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The heat transfer mechanism study of three-tank latent heat storage system based on entransy theory

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ABSTRACT

A three-tank latent heat storage system in which liquid lead–bismuth eutectic alloy (LBE) is used as sensible heat storage medium, and sodium nitrate is selected as the phase change material (PCM), is proposed in the present work. The performance of thermal storage system depends chiefly upon the heat transfer performance at superheated steam stage, and the mass flow rate of LBE can be adjustable to accommodate the specific heat change of water/steam. There exists an optimal mass flow rate ratio to maximize the performance of storage system. Generally, the more uniform the temperature difference distribution is, the higher the thermal performance of the storage system. The optimal mass flow rate of liquid LBE appears under constant mass flow rate ratio condition, in which the entransy and exergy rises of steam reach the maximum. The increasing number of transfer units at superheated steam stage improves the thermal storage performance monotonously. The exergy efficiency of this storage system runs at more than 80% through proper parameters setting.

1. Introduction

The concentrated solar power (CSP) has a competitive edge among all the current renewable energy technologies, because the energy can be stored in form of heat in CSP technology, and be converted into electricity when is required in cloudy period or at night [1]. The parabolic trough concentrator is one of the most matured solar concentrators among the CSP technologies, and has been successfully applied around the world. Accordingly, the thermal storage system for parabolic trough power has gained widely attentions recently. A survey was conducted by Herrmann and Kearney [2] on the thermal energy storage of parabolic trough power, and the results showed that the storage system where the heat transfer fluid also serves as the storage medium, was more cost-effective than concrete storage and phase change material storage. Jian et al. [3] investigated the solid sensible heat storage for high-temperature storage applications in terms of investment and maintenance costs, the results showed that the cost increases as the outlet temperature increases and the operating cost takes a large part in the total cost. The parabolic trough power has two types of working fluids: synthetic oil and water/steam [4]. The sensible heat storage system is mainly employed for synthetic oil system. In the parabolic trough power with direct steam generation (DSG), the water/steam is selected as the working fluid, and the latent heat storage system is necessary to improve the efficiency. Sharma et al. [5] presented the desirable thermophysical properties for phase change material (PCM) in storage system through the investigation and analysis of latent heat storage system using PCM for different applications. An metal alloy Mg-51%Zn was proposed as PCM for thermal energy storage by Blanco-Rodríguez et al. [1], but the metal alloy needs high pressure and price. Feldhoff et al. [6] carried out a comparison between the parabolic trough power plants with synthetic oil and DSG, and the results showed that the DSG system has advantages over synthetic oil system without considering thermal storage system; when considering thermal storage system, the DSG has higher cost than the synthetic oil system. A three-part storage system including two sensible heat storage units and one latent heat storage unit was proposed by Laing et al. [7–8], in which sodium nitrate was adopted as the PCM and two concrete storage units for preheating/superheating. Some storage systems for solar power with DSG was investigated by Seitz et al. [9], in these latent heat storage systems sodium nitrate was chosen as PCM and molten salt system was chosen for sensible heat sections.

In view of the importance of storage system on DSG, the performance analysis and optimization of storage system are very necessary for the selection and application of storage systems. In storage system for solar energy with DSG, the superheated steam coming from solar collector field is cooled to unsaturated water by storage

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Nomenclature

c_p	specific heat (J/kg K)
Ex	exergy (W/m)
f	friction factor
G	entransy rise of water/steam
G_{dis}	entransy dissipation rate (J K)
G_N	entransy dissipation number
h_{tp}	convective heat transfer coefficient at two phase flow stage (W/m^2 K)
$h_{tp,chen}$	Chen's heat transfer coefficient for two-phase flow boiling (W/m^2 K)
Ntu	Number of heat transfer units
m	mass flow rate (kg/s)
Nu	Nusselt number
P	pressure (mmHg)
P_{atm}	atmospheric pressure (mmHg)
Pr	Prandtl number
q	heat flux density (W/m)
$Q_{a,ab}$	solar energy is absorbed by selective coating on absorber (W/m)
$Q_{a,c}$	energy conducted from the outer wall of absorber to the inner wall of absorber (W/m)
$Q_{c,a-g}$	convective heat transfer from absorber to glass cover (W/m)
$Q_{c,g-e}$	convective heat loss of glass cover (W/m)
Q_{CS1}	heat released from superheated steam to liquid LBE (W)
Q_{CS2}	heat released from superheated steam to sodium nitrate (W)
Q_{CW}	heat released from unsaturated water to liquid LBE (W)
$Q_{r,a-g}$	radiative heat transfer from absorber to glass cover (W/m)
$Q_{r,g-e}$	radiative heat loss of glass cover (W/m)
R_Q	thermal efficiency
R_{Ex}	exergy efficiency
R_G	entransy efficiency
Re	Reynolds number
T	Temperature (K)

Greeks

ΔH	enthalpy rise (J)
$\mathbf{u}$	velocity vector (m/s)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant

Subscripts

c	cold fluid
C	charging process
$C–I$	cold tank to intermediate tank
D	discharging process
e	environment
f	working fluid
g	glass cover
h	hot fluid
H	hot tank
i	inner
$I–H$	intermediate tank to hot tank
L	low temperature heat exchanger
LB	liquid lead–bismuth
o	outer
S	superheated steam
w	wall
W	unsaturated water

mediums, and the heat released from superheated steam is stored in storage mediums in charging process; the unsaturated water is heated to superheated steam by storage mediums in discharging process.

Guo et al. [10] proposed a new concept of entransy to describe the heat transfer ability recently. It has been proved that the total entransy is always dissipated in the isolated systems, and the entransy dissipation can be a descriptive measure of irreversibility in heat transfer processes [10–11]. The novel concept has been widely used and made a considerable progress in recent years [12–13]. The extremum principle of entransy dissipation and the entransy-dissipation-based thermal resistance were proposed to the optimization of heat exchangers, and no paradox was found in the analysis of heat exchanger [14]. Until now, the entransy and entransy dissipation have been applied to the analysis of heat conduction [15], heat convection [16], thermal radiation [17], heat exchanger [14,18–21], heat exchanger networks [22–24], chemical heat pump [25–26], heat storage system [27–28], thermal systems with phase change [29–31] and variable thermopysical properties [32], etc. The application of entransy theory to heat-work conversion has been discussed. Cheng and Liang [33–34] proposed the concept of entransy loss to analyze the entransy change in heat-work conversion processes. There is no denying that the novel concept gives another insight on the optimization of thermal system compared with entropy and exergy analysis [35]. As for the differences between entransy and entropy, Guo [36–37] further pointed out that entropy generation represents the irreversibilities in heat transfer processes for heat-work conversion, and entransy dissipation is directly related to the optimization of heat transfer processes, as long as no heat-work conversion exists.

The thermal energy storage system focuses on the heat transfer process in charging and discharging processes, and the heat-work conversion is not involved in the storage system. Therefore, the entransy/entransy dissipation is selected to be used to investigate the performance of thermal energy storage system.

A three-tank latent heat storage system for solar energy with DSG is presented in the present work, and the system performance in charging and discharging processes is investigated based on the entransy theory, and the influences of some important operating parameters on the performance of storage system are analyzed. The present work has some guiding significations on the optimization and applications of storage system for solar power with DSG.

2. Theoretical analysis

The sketch of parabolic trough power with storage system is illustrated in Fig. 1. In the daytime, one part of the thermal energy absorbed by working fluid in solar field is stored by the storage system, which could be used when needed at night. Assuming that the solar irradiation intensity and the total length of solar receivers are constant, so the solar energy received by solar field is fixed; the heat exchanged between the working fluid and the environment is neglected.

The solar receiver includes one absorber and a glass cover, and the annular space keeps vacuum to reduce heat loss [38]. The