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The energy efficiency ratio of heat storage in one shell-and-one tube phase change thermal energy storage unit

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HIGHLIGHTS

- A parameter to indicate the energy efficiency ratio of PCTES units is defined.
- The characteristics of the energy efficiency ratio of PCTES units are reported.
- A combined parameter of the physical properties of the working mediums is found.
- Some implications of the energy efficiency ratio in design of PCTES units are analyzed.

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ABSTRACT

From aspect of energy consuming to pump heat transfer fluid, there is no sound basis on which to create an optimum design of a thermal energy storage unit. Thus, it is necessary to develop a parameter to indicate the energy efficiency of such unit. This paper firstly defines a parameter that indicates the ratio of heat storage of phase change thermal energy storage unit to energy consumed in pumping heat transfer fluid, which is called the energy efficiency ratio, then numerically investigates the characteristics of this parameter. The results show that the energy efficiency ratio can clearly indicate the energy efficiency of a phase change thermal energy storage unit. When the fluid flow of a heat transfer fluid is in a laminar state, the energy efficiency ratio is larger than in a turbulent state. The energy efficiency ratio of a shell-and-tube phase change thermal energy storage unit is more sensitive to the outer tube diameter. Under the same working conditions, within the heat transfer fluids studied, the heat storage property of the phase change thermal energy storage unit is best for water as heat transfer fluid. A combined parameter is found to indicate the effects of both the physical properties of phase change material and heat transfer fluid on the energy efficiency ratio.

1. Introduction

With the increasing power consumption of industrial, commercial, and residential activities, the problems of energy shortage and air pollution have become serious. To help relieve this situation, the use of renewable energy, such as wind energy and solar energy [1–5], on a global scale is highly recommended. However, these types of energy have some shortcomings: they are unstable and can be unreliable due to their dependence on the weather, time, and season. Thus, thermal energy storage (TES) units have become a necessary component in applying renewable energy. The main task of the energy storage, then, is to eliminate the mismatch between energy supply and energy demand.

TES includes sensible, latent, and thermal–chemical heat storage units. The latent TES system with solid–liquid phase change has gained greater attention due to its advantages. It has high energy storage density and heat charging/discharging at a nearly constant phase change temperature. These characteristics result in a greater flexibility and more compactness of the phase change material (PCM) heat storage system [6]. Therefore, phase change thermal energy storage (PCTES) has been a main topic in research for the last 20 years. The state of the art developments are summarized in many review papers [7–10]. Zalba et al. [7] carried out a review of the history of solid–liquid PCTES with phase change materials and applications. Sharma et al. [8] summarized the analysis of the available thermal energy storage systems for different applications. Agyenim et al. [9] performed a review of the materials, heat transfer, and phase change problem formulation for latent heat thermal

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Nomenclature

a	discrete equation coefficients
c	specific heat capacity (J/(kg K))
C	constant in Eq. (10)
E	energy efficiency ratio
f	fluid flow resistance factor
h	local convective heat transfer coefficient (W/(m^2 K))
H	latent heat (J/kg)
i	the first i axial node
j	the first j radial node
k	thermal conductivity (W/(m K))
l	length of the tube (m)
L	dimensionless length of the tube l/R_i
n	constant in Eq. (10)
Nu	Nusselt number $2hR_i/k_f$
Pr	Prandtl number ν_f/α_f
q	heat storage rate (W)
Q	heat energy stored (J)
r	radial coordinate (m)
R	radius (m) or dimensionless radius of the tube r/R_i
R_1	dimensionless radius of the tube R_w/R_i
R_2	dimensionless radius of the tube R_o/R_i
Ra	Rayleigh number
Re	Reynolds number $2UR_i/\nu_f$
St	Stanton number $h/((\rho c)_f U)$
Ste	Stefan number $H/(c_p \Delta T)$
t	time (s)
t_0	time (s) R_i/U
T	temperature (K)
U	velocity (m/s)
w, e, n, s	west, east, north, and south faces of control volumes
P, N, S, W, E	the center, north, south, west, and east nodes
W	mechanical energy (J)
x	axial coordinate (m)
X	dimensionless axial coordinate x/R_i

Greek symbols

Δp	pressure drop (Pa)
ΔR	dimensionless radial space step $\Delta r/R_i$
ΔX	dimensionless axial space step $\Delta x/R_i$
α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (/K)
ε	energy efficiency ratio
Φ	related stored heat energy (m^3)
φ	liquid fraction
Λ	specific heat capacity ratio $\rho c/(\rho c)_f$
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
Π	thermal diffusion ratio α/α_f
Θ	dimensionless temperature
ρ	density (kg/m^3)
τ	dimensionless time t/t_0
$\Delta\tau$	dimensionless time step $\Delta t/t_0$
ψ	related mechanical energy (m^3)

Superscripts

k	iteration k
0	old value

Subscripts

e	effective
f	heat transfer fluid (HTF)
front	the melt front surface of PCM
hcp	PCM relative HTF
hcw	tube wall relative HTF
i	internal tube or initial
in	inlet
l	liquid phase
m	melting
o	external tube
out	outlet
p	phase change material
P, N, S, W, E	the center, north, south, west, and east nodes
r	radial direction
s	solid phase
t	time
thermp	PCM relative HTF
thermw	tube wall relative HTF
w	tube wall
w, e, n, s	west, east, north, and south faces of control volumes
τ	dimensionless time

energy storage systems. Al-Abidi et al. [10] completed a review of thermal energy storage for air conditioning systems.

In most PCTES systems, as shown in Fig. 1, a shell-and-tube is the core unit of PCTES. There are many reported studies on this unit [11–22]. Refs. [11–15] use experimental methods to investigate the performance characteristics of this unit. Trp [11] experimentally analyzed the transient heat transfer performance during phase change material melting and solidification. Akgun et al. [12,13] studied on melting/solidification characteristics of three kinds of paraffin as PCM. 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. Wang et al. [14] used β-aluminum nitride as additive to enhance the thermal conductivity and thermal performance of form-stable composite phase change materials. Mddrano et al. [15] experimentally evaluated the performance of commercial heat exchanger used as PCM thermal storage systems. Numerous experimentally validated mathematical models of the unit have been developed over the years. These models have been used to determine the performance of the unit for design [16–21]. Trp et al. [16] presented a mathematical model regarding the conjugated problem of transient forced convection and solid–liquid phase change heat transfer based on the enthalpy formulation. The transient heat transfer phenomenon of the unit was analyzed. Fang et al. [17] investigated the effects of different multiple PCMs on the melted fraction, heat storage capacity and heat transfer fluid (HTF) outlet temperature of the unit. Adine and Qarnia [18] numerically analyzed the thermal behavior of the unit. Tao et al. [19,20] performed the numerical study on thermal energy storage performance of PCM in the unit with enhanced tubes. Wang et al. [21]

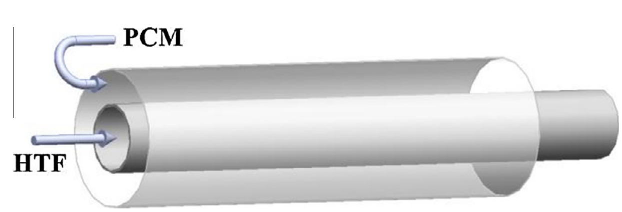

Fig. 1. Schematic of the shell-and-tube phase change thermal energy storage unit.