Applied Energy 173 (2016) 255–271

Contents lists available at ScienceDirect

Applied Energy

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

Thermal energy storage and retrieval characteristics of a molten-salt latent heat thermal energy storage system

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HIGHLIGHTS

- A shell-and-tube latent heat thermal energy storage (LHTES) system using molten salt as the PCM is built.
- Thermal energy storage and retrieval characteristics of the LHTES system are experimentally and numerically studied.
- The performances of eutectic molten salt and nickel foam/salt composite as the PCMs are comparatively studied.
- A 3D numerical model is developed to depict the thermal energy storage and retrieval of the LHTES system.

ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form 30 March 2016
Accepted 6 April 2016

Keywords:
Latent heat thermal energy storage
Nitrate molten salt
Nickel foam
Heat transfer characteristics
Thermal energy storage and retrieval

ABSTRACT

In the present study, a shell-and-tube latent heat thermal energy storage (LHTES) system is built using the eutectic molten salt as the phase change material (PCM) to make an efficient use of solar energy at medium-temperature of around 200.0 °C. The nickel foam is embedded in pure PCM (molten salt) to form composite PCM to improve the performance of the LHTES system through enhancing the effective thermal conductivity of the PCM. The performances of the systems using pure molten salt and composite PCM are investigated both experimentally and numerically. The oil is used as the heat transfer fluid (HTF) and the influence of mass flow rate of the HTF on the thermal energy storage and retrieval is investigated in the experiments. The charging and discharging time durations, mean power and energy efficiency are estimated to evaluate the performance of the LHTES system. Meanwhile, a three-dimensional (3D) numerical model is developed based on the enthalpy-porosity model and two-temperature energy equations to investigate the thermal energy storage and retrieval of the LHTES system, and the detailed heat transfer characteristics during the melting/solidification of the PCM are understood. The results indicate that encapsulating molten salt with nickel foam to enhance the effective thermal conductivity of the PCM can improve the performance of the LHTES system. The information provided in the present study will be helpful for the LHTES system design, construction and application using molten salt for solar energy storage.

1. Introduction

Due to significant consumption of the fossil fuels, energy shortage has become a stringent issue that might restrict the development of the economy and human society. In addition, excessive consumption of the fossil fuels leads to serious environment pollution. Therefore, the effective measures of improving energy efficiency and developing the renewable energy have attracted many attentions to alleviate the above issues [1]. Solar energy as one of the renewable energy sources is appealing due to such advantages as clearness, low cost, widespread distribution compared with other renewable energy sources [2]. However, the widespread application of solar energy is limited by its intermittent and instable characteristics. Thermal energy storage is one of the useful methods to overcome such defects through temporally and spatially balancing the energy supply and demand. There are three ways for the thermal energy storage: sensible heat thermal energy storage (SHTES), LHTES and thermochemical energy storage [3]. Although the SHTES posses the advantages like easy implementation, simple operation, low cost, etc., it cannot maintain a stable temperature during the energy retrieval process and the energy storage density of the SHTES is very small. Thermochemical energy storage is with large energy storage density, but there are some disadvantages limiting its application, for example, the complex technology involved, high cost and low overall

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http://dx.doi.org/10.1016/j.apenergy.2016.04.012
0306-2619/

Nomenclature

A	cross-section area (m^2)
A_s	additional term in momentum equation
a_{sf}	specific surface area (m^{-1})
C	mushy zone constant
c_p	specific heat capacity, kJ/(kg K)
D	diameter (m)
d_e	equivalent hydraulic diameter (m)
d_p	pore diameter (m)
d_f	fiber diameter (m)
d_k	characteristic length (m)
E	energy (kJ)
F	inertial coefficient
g	gravitational acceleration (m/s^2)
h	convection heat transfer coefficient ($W/(m^2\,K)$)
h_{sf}	interfacial heat transfer coefficient ($W/(m^2\,K)$)
K	permeability (m^2)
L	latent heat (kJ/kg)
N	parameter in model of Boomsma and Poulikakos
n	external normal direction of the wall
$\overline{P}$	mean power (kW)
P	pressure (Pa)
P_c	wetted perimeter (m)
Pr	Prandtl number
q_m	mass flow rate (kg/s)
Re	Reynolds number
S	shape factor
T	temperature (°C)
t	time (s)
$\overrightarrow{V}$	velocity vector
u, v, w	velocity in x, y, z direction (m/s)
x, y, z	Cartesian coordinates

Greek symbols

β	thermal expansion coefficient (K^{-1})
χ	tortuosity coefficient
ε	porosity
γ	liquid fraction
η	energy efficiency
λ	thermal conductivity (W/(m K))
μ	dynamic viscosity, (kg/(m s))
ρ	density (kg/m^3)
σ	constant in model of Boomsma and Poulikakos
ω	pore density, pore per inch (PPI)
ξ	small constant in additional term of momentum equation

Subscripts

0	initial, environment
c	charging
d	discharging
e	effective value
m	melting
$m1$	the lower limit of melting state
$m2$	the upper limit of melting state
s	metal foam
td	thermal dispersion
in	inlet
out	outlet
HTF	heat transfer fluid
PCM	phase change material
exp	experiment
wall	wall of the thermal energy storage tank

efficiency. Therefore, the LHTES with low cost is much more attractive due to large energy storage capacity and the characteristic of almost constant temperature during the phase change process compared with the other two methods [4–6].

There were plenty of investigations on the thermal performances of the LHTES systems with different configurations and operational conditions. It was found that shell-and-tube type LHTES system was more common in thermal energy storage applications due to easy implementation [7,8]. Akgun et al. [9] experimentally investigated the influence of the Reynolds number of the HTF and the Stefan number on the melting/solidification characteristics of paraffin in a shell-and-tube LHTES system. They found that the Stefan number showed a greater effect on the melting time than the Reynolds number. Adine and Qarnia [10] numerically studied the performance of a shell-and-tube LHTES system which was filled with two kinds of PCMs. They analyzed the influences of the parameters, i.e., the HTF inlet temperature, mass flow rate of the HTF and mass ratio of two PCMs, on thermal performance of the system. Agyenim et al. [11] investigated the heat transfer characteristics of two different structures used in the storage units, i.e., finned tubes and multitube, and the results showed different features during the charging and discharging processes. Ismail et al. [12] studied the influence of the finned tubes on the heat transfer characteristics of the LHTES system, and they found that the solidification time was significantly affected by the parameters such as length, thickness, numbers of the fin, etc. Medrano et al. [13] experimentally investigated the performance of five small heat exchangers which was filled with PCM to work as the LHTES systems. The average thermal power was estimated to evaluate the performance of the system, and they found that the maximum average thermal power was achieved using the compact heat exchanger. Zhao and Tan [14] integrated a shell-and-tube LHTES unit with fins into a conventional air-conditioner to improve the performance, and they numerically analyzed the effects of mass flow rate of the HTF and fin height on the performance of the LHTES unit.

There are many kinds of PCMs that can be used in different temperature ranges. Molten salt is a most commonly used PCM for the medium-temperature solar energy application due to the suitable phase change temperature and large heat capacity [15–17]. Many studies about the molten salt have been reported in recent years. Solar salt is a typical nitrate molten salt obtained through mixing the sodium nitrate and potassium nitrate in a certain mass fraction, e.g., $NaNO_3$: KNO_3 = 54:46 or 60:40. Rogers and Janz [18] measured the latent heat and specific heat of $NaNO_3/KNO_3$ composite using DSC and presented the phase diagram of such binary system. Iverson et al. [19] measured the thermo-physical properties of three typical salts, i.e., solar salt, HITEC salt (40 wt.% $NaNO_2$, 7 wt.% $NaNO_3$, 53 wt.% KNO_3) and a Na–K–Li–Ca nitrate salt, at different temperatures. The results showed that both the thermal and mechanical properties of the salt such as specific heat, thermal conductivity and Young's modulus varied with the temperature. A similar study of other three salts (Na–K–Li, Na–K–Ca, Na–K–Li–Ca) was conducted by Siegel et al. [20] and the thermo-physical properties were also found to be temperature dependent. Guillot et al. [21] investigated the corrosion effects of different molten salts on inertised asbestos-containing waste (IACW), and the results showed a good compatibility between the solar salt and