Solar Energy 170 (2018) 594–605

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Numerical analysis of a new thermal energy storage system using phase change materials for direct steam parabolic trough solar power plants

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ARTICLE INFO

Keywords:
Direct steam parabolic trough power plant
Phase change materials
Thermal energy storage system
Computational fluid dynamics

ABSTRACT

This paper presents the numerical analysis of a novel thermal energy storage (TES) system using phase change material (PCM) for direct steam solar power plants. The energy storage system consists a preheater, steam generator and superheater in a cascade arrangement. The performance of the integrated system that constitutes a novel concept of thermal storage system is analyzed, numerically. The numerical model is verified against experimental data and the realistic effects of the operating conditions on the energy storage system performance are considered. The effects of different design parameters on the performance of the system are investigated. The effects of thermal conductivity of PCM, heat transfer fluid (HTF) flow rate and the diameter of heat exchanger tubes are analyzed during the entire thermal cycling of the evaporator. The effects of HTF flow rate and temperature on the exergy efficiency of TES system are analyzed. The results indicate that thermal conductivity of PCM is the most effective parameter, and increase of this parameter from 0.5 to 5 $W\,K^{-1}\,m^{-1}$ leads to decrease of charging time from 25 to 4.5 h and increase of output steam quality from 0.2 to 0.5 during the discharging process. It is observed that cascade arrangement in preheater and superheater heat exchangers results in lower temperature gradient of the output HTF.

1. Introduction

Solar power plants are categorized as single phase and direct steam types depending on their HTF. Direct steam solar thermal power plant often has simpler arrangement comparing with other solar power plants, however, its performance is quite complicated due to phase change of the HTF during the cycling process. Guo et al. (2017)) proposed a new predictive control scheme based on a nonlinear dynamic model for parabolic trough collectors of a direct steam generation solar plant in recirculation mode. They simulated the dynamic behaviors of the entire collector field under different climate conditions and they derived water level transfer functions and outlet fluid temperature.

The intermittent nature of solar energy and transient accessibility during a year makes it necessary to store this energy for later use by implementing an effective method. The efficiency and capital cost of a thermal energy storage system are mostly affected by the cycling time and volumetric energy storage capacity (Steinmann, 2014). Thermal energy storage based on energy conversion to sensible heat, latent heat, thermochemical energy or a combination of them is one of the most promising methods due to applicability at high storage capacities and relatively low cost. Lai and Adams (2017)) presented the design and analysis of a direct steam generation concentrated solar power plant integrated with a decalin/naphthalene thermochemical energy storage system. They demonstrated the feasibility of the proposed plant to maintain base-load power productions of 250 MW_e with an overall efficiency of 14.6%. Feldhoff et al. (2012) analyzed and compared a solar parabolic trough power plant with direct steam solar power plant using different HTFs. Both of these plants are equipped with energy storage systems. It was shown that the best arrangement for the plant consists of two main parts, including the primary shell and tube heat exchanger with a PCM and a molten salt two-tank storage system which is used to provide superheated steam.

Phase change materials are utilized for thermal energy storage in the form of latent heat in different applications. Xu et al. (2015) reviewed new thermal energy storage technologies based on PCM. They discussed various PCMs and fabrication of these materials, mathematical modeling of latent heat storage and integration of PCM based energy storage system to a power plant. Prieto et al. (2018) compared different TES technologies including steam accumulators, molten salts (MS), and PCMs. They concluded that a combined system based on PCM-MS is advantageous for at least 6 h of energy storage, while steam accumulators are considered as the best option for lower than 6 h. Fornarelli et al. (2016) performed a Computational Fluid Dynamics (CFD) analysis of the melting process of PCM inside a shell and tube

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https://doi.org/10.1016/j.solener.2018.06.024
Received 1 January 2018; Received in revised form 16 May 2018; Accepted 4 June 2018

Nomenclature

Variables

A_{htf}	tube cross sectional area (m^2)
A_w	wall cross section area (m^2)
A_w^l	wall side surfaces (m^2)
A_{pcm}^l	PCM side surfaces (m^2)
C_p	specific heat capacity (kJ/kg)
C_{pcm}	PCM thermal capacity (kJ/kg)
D_i	inside diameter of pipe (m)
f	mass fraction of liquid (molten) PCM
h	heat convection coefficient (W/(m^2 K))
H_f	fluid enthalpy (kJ)
k_w	wall thermal conductivity (W/(m K))
k_{pcm}	PCM thermal conductivity (W/(m K))
k_l	thermal conductivity of liquid HTF (W/(m K))
m_{tot}	total mass of the PCM (kg)
m_l	mass of the molten PCM (kg)
Pr_l	Prandtl number of liquid
p	actual pressure (Pa)
p_c	critical pressure (Pa)
q	transferred sensible heat from the heat transfer fluid
r	radial distance (m)
Re_L	Reynolds number assuming all mass flowing as liquid
t	time (s)
T	local temperature (°C)
x	thermodynamic vapor quality

Greek

ΔH	latent enthalpy (kJ)
ρ	fluid density (kg/m^3)
θ	the difference between the local and melting temperatures (°C)
ψ	exergy efficiency

Subscripts

0	reference environment
char	charging process
dis	discharging process
eff	effective
f	fluid
htf	heat transfer fluid
m	melting
w	wall

Abbreviations

DSG	Direct Steam Generation
HTF	Heat Transfer Fluid
TES	Thermal Energy Storage
PCM	Phase Change Material

heat exchanger. Considering the temperature gradient and the effects of gravity, the Navier-Stokes equations are solved for the HTF and also the molten content of the PCM. The numerical results indicated that the charging time of the energy storage system decreased about 30% due to the existence of natural convection in the molten PCM. Birnbaum et al. (2010) compared different arrangements of a direct steam generation solar power plant integrated with thermal storage. They studied the integrated subsystems including solar field, power block, and thermal storage to evaluate the operating conditions of the thermal storage system. They concluded that utilization of a PCM storage system for steam generation leads to significantly lower discharge pressure than the required charging pressure. Moreover, various operating conditions exist due to different combinations of storage charge and discharge operations and power output variation of the solar field.

An effective energy storage method is to utilize latent heat energy storage in three integrated heat exchangers, namely preheater, steam generator and super heater. Badenhorst (2016) studied this concept by investigating the feasibility of utilizing a prilling tower to recover latent and sensible heat from a liquid salt stream inside a solar power tower. He evaluated three case scenarios and the results indicate the possibility of saving almost 20% of the overall plant capital cost due to reduction of the circulating salt flow by more than 30%. Pelay et al. (2017) compared different arrangements for thermal energy storage in concentrated solar power plants. They identified some technological barriers toward the bright foreground of latent heat energy storage, namely, thermal conductivity of PCMs, solid deposition at the contact surfaces between PCM and the HTF and transition time between charge and discharge processes. Guo et al. (2018) obtained the maximum PCMs utilizability and also the highest system efficiency using a combination of different PCMs in a cascade arrangement. Laing et al. (2011) described a three-part energy storage system for direct steam generation power plants. The 1000 $kW_{th}h$ energy storage system was an integrated heat exchanger with PCM and a concrete module.

Performance analysis of commercial-size direct steam generation parabolic trough solar plants is of high importance. Seitz et al. (2016) developed a TES system for direct steam generation plant that consists of an integrated PCM and sensible storage system at commercial scale. They optimized the entire coupled power plant system. Their results reveal that the TES system has a strong interdependency with other subsystems of the DSG power plant due to the pressure dependency of the water/steam cycle. Elsafi (2015) performed exergy and exergoeconomic analyses of a direct steam generation solar thermal power plant based on parabolic trough collectors. They observed almost 9% increase in the vapor fraction at the turbine outlet due to 100 K increase in the temperature of the low pressure turbine inlet. However, it results in less than 1.5% decrease in exergetic efficiency, and about 2% increase in cost of electricity.

Pirasaci and Goswami (2016) performed a numerical analysis of the performance of a latent heat storage system for direct steam solar power plants considering different parameters such as the system length, tube internal diameter and flow rate of heat transfer fluid. They also proposed a low cost arrangement, consisting only one heat exchanger with PCM for the entire pre-heating, vaporization/condensation and superheating processes. However, this design has no applicability to store thermal energy as it does not provide the required fluid temperature entering the steam turbine during the discharging process. They concluded that the system effectiveness can be improved by increasing the system length and decreasing the diameter of heat exchanger tubes.

Michels and Pitz-Paal (2007) conducted experimental and numerical analyses of the performance of an energy storage system with nitrate salts consisting of $NaNO_3$ and KNO_3 in a direct steam generation solar plant. Comparing to the case with a single PCM, the experimental results indicated that higher phase change rates are observed where multiple PCMs are used in a cascaded arrangement. This also increases the effectiveness of the PCM usage in the heat exchanger and provides a more uniform outlet temperature. Bayón et al. (2010) performed experimental analysis of a latent heat thermal storage system with KNO_3/$NaNO_3$ eutectic mixture as PCM to produce steam by parabolic-trough collectors at the Plataforma Solar de Almería. They observed a discrepancy between the results of steam quality and the corresponding PCM temperature variation due to utilization of improper thermal insulation and thermal inertia caused by excess mass of PCM. They