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Influence of design on performance of a latent heat storage system for a direct steam generation power plant

Tolga Pirasaci [a,b,*], D. Yogi Goswami [a]

[a] Clean Energy Research Center, University of South Florida, Tampa, FL, USA
[b] Department of Mechanical Engineering, Gazi University, Ankara, Turkey

HIGHLIGHTS

- Influence of design on PCM storage effectiveness investigated numerically.
- Length of storage has a major impact on the PCM storage effectiveness.
- Flow rate of heat transfer fluid is important on the PCM storage effectiveness.
- Diameter of the tubes has an impact on the PCM storage effectiveness.
- Distance between tubes doesn't have significant effect on PCM storage effectiveness.

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ABSTRACT

This work focuses on the design of latent heat storage unit for direct steam generation power plants. In this paper a simple model for the design of a storage unit is presented. This model includes phase change of water/steam and the sensible heat stored in phase change material. The effectiveness of the storage is considered as the design criterion in this model and the influence of various design parameters on the effectiveness is explained. Results show that:

- Length of storage has a major impact on the effectiveness.
- Flow rate of heat transfer fluid is important.
- Diameter of the tubes has an impact on the effectiveness.
- Distance between tubes does not have significant effect on effectiveness.

1. Introduction

Solar thermal power plants are one of the most suitable renewable energy technologies for electricity generation. In order to extend the use of this technology, it is necessary to reduce costs by increasing efficiency. One way to increase efficiency is to increase the operating temperature. One of the recent technologies used for this purpose is Direct Steam Generation (DSG) in the solar field. In this system water is directly evaporated and superheated in the solar field. DSG plants can only become economically competitive if a cost effective storage system is available [1–3].

There are two main types of DSG storage systems reported in the literature: sensible heat storage and latent heat storage.

In sensible heat storage, molten salts are generally used as a heat storage medium. During discharging, the heat from molten salt is transferred to the water/steam by using heat exchangers. In this process the high temperature difference between molten salt and water/steam causes lower efficiencies.

In the latent system phase change materials (PCM) is used to store the evaporation enthalpy of water/steam. The temperature profile in the storage system is matched to the temperature profile of the water/steam. Thus higher efficiencies can be obtained in these systems. Four variants of this system (Fig. 1) are explained in the literature [4–8].

Among them Variant-d (PCM-Vd) in which the PCM is used for preheating, steam generation and superheating has the simplest structure (Fig. 1d). Moreover compared to molten salts, PCM has the mass and cost advantages. Also this type of storage does not require expensive heat exchangers, pumps and freeze protection.

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* Corresponding author at: Department of Mechanical Engineering, Gazi University, Ankara, Turkey. Tel.: +90 312 5823401; fax: +90 312 2319810.
E-mail address: pirasaci@gazi.edu.tr (T. Pirasaci).

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Nomenclature

A	heat transfer area, m^2
c	specific heat, J/kg K
D	diameter, m
h	convection heat transfer coefficient, W/m^2 K
k	conduction heat transfer coefficient, W/mK
l	length of a single tank, m
L	flow path length, m
$\mathbb{L}$	latent heat, J/kg
$\dot{m}$	mass flow rate, kg/s
M	number of serially connected tanks, –
N	number of tubes, –
NTU	number of transfer units, $= (U \cdot A)/(m \cdot c)$
Nu	Nusselt number, $= (h \cdot D)/k$
p	distance between tubes, m
Pr	Prandtl number, $= (c \cdot \mu)/k$
Q	heat, W h
R	radius, m
Re	Reynolds number, $= (2\dot{m})/(\pi R \mu)$
T	temperature, °C
U	overall heat transfer coefficient, W/m^2 K
X	liquid\vapor fraction, %

Subscript

HTF	heat transfer fluid
PCM	phase change material
l	liquid
m	melting
s	solid
T	total
i	inner (left subscript)
i	control volume index (right subscript)
o	outer

Superscript

t	time index (right superscript)

Greek symbols

μ	viscosity, m^2/s
ε	effectiveness, %
ρ	density, kg/m^3

Considering these advantages PCM-Vd storage systems seem to be the best option for DSG plants. The present work focuses on the design of PCM-Vd storage unit for direct steam generation power plants.

The basic approach in the design of the heat storage unit is the determination of the amount of storage material to be used for desired storage capacity. For PCM storages the required amount of material (m_{PCM}) is determined by Eq. (1) [9].

$$m_{PCM} = \frac{Q_{storage}}{c_{PCM-s} \cdot (T_m - T_s) + \mathbb{L}_{PCM} + c_{PCM-l} \cdot (T_l - T_m)} \tag{1}$$

Here $Q_{storage}$ is the desired storage capacity, c_{PCM-s} and c_{PCM-l} are the PCM specific heat at the solid and liquid states, $\mathbb{L}_{PCM}$ is the latent heat of PCM, T_m is the melting temperature T_s is the min. operating temperature and T_l is the max. operating temperature.

However, this approach only gives information about the size of the storage unit. The impact of the construction of the unit on system performance cannot be examined by using this approach. Several studies have been conducted to examine the storage unit construction and performance relation. In these studies the similarity between the shell–tube heat exchanger and the heat storage unit is taken into account and starting from heat exchanger design methods [10,11] a relationship between storage unit construction and performance is obtained.

Trp et al. [12,13] analyzed the heat transfer phenomenon during paraffin melting and solidification, in a shell and tube thermal energy storage system both numerically and experimentally. Bayon et al. [14,15] presented the experimental measurements of a latent heat thermal storage prototype and identified the differences between the design and experimental data. Laing et al. [16] demonstrated a high temperature PCM storage module for steam generation in a 1 MW test facility for different operating modes. Hosseini et al. [17] presented a combined experimental and numerical study of the thermal behavior and heat transfer characteristics of paraffin during constrained melting and solidification processes inside a shell and tube heat exchanger. Nithyanandam and Pitchumani [18] analyzed the influence of the design and the operating parameters on the dynamic charge and discharge performance of the latent heat thermal energy storage system embedded with gravity-assisted heat pipes. Tay et al. [19,20] presented the results of CFD analyses of the tube in tank phase change thermal energy storage system for various designs. Seddegh et al. [21] investigated the thermal behavior and heat transfer characteristics of a vertical cylindrical shell and tube latent heat thermal energy storage unit, using a pure thermal conduction model and a combined conduction–convection heat transfer model. Liu et al. [22] presented a design of a cascaded latent heat storage system, which enables a discharge duration of 6 h for a 50 MW h solar tower power plant. All of these authors obtained similar melting – solidification behavior and specified governing mechanisms of the heat transfer during these processes. They also developed various numerical techniques for solving transient phase change problems. However these numerical techniques require small time steps. As a result simulation of melting and solidification processes takes very long computational time. Therefore, there is a need to develop simple design methods requiring less computational time.

A treatment of sensible heat energy storage unit was presented by Bejan [23]. In this study he considered the storage system consisting of a large liquid bath placed in an insulated vessel. Hot gas enters the system through one port, is cooled by flowing through a heat exchanger immersed in the bath and is eventually discharged into the atmosphere. He obtained the time dependence of the bath temperature, the gas outlet temperature, and the storage efficiency during the storage process analytically as a function of heat transfer surface area and fluid (storage bath, heat transfer fluid) properties under the following assumptions.

- specific heat of bath and heat transfer fluid are constant,
- there is no condensation or vaporization during the process,
- the liquid bath is well mixed (isothermal),
- the overall heat transfer coefficient is constant,
- the heat capacity of the heat transfer fluid is much smaller than the bath heat capacity.

He mentioned that there exists an optimum relationship among the heat storage design parameters which minimizes the system