Applied Thermal Engineering 127 (2017) 499–507

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Experimental studies of the discharge performance of single-medium TES for CSP applications

Dong Ho Kim *, Seok Ho Yoon, Young Kim, Chan Ho Song, Kong Hoon Lee, Jun Seok Choi

Energy Systems Research Division, Korea Institute of Machinery and Materials, Daejeon 34103, South Korea

HIGHLIGHTS

- Experimental studies of single-medium thermocline TES has been conducted.
- Feasibility of single-medium TES for high-temperature has been verified.
- Useful energy was varied greatly depending on the tank configuration.
- The high mass flow rate condition enhanced the thermal discharge performance.

ARTICLE INFO

Article history:
Received 22 February 2017
Revised 31 May 2017
Accepted 9 August 2017
Available online 10 August 2017

Keywords:
TES
Molten salt
High-temperature
Discharge
Thermocline
Thermal stratification

ABSTRACT

This paper presents the experimental results and an analysis of thermocline TES using a molten salt. A single-medium thermocline with two types of storage tanks were tested under various mass flow rates. The discharge performance of each type of thermal storage tank was evaluated according to the useful energy considering the discharge temperature, and the performance was found to vary greatly depending on the configuration of the storage tank. It was also confirmed that the high mass flow rate enhanced the performance despite the increased unnecessary mixing effect. Although the temperature maldistribution was increased under the condition of a high mass flow rate, it is considered that the reduced discharging time positively affects the performance for the corresponding Froude numbers of 0.4–1.4. This study provides meaningful experimental results for molten-salt thermocline TES and design guidelines for a thermocline TES system.

1. Introduction

Around the world, many studies are underway on renewable energy in relation to the issue of fossil fuel depletion and the desire for new energy sources. Specifically, studies using solar energy have been actively conducted over the last few decades, and solar power generation has been commercialized mainly in the United States and Spain. The “Sunshot Initiative” project started in 2011 with the efforts of the US Department of Energy (DOE), referring to a policy of creating solar energy fully competitive in terms of cost ($0.06/kWh) with conventional energy sources by 2020. With sustained long-term investments by the DOE and the efforts of different industries, several concentrating solar power (CSP) plants were connected to the US power grid in 2013, and additional CSP plants have been in operation since 2014. As of 2013, the US has produced 13 GW of electricity by solar energy (e.g., PV, CSP), enough to power two million household [1]. In 2016, the US DOE set a more innovative goal ($0.03/kWh) entitled “Sunshot 2030” [2], and current circumstances indicate that solar power generation is experiencing rapid growth.

CSP technologies generates electricity by transferring heat from solar receivers to a heat transfer fluid and then to steam, which is expanded through a turbine. CSP not only takes charge of the base load, but it also saves extra energy during the daytime. This energy can then be used at night, when solar power is lacking. Thermal energy storage (TES) is a core technology that increases the total system efficiency by increasing the plant operation time. It is essential to develop a thermal storage tank capable of efficient thermal energy storage and energy discharge.

The important issue in relation to TES for CSP plants is high-temperature storage. Generally, high-temperature thermal storage is required to produce high-temperature steam, leading to enhanced power efficiency. As far as the authors know, the maximum temperature of a solar receiver at current CSP plants (e.g., Crescent dunes, Gemasolar) using molten salt is approximately

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* Corresponding author.
E-mail address: dhkim@kimm.re.kr (D.H. Kim).

http://dx.doi.org/10.1016/j.applthermaleng.2017.08.057

Nomenclature

c_p	specific heat [kJ kg^{-1} K^{-1}]
E	total delivered energy [kJ or kWh]
Fr	Froude number
Gr	Grashof number
k	thermal conductivity [W m^{-1} K^{-1}]
L	characteristic length [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
Q	heat transfer rate [kW]
R	thermal resistance [K W^{-1}]
Re	Reynolds number
Ri	Richardson number
T	temperature [K]
u	inlet velocity [m s^{-1}]

Greek symbols

β	thermal expansion coefficient [K^{-1}]
η	efficiency
θ	non-dimensional temperature
ρ	density [kg m^{-3}]
ν	kinematic viscosity [m^2 s^{-1}]

Subscripts

act	actual
c	cold
dis	discharge
h	hot
ideal	ideal
m	molten salt
return	return
ref	reference
∞	ambient

565 °C (1050F), which may be related to the decomposition of the molten salt. In addition, price competitiveness is important in TES of CSP because TES is known to be responsible for approximately 20% of the total price. Therefore, the development of cost-competitive high-temperature TES approaches is crucial for the commercialization of CSP technology.

For high-temperature storage, molten salt is generally used as the heat transfer fluid (HTF) because the decomposition temperature of molten salt (~550 °C) is higher than that of other types of HTF (e.g., oil). However, the relatively high melting temperature and material competitiveness are still concerns. 'Hitec' and 'Solar salt' are widely used as commercial HTFs; Table 1 shows the composition and thermophysical properties of typical HTFs [3].

In order to reduce the cost of TES, thermocline TES, which enables thermal storage and discharge in one tank, has been suggested. Thermocline TES refers to a means of storing high- and low-temperature fluids in a single tank by means of thermal stratification. The core technology is to prevent the mixing of the high- and low-temperature fluids during the charge and discharge operations. The piping design and insulation technology associated with the thermal storage tank are the key technologies. Thermocline TES has not been put into practical use, but it is technically feasible enough to lower the cost of TES.

The Solar One project, started by the DOE, was the first demonstration project to apply a thermocline TES system to a CSP [4]. At the same time, the operation of a 5MWh thermocline TES system was assessed at the Plataforma Solar de Almeria (PSA) in Spain [5]. Both projects utilized dual-medium thermocline TES with oil and a filler material as the storage medium, and during this assessment, the thermocline demonstration was successful. However, to the best of the author's knowledge, no commercial CSP plants have adopted thermocline TES since that.

There have been numerous studies involving numerical analyses of solar-assisted thermal storage systems [6,7] and experimental studies of thermocline water storage systems [8,9]. However, there is limited information available on the subject of thermocline TES using molten salt as a storage medium. Specifically, feasibility testing of molten-salt thermocline TES has occurred, but most papers address numerical modeling [10–13] and filler compatibility with molten salt [14–17]. As far as the authors know, the experimental data pertaining to the transient behavior of molten salt TES by Sandia National Laboratory [16] is the only experimental work thus far, whereas most numerical analysis papers use these results to verify their models.

As discussed above, the most important issues in relation to TES are high-temperature storage and cost-competitive storage. Moreover, there is very limited information in the form of experimental data pertaining to molten-salt thermocline TES. The authors consider a single-medium (molten salt) thermocline TES system as a potentially feasible upcoming technology, and this paper describes the feasibility of single-medium thermocline TES. Experiments were conducted to find out the basic characteristics of the thermocline during the discharge process. A study of thermocline TES was carried out and the thermal characteristics of a thermal storage tank according to the operating conditions (mainly the flow rate) at a high temperature (500 °C) were investigated.

2. Thermocline TES systems and test facility setup

2.1. System description and experimental apparatus

KIMM has conducted studies of thermocline TES systems which use molten salt since 2015, and the main research themes are the development of a feasible thermal storage medium, the design of

Table 1
Composition and thermophysical properties of conventional HTF [3].

Properties	Hitec	Hitec XL	Solar salt	Therminol VP-1
Composition, wt%				
$NaNO_3$	7	7	60	
KNO_3	53	45	40	
$NaNO_2$	40			
$Ca(NO_3)_2$		48		
Freezing temp. (°C)	142	120	220	13
Upper temp. (°C)	538	505	585	400
Density (kg/m^3)@300 °C	1860	1992	1899	815
Cp (J/kg·K)@300 °C	1560	1447	1495	2319