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Optimal design for sensible thermal energy storage tank using natural solid materials for a parabolic trough power plant

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ABSTRACT

This paper presents numerical investigation of transient behavior and thermal storage capability of a sensible heat storage (SHS) unit designed for storing heat in the temperature range of 523–673 K. The objective of this study is to assess the potential of using two candidate materials as energy storage media found in Jordan. The thermal performance of using these materials in SHS tank is compared against concrete bed. A heat storage unit of cylindrical configuration with embedded charging tubes has been designed. To investigate their heat storage characteristics, a finite element based 3-D mathematical model has been developed using COMSOL Multiphysics 5.1. Numerically predicted results match closely with the data reported in the literature. Performances of the thermal storage bed of capacity of 136.7 MW in 3 h (including charging time, energy storage rate, charging energy efficiency) have been evaluated for the selected three storage materials. In order to optimize the design of energy storage tank, parametric studies are carried out by varying the number of the charging tubes, diameter of charging tubes, fins effectiveness, and storage bed diameter to its height. Simulations results showed that overall thermal performance of these materials using optimal design are satisfactory considering the problems associated with molten salt and concrete bed. More specifically, Dead Sea salt, concrete bed and Basalt rocks are more economically attractive relative to molten salt plant because they eliminate the extra cost associated with freeze protection, no pressurizing problem, no corrosion. Finally, natural stones can operate at higher temperature and do not suffer from cracking due to cyclic charging and discharging.

1. Introduction

Jordan depends on imported fossil fuels to meet its national energy demand (Jaber et al., 2004). Several studies for generating electricity utilizing different renewable energy (RE) options are conducted in Jordan (Mamlook et al., 2001; Hrayshat and Al-Soud, 2004; Hrayshat, 2008; National Electric Power Co, 2005; Central Electricity Generation Co, 2005; Tsoutsos et al., 2005). Electricity harnessed via RE sources accounted only for less than 2% of the total electricity generated in 2005 (National Electric Power Co, 2005; Central Electricity Generation Co, 2005). Jordan's Energy Master Plan aims to increase the share of RE to 10% of Jordan's primary energy consumption by the year of 2020. To achieve this goal, an investment of 450 million US$ will be placed by the Jordanian Government represented by the Ministry of Energy and Mineral Resources (MEMR).

The main factors that hinder the development of solar thermal power plants are; their low efficiency, high cost of the devices, and intermittent nature of solar energy. Advancements in solar thermal power plants have led to minimize these problems. Thermal energy storage (TES) system is introduced to overcome the intermittent availability of solar radiation. It enables keeping of excess solar energy produced during the day to be used during the absence of sufficient direct normal irradiation (DNI). An effective TES will enhance the plant reliability and profitability. It has been reported that solar thermal plants with integrated thermal energy storage have higher overall energy efficiency and annual energy generation compared to those without TES. There are three types of TES: sensible heat storage (SHS), latent heat storage (LHS), and thermo-chemical heat storage (TCHS) by reversible endothermic chemical reactions. The advantages of SHS systems include low cost of storage media, ease of handling of the material and low degradation of heat transfer between the heat exchanger and solid materials. SHS materials are the group of materials that undergo no phase change in the temperature range of the storage process and this includes both solids and liquids. The major problem with liquid storage system is that it requires bulky storage tanks for hot and cold fluids and expensive heat exchangers.

Thermal energy storage is considered important topic and is still receiving attention by many researchers. The research has concluded

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that this technology is still lacking effective storage material (Jemmal et al., 2016). The most important factors affecting the storage performance are storage material and heat transfer fluid. Good storage media should have good stability at higher temperatures, high heat capacity, and high heat conductivity. Various candidate materials for high-temperature SHS systems have been studied (Khare et al., 2013). The main difficulty in using solid media for SHS is the large size of storage bed. However, this can be minimized by using high heat capacity storage material and allowing high-temperature swing.

Alumina, rock, high temperature concrete, and graphite were found to be suitable for sensible heat storage (Price et al., 2002; Nandi et al., 2012). Among the studied material, it was found using molten salt as storage media has the best technology due to its low investment cost and lower Levelized cost of electricity (LCOE) (Montes et al., 2009; Boukelia et al., 2015; Jain et al., 2013; Khare et al., 2013). However, one major difficulty with molten salts is unwanted freezing during operation. Freezing must be usually prevented in the piping, the heat exchanger and in the storage tanks using auxiliary heating system. This will add significant extra cost for the salt plant. Further drawbacks of molten salts is that they are oxidizing agents and very corrosive and to contain them at high temperatures is problematic. Also their thermal conductivity is low and has volume change around 6% during melting process.

Utilizing solid storage media can further reduce the cost of storage unit. The cost of equivalent mass of natural stones might be two orders of magnitude cheaper than today's molten salts used for thermal energy storage. Furthermore, solid materials have broader operational temperature range, without freezing, evaporation or leakage problems. On the other hand, the heat transfer rate between heat transfer fluids and solid storage material is usually lower than for liquid storage media. Laing et al. compared between high temperature concrete and castable ceramicas as the storage medium for 350 kWh TES system with a parabolic trough collector loop up to 390 °C at Plata forma Solar de Almeria in Spain (Tamme et al., 2004). Their results showed that concrete has lower cost, higher material strength, and was easier to handle. It was reported that rock and sand have a better thermal properties, mechanical behavior, price, availability, and recyclability (Kearney et al., 2004).

Although, SHS systems have been investigated previously, but there are lack of research works on the heat transfer enhancement in solid media storage. Furthermore, it is observed from the literature survey that there is lack of studies on the optimization of SHS systems based on the charging, discharging time, and heat transfer rate. This study focuses on developing efficient and inexpensive energy storage devices using natural stones for CSP plants. The main objective is to enhance the heat transfer process between the solid and heat transfer fluid so that this technology can replace the more expensive storage using molten salt. The study investigates the thermal characteristic of two candidate materials as energy storage media found in Jordan. These materials are locally available, have adequate thermal properties, chemically stable, non toxic, nonflammable, can operate up to 500 °C. In in order to assess their feasibly, the thermal performance of these media are compared against SHS system using concrete bed. Furthermore, comparisons are performed in terms of charging efficiency and energy stored during the different stages of the work cycle. Number of charging tubes, fins effectiveness, ratio between storage tank height and its diameters are optimized based on the charging time of SHS bed using COMSOL Multi-physics software. The thermal storage characteristics of the selected SHS models are predicted considering the capacity of 137 GJ. Enhance thermal performance of energy storage systems improve the technical feasibility of a solar thermal energy storage system. The cost of a solar thermal energy storage system mainly consists of three parts i.e., storage material, heat exchanger and land cost. High thermal energy storage performance reduces the system volume and hence, the storage cost.

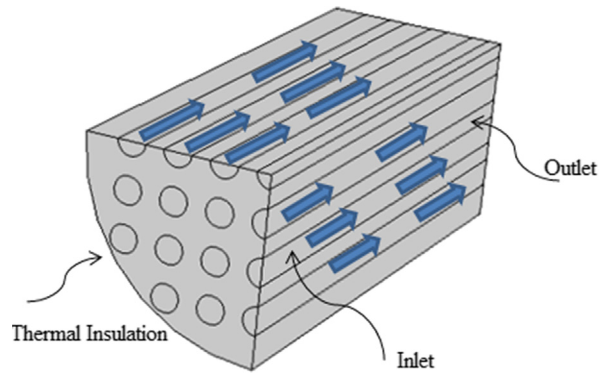

Fig. 1. Sectional View of SHS system.

2. Mathematical modeling

This section describes the mathematical model employed for simulating the transient behavior of SHS unit. Fig. 1 shows the sectional view of the SHS bed model with embedded charging tubes. It consists of a cylindrical bed with charging tubes embedded into it. The HTF at high temperature is supplied to the storage bed from the left end and it exits from the right by exchanging the heat with tube wall through convection. Heat is transferred through the charging tubes to solid media via conduction. The outer surface of bed is well insulated to avoid heat losses to ambient.

Fluid flow, heat transfer by conduction and convection are the three main physical processes involve in TES. The minimum volume of SHS material required for storing energy is:

$$Q = \rho_s V C_{PS} \Delta T_{Ch} \,(\text{J}) \tag{1}$$

Volume of SHSM with fins (on the surface of the charging tubes) is estimated as:

$$V = \left[\frac{\pi}{4}(D^2 - nd^2) - nn_{fin} bh\right] L \tag{2}$$

In order to simplify the mathematical model, the following assumptions are considered; (a) fully developed inlet mas flow rate profile of HTF, (b) frictional pressure drop of HTF through the tubes is neglected, (c) ignore axial conduction in HTF, (d) isotropic SHS material, and (e) non-isothermal fluid flow.

The flow behavior of HTF flowing inside the charging tube is obtained by solving the continuity equation and the Navier–Stokes equations. The continuity equation is:

$$\frac{\partial \rho_f}{\partial t} + \vec{\nabla} \cdot (\rho_f \vec{v}) = 0 \tag{3}$$

Where ρ_f is the density of HTF and $\vec{v}$ is the velocity vector. The Navier–Stokes equation in cylindrical coordinates are:

$$\rho_f \frac{D\rho_f}{Dt} = -\vec{\nabla} P + u\nabla^2 \vec{v} = 0 \tag{4}$$

where P is the pressure and u is the dynamic viscosity of the HTF. In order to find the convection heat transfer from the HTF to the wall of the pipe, the complete energy equation has to be solved using the velocities found from the solutions of Eqs. (3) and (4). The energy equation describing convective heat transfer process is:

$$\rho_f C_{pf} \frac{DT}{Dt} = k_s \nabla^2 T \tag{5}$$

where C_{pf} is the specific heat of the HTF, k_s is the thermal conductivity of solid and T is the temperature. The effect of convection on the heat transfer process is taking care of in the material derivative term DT/Dt of Eq. (5). The conduction heat transfer from the charging tubes to the sensible heat storage material is obtained by solving: