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Modeling on heat storage performance of compressed air in a packed bed system

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HIGHLIGHTS

- The heat storage performance of compressed air in PBTES is presented.
- Effects of porosity, particle diameter and CA pressure on thermal behavior are investigated.
- The inlet CA pressure has significant influence on the thermal performance of PBTES.
- A packed bed filled with multiple HSMs has better charge efficiency.

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ABSTRACT

Compressed Air Energy Storage (CAES) incorporates a Packed Bed Thermal Energy Storage (PBTES) represents a promising larger scale storage technology. The heat storage performance of compressed air (CA) in PBTES is presented and numerically analyzed in this paper. Phase change material (PCM) particles are used as the filler. The unsteady two-phase energy conservation equations considering the phase change phenomena inside the PCM particles are developed and solved numerically by finite difference method. This model has been validated with Izquierdo-Barrientos' experimental data. Then, the effects of porosity (ε), PCM particle diameter (d_p), CA inlet pressure (P) and filling approach on PBTES thermal behaviors (such as temperature profiles, heat storage capacity and charge efficiency) are investigated.

It was found that increasing particle diameter results in a decrease in the charge efficiency, and the charge efficiency increases with an increase in CA inlet pressure. The PBTES filled with three kinds of materials has better charge efficiency compared with the packed bed filled with single PCM or rock.

1. Introduction

As the energy crisis and environment pollution growing severely, the renewable energy sources is developed very fast for its inexhaustible, clean and environmentally friendly, especially of the solar and wind energy. However, they are intermittent by nature environment, which creates a demand for the energy storage system for the times when the source of energy is not available. The Compressed Air Energy Storage (CAES) is a promising and large-scale energy storage system which seems to be the good solution for the discontinuous problem of solar and wind energy [1–3].

For the traditional CAES system, the compressed air is released from the tank and heated up by additional energy sources like nature gas, fossil fuel, and then being expanded in a gas turbine. In order to avoid the use of additional energy, a new CAES system is developed. The heat generated during compression is stored and later released for heating up the compressed air before its expansion. A Packed Bed Thermal Energy Storage (PBTES) is adopted for this newly CAES system for its low cost, high efficiency and reliability.

Many researchers paid attention to the performance of PBTES system in recent years with different heat transfer fluids, such as molten salt [4–7], air [8,9], and water [10], not only for sensible PBTES, but also for latent PBTES. Ismail and Stuginsky [11] presented four kinds of models (Continuous solid phase model, Schumann's model, Single phase model and Thermal diffusion model) for simulating the thermal behavior of PBTES system. And the results of these models were compared and analyzed, both for sensible and latent.

Zanganeh et al. [12] designed a 7.2 GW h_{th} conical PBTES and the effects of the operational and design parameters on the performance of TES system were analyzed. Li et al. [13] studied the energy charge and discharge effectiveness of thermal storage

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Nomenclature

A	area of bed cross section (m^2)
A_w	wall effect correction term
B_w	wall effect correction term
D	diameter of storage tank (m)
E_{stored}	energy stored in the PCM particles (J)
E_{pump}	pumping energy (J)
E_{input}	input energy of molten salt (J)
Gr	Grashof number
H	storage tank height (m)
L_p	latent heat of PCM (kJ/kg)
M	maximum iterations for diameter of PCM sphere
N	maximum iterations for time step
Nu	Nusselt number
Pr	Prandtl number
ΔP	pressure drop (Pa)
R	Radius of storage tank
Re	Reynolds number
T	temperature (K)
T_{m1}	peak temperature of the PCM during the solid–solid transition (K)
T_{m2}	peak temperature of the PCM during the solid–liquid transition (K)
ΔT	temperature difference (K)
c_p	specific heat (J/kg K)
d_p	diameter of PCM spheres (m)
g	gravity (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_a	volumetric heat transfer coefficient between air and solid (W/m^3 K)
h_l	overall heat loss coefficient
h_w	volumetric heat transfer coefficient between tank and ambience (W/m^3 K)
r	radius of PCM spheres (m)
t	time (s)
u	velocity (m/s)
x	location across the axis of the tank (m)

Greek symbols

ε	porosity
ρ	density (kg/m^3)
k	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
γ_{lh}	latent heat (J/kg)
η	charge efficiency
β	volumetric heat expansion coefficient of fluid (1/K)

Subscripts

a	air
ave	average
end	end
f	fluid
i	index for axial direction
in	inlet
out	outlet
l	liquid of PCM
L	low temperature
H	high temperature
m	index for radial direction
o	outer
p	particles
s	solid
surface	the surface of the tank

Superscripts

n	index for time step

tank. Zalba et al. [14] summarized the study of thermal energy storage, including materials, heat transfer and applications. Barton [15] presented simulation of thermal storage in a rock bed by considering the temperature-dependent density, and the effects of particle size, depth of bed and air flow rate were investigated. Bindra et al. [16] analyzed the recovered and lost exergy of PBTES system during cyclic storage and recovery. They found that the exergy efficiency of sensible heat storage system was higher than PCM storage system. Yang and Garimella [17] developed a model to study thermocline performance of the charge and discharge cycles of molten-salt in a PBTES system. Aldoss and Rahman [18] presented a new design for a PBTES system, and compared the thermal performance between the multi-PCM and single-PCM. Zanganeh et al. [19] designed a new TES filled with PCM and rocks. The simulations indicated that a PCM volume of 1.33% of the total storage volume was sufficient to achieve stabilization of the outflow air temperature when discharging. Anderson et al. [20] presented a packed bed filled with alumina and air was used as HTF, the thermal behavior of the PBTES was investigated both experimentally and numerically. Chai et al. [21] carried out an experimental study of a close loop PBTES system. It was found that the air flow direction has significant influence on the energy and exergy efficiencies. Chai et al. [22] also performed the experimental works on a cryogenic PBTES with liquid nitrogen as working fluid, and the influence of working pressure on the energy storage performance was analyzed.

Although there are many practical applications of PBTES system, however, very few works have been reported in literature on the topic of PBTES combined with a CAES system in general. Most recently, Liu et al. [23] published an important experimental study on the thermal performance of supercritical air blowing through a rock bed. The air pressure is ranged from 0.22 MPa to 6.55 MPa. As in their work, the air-to-solid heat transfer coefficients were measured and compared with various published correlations [24–28]. While the Yang's equations of non-uniform spherical particles were found to predict that coefficients very well. Also the effects of air pressure, mass flow rate and the entrance distances on the heat transfer coefficients were studied.

It is clear that Liu's work focuses on the heat transfer characteristics between the air and solid particles in packed bed system, however, the heat storage performances, such as heat storage capacity, charge efficiency were not performed. Besides, up to our knowledge, the thermal behavior of compressed air in PBTES has not been studied in the literature. Even though some well-developed models, as mentioned in Ref. [11], are capable of revealing the straight-forward phenomenon of CA in PBTES. It is also lack in a clear knowledge about the following two aspects so far: (1) the effects of some important factors, especially the CA pressure. Air is compressible fluid which is different from other heat transfer fluids, e.g., water or molten salts. The air properties variation with pressure is evident, that will affect the heat transfer performance in PBTES and need to be fully discussed; (2) various filling approaches. Most of previous works were considering the PBTES filling with single heat storage materials, the multiple filling approaches have not been evaluated.

Accordingly, it is the goal of the present work to present a numerical model of CA in PBTES system. As indicated by Ref. [23], Yang's correlations are adopted to calculate the air-to-solid