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Three-dimensional simulation of high temperature latent heat thermal energy storage system assisted by finned heat pipes

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ABSTRACT

The startup process of a high temperature latent heat thermal energy storage system assisted by finned heat pipes was studied numerically. A transient three-dimensional finite volume based model was developed to simulate the charging process of phase change material with different configuration of embedded heat pipes. The melting of the phase change material was modeled by employing enthalpy-porosity technique. A eutectic mixture of sodium nitrate and potassium nitrate with melting temperature of 220 °C enclosed by a vertical cylindrical container was used as the phase change material. The effects of different heat pipe arrangement and the heat pipe quantities as well as the influence of natural convection on the thermal behavior of the latent heat thermal energy storage system were studied. The results indicate that the heat pipe configurations and the quantities of heat pipes integrated in a thermal energy storage system have a profound effect on the thermal response of the system. Employing more heat pipes decreases the thermal resistance within the system, leading to the acceleration of charging process and the decrease of container base wall temperature. It was also found that the inclusion of natural convection heat transfer in the charging process of the system renders to higher melting rate and lower base wall temperature.

1. Introduction

A desirable feature of concentrated solar power (CSP) with integrated thermal energy storage (TES) unit is to provide electricity in a dispatchable manner during cloud transient and non-daylight hours. Latent heat thermal energy storage (LHTES) offers many advantages relative to sensible heat thermal energy storage (SHTES), which is the current standard for trough and tower CSP systems. These advantages include: (1) latent heat thermal energy storage provides two to five times the energy density of sensible heat thermal energy storage in molten salt, (2) the salt is contained in a single hermetically sealed containment vessel that avoids hot salt pumps, transport lines and heat tracing, (3) eutectic or pure salt options can support a wide range of operating temperatures up to 1300 °C, and (4) nearly all of the LHTES heat delivered to the power conversion system is very close to the salt melting temperature.

In addition to CSP applications, LHTES have been used in a wide range of other applications such as electronic cooling [1,2], building heating, air conditioning, hot water [3–7], refrigeration [8,9], waste heat recovery and drying equipment [10,11]. Despite the advantages mentioned above, LHTES systems performance is often limited by low thermal conductivity of commonly used, low cost phase change materials (PCMs). Several heat transfer enhancement methods have been developed to fix this drawback of the LHTES systems, such as using multiple PCMs [12–14], employing extended surfaces and fins [15–17], embedding the PCM in a matrix made of high conductivity material such as graphite, metal foam or foil [18–21], as well as dispersing high thermal conductivity particles in the PCM [22–24]. A comprehensive review of the above mentioned enhancement methods was presented by Fan and Khodadadi [25].

Research and development of passive heat transfer devices, such as heat pipes (HPs) to enhance the heat transfer in the PCM has received considerable attention [26–30]. Due to its high effective thermal conductivity, heat pipe can transport large amounts of heat with relatively small temperature difference.

Numerous experimental and numerical investigations have been performed on the melting and solidification of PCM in LHTES systems to evaluate the effects of different parameters on the performance of these systems. Computational fluid dynamics (CFD) is an effective numerical modeling tool that has been used to design and analyze LHTES systems [31]. Majority of the computational studies reported so far have used two-dimensional models

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Nomenclature

Latin

A_{mush}	mushy zone constant
c_p	specific heat (J kg^{-1} K^{-1})
d	diameter (m)
f_l	liquid fraction
Fo	Fourier number
g	gravitational acceleration (m s^{-2})
h	sensible enthalpy (kJ kg^{-1})
h_{sl}	latent heat of fusion (kJ kg^{-1})
H	enthalpy (kJ kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
N_{hp}	Number of heat pipe
P	pressure (Pa)
q	heat flux (Wm^{-2})
R	inner radius of container (m)
r	radial coordinate
S	spacing (m)
Ste	Stefan number
t	thickness (m)
T	temperature (K)
v	velocity component (m s^{-1})
z	axial coordinate

Greek

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
ΔH	latent heat (kJ kg^{-1})
θ	azimuthal coordinate
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
τ	time (s)

Subscripts

e	evaporator
f	fin
hp	heat pipe
l	liquid
m	melting
0	reference value
r	component of r direction
z	component of z direction
θ	component of θ direction

and very few of them considered three-dimensional effects on the flow and temperature fields.

In a numerical and experimental study, Ben-David et al. [32] investigated the melting of gallium (T_m = 30 °C) in a rectangular container. They used both two-dimensional and three-dimensional models in their numerical modeling and compared the results with their experimental data. It was shown that the results of three-dimensional numerical model are in better agreement with experimental data because the intense effect of container boundaries on the phase change process is considered in the three-dimensional model. In another combined experimental and numerical study, Hosseini et al. [33] analyzed the melting of a low melting temperature PCM (paraffin RT500, $T_m \approx 50$ °C) in a shell and tube heat exchanger. They conducted experiments along with three-dimensional computational modeling to investigate the effects of heat transfer fluid (HTF) inlet temperature on the charging process. Costa et al. [34] numerically studied the melting of n-octadecane (T_m = 27.5 °C) inside a horizontal cylinder using both two-dimensional and three-dimensional models. The effects of three-dimensional behavior on the flow patterns, mass melt fraction and heat transfer on the cylinder surface were studied. The results from their three-dimensional model were compared to that of two-dimensional model. Tay et al. [35] developed and validated a three-dimensional numerical model with experiment data for a cylindrical thermal energy storage unit, where water was used as the PCM. They neglected the influence of natural convection during the melting and solidification processes in their modeling and discovered different thermal behavior of the PCM in comparison to the experimental results. A three-dimensional transient simulation was performed by Zukowski [3] to analyze the thermal performance of encapsulated paraffin wax within a ventilation duct. The effects of geometrical parameters on the storage unit performance as well as 24 h operation of the system were studied. Kandasamy et al. [36] investigated a PCM-based heat sink using three-dimensional computational model and experimental testing. It was shown that implementing paraffin as a PCM in the heat sink cavities enhances cooling performance in comparison to the case without PCM. Wang and Yang [1] studied the charging and discharging modes of a hybrid PCM based multi-fin heat sink using a transient three-dimensional numerical model. They analyzed the effects of fin numbers, system orientation and heating power on the heat transfer performance of the system with n-eicosane (T_m = 35–37 °C) as the PCM. In another work using the same PCM, Yang and Wang [2] carried out a transient three-dimensional numerical analysis of a PCM based heat sink for electronic cooling. Hydrodynamics and thermal characteristics of the system were studied at different input power levels and various orientations. Charging and discharging processes of the system were modeled numerically.

In conclusion, most of these three-dimensional studies were concentrated on the utilization of low melting temperature PCMs. In one of scarce three-dimensional numerical simulations of high melting temperature PCM, Zhao et al. [37] analyzed a LHTES system with graphite foam as the thermal conductivity enhancement material and magnesium chloride ($MgCl_2$, T_m = 714 °C) as the PCM. They neglected the effects of natural convection on the molten PCM during the phase change. The results revealed that graphite foam remarkably improved the performance of LHTES system. Nithyanandam and Pitchumani [38], using a transient three-dimensional model, simulated a shell and tube LHTES with heat pipes. In their analysis potassium nitrate (KNO_3, T_m = 335 °C) was used as the PCM. They analyzed the effects of different parameters on the storage system effectiveness during the charging and discharging process. Tiari et al. [39] numerically investigated the startup process of a high temperature LHTES system assisted by finned heat pipes. They used a transient two-dimensional model to simulate the charging of potassium nitrate PCM enclosed in a square container. The effects of natural convection on the molten salt were included. The influences of heat pipe spacing, fin numbers and length on thermal performance of the system were studied. Based on their computational results, it was found that the natural convection within the molten PCM has a crucial role on the thermal performance of the system. It was also shown that the decrease of heat pipe spacing and the increase of fin length result in higher melting rate and lower base wall temperature. Qiu et al. [40] experimentally studied a hybrid CSP system, where PCM-Heat pipe based TES system was coupled to a free piston Stirling engine. The TES system consisted of a