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Experimental study on discharging performance of vertical multitube shell and tube latent heat thermal energy storage

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ABSTRACT

An experimental investigation on the thermal performance of vertical multitube shell and tube based latent heat thermal energy storage system (LHTES) during discharging process for solar applications at medium temperature (~200 °C) is presented in this paper. A commercially available organic phase change material (PCM), A164 having melting temperature of 168.7 °C is stored in the shell side and a thermic oil, Hytherm 600 as heat transfer fluid (HTF), is flown through seven tubes. The effects of three operating parameters, such as inlet HTF temperature, mass flow rate and initial PCM temperature on the outlet HTF temperature are investigated during discharging period. The total energy released, discharging efficiency and heat fraction are analyzed to understand the solidification process of PCM in the multitube LHTES. Thermal Performance Index (TPI) is calculated to evaluate the overall thermal performance of the LHTES under different conditions. The results indicate that the energy released and discharging efficiency increase with increasing mass flow rate and initial PCM temperature and with decreasing inlet HTF temperature. The maximum discharge efficiency and TPI is obtained for the initial PCM temperature of 210 °C with the inlet HTF temperature of 100 °C and the mass flow rate of 0.097 kg/s in this study. Heat fraction is found to be maximum for high mass flow rate, low inlet HTF temperature and higher initial PCM temperature.

1. Introduction

The effective use of various renewable energy sources has gained an importance due to the increased level of greenhouse gases and the need to reduce the use of fossil fuels in electricity generation. Solar energy could be one of the attractive renewable energy sources due to its cleanness, widespread and low cost compared to other renewable sources. However, solar radiation is not available after sunset, hence the solar power plant can not be operated to generate electricity continuously for an entire day. Therefore, there is a need for thermal energy storage system (TES) to store excess energy during daytime, that can be utilized for power generation after sunset. Thermal energy storage systems can store energy in the form of sensible heat, latent heat and thermochemical [1]. Among several thermal energy storage techniques, latent heat thermal energy storage possesses high energy density per unit volume compared to sensible heat storage [1–4] and the ability to store and release energy almost isothermally with small temperature difference. Different phase change materials (PCMs), *viz.* salt hydrates, salts, paraffin, fatty acid, organic salt are used to store energy in the latent heat thermal energy storage system (LHTES) [5]. The choice of PCM in LHTES depends on the application temperature [1]. A variety of PCMs has been reviewed and studied by many researchers for medium temperature applications (~ 200 °C) [4–7].

The design of suitable heat exchanger for latent heat thermal storage system is equally important as the selection of PCM. The low thermal conductivity and diffusivity of most of the PCMs strongly affect the charging and discharging times, therefore efficient design of the heat exchanger configuration can improve thermal performance of the storage system. Various configurations of heat exchangers have been suggested for LHTES. Among various configurations, the shell and tube heat exchanger type LHTES is the most common TES due to easy manufacturing and implementation [7,8]. The heat transfer fluid (HTF) flows in the tube or tubes and the PCM is kept in the shell. Extensive experimental studies are reported in literature on the low temperature (< 100 °C) shell and tube LHTES [8–17].

Kibria et al. [18] studied shell and tube based thermal energy storage system numerically as well as experimentally using paraffin wax (melting temperature: 61 °C) and water as PCM and HTF, respectively. The experimental results were used to validate the numerical model. Thermal performance of the TES was evaluated considering mass flow

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Nomenclature

As	Outer surface area (m2)
c_p	Specific heat capacity (J/kg.K)
d_i	Inner diameter of HTF tube (m)
d_o	Outer diameter of HTF tube (m)
d_s	Outer diameter of shell (m)
D_i	Top surface inner diameter of the expander/ nozzle (m)
E	Energy (J)
G	Acceleration due to gravity (m/s^2)
Gr	Grashof number $\left(Gr = \frac{g\beta(T_{s,avg} - T_{amb})L^3}{\gamma^2}\right)$
h	Heat transfer coefficient (W/m^2.K)
k	Thermal conductivity (W/m.K)
L_{latent}	Latent heat of fusion (J/kg)
$\dot{Q}$	Heat transfer rate (W)
$\Delta\dot{Q}$	Uncertainty in heat transfer rate (W)
Q^+	Heat fraction
$\dot{m}$	Mass flow rate (kg/s)
M	Mass of PCM (kg)
Nu	Nussult number $\left(Nu = \frac{h\, d_s}{k}\right)$
Pr	Prandtl number $\left(Pr = \frac{\mu c_p}{k}\right)$
ΔP	Pressure drop in LHTES (Pa)
Re	Reynolds number $\left(Re = \frac{4\dot{m}\rho}{\pi D_i \mu}\right)$
T	Temperature (°C or K)
T_{amb}	Ambient temperature (°C or K)
T_f	Film temperature (°C or K) $\left(T_f = \frac{T_{s,avg} + T_{amb}}{2}\right)$
T_{in}	Inlet HTF temperature (°C or K)
T_{ini}	Initial PCM temperature (°C or K)
T_s	Surface temperature (°C or K)
$T_{s,avg}$	Average surface temperature (°C or K) $\left(T_{s,avg} = \frac{T_{s,t=0} + T_{s,t=3000\,s}}{2}\right)$
t	Time (s)
t_d	Discharging period (s)
V	Volume of PCM in storage (m^3)
x, y, z	Coordinate axes

Greek symbols

β	Thermal expansion coefficient (K-1)
ε	Emissivity
μ	Dynamic viscosity (kg/m.s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Stefan Boltzmann constant (W/m^2. K^4)
η_d	Discharging efficiency

Subscripts

abs	Absolute
avg	Average
conv	Convection
exp	Experimental
ext	Extracted
HTF	Heat transfer fluid
i	Inner
in	Inlet
ini	Initial
loss	Loss
m	Melting
out	Outlet
P	Pressure
PCM	PCM
rad	Radiation
s	Surface
stored	Stored
T	Temperature
tot	Total

rate and inlet HTF temperature. Authors concluded that the inlet HTF temperature is the most influencing parameter. Further the numerical model was used for the parametric study with different shell diameters and thickness of TES. It was noted that for better heat transfer between HTF and PCM, the change in shell diameter was important parameter than the thickness. Agyenim et al. [19,20] performed experiments on horizontal shell and tube based TES using Erythritol (melting temperature: 117.7 °C) and silicon oil as PCM and HTF, respectively. Authors compared the thermal characteristics of single and multitube energy storage systems and noted that the multitube system enhances heat transfer more compared to the single tube control system. Wang et al. [21] presented experimental results with vertical shell and tube LHTES using Erythritol as PCM and air as HTF for charging and discharging processes. Authors concluded that the increasing mass flow rate and inlet HTF temperature enhance heat transfer during the charging process and the increase in HTF pressure with constant mass flow rate has an insignificant effect on heat transfer. During the discharging period, the increase in the mass flow rate enhances heat transfer from PCM to HTF. Very recently, Zhang et al. [22] experimentally and numerically studied the effect of mass flow rate on the heat transfer characteristics of shell and tube based LHTES at medium temperature of ∼200 °C using eutectic mixture of $NaNO_3$ and KNO_3 molten salt and nickel foam based composite PCM. It was found that the increase in mass flow rate results in smaller HTF temperature difference between inlet and outlet of the LHTES. The effect of natural convection of liquid PCM on melting and solidification process was analysed by Tao and He [23] numerically in horizontal concentric tube, where 80.5% LiF and 19.5% CaF_2 (melting temperature: 1040 K) is stored in the shell side and the mixture of He/Xe flows through the inner tube. The heat transfer rate was found to increase with natural convection in liquid PCM, but produces large non-uniformity in solid-liquid interface in the melting process.

From the foregoing discussion, it is found that the study on experimental evaluation of thermal performance of multitube shell and tube based LHTES using organic PCM during discharging process for medium temperature solar applications (∼ 200 °C) is limited in literature. There are several advantages of organic PCM over other materials, such as high latent heat of fusion, no segregation, safe, chemically stability and wide compatibility with conventional container materials. Therefore, there is a need for an extensive study on the thermal behaviour of LHTES using organic PCM at the temperature range of 200 °C before its implementation in solar applications as storage system. Accordingly, in this paper, the thermal performance of vertical multitube shell and tube based LHTES using a commercially available organic PCM, A164 (melting temperature = 168.7 °C) and a thermic oil, Hytherm 600 as HTF, is experimentally studied during discharging period of 3000 s for different operating parameters. An experimental setup is developed to evaluate the effects of inlet HTF temperature, mass flow rate and initial PCM temperatures on the outlet HTF temperature during the discharging process, while PCM is undergoing solidification. Energy extracted from the PCM is evaluated and the discharge efficiency is obtained for various operating parameters. The heat fraction is calculated to understand the fraction of energy extracted with time from the LHTES during solidification of PCM.