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Investigation on the performance of a high-temperature packed bed latent heat thermal energy storage system using Al-Si alloy

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ABSTRACT

High-temperature energy storage system plays an important role in improving the efficiency of the concentrated solar power plants. The latent heat thermal energy storage (LHTES) is one of the most competitive thermal energy storage approaches because of the large heat storage density and approximately constant temperature during the phase change process. The Al-Si alloy has been considered as the high-temperature phase change material (PCM) used in the LHTES system because of its advantages such as large latent heat, suitable phase change temperature, high thermal conductivity and cost-effective. A three-dimensional numerical model of the packed bed LHTES system, using Al-25 wt%Si alloy as the PCM and air as the heat transfer fluid (HTF), is built to investigate the performance of the system based on the enthalpy-porosity model and surface-to-surface radiation model. The numerical model is validated through comparing with the experimental results reported in literature. The performance of the system is evaluated from the aspects of charging/discharging time, energy transfer efficiency and mean power. The results indicate that the PCM shows better performance than the rock in the energy storage system due to the involvement of latent heat and high thermal conductivity of the PCM. The influences of the radiation heat transfer and inlet temperature of the HTF on the system performance are also investigated. It is found that the radiation heat transfer shows a significant effect on the heat transfer in the high-temperature LHTES system. The temperature difference between the inlet temperature and phase change temperature dominates the charging/discharging time because the phase change time accounts for a large proportion in the total charging/discharging time. The effect of the wall thickness of the thermal energy storage unit is also studied and the results suggest that the wall thickness of the thermal energy storage unit cannot be neglected because of its relatively large thermal resistance.

1. Introduction

The energy demand is growing with the rapid development of civilization, and the conventional fossil fuels cannot sustainably meet such drastic energy consumption due to the gradual depletion. In addition, it is also a serious problem that the consumption of fossil fuels usually produces contaminants which lead to environmental pollution and greenhouse effect. Therefore, the development of the renewable energies such as solar energy, wind energy, geothermal energy, etc. is imperative to optimize the energy composition. Solar energy as a low cost, clean, widely distributed and abundant renewable energy has been utilized for decades [1,2]. Concentrated solar power (CSP) technology is one of the most attractive ways to utilize the solar energy as indirect photoelectric conversion, which is much more suitable for large-scale application compared with photovoltaic [3]. The CSP technology produces a large amount of heat through focusing solar radiation energy and then the thermal energy is converted into electricity by the thermal power generator. There are four types of CSP systems, and the operation temperature ranges from ambient temperature (about 300 K) to significantly high temperature (nearly 1800 K), based on the different heat collection methods: solar power tower (SPT), parabolic trough collector (PTC), linear Fresnel reflector (LFR) and parabolic dish collector (PDC) [4]. However, due to the features of intermittency and instability of solar energy, the CSP system is usually integrated with the thermal energy storage (TES) system to improve the efficiency. The TES system can collect the excess heat at low load or ample sunshine and release it at high load or poor sunshine such that the disadvantages of solar energy and peak-valley difference for power consumption can be overcome [5]. In fact, the TES system also has wide application in the field of industrial high-temperature waste heat recovery such as the steel-making industrial [6]. Because the operation requirements for the most CSP systems and waste heat recovery systems are usually at elevated temperature (above 400 K), it is essential to investigate the performance of the TES system and the related thermal energy storage

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Nomenclature

A	area, m^2
A_s	additional term in momentum equation, –
C	mushy zone constant, –
c_p	specific heat capacity, kJ/(kg K)
E	energy, kJ
E_b	black-body radiation, W/m^2
G	irradiation, W/m^2
g	gravitational acceleration, m/s^2
J	radiosity, W/m^2
L	latent heat, kJ/kg
l	equivalent hydraulic diameter, m
$\boldsymbol{n}$	external normal direction of the wall
$\overline{P}$	mean power, W
P	pressure, Pa
P_c	wetted perimeter, m
q	heat flux, W/m^2
Re	Reynolds number, –
r	distance between two surfaces, m
S	energy source term, W/m^3
T	temperature, K
t	time, s
U	characteristic velocity, m/s
$\vec{V}$	velocity vector, m/s
X	shape factor, –
u, v, w	velocity in x, y, z direction, m/s
x, y, z	Cartesian coordinates

Greek symbols

β	thermal expansion coefficient, K^{-1}
γ	liquid fraction, –
ε	emissivity, –
ζ	small constant in additional term of momentum equation, –
η	energy transfer efficiency, –
θ	angle, °
λ	thermal conductivity, W/(m K)
μ	viscosity, kg/(m s)
ξ	variation degree of the phase change time, –
ρ	density, kg/m^3
φ	reflectivity, –

Subscripts

m	melting
m1	the lower limit of melting state
m2	the upper limit of melting state
in	inlet
out	outlet
HTF	heat transfer fluid
PCM	phase change material
shell	wall of the thermal energy storage unit
interface	interface between the PCM and the wall of the thermal energy storage unit
ini	initial
i, j	surface number
wall	wall of the storage tank

materials in such temperature range.

The TES system is classified into three types in view of the different heat storage methods: sensible heat thermal energy storage (SHTES), LHTES, and the thermochemical energy storage. SHTES utilizing the sensible heat of the material is mainly dependent on the specific heat and temperature variation of the material. There are many different kinds of materials for the high-temperature SHTES system such as concrete, rock and sands, etc. [7–11]. Xu et al. [7] prepared a series of Sialon-Si_3N_4-SiC composite ceramics with different composition ratios for the CSP SHTES system through noncontact graphite-buried sintering method. They found that the sintering temperature and cost of the composite ceramic could be reduced due to the involvement of Si_3N_4 and O'-Sialon. And the composite ceramic also showed excellent performance on thermal conductivity and thermal shock resistance. Girardi et al. [8] developed two types of concretes through cast-moulding and vibro-moulding, and both were filled with the recycled materials such as polyamide fibers and metallic powders to improve the thermal conductivity of the concrete. It was indicated that the vibro-moulding concrete showed better performance than cast-moulding concrete either on mechanical property or thermal conductivity. Bruch et al. [9] experimentally investigated the performance of a thermocline TES system using the rock and sand as thermal energy storage materials. The results showed that flow and heat transfer in the storage tank were homogeneous without by-pass. They also proposed a one-dimensional model and numerically studied the temperature profiles in the TES system, and the numerical results agreed well with the experimental results. Okello et al. [10] experimentally investigated the temperature distribution of rock in a TES system. It was shown that the thermal degradation would result in the decrease of temperature of rock bed which was detrimental to the application of the TES system. The results also showed that the temperature of rock in upper hot part decreased quicker than that in lower cold part. However, it should be noted that the SHTES system is not suitable for the large-scale application due to the small energy storage density, although it has advantages of low cost, mature and simplicity. Among the three types of TES systems, thermochemical energy storage based on reversible chemical reaction has the highest energy storage density which is nearly 5–10 times of the other two types [11–13]. Kato et al. [11] prepared a mixed hydroxide composed of magnesium hydroxide and nickel hydroxide, which could be used as a middle-temperature TES material ranging from 473 K to 573 K. Compatible operation temperature can be obtained through changing the composition ratio of the two types of hydroxides. Schaube et al. [12] theoretically analyzed the performance of a fixed bed reactor through a one-dimensional model. They showed that the low thermal conductivity of solid reactants limited the heat transfer between the fixed bed and the wall. And direct heat transfer through accessing gas into the solid reactants could improve the performance of the reactor. Roßkopf et al. [13] added a small amount of SiO_2 nanoparticles into $CaO/Ca(OH)_2$ thermochemical storage system to prevent the agglomeration of reactant powders. The results showed that the performance of the heat and mass transfer of the system was enhanced and there was little agglomeration after several cycles. The main defect limiting the application of thermochemical energy storage is the complex process and highly technical difficulty. The investigation of thermochemical energy storage is still in its early stage and most of the studies are still at laboratory scale.

Therefore, the LHTES system using the PCM has a great potential for the practical applications [14,15], because it has large energy storage density due to the latent heat and little variation of temperature during the phase change process compared with the SHTES system. And the technology of the LHTES system is significantly more mature than thermochemical energy storage system. Many kinds of PCMs can be available for the LHTES system across a wide range of temperature. The most common PCMs applied for the high-temperature LHTES system are inorganic salts, eutectic molten salts, metals and metal alloys. In order to achieve suitable phase change temperature and high latent