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Analytical modeling of PCM solidification in a shell and tube finned thermal storage for air conditioning systems

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ABSTRACT

Due to the advantages offered by latent heat thermal storages, phase change materials (PCM) are used in numerous applications including building air conditioning systems. In this study, the development is reported of an approximate analytical model for the solidification process in a shell and tube finned thermal storage. A comparative study is presented for solidification of the PCM in cylindrical shell and rectangular storages having the same volume and heat transfer surface area. The PCM solidification rate in the cylindrical shell storage is found to exceed that for the rectangular storage. The effects are investigated of heat thermal fluid (HTF) inlet temperature and flow rate on thermal storage performance.

1. Introduction

Thermal energy storage (TES) facilitates the utilization of renewable energy sources and the improvement of the energy efficiency. Latent heat thermal storage (LHTS), using phase change materials (PCMs) to store thermal energy, has many uses. Important LTHS applications and advances in LHTS materials and heat transfer have recently been reviewed [1–4]. Due to rising energy costs, thermal storages systems designed for the heating and cooling of buildings are becoming increasingly important [5–7].

Heat transfer in PCM storages is a transient, non-linear phenomenon with a moving solid–liquid interface. The non-linearity is the principle challenge in moving boundary problems and analytical solution for these problems (Stefan problems) are known only for a one-dimensional domain with simple boundary conditions. Some analytical approximations of moving boundary problems have been reported [8]. Solomon et al. [9] solved the Stefan problem in a slab with a convective boundary condition end using a quasi-stationary approximation. Vakilaltojjar and Saman [10] developed a semi-analytical method for phase change in a rectangular storage for air conditioning applications, and investigated the effect of slab thickness on storage performance. Reviews of various mathematical methods have been reported by Dutil et al. [11] and Verma et al. [12]. Hawala et al. [13] introduced a phase change processor method for solving the one-dimensional phase change problem with a convective boundary which takes into account the sensible effects during the overall process of PCM melting and solidification. Costa et al. [14] and Sharma et al. [15] employed an enthalpy formulation developed by Voller [16] to model a PCM slab one- and two-dimensionally. Tan and Leong [17] experimentally investigated PCM solidification under constant heat rate conditions, and found that the enclosure with lower height to width ratio has higher solidification rate. Liu et al. [18] investigated experimentally PCM solidification in a vertical annulus energy storage; they obtained radial temperature distributions and determined that the PCM temperature variation is insensitive to Reynolds number. Akgun et al. [19] experimentally studied PCM melting and solidification in a shell and tube heat exchanger. Kalaiselvam et al. [20] analyzed the melting and solidification processes for a PCM encapsulated in a cylindrical enclosure, and examined the effect of Stefan number on the time for complete solidification.

Due to the relatively low thermal conductivity of PCMs, many investigations have been performed to improve the heat transfer in LHTS [21–23]. One method is to increase the heat transfer surface area by employing finned surfaces. Numerous investigations have been reported of the effect of fins with rectangular cross-sections on the rate of PCM melting/solidification. For instance, Zhang and Faghri [24] studied the heat transfer enhancement in a LHTS system using a finned tube, solving the phase change problem via the temperature transforming method proposed by Cao and Faghri

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Nomenclature

A_c	cross-section area, m^2
c	specific heat, $J\,kg^{-1}\,K^{-1}$
D	tube diameter, m
h	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
l	length, m
L	latent heat of fusion, $J\,kg^{-1}$
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
$\overline{Nu}$	mean Nusselt number
Pr	Prandtl number
R	radius, m
Re	Reynolds number
t	time, s
T	temperature, °C
u	velocity, $m\,s^{-1}$
Z	distance of solid–liquid interface in z-direction, m

Greek symbols

α	thermal diffusivity, $m^2\,s^{-1}$
δ	half thickness of fin, m
Λ	dimensionless fluid temperature $(T_w - T_\infty)/(T_w - T_{\infty,inlet})$
θ	dimensionless fin temperature $(T_f - T_m)/(T_\infty - T_m)$
ρ	density, $kg\,m^{-3}$
Ω	distance of solid–liquid interface in r-direction, m

Subscripts

c	cell
f	fin
∞	heat thermal fluid
s	solid
w	wall

[25]. Stritih [26] studied numerically phase change in a rectangular LHTS with a finned surface for thermal storage applications in buildings. Inaba et al. [27] studied numerically a finned rectangular LHTS with constant-temperature boundary conditions, and found that fin pitch influences on solidification. Baure [28] developed an approximate analytical model based on the effective method properties of the PCM-fin in order to predict total solidification time of a PCM with constant wall temperature. His method is applicable for a cell aspect ratio (the ratio of the half height of the cell to fin length) smaller than 0.5.

In this article, we present an approximate analytical solution for the two-dimensional solidification process of a PCM in a shell and tube geometry with radial fins (see Fig. 1). The main objective is to provide a convenient analysis and design tool for a finned LHTS that is reasonably accurate, convenient and physically meaningful. During solidification, heat transfers by conduction from the solid PCM and the fins' influence on the solidification is more than melting [29]. The PCM is cooled and solidified using atmospheric air as the HTF, flowing on tube side. The outer side is insulated.

2. Model description

The heat transfer in PCM storages with internal fins cannot be determined analytically for a two-dimensional case. A simplified analytical model is introduced to determine the location of the solid–liquid interface during solidification by dividing the storage into two regions as shown in Fig. 2. In region 1, the only heat sink is the HTF and the fin does not influence the solidification process.

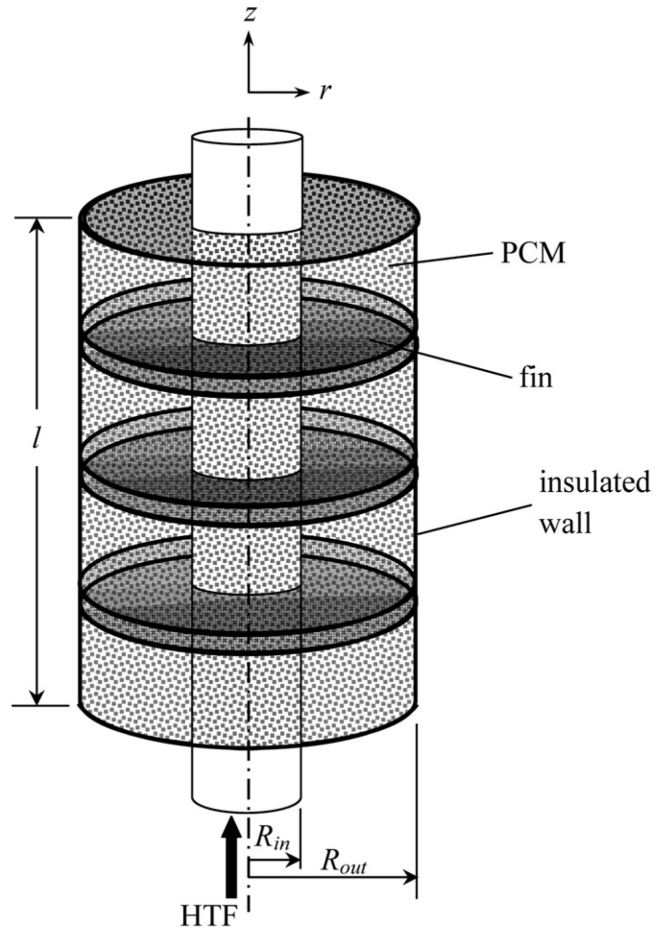

Fig. 1. Schematic of the thermal energy storage system.

Heat is transferred from the wall in r-direction. In region 2, heat is released by the fin. The main heat transfer mode during solidification is conduction. Although natural convection is significant, it has a negligible effect on the solid–liquid interface position compared to conduction [30,31].

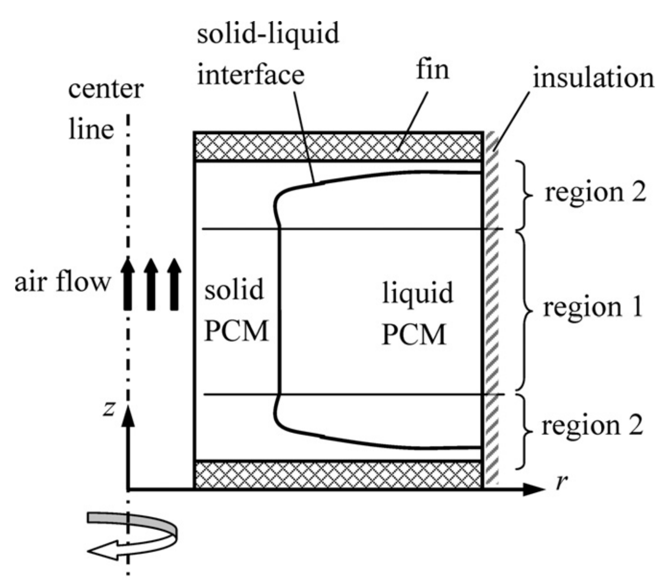

Fig. 2. Schematic of energy storage, showing division into two region and symmetry cell.