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Technical note

Numerical analysis and parameters optimization of shell-and-tube heat storage unit using three phase change materials

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ABSTRACT

In this paper, a mathematical model of shell-and-tube latent heat thermal energy storage (LHTES) unit of two-dimension of three phase change materials (PCMs) named PCM1, PCM2 and PCM3 with different high melting temperatures (983 K, 823 K and 670 K, respectively) and heat transfer fluid (HTF: air) with flowing resistance and viscous dissipation based on the enthalpy method has been developed. Instantaneous solid–liquid interface positions and liquid fractions of PCMs as well as the effects of inlet temperatures of the air and lengths of the shell-and-tube LHTES unit on melting times of PCMs were numerically analyzed. The results show that melting rates of PCM3 are the fastest and that of PCM1 are the slowest both x, r directions. It is also found that the melting times of PCM1, PCM2 and PCM3 decrease with increase in inlet temperatures of the air. Moreover, with increase in inlet temperatures of the air, decreasing degree of their melting times are different, decreasing degree of the melting time of PCM1 is the biggest and that of PCM3 is the smallest. Considering actual application of solar thermal power, we suggest that the optimum lengths are $L_1 = 250$ mm, $L_2 = 400$ mm, $L_3 = 550$ mm ($L = 1200$ mm) which corresponds to the same melting times of PCM1, PCM2 and PCM3 are about 3230 s and inlet temperature of the air is about 1200 K. The present analysis provides theoretical guidance for designing optimization of the shell-and-tube LHTES unit with three PCMs for solar thermal power.

1. Introduction

The quest for solar thermal power systems to avert the growing concern about the imminent energy shortage, the high cost of energy has been a scientific concern over the last three decades. Solar thermal power systems utilize the heat generated by collectors concentrating and absorbing the sun's energy to drive heat engines/generators and produce electric power. Because solar radiation is a time-dependent energy source, the integration of solar thermal energy storage in a solar thermal power system is crucial, it can increase the system reliability and generation capacity as well as reduce costs of electricity generation [1].

There are two basic types of solar thermal energy storage, sensible heat thermal energy storage storing sensible heat in fluid or solid and latent heat thermal energy storage (LHTES) utilizing latent heat during the phase change process. Compared to a conventional sensible heat thermal energy storage, LHTES is particularly an attractive technique because it provides a high energy storage density, requires a smaller weight and volume of material for a given amount of energy, stores heat of fusion at a constant or near constant temperature which corresponds to the phase transition temperature of PCMs [2–5].

The development of LHTES involves the understanding of heat transfer in PCMs when they undergo solid-to-liquid phase transition in the required operating temperature range. Therefore, LHTES with a single PCM has gained considerable attention worldwide recently [6–14].

However, most PCMs have low thermal conductivity ranging from 0.1 to 0.6 W m^{-1} K^{-1} [25], as a result, leading to slow charging and discharging rates, hence heat transfer enhancement techniques are necessary for most LHTES applications. Several studies have been conducted to study heat transfer enhancement techniques in PCMs [15,16]. The charging and discharging rates are also affected by the temperature difference between PCMs and the HTF. The high rates of charging and discharging can be obtained by the employment of PCMs having different melting temperatures [17]. During the past decade, several researchers [18–23] studied multiple PCMs in LHTES to increase the charging and discharging rates of the units.

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Nomenclature

C_p	constant pressure specific heat capacity of air, J kg^{-1} K^{-1}
D	diameter of the inner tube, mm
f	liquid fraction
g	acceleration of gravity, m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
h	sensible heat, J m^3 or convection heat transfer coefficient, W m^{-2} K^{-1}
L	length of the tube, mm
m	mass flow rate of heat transfer fluid, kg s^{-1}
P	flow resistance, Pa
T	temperature, K
t	time, s
R	radius, mm
Re	Reynold's number
r	radial coordinate, mm
x	axial coordinate, mm

Greek symbols

ΔH	latent heat, J kg^{-1}
ϕ	$T - T_{\mathrm{m}}$, K
μ	dynamic viscosity, N s m^{-2} or velocity, m s^{-1}
ρ	density, kg m^{-3}
ν	cinematic viscosity, m^2 s^{-1}

Subscripts

1	PCM1
2	PCM2
3	PCM3
a	air
c	charge
e	environment
f	heat transfer fluid (HTF)
i	internal tube, initial or interface PCM1/PCM2/PCM3
in	inlet
m	melting
o	external tube
out	outlet
p	phase change material

Domanski and Fellah [18] presented evaluation of the performance of phase change thermal energy storage unit which were melted and solidified by the same hot and cold working fluids from the second-law viewpoint, and found that the second-law efficiency can be improved significantly by employing more than one unit connected in series.

Gong and Mujumdar [19] studied a thermodynamic analysis of the energy charge/discharge processes in a latent heat thermal storage system using multiple PCMs, and concluded that the energy efficiency can be enhanced dramatically using multiple PCMs compared with a single PCM.

Wang et al. [20] developed one-dimensional physical model for LHTES systems using multiple PCMs, and found that the phase change time of multiple PCMs with optimum linear PCM distributions can be decreased by as much as 25–40%, compared with that of a single PCM.

Fang and Chen [21] proposed a theoretical model for the performance of a shell-and-tube LHTES using multiple PCMs. Numerical results indicated that fraction and melting temperatures of PCMs play an important role in the performance of the LHTES unit.

Adine and Qarnia [22] presented a numerical study of a LHTES unit using two PCMs consisting of a shell-and-tube. HTF was water. Several numerical investigations were conducted in order to examine the impact of the key parameters: the HTF inlet temperature (ranges from 50 to 60 °C), the mass flow rate of the HTF and the proportion mass of PCMs, on the thermal performance of LHTES during charging process.

Li et al. [23] investigated a mathematical model for the overall exergy efficiency of two phase change materials named PCM1 and PCM2 storage system with a concentrating collector for solar thermal power based on finite-time thermodynamics, and their model takes into consideration the effects of melting temperatures and number of heat transfer unit of PCM1 and PCM2 on the overall exergy efficiency.

From the review of the previous investigations presented above, a lot of studies have been performed on LHTES. But about the shell-and-tube LHTES (Because of its high efficiency and relative small volume, the shell-and-tube heat storage unit is widely used in practical LHTES system [21,22]) using multiple PCMs, only Fang and Chen [21] and Adine and Qarnia [22] studied it ignoring flowing resistance and viscous dissipation of the HTF. Moreover, involved the melting temperatures of PCMs are low (not more than 313 K) and the system is used in building or drying. In this paper, a three high temperature PCMs filled in the shell-and-tube LETES unit for solar thermal power is numerically modeled using FLUENT software considering flowing resistance and viscous dissipation of the air. The main objectives of the present study are to analyze the effects of inlet temperatures of the air and lengths of the shell-and-tube LHTES unit on the melting times of PCM1, PCM2 and PCM3 and to investigate the optimum melting times of PCM1, PCM2 and PCM3 and lengths of the shell-and-tube LHTES unit.

2. Physical model

The schematic diagram of a LHTES with three PCMs for solar thermal power is shown in Fig. 1.

It consists of a solar air receiver, a LHTES with three PCMs named PCM1, PCM2 and PCM3 (the melting temperatures$T_{\mathrm{m1}} > T_{\mathrm{m2}} > T_{\mathrm{m3}}$), a steam turbine. During charging, releasing heat HTF (the air) absorbs solar energy and its temperature increases in solar air receiver (according to Ref. [24], since the past 10 years, the air receiver has become a popular area of research, allowing an incident radiation flux of about 1 MW/m^2). The air with a high temperature enters into the LHTES containing PCM1, PCM2 and PCM3 respectively, releases its thermal energy to PCM1, PCM2 and PCM3, which absorb thermal energy and melt from solid to liquid. During discharging, absorbing heat HTF with low temperature (water) enters the LHTES from reversed flow direction of the air, absorbs thermal energy and its temperature increases from PCM3, PCM2 and PCM1, which releases thermal energy and solidify from liquid to solid. In this paper, we only investigate the shell-and-tube heat storage unit and the heat storage process (charging process).

The physical model of the shell-and-tube LHTES with PCM1, PCM2 and PCM3 is presented in Fig. 2.

The LHTES unit consists of an inner tube, an outer tube and an annulus filled with PCM1, PCM2 and PCM3 with different melting temperatures. The outer tube is well insulated and PCM1, PCM2 and PCM3 are separated by thermal thin walls. The air flows through the inner tube and exchanges heat with PCM1, PCM2 and PCM3. During the charging (melting process), the air circulates in the direction of the melting temperature decrease of PCMs.