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Estimation of thermal performance and design optimization of finned multitube latent heat thermal energy storage

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ABSTRACT

This paper presents the effectiveness of finned multi-tube latent heat thermal energy storage system (LHTES) for medium temperature (~200 °C) solar thermal power plant in reducing the fluctuations in heat transfer fluid (HTF) temperature caused due to the intermittent solar radiation. Commercially available phase change material (PCM) of melting temperature 168.7 °C is used as the storage material in the shell of LHTES, whereas a thermic oil based HTF passes through the tubes. Majority of the available PCMs have very low thermal conductivity (~0.2–0.5 W/m.K), which drastically affects the thermal performance of the thermal storage system. Hence, in this study, thermal conductivity enhancer (TCE) in the form of fin is used to enhance heat transfer in the PCM. The fluid flow and heat transfer behaviour latent heat thermal energy storage system in the LHTES is studied by using a numerical model coupled with the enthalpy technique to account for the phase change process in the PCM. The developed numerical model, which is validated with the lab-scale experimental setup, is used to investigate the effect of number of fin, fin thickness and fin height on the HTF temperature at the outlet of the storage system. It is found that the number of fins and fin thickness significantly affect the thermal performance of the storage system, whereas the enhancement in heat transfer for high thermal conductivity material fin is marginal. Further, optimization of LHTES is performed for a defined objective function to identify the best configuration.

1. Introduction

Concentrating solar power (CSP) plant uses solar radiation to transfer heat to the fluid, which can be used for electricity generation. Due to intermittency nature of solar radiation during the day, thermal energy storage system (TES) can bridge the gap between the energy demand and supply during insufficient solar radiation to generate electricity uninterruptedly. TES temporarily stores excess thermal energy in the substance for later utilization. Materials for TES can be classified based on the mode of energy storage, *viz.* sensible heat, latent heat and thermochemical energy [1]. Among the TES materials, phase change material (PCM) based thermal energy storage system (LHTES) has the ability to store large latent energy around its phase change temperature. Thus, it is an excellent energy storage material due to its high density per unit volume as compared to other storage material used in sensible thermal energy storage systems [2]. This storage system can be more effectively used in controlling fluctuation in heat transfer fluid (HTF) temperature in CSP plant during intermittent solar radiation by charging and discharging of PCM. During charging, heat is supplied to the PCM which melts and stores the thermal energy by the virtue of latent heat of fusion during its phase transformation. During discharging, heat is extracted from the PCM as it solidifies.

A detailed review of various phase change materials, which can be used to store thermal and solar energy, was performed by Kenisarin [3]. However, data on thermophysical properties of PCMs is scattered across the published literature, as well as these properties are not reliable. Few thermophysical properties like melting temperature, thermal conductivity, and heat of fusion of the phase change materials and their compositions, which were reported, should be evaluated before their applications. The selection of PCM for an application depends on the application temperature. One of the major disadvantages of using PCMs is their poor thermal conductivity, which drastically affects the performance of the unit [4]. The effect of low thermal conductivity is reflected in slow heating and cooling processes during charging and discharging of the PCM. As a result, the rate of phase change is not up to the desired level and the utilization of TES in large-scale is unsuccessful. Therefore, it is imperative to enhance the effective thermal conductivity of the PCM. Several improvement techniques are employed which can

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Nomenclature

a	Coefficient in the discretized energy equation [-]
A	Porosity function for the momentum equation [-]
b	Computational constant [-]
c	Specific heat [J/kg.K]
D_h	Hydraulic diameter [m]
D_i	Outer diameter of thermal energy storage [m]
E	Total enthalpy [J]
ΔE	Nodal latent heat [J]
e	Sensible enthalpy [J]
f	Latent heat function [-]
g	Acceleration due to gravity [m/s^2]
h	Sensible enthalpy [J/kg]
H	Fin height [m]
k	Thermal conductivity [W/m.K]
L	Length [m]
M	Morphological constant [-]
N	Number of fins in PCM side [-]
P	Effective pressure [N/m^2]
Re	Reynolds number $\left(=\frac{\rho u_{in} D_h}{\mu}\right)$ [-]
S	Source term [-]
S_b	Buoyancy source term for momentum equation in y direction [-]
S_e	Source term for energy equation [-]
t	Time [s]
T	Temperature [ºC]
T_m	Melting temperature of PCM [ºC]
u	Velocity components in x, y and z directions [m/s]
u_{in}	Inlet velocity [m/s]
∀	Volume [m3]
x, y, z	Cartesian axis direction [-]
X	Dimensionless length [-]
W	Fin thickness [m]

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Thermal expansion coefficient [K^{-1}]
ε	Liquid fraction [-]
λ	Latent heat of fusion [J/kg]
μ	Dynamic viscosity [Pa.s]
ρ	Density [kg/m^3]
η	Efficiency [-]

Subscripts

c	Charging
d	Discharging
f	Fin
in	Inlet
m	Melting point
o	Outlet
pcm	PCM
$pipe$	HTF pipe

be broadly classified into two groups, *viz.* (i) by introducing thermal conductivity enhancer (TCE) into the PCM using high thermal conductivity material and (ii) by increasing the surface area for heat transfer [5]. In the first approach, the high thermal conductivity material could be (i) widely used graphite [6,7], (ii) metallic particles dispersed in PCM [8,9], (iii) fins [10–13], (iv)metal matrix/foam [14–16]. In the second approach, several techniques employed are (i) extensively used cylinder-tube geometry in various arrangements [17–22], (ii) encapsulated PCMs [23–26], (iii) agitation of rings and bubble in PCM [27]. In this work, thermal performance of multitube shell and tube latent heat thermal storage with fin as thermal conductivity enhancer (TCE) is studied during charging and discharging periods.

Several studies have been performed to investigate the effect of fin structure on the melting and solidification of PCM [28–36] in the low-temperature solar application (< 150 °C). Velraj and Seeniraj [37] examined the variation in the effective thermal conductivity of the storage when various highly conductive metallic structures were inserted into the PCM. They used a plain tube, a tube with Lessing rings, a tube with fins and a tube with bubble agitation, for the augmentation of heat transfer. The study concluded that fin configuration was the most effective. Velraj et al. [38] experimentally and numerically studied the solidification process of a PCM inside an internally aluminium finned vertical tube where the tube was cooled from outside. Stritih [39] experimentally investigated the heat transfer characteristics of a latent-heat storage system with a finned surface using paraffin with the melting point of 30 °C for melting and solidification processes. The author determined Nusselt number as a function of Rayleigh number and calculated the fin effectiveness. The presence of fin was found to reduce the melt convection in PCM.

Seeniraj et al. [40] studied the thermal performance of externally thin finned tube LHTES for solar based power plant or such similar energy storage applications for charging mode. The study showed that with the increase in number of fin, the heat transfer rate increases. Sparrow et al. [41] noted that the solidification of PCM is retarded by natural convection, eventually terminates the process. As a result, the thermal performance of the thermal energy storage deteriorates and the rate at which the heat is extracted from the phase change material decreases. Therefore, it is necessary to enhance heat transfer during solidification. Very recently, Niyas et al. [42,43] performed experimental and numerical analyses to evaluate the thermal performance of shell and tube type latent heat storage system with fins embedded in PCM under charging and discharging operations. Authors concluded that the natural convection is significant during the charging process, whereas the conduction heat transfer is the dominant mode of heat transfer during the discharging process. The charging time is found to be less compared to the discharging time.

From the forgoing detailed literature review, it can be noted that although there are various studies conducted for different configurations possible with fins outside or inside the tube, the cylindrical tube with external and internal longitudinal fins has not been investigated extensively for sequential charging and discharging process. Most of the HTFs other than water, such as thermic oils, have inherently poor thermal conductivity ($k\sim$ 0.1 W/m.K). As a result, Nusselt number and thereby, convective heat transfer coefficient in the laminar flow region is low. In such situations, the convective thermal resistance on the HTF side could be high compared to the thermal resistance on the PCM-side with fins, hence, the PCM-side is no longer the limiting thermal resistance in the storage system. Therefore, it is imperative to use fins on the HTF side to increase the heat transfer from HTF to PCM. To the authors' best knowledge, none of the previous studies with this heat transfer enhancement technique during melting and solidification of PCM focuses on the application prospective. Hence, in this paper, a numerical approach is adopted to investigate the performance of TES using PCM with longitudinal fins on the HTF and PCM sides under fluctuating inlet condition of heat transfer fluid (HTF) represented by a cycle, which consists of sequential charging and discharging process. During the charging period of 1800 s, the HTF inlet temperature (T_{in}) is maintained at 200 °C, while in the discharging period of the same duration, T_{in} is kept at 137.4 °C. As the thermal conductivity of PCM is