International Journal of Thermal Sciences 112 (2017) 345–357

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Solid-liquid phase change around a tube with periodic heating and cooling: Scale analysis, numerical simulations and correlations

Christian Chabot, Louis Gosselin*

Department of Mechanical Engineering, Université Laval, Québec, QC, G1V 0A6, Canada

ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form
10 October 2016
Accepted 19 October 2016

Keywords:
Phase change materials (PCM)
Heat storage
Transient boundary condition
Solidification and melting
Natural convection
Latent heat storage

ABSTRACT

This work studies solid-liquid phase change around a tube in a latent energy storage unit with cyclic thermal loading and unloading (i.e. alternate heating and cooling), while taking into account natural convection. A scale analysis is used to predict the tube surface temperature and the extent of the molten and solidified zones around the tube as a function of the main governing dimensionless parameters (the Stefan and Rayleigh numbers, and the period of the imposed sinusoidal heat transfer rate). A numerical model is then developed to simulate the process under a periodic regime and verify the scale analysis. Temperature, liquid fraction and flow fields are reported as a function of the main governing parameters. A frequency analysis is also proposed to develop a better understanding of how the system behaves. It is shown that the dimensionless group $\mathrm{Pr}/(\sim\tau \mathrm{Ra}^{1/5}\mathrm{Ste})$ allows to determine the importance of natural convection in the system. Results indicate that the size of the zone affected by the alternate heating and cooling increases when the period or the Stefan number increased, but was less sensitive to the Rayleigh number. Correlations are proposed to determine the maximal dimensions reached by the melt and by the solid around the tube.

1. Introduction

Nowadays, a lot of efforts are devoted to promoting the use of renewable and sustainable energy sources. For several options, such as solar energy, different issues can arise. First, these systems often lack economic competitiveness against conventional systems relying on fossil fuels [1]. Second, energy availability does not always coincide with demand. An efficient thermal energy storage (TES) is required to collect heat when it is available and to discharge it when it is needed. Even when integration of solar technology is not considered, TES can provide significant environmental and economic advantages by shifting the energy consumption to off-peak hours, especially where electricity rates are different during daytime and nighttime or when customers are charged for their power peak demand.

Thermal energy storage systems can be separated into two families, depending on whether they rely on sensible heat (SHTES) or latent heat (LHTES). Generally, phase change materials (PCM) require much less mass or volume to store the same amount of energy at a more or less constant temperature [2] but can be about twice as expensive as hot water systems [1] and suffer from slow discharge rate compared to SHTES due to low thermal conductivity in the solid phase [3]. PCM class and properties, and the applications in which they are used in building are well documented [2,4–9]. Commercial grade PCMs are preferred due to their large-scale availability and low cost [4]. Among them, paraffins are known to have an excellent thermal stability to cycles of melting and solidification and not to degrade in contact with metals [10]. Moreover, different varieties are offered covering a large range of melting temperature which makes them suitable for many building related applications [9].

Phase change processes in thermal storage units using paraffin as PCM have been analysed numerically and experimentally. The numerical technique to solve this moving boundary problem is often the enthalpy method [11]. This technique was used and validated with experimental data by Lacroix [12] to predict the transient behavior of a shell-and-tube storage unit with PCM on the shell side and heat transfer fluid circulating inside the tubes. Natural convection in the melt was taken into account by employing an effective thermal conductivity. Trp [13] carried out experimental and numerical investigation for paraffin melting and solidification in a shell-and-tube LHTES unit. The results obtained showed that

* Corresponding author.
E-mail address: Louis.Gosselin@gmc.ulaval.ca (L. Gosselin).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.10.017
1290-0729/

Nomenclature

a	Fourier transform amplitude
A	mushy zone constant
c_p	specific heat, J kg^{-1} K^{-1}
D	tube diameter, m
f	liquid fraction
f	dimensionless frequency
g	gravitational acceleration, m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
p	pressure, Pa
Pr	Prandtl number
q'	heat transfer rate per unit of tube length, W m^{-1}
r	radial coordinate, m
Ra	Rayleigh number
s	source term
S	phase change front extension, m
Ste	Stefan number
t	time, s
T	temperature, K
u,v	velocity, m s^{-1}
x,y	Cartesian coordinate, m

Greek Symbol

α	thermal diffusivity, m^2 s^{-1}
β	thermal expansion coefficient, K^{-1}
δ	boundary layer thickness, m
ε	small number
θ	normalized temperature
λ	phase change enthalpy, J kg^{-1}
μ	dynamic viscosity, kg s^{-1} m^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
τ	cyclic period, s
ϕ	Fourier transform phase
ψ	dimensionless stream function

Subscripts

0,1,2 …	Fourier transform harmonics
b	buoyancy
c	cooling
d	downward
h	heating
i	initial
m	melting
mush	mushy zone
s	sideward
S	surface
T	thermal
u	upward
~	dimensionless

Acronyms

PCM	phase change material
SHTES	sensible heat thermal energy storage
LHTES	latent heat thermal energy storage
CFD	computational fluid dynamics
FFT	Fast Fourier Transform

melting of paraffin occurred non-isothermally but solidification occured isothermally. Rösler and Brüggemann [14] presented a good agreement between numerical and experimental results of the liquid-solid interface evolution in time as well as thermal power and energy stored in a shell-and-tube LHTES unit.

Several studies have focussed on either the charging or the discharging of LHTES [15–18]. Sugawara et al. studied the melting and freezing around a single horizontal cylinder [15] and around a vertical array of 4 horizontal cylinders [16]. It was shown that the main heat transfer phenomenon during the charging phase (melting) is natural convection, while conduction dominates during the discharging phase (solidification). Solidification is axisymmetric around tubes while melting is not. Ezan [17] studied the impact of the inlet temperature of heat transfer fluid, thermal conductivity of the tube material and the diameter of shell on the charging and discharging time of shell-and-tube type LHTES systems. Liu and Groulx [18] analysed experimentally the effect of heat transfer fluid inlet temperature, flow rates and fins on the entire solidification and melting times.

In most available work, boundary conditions are considered constant and the initial condition is either fully liquid for solidification analysis or fully solid for melting analysis. However, the real operating mode of LHTES systems is characterized by transient boundary conditions and non-uniform temperature profile at all times. For example, heat transfer fluid temperature may change over time and the domain might not undergo full phase change. This aspect was studied by Tao and He [19] who investigated the phase change process under non-steady-state inlet boundary condition in regard to the melting time, melting fraction, TES capacity, solid-liquid interface, heat flux on tube surface and heat transfer fluid outlet temperature. Gong and Mujumdar [20] analysed the effect of the heat transfer fluid flow rate, inlet temperature and duration of the charge/discharge period under cyclic conditions on the energy charge/discharge rate of a shell-and-tube LHTES unit. However, that study neglected natural convection. Alternate melting and solidification in a square geometry was investigated by Wang et al. [21]. Their results showed that heat transfer during melting in a LHTES system was more efficient than during solidification and the authors proposed three approaches to achieve a balance between charging and discharging.

Considering the current state of the art, there is thus a lack of studies on periodic melting and solidification occurring in LTHES in order to provide guidelines for their design, and assess their performance in real situations. Therefore, the objectives of the present study are to: (1) improve the understanding of alternate melting and solidification around a tube while taking into account natural convection and (2) analyze the effect of major design and operating variables on the performance of the system under such transient boundary conditions. A mathematical model is presented in Section 2, followed by a numerical model in Section 3. Then, a scale analysis is performed in Section 4 to predict the main heat transfer features of the system. A reference case is described in Section 5 which allows introducing the different indicators or measures that will be compared in the next sections for different scenarios: the temperature and fluid flow profiles, the maximal extent of the solid and liquid zones during the cycle and the results of a frequency analysis. The effects of the Rayleigh number, Stefan number, period and far-field temperature are presented in Sections 6, 7, 8 and 9 respectively. Finally, correlations are proposed in Section 10.