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Thermal storage using sand saturated by thermal-conductive fluid and comparison with the use of concrete

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ABSTRACT

The present study considers sand saturated with thermal conductive fluid as a new low-cost thermal storage material that can have better heat transfer than using concrete or sand alone and also avoids issues of heat transfer degradation associated with the mismatch of thermal expansion in concrete. The new thermal storage material (sand saturated with Xceltherm® 600 heat transfer oil) was tested in a lab-scale experimental setup from 27 °C to 55 °C to show the concept and also validate a 1D transient enthalpy-based model for simulation of thermal storage. The model was then applied to study and compare the thermal storage performance of sand saturated by Hitec® (heat transfer fluid) and concrete for a 600MW$_{ele}$ CSP power plant at a thermal efficiency of 35% and thermal storage temperatures ranging from 400 °C and 500 °C. It was found that more energy can be stored and extracted if Hitec®-saturated sand is used as storage media, which may result in appreciable cost reduction than using concrete thermal storage system based on a study for a 600 MW$_{ele}$ CSP system in operation for one year. As a result, Hitec®-saturated sand can be used to replace concrete as the thermal storage media in high temperature operating range (>400 °C). It is expected that such a new approach of sensible heat storage is of significance to solar thermal energy storage technologies.

1. Introduction

Rising energy costs and the adverse effects on the environment caused by the combustion of fossil fuels have triggered extensive research into alternative sources of energy. Harnessing the solar energy has been one of the most attractive approaches [1–4]. However, to development an efficient and economical solar energy storage system is a big topic. Effective utilization of renewable energy resources relies on appropriate energy storage that reduces the mismatch of time between energy supply and demand [5]. Capable of storing a large amount of thermal energy for power generation and extending the operation of solar power plants to the late afternoon and evening time at a relatively low cost, concentrated solar power (CSP) is expected to contribute to the world's energy supply significantly in the future [6]. Technical subjects related to CSP have already drawn a lot of attention during the past decade [7].

According to US Department of Energy (DOE), the cost per kilowatt hour electricity from current solar energy technologies is high at approximately \$0.15–\$0.20/kWh$_{ele}$, if the cost of thermal energy storage is at the level of \$30.00/kWh$_{th}$. Based on conventional means of electricity generation using fossil fuels, the cost of electricity is \$0.05–\$0.06/kWh. Clearly, current solar energy technologies cannot compete with conventional fossil-fuel-based electricity generation. To improve the competitiveness of solar energy technologies, the DOE has established a goal of reducing the cost of solar-energy-based electricity to \$0.06/kWh$_{ele}$. For this target, the cost of thermal energy storage in CSP systems must be below the cost of \$15.00/kWh$_{th}$ [8].

The materials used for thermal energy storage (TES) are classified into three categories according to the storage mechanisms: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and thermochemical energy storage (TCTES) [9,10]. SHTES is the most developed technology and there are a large number of low-cost materials available [11–13], but with relatively low heat storage capacity. LHTES has much higher storage capacity, but poor heat transfer usually accompanies, which needs heat transfer enhancement [14–16]. TCTES has the highest storage capacity, but a lack of long-term durability (reversibility) prevents its practical application [17,18]. As a

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Nomenclature

C	Heat capacity (kJ/kg K)
C_f	Specific heat (kJ/kg K)
f	Darcy friction factor
h	Convective heat transfer coefficient (W/m^2 K)
$\overline{h}$	Enthalpy (J/kg)
$\dot{m}_f$	Mass flow rate (kg/s)
k	Thermal conductivity (W/m K)
L	Length of thermal storage tank (m)
N_{cycle}	Number of cycles
Nu	Nusselt number
Pr	Prandtl number of fluid
Q	Heat flux (W/m^2)
r	Radius of tubes (m)
R	Radius of tank (m)
Re	Reynolds number
S_r	Heat transfer surface area per unit length of tank (m)
T	Temperature (K)
T_f^{in}, T_f^{out}	Inlet and outlet temperatures of HTF, respectively (K)
t	Time (s)
$\overline{T}_s^{t_0}$	Initial cold average temperature of the thermal storage material (K)
U	Fluid flow velocity in porous media (m/s)
U_h	Total heat transfer coefficient (W/m^2 K)
V	Volume (m^3)
Z	Location of length from fluid inlet of a charging or discharging process

Greek Symbols

ε	Void fraction or porosity
δ	The gap of a crack (m)
η	Ratio of tube radius versus the radius of the cylindrical control volume.
η_{th}	Thermal efficiency
μ	Dynamic viscosity (Pa s)
ν	Kinetic viscosity (m^2/s)
ρ	Density (kg/m^3)

Subscript

air	Air
ele	Electrical
eq	Equivalent
f	Fluid
f_s	Fluid at the tube surface
in	Flow in
Ideal	Thermal energy storage in ideal situation
L	Defined acceptable low temperature of HTF
mix	Mixture of sand particles with fluid
out	Flow out
r	Solid material (rocks)
r_o	Reference parameter
s	Sands
s_air; *s_wall*	Surfaces of air side and concrete wall side
tank	Thermal storage tank
th	Thermal
TES	Thermal energy storage

Superscript

t_o	Initial time

consequence, the proper choice of thermal storage approach and materials is of significance for solar thermal storage, and the reduction of the cost of materials is one critical step toward the goal set by the DOE.

Currently, LHTES and TCTES are still in the stage of research due to too many unknown factors. However, SHTES has already been commercialized in large-scale applications all over the world during the past decades. High temperature molten salts, such as Solar salt®, Hitec® and Hitec®-XL [19], have been widely used as the sensible thermal storage materials since 1980. Recently, to further reduce the cost of sensible thermal energy storage materials compared to using molten salts, dual-media thermal storage systems, such as shell-and-tube concrete or a packed-bed sand or rocks, have drawn some attention [20,21]. Sandia National Lab built a dual-media SHTES system using quartz and silicon sands as storage materials and molten salt was adopted as HTF directly flowing through the packed-bed sand [22]. Laing et al. [23] established a shell-and-tube thermal storage system, as shown in Fig. 1, using concrete as sensible heat storage material, and water/steam flowed through pipes which were imbedded into the concrete to charge and discharge heat. Due to the insufficient heat transfer between concrete and embedded pipes, heat transfer enhancement is necessary. Concrete can also be fragile and easy to crack after a number of charge/discharge cycles at high temperature (>400 °C) due to the mismatch of the thermal expansion coefficient between metal tubes and concrete [24], which will result in large thermal contact resistances, as shown in Fig. 2. Skinner et al. [25] conducted some tests on concrete thermal storage, and concrete was chosen as a sensible storage material between 400 °C and 500 °C, a molten nitrate salt was used as the HTF. During charging process, significant cracking occurs in both the radial and longitudinal directions in the concrete prisms, as shown in Fig. 2. The cracking was due to hoop stress induced by the dissimilar thermal strain rates of concrete and stainless steel. Skinner et al. [25] successfully reduced cracking to hairline levels by applying some interface materials, such as Polytetrafluoroethylene (PTFE) and a heat-curing, fibered paste (HCFP). Even though the cracking can be minimized by using the interface material, but in a long term cyclic heat charging/discharging, those cracks still cause significantly negative effects to the heat transfer between concrete and embedded pipes. As a consequence, it is necessary to find proper approaches to avoid these issues while still use the low-cost materials, such as sands and rocks.

In the current study, sand was considered as low-cost thermal storage material in a dual-media shell-and-tube storage unit to take the advantage of the ability of easy handling in construction, high durability, and easy of fitting and surrounding the embedded pipes. Contrast to concrete, packed sand has no concern on the mismatch of thermal expansion with embedded pipes due to its certain level of flowing ability, while still maintaining the advantage of low-cost. However, packed sand is a porous material with air filled in the pores and the heat transfer in sand is therefore not sufficiently high. In order to obtain a better heat transfer between storage material and embedded pipes, a thermal conductive fluid was used to saturate the packed sand, which forms a new storage material with better heat transfer than using concrete or sand alone. In this study, the new thermal storage material (sand saturated with Xceltherm® 600 heat transfer oil [26]) was tested and compared with sand in a lab-scale experimental setup from 27 °C to 55 °C. The results were also used to validate a 1D enthalpy-based transient model. In order to compare the thermal storage performance between concrete and fluid-saturated-sand at higher temperature range, Xceltherm® 600 heat transfer oil was replaced by Hitec®, and a 1D transient enthalpy-based model was applied to compare the thermal storage performance between concrete and Hitec®-saturated sand. The study was conducted for a 600MW$_{ele}$ CSP power plant with 35% thermal