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Dynamic of plumes and scaling during the melting of a Phase Change Material heated from below

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ABSTRACT

We identify and describe the main dynamic regimes occurring during the melting of the PCM n-octadecane in horizontal layers of several sizes heated from below. This configuration allows to cover a wide range of effective Rayleigh numbers on the liquid PCM phase, up to $\sim 10^9$, without changing any external parameter control. We identify four different regimes as time evolves: (i) the conductive regime, (ii) linear regime, (iii) coarsening regime and (iv) turbulent regime. The first two regimes appear at all domain sizes. However the third and fourth regime require a minimum advance of the solid/liquid interface to develop, and we observe them only for large enough domains. The transition to turbulence takes places after a secondary instability that forces the coarsening of the thermal plumes. Each one of the melting regimes creates a distinct solid/liquid front that characterizes the internal state of the melting process. We observe that most of the magnitudes of the melting process are ruled by power laws, although not all of them. Thus the number of plumes, some regimes of the Rayleigh number as a function of time, the number of plumes after the primary and secondary instability, the thermal and kinetic boundary layers follow simple power laws. In particular, we find that the Nusselt number scales with the Rayleigh number as $Nu \sim Ra^{0.29}$ in the turbulent regime, consistent with theories and experiments on Rayleigh-Bénard convection that show an exponent 2/7.

1. Introduction

The high latent heat involved in the solid/liquid phase change allows Phase Change Materials (PCM) to store or release a significant amount of energy during melting or solidification barely changing the temperature. Many technological applications take advantage of this stability on external temperature variations and thermal storage capacity to use these materials in electronic cooling, air conditioning in buildings, waste heat recovery, to compensate the time offset between energy production and consumption in solar power plants, or combining with construction materials to increase the thermal energy storage capacity of with lighter structures [49,30,45,70].

The usage of PCM for latent heat storage is attracting much interest and promotion of regulatory authorities during the last years due to environmental issues and requirements of efficiency of renewable energy sources [51,59]. The melting temperature allows classifying the PCM in low temperature ($< 200\,^{\circ}C$) and high temperature ($> 200\,^{\circ}C$) categories [22]. Organic PCM such as paraffins are common among the low temperature category due to their stability in melting and freezing cycles, non-corrosive and suffering no under-cooling. An enormous amount of experimental, numerical and modeling work has been carried out to understand the heat transfer performance of these materials taking into account only conductive heat transport within the liquid phase of the PCM and including as well convective transport [8,32,58].

The operation cycle of PCM consists of two phases: (i) a charging phase when the PCM melts, releasing the latent heat of the solid to liquid transition and developing a solid/liquid front that moves from hotter to colder regions, (ii) a discharging phase when the PCM solidifies creating a front moving in the opposite direction. We will focus on this work in the melting phase of the cycle. When only conductive transport is involved, the symmetry of the system dictates the form of these fronts. However, when convective transport appears the coupling between hydrodynamics, temperature field, phase change and propagation of the interface results in corrugated fronts. The shape of the fronts is more readily

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Nomenclature

PCM	Phase Change Material
Ra	Rayleigh number
Pr	Prandtl number
ρ	density
g	magnitude of gravity acceleration
$\mathbf{e_y}$	unit vector pointing in the vertical direction upwards
α	thermal expansion coefficient
$\mathbf{u} = (u_x, u_y)$	fluid velocity
δ	tiny constant
Δh	latent heat
T_h	temperature at the bottom wall
T_i	initial temperature at the solid state
h	averaged height of the melted PCM
δ_u	thickness of the kinetic boundary layer
δ_T	thickness of the thermal boundary layer
C_s (C_l)	specific heats in the solid (liquid) phase
λ_s (λ_l)	conductivity in the solid (liquid) phase
Nu	Nusselt number
T	temperature
μ	dynamic viscosity
p	pressure
T_{ref}	reference temperature
f_l	volume liquid fraction
C	Darcy coefficient
H	enthalpy
L	domain size
T_m	mean temperature
Ste	Stefan number
t	time

available on experiments than velocity and temperature fields in the liquid phase of the PCM. Hence this shape can provide information on the melting state of a PCM if a relation with the front shape can be established. We will show in this work how melting regimes have distinct front shapes.

After the selection of the PCM material, the geometry of the PCM container is the most influential factor in the heat transport performance of PCM systems. Many of the studies have been concerned with the heat transfer in cylinders, cylinder shells, rectangular cavities heated from the side [20,23,39,6,34,58,29] or even irregular non-symmetric geometries [52,16,42]. However, the configuration of a PCM within a rectangular container heated from below has received comparably less attention. From a practical point of view, this configuration is important to dissipate heat from electronic devices. From a theoretical point of view, it offers the opportunity to understand the effect of the phase change on convection when comparing with well established results of the classic Rayleigh-Bénard problem on convective features, heat transport, stability and scaling [33,5]. This problem of a PCM contained within rectangular cavities and heated from below has been studied in simulations with paraffins, ice slurries or cyclohexane, etc. [25,35,67,4], and experiments with cyclohexane, n-octadecane or magma, among others [28,17,15].

We focus on this work at studying the dynamic of melting of the paraffin n-octadecane, which belongs to the low temperature group of PCM. The n-octadecane is contained in squares with periodic boundary conditions in the horizontal direction of different sizes and heated from below. This configuration makes possible to explore a broad range of effective Rayleigh numbers, taking as characteristic length the gap of the melted PCM, without changing any external parameter. For the largest domains, we reach Rayleigh numbers $\sim 10^9$. At this high numbers, the convective features depend very meaningfully on the existence of persistent thermal plumes [38]. We study in this work how they emerge and evolve during the charging phase.

The Rayleigh-Bénard problem of a liquid layer heated from below is characterized by three physical magnitudes: the difference of temperature between the plates, the heat flux, and the type of fluid. These provide three dimensionless numbers: Rayleigh Ra, Nusselt Nu and Prandtl Pr; respectively, which characterize the solutions of this problem. At the regime of high numbers, the relation between Rayleigh and Nusselt numbers $Nu \equiv Nu(Ra, Pr)$ has been thoroughly studied and found that mostly matches a power law $Nu \sim Ra^{\alpha}$ [3]. The exponent α generally is within a range between 1/4 and 1/3 and the numerical results show a dependence of the exponent with Ra [56,26,27,55] as well as experiments [7,9,47,10].

A theory by Malkus [44], based on arguments of marginal stability of the thermal boundary layer, predicts $Nu \sim Ra^{1/3}$ and a large number of experiments agree with this scaling [12]. However, when heat transfer and turbulence decouple from the thermal and viscosity transport coefficients there is as well a theoretical prediction for an asymptotic regime following $Nu \sim Pr^{1/2} Ra^{1/2}$ [36,54]. Interestingly, the limit of infinite Prandtl number predicts as well $Nu \sim Ra^{1/3}$ for the regime of asymptotically high Rayleigh numbers [26,19]. Nevertheless, it must be noticed that not all the experimental studies have agreed with the theoretical scalings. Thus, models based on a mixing layer [7], turbulent boundary layer [53] and extensions to low Prandtl fluids [14] predict an exponent 2/7.

We aim in this work at studying the convective motion in the presence of a solid/liquid phase change. The presence of a phase change complicates the problem by introducing the Stefan number related to the latent heat source. In spite of that, we find that the averaged value of the numeric exponent 0.29 is consistent with a group of experiment results [7,11,14,24,18] on moderately high Rayleigh numbers $Ra < 10^{10}$, and theoretical models predicting 2/7.

The article is organized as follows. Section 2 describes the governing equations of the mathematical model we use to simulate the behavior of a PCM in the presence of conductive and convective transport. The numeric procedure and code to solve the previous equations are explained in Section 3. We present in Section 4 the results of our simulations, where we explain the observed melting regimes, transitions between them and establish relations between dynamic quantities characteristics of the melting process. Finally, we discuss in Section 5 our most important findings and provide a brief outline of our work.

2. Model of Phase Change Materials

We consider a PCM whose solid phase is modeled with a heat equation to account for conductive transport of the heat, and the liquid phase is modeled with the Navier-Stokes equations for momentum coupled to the energy equation to include in this phase the heat transport by convection. The Navier-Stokes equations are modified with a Darcy term to model a diffuse interface between the solid and liquid phases, and the energy equation includes a source term to account for the release of latent heat during melting. A comprehensive derivation and explanation of the model