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Numerical analysis of latent heat thermal energy storage using encapsulated phase change material for solar thermal power plant

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ABSTRACT

Thermal energy storage improves the load stability and efficiency of solar thermal power plants by reducing fluctuations and intermittency inherent to solar radiation. This paper presents a numerical study on the transient response of packed bed latent heat thermal energy storage system in removing fluctuations in the heat transfer fluid (HTF) temperature during the charging and discharging period. The packed bed consisting of spherical shaped encapsulated phase change materials (PCMs) is integrated in an organic Rankine cycle-based solar thermal power plant for electricity generation. A comprehensive numerical model is developed using flow equations for HTF and two-temperature non-equilibrium energy equation for heat transfer, coupled with enthalpy method to account for phase change in PCM. Systematic parametric studies are performed to understand the effect of mass flow rate, inlet charging system, storage system dimension and encapsulation of the shell diameter on the dynamic behaviour of the storage system. The overall effectiveness and transient temperature difference in HTF temperature in a cycle are computed for different geometrical and operational parameters to evaluate the system performance. It is found that the ability of the latent heat thermal energy storage system to store and release energy is significantly improved by increasing mass flow rate and inlet charging temperature. The transient variation in the HTF temperature can be effectively reduced by decreasing porosity.

1. Introduction

Solar energy is one of the most abundant forms of renewable energy sources in many parts of the world. However, meeting energy demand from this source is challenging due to its intermittent and unpredictable nature over short time scales during the day time. The energy production is driven by the efficiency of systems as well as by the economics of power generation. Thermal energy storage technologies have the potential to make solar radiation a reliable option for electricity generation by Organic Rankine Cycle (ORC)-based solar thermal power plants either integrated with the national power grid or installed in the non-interconnected electric network, compensating for the variability in the solar radiation and thus, making the solar power production to be a cost effective and very efficient method. Ibrahim et al. [1], therefore studied various storage solutions that will enable stable electricity generation and maintain the load level. Gil et al. [2], noted that the thermal energy storage (TES) can improve the effectiveness of the thermal energy systems with the advantage of large-scale switching. TES has the potential to eliminate the mismatch between the energy supply and demand of energy. It absorbs thermal energy in the form of either sensible heat or latent heat. The sensible storage system has low heat capacity per unit volume and its energy content depends on the temperature change of the substance, which results in high capital cost [3]. In this context, latent heat thermal energy storage system (LHTES) using phase change material (PCM) could be an attractive solution, as PCM has high energy density per unit volume and it absorbs and releases heat almost isothermally within a small temperature difference. However, the major drawback in using PCM is its low thermal conductivity which causes high thermal resistance to heat transfer during the charging and discharging period. Several methods are reported in the literature that to enhance heat transfer in PCM, such as copper foam with fin [4], circumferentially positioned fin [5], lauric acid based nanocomposites using chemically functionalized graphene nanoplatelets [6], carbon nanostructures, carbon nanotubes, nanoparticles of metallic (Ag, Al, C/Cu and Cu) and metal oxide (Al_2O_3, CuO, MgO and TiO_2) and silver nanowires [7], modified silicon nitride powders in microencapsulated PCM made of *n*-

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Nomenclature

A	Cross sectional area of storage, m^2
$c_{p,l}$	Specific heat of storage material in liquid phase, J/kg.K
$c_{p,s}$	Specific heat of storage material in solid phase, J/kg.K
C_2	Inertial resistance coefficient, m^{-1}
D	Diameter, m
d_p	Encapsulation shell diameter, cm
E_l	Total energy of fluid, kJ
E_s	Energy stored, kJ
E_r	Energy released, kJ
f_l	Liquid fraction of PCM
g	Acceleration due to gravity, m/s^2
ΔH	Enthalpy content in PCM during phase change, kJ/kg
h_f	Volumetric Interstitial heat transfer coefficient, W/m^3.K
k_l	Thermal conductivity of fluid, W/m.K
k_s	Thermal conductivity of solid, W/m.K
L	Length, cm
L_{latent}	Latent heat of fusion, kJ/kg
$\dot{m}$	Mass flow rate of heat transfer fluid, kg/s
Re_D	Reynolds number based on storage diameter $(= \dot{m}D/\mu A)$
Re_p	Reynolds number based on particle diameter $(= \rho_l U d_p/\varepsilon\mu)$
$Re_{p,cr}$	Critical Reynolds number based on particle diameter
P	Pressure, Pa
Pr	Prandtl number $(= \mu C_{p,l}/k_l)$
T_s	Temperature of the solid medium, °C
T_l	Temperature of the fluid, °C
T_i	Initial temperature, °C
T_m	Melting temperature, °C
T_{in}	Inlet temperature of heat transfer fluid, °C
T_{out}	Outlet temperature of heat transfer fluid, °C
ΔT	Difference between maximum and minimum temperature of heat transfer fluid at outlet, °C
t	Time, s
t_c	Charging time, s
t_d	Discharging time, s
Δt	Time interval, s
U	Superficial velocity of heat transfer fluid $(= \dot{m}/\rho_l A)$, m/s
U_0	Interstitial velocity $(= U/\varepsilon)$, m/s
u	Velocity vector, m/s

Greek symbols

Φ	Porosity
μ	Dynamic viscosity, kg/m.s
α	Permeability, m^2
λ	Relaxation factor
ρ	Density, kg/m^3
ε	Effectiveness

Subscript

c	Charging
d	Discharging
l	Liquid
max	Maximum
min	Minimum
n	n^{th} time step
o	Overall
s	Solid

Abbreviation

CSP	Concentrating Solar Power
HTF	Heat Transfer Fluid
LHTES	Latent Heat Thermal Energy Storage
ORC	Organic Rankine Cycle
PCM	Phase change material
SHS	Sensible Heat Storage
TES	Thermal Energy Storage
UDF	User Defined Function
UDS	User Defined Scalar

octadecane core and polymethylmethacrylate shell [8], micro-encapsulated PCM and polyethylene composite material [9], spongy graphene (G22) and docosane as a composite [10], highly conductive calcium carbonate shell for microencapsulating paraffin based binary cores via self-assembly method [11], dispersion of metallic particles in PCM [12,13], multi-tube [14], rings and bubble agitation in PCM [15], encapsulated PCM [16–18] and addition of fins [19–21]. Among these enhancement techniques, PCM encapsulated in small capsules is a promising approach as it offers larger surface area relative to volume for heat transfer between the heat transfer fluid (HTF) and PCM, thereby reducing the charging and discharging time. Encapsulated PCMs filled in a storage system form packed bed latent energy storage system.

Packed bed sensible and latent energy storage systems are among the important class of thermal storage systems which can be used to maintain the balance of supply and demand of energy. Several researchers have studied the thermal behaviour and economical aspects of packed bed sensible storage system numerically [22–29]. Ismail and Henriquez [30] developed a transient one-dimensional numerical model for spherical capsules filled with water as the PCM in a cylindrical tank. The solidification process inside the capsule was modelled using conductive phase change and convective boundary condition on the surface of capsule. The convection in molten PCM is considered using an effective heat conduction coefficient. The energy equation are solved using finite difference method and moving the grid inside the PCM capsules to investigate charging and discharging times of the storage system. Arnold [31] identified variable rates of heat transfer for freezing and melting of encapsulated ice by considering macro level fluid flow and micro level freezing and melting of ice in the capsule and linking them by the heat transfer across the wall of the capsule. Regin et al. [16] numerically studied the thermal behaviour of a packed bed thermal energy storage using spherical capsules filled with paraffin as a PCM for a solar-water heating application. The melting time was found to be reduced by 31.6% for PCM that melts within a range of temperature as compared to a PCM with a single melting point. Wu and Fang [32] investigated the dynamic behaviour of a packed bed composed of spherical capsules filled with Myristic acid as a PCM for solar heat storage system. The influence of HTF inlet temperature, packed bed initial temperature and mass flow rate of HTF during the discharging process were studied using a mathematical model based on the energy balance of HTF and PCM. Benmansour et al. [33] analysed the transient behaviour of cylindrical packed bed TES system, filled with spherical PCMs (paraffin wax) using a two-dimensional separate phases methodology. Flueckiger and Garimella [34] developed a new finite volume