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Review

Phase change heat storage in an enclosure with vertical pipe in the center

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ABSTRACT

This paper documents the fundamentals of heat storage by melting a phase-change material inside a cylindrical enclosure with a vertical heated pipe on its axis. The phenomenon is studied analytically and numerically. The analysis consists of the scale analysis of the early stages of natural convection in the liquid, and an analysis of the entire duration of the melting process. The numerical simulations cover the entire process, and validate all the features predicted by theory.

Contents

1. Introduction

The fundamentals of heat transfer in phase change materials (PCM) have received considerable attention during the past two decades. This is due to the fact that the heat transfer applications of such materials are extremely broad: they range from thermal energy storage and manufacturing, to metallurgy and the cooling of electronics. For reviews on this body of work, see Refs. [1–9]. In recent years, we have seen a surge in interest in this domain because of environmental concerns combined with fossil fuel consumption and its consequences [10–23].

The focus of the present paper is on thermal energy storage, and more specifically on latent heat thermal storage. One reason is that air conditioning is responsible for a large fraction of the energy consumption in buildings, which is why latent heat thermal storage systems have been used as solution to mitigate the mismatch between energy demand and supply. For example, when the energy supply is provided by solar collectors, the technique consists of melting the PCM during day time, and releasing the stored energy (solidifying the PCM) during night time [24].

The main objective of this paper is to propose a theoretical analysis of the PCM melting process with natural convection in a cylindrical enclosure. The analysis is backed by full time, dependent numerical simulations. Special attention is dedicated to predicting the propagation of the phase-change front and the history and performance of the phase-change process.

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Nomenclature

A	cross section (m^2)
C	constant
c_P	heat capacity at constant pressure (kJ/kg K)
D	diameter of the tank (m)
d	diameter of the tube (m)
F	volume force (N)
g	gravity (m^2/s)
H	height of the tank (m)
h	height of the boundary layers (m)
h_S, h_F	specific enthalpy of solid, fluid (J/kg)
k	thermal conductivity (W/m K)
L_f	latent heat of fusion (J/kg)
m	mass (kg)
P	pressure (Pa)
Pr	Prandtl number
Q	heat transfer (J)
q''	heat flux (W/m^2)
Ra	Rayleigh number
r	radius (m)
T	temperature (K)
t	time (s)
U	internal energy (J)
V (V_r, V_θ, V_z)	velocity vector
z	axial coordinate (m)
z_L	thickness of the melting front (m)

Greek letters

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
δ	radial thickness of the melted domain (m)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ν	kinematic viscosity (m^2/s)
τ	temperature interval (K)

Subscripts

f	final
L	latent
s	sensible
w	wall
0	reference

Symbol

$\sim$	nondimensional

2. Scale analysis

The phase change material is placed in a vertical cylindrical enclosure of diameter D and height H. A heated pipe is placed on the axis of the enclosure, Fig. 1. The outer surface of the enclosure is adiabatic. The PCM is initially at a temperature T_0 lower than the temperature of the pipe.

Modeling the PCM in liquid state, assume that the flow of the liquid is incompressible. The flow and the heat transfer are governed by the laws of conservation of mass, momentum and energy throughout in the enclosure,

$$\nabla V = 0 \tag{1}$$

$$\rho \frac{DV}{Dt} = -\nabla P + \mu \nabla^2 V + F \tag{2}$$

$$\rho c_P \frac{DT}{Dt} = k \nabla^2 T \tag{3}$$

where V is the velocity vector of components (V_r, V_θ, V_z), and F is the body force in the vertical direction. We assume that the liquid PCM obeys the Boussinesq approximation, therefore $\rho = \rho_0 [1 - \beta(T - T_0)]$.

Immediately after the pipe temperature is set equal to T_w, the melt layer expands in the radial direction. Following the scale analysis developed in [1], from Eq. (3) we derive

$$\frac{\Delta T}{t} \sim \alpha \frac{\Delta T}{\delta^2} \tag{4}$$

and

$$t \sim \frac{\delta^2}{\alpha} \tag{5}$$

where δ is the radial thickness of the melted domain. Assuming that convection develops, the scale analysis of the complete energy conservation equations shows the balance between inertia, convection and conduction. As time passes, the inertia term decreases and the balance between convection and conduction yields

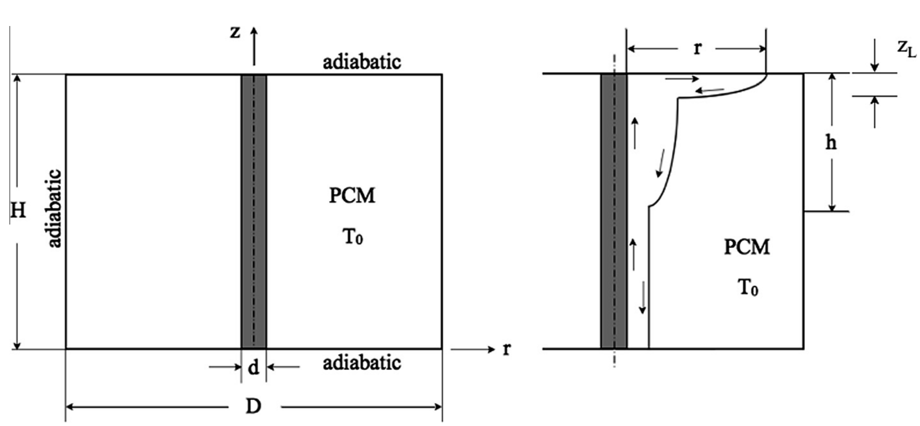

Fig. 1. Cylindrical enclosure filled with phase change material (PCM).