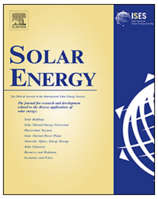
Solar Energy 174 (2018) 489–501

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener



The error of neglecting natural convection in high temperature vertical shell-and-tube latent heat thermal energy storage systems

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A R T I C L E I N F O

Keywords:
High temperature
Latent heat
Phase change material (PCM)
Natural convection
Error correlation
Shell-and-tube

A B S T R A C T

There is little understanding of the relative importance of natural convection when designing latent heat thermal energy storage (LHTES) systems based on geometric parameters and/or phase change material (PCM) properties. For high temperature shell-and-tube LHTES systems, this study aims: (i) to determine the error of ignoring natural convection, and (ii) to quantify this error for different geometric parameters and PCM properties. In particular, the study defines the circumstances under which natural convection is important and the error of choosing a 'conduction-only modelling approach'. To do so, the performance of LHTES systems with nine geometric aspect ratios and three commercial PCMs (of different melting points) were analyzed by means of a validated CFD model.

The results showed that the error is a function of the process under analysis (melting or solidification) and the ratio of stored/delivered energy divided by the maximum capacity of PCM (i.e. its effectiveness). Geometry also plays a critical role in the relative importance of natural convection. The study demonstrates that a specific system geometry (i.e. a dimensionless number defined based on the inner and outer radius as well as the length of shell-and-tube geometry: $S = \frac{R^2 - r_O^2}{2r_O L}$) can be used to determine the relevance of natural convection. It was found that regardless of PCM type, the error is of neglecting natural congestion is small if $S < 0.005$. For $S > 0.005$, the error depends on the following non-dimensional groups: $\frac{r_O}{L}$, Ra, Ste, and Bi. As might be expected, the Rayleigh number was found to be the most influential group. Notably, a critical Rayleigh number value (8×10^5) was found, below which the error of neglecting natural convection is < 1%. Finally, two correlations were developed in order to quantify the error achieved – one for melting and another for solidification.

1. Introduction

Thermal energy storage (TES) is a key component in intermittent energy conversion cycles like solar energy plants, where there is a mismatch between supply and demand (Tehrani et al., 2013a, 2013b). While sensible heat storage currently dominates the market for this type of TES technology (Dincer and Rosen, 2002; Kuravi et al., 2013; Seddegh et al., 2015b; Tehrani et al., 2017), latent heat thermal energy storage (LHTES) systems have gained prominence in recent years as they represent a promising alternative to traditional TES systems (Cárdenas and León, 2013; Dutil et al., 2011). These systems use phase change materials (PCMs), in a single or cascaded configuration (Tehrani et al., 2018b), which store the latent heat of melting and release it upon solidification. Compared to sensible heat storage, PCMs enable more compact designs, which can result in lower storage media costs (Liu et al., 2012; Zalba et al., 2003). Advanced high temperature systems are currently under development to increase the efficiency of concentrated solar power-tower (CSP-tower) plants, where the heat transfer fluid is heated up to approximately 565 °C in order to produce electricity (Mostafavi Tehrani et al., 2018; Gil et al., 2010; Jacob et al., 2016; Kuravi et al., 2013; Liu et al., 2016; Tehrani and Taylor, 2016; Tehrani et al., 2017).

Among the different configurations of LHTES systems, shell-and-tube heat exchangers represent a promising and straightforward high temperature PCM design (Seddegh et al., 2018). As a result, this configuration is gaining interest (Agyenim et al., 2010; Nithyanandam and Pitchumani, 2011; Tehrani et al., 2017). One of the most important challenges facing this kind of system is the geometric design optimization (Li et al., 2017; Mahdavi et al., 2016; Nithyanandam and Pitchumani, 2011, 2014; Tiari and Qiu, 2015) – task that is usually

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https://doi.org/10.1016/j.solener.2018.09.048
Received 4 July 2017; Received in revised form 20 August 2018; Accepted 16 September 2018

Nomenclatures

A	area [m^2]
C_P	specific heat at constant pressure [J/kg K]
d	inner diameter of latent heat storage unit [m]
f	liquid fraction [–]
h	enthalpy [J/kg]
H, ΔH	latent heat of fusion [J/kg]
k	thermal conductivity [W/m K]
L	length of tank [m]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [Pa]
Q	amount of stored/discharged energy [J]
$\dot{Q}$	amount of stored/discharged energy [W]
R	outer radius of a cylinder [m]
r_o	inner radius of pipe [m]
t	total time of simulation [s]
T	temperature [K]
T_{m1}	lower melting point [K]
T_{m2}	upper melting point [K]
$\vec{v}$	velocity [m/s]

Greek symbols

β	volumetric expansion coefficient [1/K]
ρ	density [kg/m^3]
μ	dynamic viscosity [kg/m s]

Subscripts

l	liquid
r	radial direction
z	axial direction

Abbreviations

ALF	average liquid fraction
HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
Nu	Nusselt number
PCM	phase change material
Ra	Rayleigh number
Ste	Stefan number
TES	thermal energy storage

performed via modelling. However, the accurate simulation of two-phase heat transfer problems is complex because of the moving melting/solidification boundary (Fornarelli et al., 2016).

To date, several computational fluid dynamics (CFD) models have been reported in the literature as for the modelling of phase change processes (Riahi et al., 2017; Tehrani et al., 2016b). Conduction-only models are much faster than full convection models, so they are often used for design optimization. In fact, several recent studies only consider the conduction mechanism (See Table 1). However, this approach can lead to non-negligible errors depending on the conditions.

As demonstrated in a recent review on the topic (Dhaidan and Khodadadi, 2015), upon melting, natural convection drives a recirculation zone inside the liquid region. This phenomenon increases the heat transfer within the liquid PCM and causes non-uniformities in the solid-liquid interface and temperature distribution during melting. Solidification, on the other hand, is mainly dominated by conduction, although initially (at high liquid fractions) convection and conduction transfer a similar amount of heat. Consequently, various researchers have investigated the fundamentals of natural convection.

Fornarelli et al. (2016) compared the results obtained from convective and pure conductive models of a high temperature shell-and-tube LHTES system for a CSP application during the melting process. The study confirmed that the convective motion increases the heat flux to the PCM, effectively increasing the heat transfer rate (e.g. reducing

Table 1
Selected shell-and-tube LHTES system studies.

Ref.	T_m(°C)	Melting/Solidification	Convection Considered?	Method	$L(m)$	R/r_o	L/d
(Wang et al., 2015)	26	Melt.	Yes	2D Num.	–	1.2–5	25–150
(Wang et al., 2013)	26	Melt./Sol.	Yes	2D Num.	1	2	78
(Tao and He, 2011)	26	Melt.	Yes	2D Num.	1	1.8	83
(Trp, 2005; Trp et al., 2006)	26	Sol.	No	Exp./2D Num.	1	3.7	30
(Lacroix, 1993)	26	Melt.	Yes	2D Num.	1	1.6	78
(Adine and El Qarnia, 2009; El Qarnia, 2009)	26	Melt./Sol.	Yes	2D Num.	1	1.6	78
(Longeon et al., 2013)	35	Melt./Sol.	Yes	Exp./CFD	0.4	2.9	26
(Kalhori and Ramadhyani, 1985; Kemink and Sparrow, 1981)	36	Melt.	Yes	2D Num.	0.2	8.4	10
(Mendes and Brasil, 1987)	36	Melt.	Yes	Exp.	0.17	6	5
(Esen et al., 1998)	29–46	Melt.	No	2D Num.	3.2	1.09–1.2	20–48
(Fang and Chen, 2007)	20–80	Melt.	No	2D Num.	2	2	100
(Seddegh et al., 2016)	51	Melt./Sol.	Yes	CFD	1	3.9	12
(Seddegh et al., 2015a)	58	Melt./Sol.	Yes	CFD	1	4	30
(Xiao and Zhang, 2015a, 2015b)	60	Melt./Sol.	Yes	Exp./2D Num./CFD	0.75	–	10.7
(Akgün et al., 2007)	75	Melt./Sol.	Yes	Exp.	0.5	3.3	17
(Wang et al., 2016)	121	Melt./Sol.	Yes	Exp.	0.9	2.4	20
(Fan et al., 2014)	169	Melt./Sol.	No	2D Num.	1.4	1.25	87
(Pointner et al., 2016)	215	Melt.	Yes	2D Num.	1	–	–
(Fornarelli et al., 2016)	230	Melt./Sol.	Yes	CFD	0.5	5	35
(Tehrani et al., 2016b)	300–500	Melt./Sol.	No	2D Num.	1–5	1.3–3	10–100
Present study	300–500	Melt./Sol.	Yes	CFD	0.5–2	1.5–3	15–60
(Riahi et al., 2017)	306	Melt./Sol.	Yes	CFD	0.6	3.15	29
(Muhammad et al., 2015a)	306	Melt./Sol.	Yes	CFD	0.9	5.41	155
(Tao and Carey, 2016)	400–600	Melt.	No	2D Num.	1	2	40
(Li et al., 2013)	400–700	Melt.	No	2D Num.	1.2	2	120
(Pirasaci and Goswami, 2016)	550	Sol.	No	2D Num.	10–150	1–3	10–150
(Bellecci and Conti, 1993a, b)	734	Melt.	No	2D Num.	–	2.6–5	12–150
(Tao et al., 2014; Tao et al., 2012)	766	Melt.	No	2D Num.	1.5	2	60