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Numerical study on thermal energy storage performance of phase change material under non-steady-state inlet boundary

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ABSTRACT

Due to the solar radiation intensity variation over time, the outlet temperature or mass flow rate of heat transfer fluid (HTF) presents non-steady-state characteristics for solar collector. So, in the phase change thermal energy storage (PCTES) unit which is connected to solar collector, the phase change process occurs under the non-steady-state inlet boundary condition. In present paper, regarding the non-steady-state boundary, based on enthalpy method, a two dimensional physical and mathematical model for a shell-and-tube PCTES unit was established and the simulation code was self-developed. The effects of the non-steady-state inlet condition of HTF on the thermal performance of the PCTES unit were numerically analyzed. The results show that when the average HTF inlet temperature in an hour is fixed at a constant value, the melting time (time required for PCM completely melting) decreases with the increase of initial inlet temperature. When the initial inlet temperature increases from 30 °C to 90 °C, the melting time will decrease from 42.75 min to 20.58 min. However, the total TES capacity in an hour reduces from 338.9 kJ/kg to 211.5 kJ/kg. When the average inlet mass flow rate in an hour is fixed at a constant value, with the initial HTF inlet mass flow rate increasing, the melting time of PCM decreases. The initial inlet mass flow rate increasing from 2.0×10^{-4} kg/s to 8.0×10^{-4} kg/s will lead to the melting time decreasing from 37.42 min to 23.75 min and the TES capacity of PCM increasing from 265.8 kJ/kg to 273.8 kJ/kg. Under all the studied cases, the heat flux on the tube surface increases at first, until it reaches a maximum then it decreases over time. And the larger the initial inlet temperature or mass flow rate, the earlier the maximum value appearance and the larger the maximum value.

1. Introduction

A number of researches on the utilization of solar energy have been carried out due to the globe energy crisis and environmental pollution. However, solar energy has a serious shortcoming that it is unstable and discontinuous with different weathers, times and seasons. So, in order to ensure the solar energy system continuous and stable operation with high efficiency, thermal energy storage (TES) unit becomes a necessary component in the solar thermal utilization systems, such as solar buildings [1,2], solar water heating systems [3,4] and solar energy generation systems [5,6]. Due to the high energy storage density and constant phase change temperature, phase change thermal energy storage (PCTES) has gradually become the preferred TES pattern.

Thermal energy storage with phase change materials has been a main topic in research for the last 20 years. Zalba et al. [7] performed a review on the history of solid–liquid phase change thermal energy storage on materials, heat transfer and applications. Sharma et al. [8] summarized the investigation and analysis of the available thermal energy storage systems incorporating PCMs for different applications. Agyenim et al. [9] carried out a review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage system over the last three decades.

In recent years, a lot of numerical and experimental studies on the characteristics of PCTES process have been performed. In numerical studies, Sharma et al. [10] numerically studied the heat transfer performance of a latent heat storage system with fatty acids as PCMs. The effects of PCMs physical properties, heat exchanger materials and patterns on the PCTES performance were analyzed. A mathematical model regarding the conjugated problem of transient forced convection and solid–liquid phase change heat transfer based on the enthalpy formulation was presented by Trp et al. [11]. The transient heat transfer phenomenon during charging and discharging of the shell-and-tube latent thermal energy storage system was analyzed. Fang and Chen [12] investigated the effects of different multiple PCMs on the melted fraction, stored thermal energy and fluid outlet temperature of the

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Nomenclature

a	coefficient in Eq. (5)
a'	coefficient in Eq. (6)
b	coefficient in Eq. (5)
b'	coefficient in Eq. (6)
c_p	specific heat, J kg^{-1} K^{-1}
f	liquid fraction
h	heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	length of the PCM unit, m
$\dot{m}$	mass flow rate, kg s^{-1}
Pr	Prandtl number
Q	thermal storage capacity, kJ kg^{-1}
r	radial coordinate, m
R_i	inner radius of the tube, m
R_o	inner radius of the shell side, m
Ra	Rayleigh number
T	temperature, °C
t	time, s
x	axial coordinate, m

Greek symbols

δ	melt layer thickness, m
μ	dynamic viscosity, Pa s
θ	relative temperature $(T - T_m)$, K
ρ	density, kg m^{-3}
υ	kinetic viscosity, m^2 s^{-1}
ΔH	enthalpy, kJ kg^{-1}
Φ	heat flux, W

Superscripts

*	last time layer value

Subscripts

f	heat transfer fluid
i	initial state
in	inlet boundary
l	liquid
m	melting point
out	outlet boundary
p	phase change material
s	solid

shell-and-tube latent thermal energy storage unit. Guo and Zhang [13] numerically studied the effects of geometry parameters and boundary conditions on the performance of a new type high temperature latent heat thermal energy storage system. Qarnia [14] developed a theoretical model to predict the thermal performance of a solar latent heat storage unit and three kinds of PCM (*n*-octadecane, Paraffin wax and Stearic acid) were examined to find the optimum design for a given climatic conditions. Adine and Qarnia [15] numerically studied a latent heat storage unit consisting of a shell-and-tube filled with P116 and *n*-octadecane. Wu et al. [16] performed the simulations of a packed bed cool thermal energy storage system with *n*-tetradecane as phase change material.

In experimental studies, Trp [17] experimentally analyzed the transient heat transfer characteristics during phase change material melting and solidification. Akgun et al. [18,19] analyzed the latent thermal energy storage system of the shell-and-tube type with three kinds of paraffin as PCMs. A novel tube-in-shell storage geometry was introduced and the effects of the Reynolds number and Stefan number on the melting and solidification behaviors were examined. Long [20] investigated heat transfer performance of a triplex concentric tube thermal energy storage unit. Wang et al. [21] adopted β-Aluminum nitride as additive to enhance the thermal conductivity and thermal performance of phase change materials. Mddrano et al. [22] experimentally evaluated the performance of commercial heat exchanger used as PCM thermal storage systems.

The foregoing literature review shows that a lot of studies have been performed on the shell-and-tube PCTES unit. But most of them were performed under the constant HTF inlet temperature and mass flow rate. However, for the solar thermal utilization system, the HTF comes from the solar collector, the HTF inlet conditions for the PCTES unit depends on the HTF outlet conditions at the solar collector. Due to the unstable and discontinuous characteristics of the solar radiation intensity and the complicated heat transfer and fluid flow process in the collector [23–25], the HTF outlet condition presents obvious non-steady-state. So, the inlet conditions (HTF temperature or mass flow rate) for the PCTES unit inevitably present non-steady-state characteristics, which will greatly affect the melting rate and stored thermal energy of PCM and the outlet temperature of HTF.

In present study, regarding the non-steady-state characteristics of HTF temperature or mass flow rate at the inlet of the PCTES unit, based on enthalpy method, a two dimensional physical and mathematical model for the phase change process in water/*n*-octadecane shell-and-tube PCTES unit was established and the simulation code was self-developed. Then the numerical study on the performance of the PCTES unit was performed and the effects of the non-steady-state HTF inlet conditions on the PCTES performance were analyzed.

2. Physical model and governing equations

2.1. Physical model

The physical model for PCTES unit is shown in Fig. 1, which is a shell-and-tube configuration. Water is selected as HTF and flows in inner tube. The shell side is full of PCM (*n*-octadecane). In the charging process, thermal energy transfers from HTF to PCM through the tube surface and is stored in PCM, and in discharging process, thermal energy stored in PCM releases to HTF. The length for the computation domain (L) is 1.0 m, the inner radius for the tube (R_i) is 6.35 mm, inner radius for shell side (R_o) is 11.35 mm. The thickness of tube wall is neglected. The thermophysical properties for HTF and PCM are shown in Table 1.

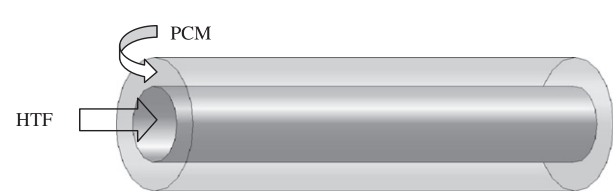

Fig. 1. The schematic of the shell-and-tube PCTES unit.