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General volume sizing strategy for thermal storage system using phase change material for concentrated solar thermal power plant

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HIGHLIGHTS

- We present a method of sizing a thermocline thermal storage system for a CSP plant.
- Phase change materials (PCM) are considered for this study.
- Sizing criterion is that the discharged fluid temperature is above a cutoff point.
- The sizing procedures were presented through one design example.

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ABSTRACT

With an auxiliary large capacity thermal storage using phase change material (PCM), Concentrated Solar Power (CSP) is a promising technology for high efficiency solar energy utilization. In a thermal storage system, a dual-media thermal storage tank is typically adopted in industry for the purpose of reducing the use of the heat transfer fluid (HTF) which is usually expensive. While the sensible heat storage system (SHSS) has been well studied, a dual-media latent heat storage system (LHSS) still needs more attention and study. The volume sizing of the thermal storage tank, considering daily cyclic operations, is of particular significance. In this paper, a general volume sizing strategy for LHSS is proposed, based on an enthalpy-based 1D transient model. One example was presented to demonstrate how to apply this strategy to obtain an actual storage tank volume. With this volume, a LHSS can supply heat to a thermal power plant with the HTF at temperatures above a cutoff point during a desired 6 h of operation. This general volume sizing strategy is believed to be of particular interest for the solar thermal power industry.

1. Introduction

During the past few years, Concentrated Solar Power (CSP) generation is becoming attractive because of its ability to store excessive energy and extend the daily operation of a CSP plant during periods of intermittent sunlight and nights. It also can smooth out the short-term transients such as the mismatch between energy supply and demand by providing load leveling [1]. A CSP plant uses solar tower, parabolic troughs, or linear Fresnel reflectors to concentrate sunlight and produce intense heat for heat transfer fluid (HTF) which carries heat for thermal energy storage as well as for thermal cycles in conventional power block [2]. A key requirement to make this energy option competitive, however, is the use of a thermal energy storage system which is filled with energy storage materials [3].

With respect to the storage material, the thermal energy storage tank can be operated on sensible heat, latent heat, or a combination of both. Since the latent heat or combined latent/sensible heat storage system can offer a larger thermal storage capacity and a significant reduction of storage tank volume compared to the use of sensible heat alone [4,5], a CSP plant using PCM latent heat storage system (LHSS) is promising for large scale solar thermal energy application. During the past few years, LHSS has been getting a lot of attention [6]. A major technology barrier limiting the use of PCM, however, is the higher thermal resistance provided by its intrinsically low thermal conductivity. As a result, it requires a large heat transfer surface area of interaction between HTF and PCM. One promising approach is to incorporate the PCM in small capsules [7]. For example, PCM stored in capsules with a diameter of 10 mm offers a surface area of more than 300 square meters per cubic meter [8]. Because of this motivation, research to find suitable materials and processes to encapsulate high temperature PCM mixtures is underway [9,10]. In the current work, encapsulated PCM

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Nomenclature

H	overall height of storage tank (m)
R	radius of storage tank (m)
r	radius of encapsules (m)
d_r	diameter of encapsules (m)
ε	equivalent void fraction
V	volume (m^3)
S_r	surface area per length scale (m)
f_s	surface shape factor
ρ	density (kg/m^3)
C	specific heat capacity (J/kg K)
$\dot{m}$	mass flow rate (kg/s)
h	intrinsic heat transfer coefficient (W/m^2 K)
h_{eff}	effective heat transfer coefficient (W/m^2 K)
T	temperature (°C)
$\bar{h}$	enthalpy (J/kg)
U	axial velocity of HTF (m/s)
Re	Reynolds number
ν	kinematic viscosity (m^2/s)
Pr	Prandtl number
L	latent heat of fusion (J/kg)
k	thermal conductivity (W/m K)

t	time (s)
z	axial tank location from reference (m)
Stf	Stefan number
H_{CR}	dimensionless heat capacity ratio
τ_r	dimensionless time scale
θ	dimensionless temperature
η_r	dimensionless enthalpy
η	energy storage efficiency
Π_d	dimensionless required time of discharge
P_{ele}	total electrical power output (W)
N_{cycle}	number of charge/discharge cycles

Subscripts

f	refer to HTF
r	refer to solid filler material
r_melt	refers to a filler melting point value
r_s	refers to the filler in a solid phase state
r_l	refers to the filler in a liquid phase state
r_ref	refers to a filler reference value
H	refers to the highest value of a variable
L	refers to the lowest value of a variable

would be used as filler material in contact with HTF in the thermal storage tank.

A dual-media or a solid-packed thermal storage system is believed to significantly reduce the amount of HTF in the system, compared to the two-tank direct storage system [11]. It will, however, more or less sacrifice the energy storage efficiency due to the heat transfer between the HTF and solid filler material [12]. During the heat charge process, hot HTF flows downward through the storage tank from the top and gives thermal energy to the storage material, while during a discharge process, cold HTF flows into the tank from the bottom, and flows out with a high temperature from the top after obtaining heat. The process is shown in Fig. 1.

Buoyancy force ensures stable thermal stratification of hot and cold fluids within the single storage tank which is also called a thermocline storage tank [13]. The charge process takes place during the day when solar energy is available, while discharge occurs whenever the sun is not available or when there is a peak demand in electricity. The sequence of a single charge process followed by a discharge process is referred to as one cycle, and a cyclic periodic steady state will finally be reached after several repeated cycles. Then the temperature distribution of filler material and HTF will be independent of the most-initial condition in the tank [14]. Li et al. [15] has performed numerical simulations to verify the existence of cyclic periodic steady state. In this paper, all computations are processed to repeat charge/discharge cycles, and cyclic periodic steady state solutions were obtained as the results.

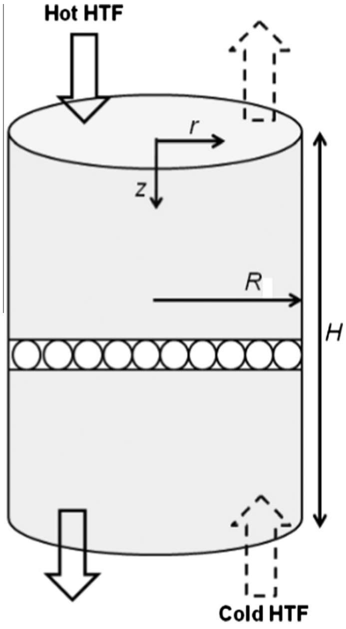

Fig. 1. Schematic of thermal energy storage tank with encapsulated PCM.

During the past two years, researchers have done a lot of work to explore the sensible thermocline storage system. Li et al. [16,17] provided a generalized chart for the design and calibration of thermocline sensible heat storage system. Wu et al. [18] investigated the impact of concrete structure on the thermal performance of the dual-media thermocline thermal storage tank using concrete as the solid medium. Prasad and Muthukumar [19] numerically studied the transient behavior and thermal storage capability of a sensible heat storage unit with embedded charging tubes by employing three storage materials, namely, concrete, cast steel, and cast iron. Xu et al. [20] presented a comprehensive transient, two-dimensional, two-phase model for heat transfer and fluid dynamics within the packed-bed thermocline sensible storage system. Yang and Garimella [21] developed a comprehensive, two-temperature model to investigate the cyclic operations of a thermocline with a commercially available molten salt as the heat transfer fluid and quartzite rocks as the filler.

Relatively few works on the performance of LHSS are found in the literature. Nevertheless, there are still some papers presented numerical modeling of LHSS. A model by Felix Regin and Solanki [22] considered a simple charge process of a tank with PCM filler for a parametric study of material properties. Following that, a model by Wu and Fang [23] applied an implicit finite difference method to solve the equations for the case with the presence of PCM filler in the tank to consider general scenarios. Results from that model, however, featured numerous oddities and oscillations in temperature distribution profiles. To overcome the lower thermal conductivity of PCM material, Nithyanandam and Pitchumani [24,25] introduced heat transfer augmentation using