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Impact of periodic flow reversal of heat transfer fluid on the melting and solidification processes in a latent heat shell and tube storage system

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HIGHLIGHTS

- Periodic flow reversal method enhances heat transfer performance in PCM systems.
- Smaller temperature gradient in time and space leading to higher exergy recovery.
- Reduction in charging and discharging duration by 10% and 12%, respectively.
- 6% enhancement in time-average heat transfer rate in charging and discharging.
- Periodic flow reversal leads to a cost-effective system with higher power density.

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ABSTRACT

A numerical study has been conducted on a shell and tube latent heat storage system whereby the inlet heat transfer fluid direction is periodically reversed during charging and discharging. The impact of varying the boundary condition at the interface of the tubes carrying the heat transfer fluid and phase change material (PCM) on the evolution of the phase change front, heat transfer area and heat transfer rate have been evaluated during the charging and discharging processes. Results for the charging processes show a higher heat transfer area develops during the early stages and amplification of natural convection after 40% melt fraction, leading to a higher heat transfer rate. In comparison to the fixed flow condition, periodic flow reversal for the discharge cases results in an increased heat transfer area for a longer period of time, leading to a higher heat transfer rate particularly after 75% solidification. This effect is more important for discharging cases in the absence of convection heat transfer. Periodically reversing the direction of heat transfer fluid, which produced a periodic boundary condition at the tube-PCM interface, also resulted in a lower temperature gradient in space and time and consequently higher exergy recovery, and about a 6% increase in the time-average heat transfer rate in the charging and discharging cases. The novel reversal flow method provides a means to implement a periodic boundary condition without changing the heat source/sink, enhancing the thermal performance and cost effectiveness of latent heat storage systems. Phase change storage systems incorporating periodic flow reversal provide higher energy delivery rates, greater power density and more exergy recovery. This method can support fast heat release to respond to a peak load in a CSP plant or fast heat storage to protect a tubular receiver from high thermal stresses.

1. Introduction

In a latent heat thermal energy storage (LHTES) unit, heat is stored via a phase change material (PCM) which can then be supplied at a later time to the heat transfer fluid (HTF) for applications such as concentrated solar power (CSP). Energy is stored by melting the PCM, and is subsequently discharged by solidification of the PCM. Thermal storage must be able to meet both objectives of storing sufficient amounts of energy and providing adequate heat transfer rates during extraction. PCMs have high volumetric energy densities, however due to the low thermal conductivity of most candidate materials, development of more effective configurations of LHTES systems is required. A promising configuration for PCM thermal storage systems is the shell and tube arrangement where the heat transfer fluid flows through tubes surrounded by the PCM.

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Nomenclature

A_{mush}	mushy zone constant
c	specific heat (J/kg K)
f	non-dimensional frequency
g	gravitation acceleration (m/s^2)
h	sensible specific enthalpy (J/kg)
H	specific enthalpy (J/kg)
k	thermal conductivity (W/m K)
L	Latent heat of fusion (J/kg)
Nu	Nusselt number
P	pressure (Pa)
q″	heat flux (W/m^2)
Pr	*Pr* number (ν/α)
R	width of enclosure (m)
Ra	Rayleigh number, $g\beta Z^3(T_h - T_m)/\nu\alpha$
S	source term in momentum equation
Ste	Stefan number, $c_l\ (T_h - T_m)/L$
t	time (s)
T	temperature (°C)
v	velocity (m/s)
w	dimensional period
x,y	coordinates
Z	height of enclosure (m)
α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
δl	liquid fraction
δs	solid fraction
ε	small number (0.001)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

h	hot wall subscripts
l	liquid
m	melt
o	reference
p	pressure

An optimal design for every configuration including the shell and tube, should use the highest volume fraction of PCM and deliver the highest heat transfer density with the lowest temperature gradient [1]. In reality this means the smallest unit with a uniform melting or solidification process of PCM in space and time without hot-spots [2], leading to a cost-effective thermal storage system. Design criteria demand different priorities for different applications, due to the specific constraints and variables. For instance, targeting 6 h duration for a charging process in a CSP plant and varying other parameters might lead to an optimal design. However, in cases where LHTES is used to protect a receiver from high temperatures [3], or as an auxiliary source of energy during peak energy demand periods in a CSP plant, higher rates of energy release might be necessary.

There has been considerable research in regards to various heat transfer enhancement methods in LHTES systems. This has been summarized comprehensively by Liu et al. [4] and in a recent review by Liu et al. [5]. The traditional approach in designing more effective LHTES systems has been through enhancing the heat transfer in the PCM using fins, foams or encapsulated PCM [6–10]. However, these techniques increase cost.

Kurnia et al. [8], numerically studied different configurations of U-tube in PCM. Examples include a U-tube with inline and staggered fin, and a form of serpentine. They investigated the impact of different types of fins on natural convection and the heat transfer rate.

Through a numerical investigation, Liu et al. [9] studied the heat transfer enhancement effect of including metal foam in an element of a horizontal shell and tube LHTES system. An example was using PCM/foam in the outer tube and HTF in the inner tube of an annulus. Introducing an effective thermal conductivity for the PCM and metal foam, the evolution of melting front, temperature and velocity fields were explored.

Through a numerical and experimental investigation of a horizontal shell and tube (with fin) PCM system with two HTFs, water and air, Zhao and Tan [10] proposed a storage system for air conditioning purposes with an effectiveness higher than 0.5. Using the proposed system instead of cooling tower provided 26.5% improvement in COP for a water cooled air conditioning system.

Tube based LHTES systems are fundamentally tubes bundled in a shell, however limited research has investigated the characteristics of different flow arrangements with different boundary conditions to serve the specific design criteria. Limited research has been conducted in regards to heat transfer between a parallel tube bundle and high temperature PCMs, with a specific focus on the boundary condition imposed on the PCM. In most cases the tube to PCM boundary condition was taken to be a fixed temperature or a fixed heat flux, and generally considered as a single tube [11–15]. Nevertheless, in most real applications, the HTF flows via several tubes and depending on the tube and PCM arrangement, different boundary conditions can be implemented at the tube-PCM interface.

In a recent two part study, Belusko et al. [16,17] numerically investigated an effective tube-in-tank system as LHTES for CSP plants. In the first study, the impact of different tube and flow arrangements (e.g. single pass parallel flow, one and two dimensional counter flow) on the PCM boundary conditions and discharging effectiveness were assessed. The main conclusion from the first study [16] is that different arrangements of HTF flow in the tube bundle influences the evolution of the phase front and the heat transfer area during a steady phase change process. Results of the second study [17] showed that for cases of a latent heat dominant system, the counter flow arrangement delivers a higher effectiveness while for the cases of a sensible heat dominant storage system, parallel flow was the better choice. However, this study ignored natural convection.

Through an analytic and numerical attempt, Lorente et al. [12] studied the evolution of vertical and horizontal melting fronts, temperature field and heat storage during a melting process in a vertical cylinder with a fixed heated bar in the centre. In another analytical and numerical study, Lorente et al. [1] found an optimal configuration of two concentric helices at fixed temperature immerged in a cylindrical tank of PCM. Using constructal law and numerical calculations, for a fixed period of heat storage (8 h) and 95% volume fraction of PCM, the authors proposed parameters such as helices diameter and pitch to deliver a more uniform melting rate with increased global performance. The scale-analysis also showed the optimal energy storage can be delivered through uniform melting or least temperature gradient in space and time. This means using less material, leading to a more cost-effective LHTES unit.

In an experimental and numerical investigation, Longeon et al. [18] studied the effect of injecting the HTF from the top and bottom of an element of a parallel tube bundle immersed in PCM,