	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
l	liquid
m	melt
o	reference
p	pressure

Abbreviations

CF	counter flow
PF	parallel flow
CFV	counter flow vertical
CFHB	counter flow horizontal, bottom HTF inlet
CFHT	counter flow horizontal, top HTF inlet
PFV	parallel flow vertical
PFH	parallel flow horizontal
MC	melt and convection
MWC	melt without convection
SC	solidification and convection
SWC	solidification without convection

essentially depends on the heat transfer area between the HTF and the PCM.

In order to achieve a suitable design at reasonable cost, an understanding of the performance of different configurations is needed. There has been considerable effort to enhance the heat transfer and improve the low thermal conductivity of PCMs including encapsulated PCM, cascade-PCMs (e.g. with different melting temperatures), nano-PCM (including nano-particles), embedded foam or metal mesh in PCM, and thermosiphons or heat pipes (Elmozughi et al., 2014; Ettouney et al., 2005; Guo and Zhang, 2008; Ho and Gao, 2013; Jacob et al., 2016; Li et al., 2013; Liu et al., 2013; Wang et al., 2015; Zheng et al., 2015).

In a numerical study, Li et al. (2013) investigated the melting process of three PCMs with different melting temperatures confined in a shell along a tube with air as the HTF. Through a parametric analysis while ignoring natural convection, the authors proposed an optimised design of a LHTES to be used in a CSP plant. In another numerical study using Fluent, Wang et al. (2015) proposed a multi-PCM system in conjunction with a zigzag passage for air as the HTF to extend the heat transfer surface between the HTF and PCM.

From the results of a numerical study, Guo and Zhang (2008) proposed the integration of aluminum foil in high temperature PCM as an effective solution to enhance the heat transfer in a LHTES system. Using ANSYS Fluent, Liu et al. (2013) studied the impact of metal foam in an element of shell and tube latent heat thermal storage while constant heat flux was used at the tube side. The melting process in the porous medium, considering pure conduction heat transfer showed enhanced heat transfer due to the high thermal conductivity of the metal foam.

In the experimental and numerical work by Zheng et al. (2015), the performance of a LHTES system including encapsulated sodium nitrate in a cylindrical shell was examined at pilot scale. Results showed high energy storage density, about 211 kJ/kg of the capsule weight (from which 95% stored in PCM) while about 42% of the heat storage resulted from the latent heat transfer. Other examples with encapsulated PCM are an experimental study using low temperature PCM (wax) by Ettouney et al. (2005) and a numerical study using high temperature PCM (Na NO_3) in cylindrical and spherical capsules by Elmozughi et al. (2014). In a recent experimental examination, a geopolymer encapsulation was proposed by Jacob et al. (2016) to cope with the corrosive nature of high temperature eutectic salts as PCM. The stability and performance of the system proved to be acceptable.

The impact of nano-particles of Al_2O_3 in the melting of wax as PCM was investigated in an experimental work by Ho and Gao (2013). The LHTES system was a cavity filled with PCM and the side walls were kept at different hot and cold temperatures. For a 10% (wt) of $Al_2O_{3,}$ the results showed more than 60% reduction in the convection heat transfer rate which outweighed the benefit from the enhancement of conduction heat transfer. Adding nano-particles of graphite to a macro-encapsulated PCM (i.e. capsule diameter of 5 cm) was experimentally and numerically investigated by Calvet and et al. (2013), using COMSOL. For a 13% (wt) graphite load, the authors reported 35–58% reduction in charging and discharging time without any reduction in the thermal storage.

A numerical investigation by Nithyanandam and Pitchumani (2013), studied the impact of embedded thermosiphons on the thermal behavior of PCM in a LHTES system. Using Fluent, modeling of the charging and discharging processes was performed to find the optimal arrangements of tubes and heat pipes with improved effectiveness.

In another experimental and numerical effort, Malan et al. (2015) proposed the integration of both heat pipe and metal fins as a solution to enhance the performance of LHTES systems. Garcia et al. (2015) experimentally and numerically investigated a finned tube LHTES at pilot scale for use in a Direct Steam