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Numerical analysis of thermal storage performance with high-temperature phase change materials operated by condensing steam

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Abstract

This paper numerically investigated the heat storage behaviors of a shell-and-tube storage unit filled with high-temperature phase change material (PCM) using steam as the heat transfer fluid. A two dimensional heat transfer model using the enthalpy method was established, and the characteristics of the variations in the PCM melting time, charging rates from the steam to the PCM, and the steam condensation with time were studied. The influences of the thermal conductivity of PCM, the steam flow rate and the diameter ratio on the charging performance were evaluated. The results show that the heat charging rate can be not only significantly increased by increasing the PCM thermal conductivity, but also considerably increased by increasing the steam flow rate or decreasing the diameter ratio. As a result, the total charging time decreases with the increase of the PCM thermal conductivity or the decrease of the diameter ratio, and it can also be regulated by adjusting the steam flow rate. The liquefaction ratio can also be increased by increasing the PCM thermal conductivity during the design procedure, and can be effectively regulated by varying the steam flow rate during the operation.

Keywords: Thermal energy storage; PCM; DSG; Solar energy

1. Introduction

The use of solar energy to generate steam, which can be subsequently used for electricity generation and industrial applications, is a promising and effective means of solar energy utilization. For example, in concentrating solar power (CSP) technology, the direct steam generation (DSG) system has been regarded as a cost-effective CSP technology with high efficiency (Michels and Pitz-Paal, 2007; Laing, 2013). A need exists to store solar energy so that a power plant can continue generating electricity in spite of the fluctuations in solar intensity. Accumulators in small scales are used to store and regenerate steam. However, the cost of the accumulators with large capacities becomes catastrophically big, which inhibits its wide use in CSP plants with DSG. A cost-effective and viable way to store and regenerate steam becomes a significant obstacle for large-scale applications of CSP plants with DSG. Phase change materials (PCMs) have high energy storage densities and constant phase change temperatures. Thermal energy storage units using high-temperature PCM are viable and cost-effective solutions for large-scale solar steam storage.

Over the past decades, thermal energy storage using high-temperature PCM has attracted worldwide attention.

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Nomenclature

c_p	specific heat capacity, J kg^{-1} K^{-1}
d_{out}	outside diameter of PCM storage unit, m
d_{in}	diameter of the tube, m
f	PCM melting fraction
G	total mass flux of steam, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
H	specific enthalpy, J kg^{-1}
ΔH	heat of fusion, J kg^{-1}
p_r	reduced pressure of the steam
Pr_l	Prandtl number of liquid
q	heat charging rate, J
Re_{LT}	Reynolds number assuming all mass flow as liquid
r	radial coordinate, m
T	temperature, K
t	time, s
x	axial coordinate, m
x_s	steam quality

Greek

θ	surplus temperature, K
μ	dynamic viscosity,
ρ	density, kg m^{-3}
λ	thermal conductivity, W m^{-1} K^{-1}

Subscripts

f	heat transfer fluid
g	gas
l	liquid
m	value at phase change
p	PCM

Most of the studies have focused on heat storage characteristics of thermal storage units with PCMs using single-phase fluids as the heat transfer fluids (HTFs) (Seeniraj and Narasimhan, 2008; Liu et al., 2014; Yang et al., 2013). Michels and Pitz-Paal (2007) experimentally and numerically investigated cascaded shell-and-tube latent heat storages using alkali nitrate salts as the PCM and synthetic oil as the HTF. The PCM was simplified as a lumped mass with a uniform temperature in their model. The results showed that the cascaded PCM storage system had a higher utilization of the PCM and a more uniform outlet temperature over time compared to a non-cascaded system. The performances of a sensible energy storage system and a PCM thermal energy storage system were numerically compared by Wang et al. (2012). Both of the systems encapsulate the thermal storage material in vertical annuli. A temperature transforming method was used to solve the energy equation of the PCM. The effect of natural convection on the moving of the melting front for the PCM system was discussed. Tao et al. (2012, 2014) numerically investigated the thermal performance of a shell-and-tube high-temperature PCM storage unit based on the enthalpy method. The mixture of He/Xe was used as the HTF and a molten salt was used as the PCM. Effects of various operating conditions and the enhancement of the PCM melting performance were discussed. More state-of-the-art research about the high-temperature PCM thermal storage can be found in (Gil et al., 2010; Liu et al., 2012; Cárdenas and León, 2013; Kuravi et al., 2013).

Recently, with increasing interests in solar steam systems, studies on PCM thermal storage systems using steam as the HTF have been reported. Steinmann and Tamme (2008) reported the progress of the European DISTOR project which aimed to develop molten-salt PCM storage systems using steam generated by parabolic trough collectors as the HTF. Concepts of various PCM systems including sandwiched structure, macro-encapsulation and composite PCM material were reported and evaluated. Bayón et al. (2010) experimentally analyzed the behavior of a 100 kW h PCM storage prototype under real operating conditions with steam generated by a parabolic-trough collector test facility at the Plataforma Solar de Almeria (PSA) in Spain. In their experiments, the eutectic mixture of KNO_3/$NaNO_3$ was used as the PCM and expanded graphite fins were arranged in a sandwich configuration for improving heat transfer. A quasi static model was also developed to analyze the results. The model assumed that the PCM was kept at the melting temperature during the charging/discharging processes. Laing et al. (2010, 2011, 2013) introduced a three-part storage system where PCM storage was deployed for the steam evaporation/condensation while concrete storage was used to store the sensible heat. A 1 MW h pilot-scale storage system including a 700 kW h PCM storage module was built and tested in a DSG test facility in Spain. The $NaNO_3$ salt was used as the PCM and radially finned tubes were applied in the PCM storage module to enhance the heat transfer. The PCM storage had been successfully tested under various operating modes and showed potential to reduce the cost of the storage system in the future (Laing et al., 2011, 2013).

The thermal characteristics of PCM storage for steam condensation and generation have also been investigated numerically. Guo and Zhang (2008) numerically investigated the enhancement of heat transfer in a PCM storage unit after adopting aluminum foils. The enthalpy-porosity model was used for the phase change process of the molten-salt PCM. The temperature was set as a constant