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Melting of a phase change material in a rectangular cavity in the presence of metallic fins

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Abstract. The melting of the phase change material (PCM) octadecane, confined in a rectangular cavity heated from the bottom, is numerically studied. Simulations are performed through finite element software in order to analyze the impact of metal fins within the enclosure on the melting time. The results are analyzed in terms of the time-dependent position of the melting front, time-dependent average liquid fraction, and time needed for the PCM melting. The obtained outcomes highlight how, with a low number of metallic fins, the initial melting regime dominated by conduction at a certain time gives way to a convective melting regime characterized by Rayleigh–Bénard cells, in full agreement with the results of the theoretical analysis. On the contrary, with a high number of metallic fins, conduction is the only mechanism that governs heat transfer and the rapid melting slows down when the phase change front reaches the top of the fins. More specifically, the addition of the fins within the cavity yields a reduction in the time needed for the complete PCM melting up to 90% in the analyzed cases. The reported results provide new insights regarding the heat transfer mechanisms involved in PCMs melting within bottom-heated enclosures.

1. Introduction

In the last years, Phase Change Materials (PCMs) have been widely used as heat storage materials thanks to their capacity to exploit the latent heat of fusion to store and release huge amounts of thermal energy. On the other hand, one of the main drawbacks of these materials is their characteristic low value of thermal conductivity, which increases the thermal resistance and slows down the melting/solidification processes [1]. In order to overcome this issue, several techniques have been adopted, such as enhancing convective heat transfer [2] or adding high-conductivity inserts such as metal foams [3] or metal fins [4]. For instance, Kamkari et al. [5] experimentally studied a pure PCM (lauric acid) melting in a rectangular enclosure at various inclination angles, showing that the horizontal inclination yields the formation of natural convection cells that enhance the heat transfer rate and reduce the melting time. Kamkari and Amlashi [6] enriched the analysis by means of numerical simulations to further study the impact of natural convection on the lauric acid melting in inclined rectangular enclosures and developed correlations to predict the instantaneous melt fraction. Recently, Kamkari and Groulx [7] experimentally investigated the improvement in the melting rate of lauric acid due to the addition of fins in rectangular enclosures under different inclination angles, proving that the 3-fin horizontal enclosure exhibits the minimum melting time. In addition, Groulx et al. [8] numerically studied the melting of the PCM RT25 inside a rectangular enclosure, finned and inclined, for temperature control of a finned PV panel. Their results showed that the most efficient configuration is obtained with a full-width fin simultaneously attached to the front and back plates, since the PCM melting is dominated by natural convection from both sides of the enclosure.

To the authors' knowledge, the heat transfer mechanisms involved in a PCM melting as functions of the fin number have not been investigated thoroughly so far. The present study aims at contributing in this regard by analyzing the melting of a PCM, placed in a rectangular cavity and heated from the bottom, both with and without metal fins. The results of a theoretical analysis are compared to the numerical outcomes in order to highlight the main scales of the problem and the impact of the fin presence on the melting processes (conduction vs convection), the evolution of the melting front, and the time needed for the phase change process.

2. Numerical model

A rectangular cavity of length 0.10 m and height 0.02 m is considered, filled with the PCM octadecane (phase change temperature range 29.85-30.85 °C, latent heat of fusion L = 125 kJ/kg, thermal conductivity k = 0.2 W/(m K), density ρ = 800 kg/m^3, specific heat capacity c_p = 1.25 kJ/(kg K), dynamic viscosity μ = 0.008 Pa s, thermal expansion coefficient β = 0.002 K-1 [9]). The enclosure either includes only the PCM or contains also 3 or 17 aluminum fins, each 0.018 m high and 0.001 m wide, inserted from the cavity bottom and equally spaced. The main aluminum properties are: thermal conductivity 237 W/(m K), density 2700 kg/m^3, specific heat capacity 897 J/(kg K). Figure 1a shows the case with 3 fins. It is worth noting that the two lateral fins are half as thick as the others, in order to limit the edge effects. The initial temperature of the entire domain is set equal to the lower limit of the phase change temperature range, i.e., T_m = 29.85 °C. The bottom wall is heated at the constant temperature T_b = 37 °C, whilst the other walls are kept adiabatic. Both PCM and aluminum fins have isotropic properties; the PCM in the liquid phase is incompressible and the flow is laminar, in accordance with the Boussinesq approximation. The governing equations (mass, momentum, and energy conservation) are solved by means of the finite element software Comsol Multiphysics, employing the apparent heat capacity formulation to simulate the phase change [10]. The selected mesh is unstructured, with about 11300, 13000, and 29100 triangular elements in the cases with 0, 3, and 17 fins, respectively. Mesh independence tests and model validation against results from the literature [11] have been performed.

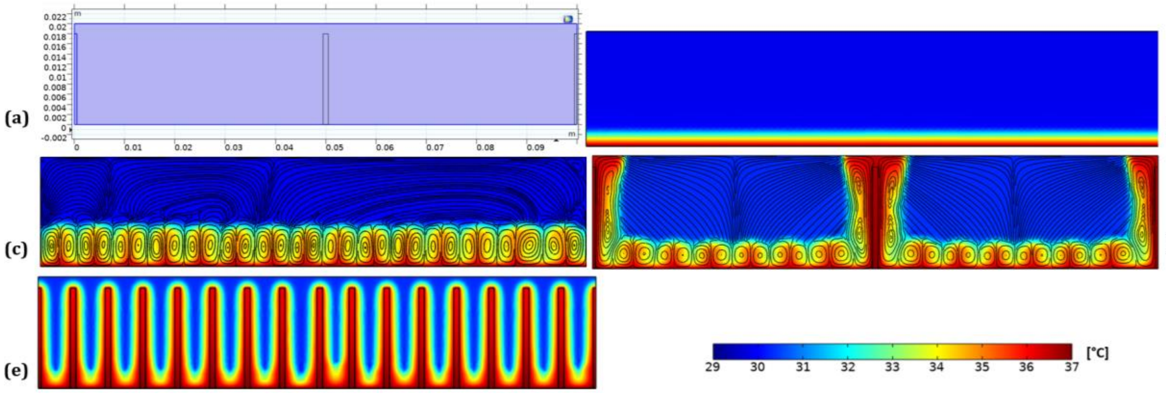

Figure 1. Rectangular enclosure with 3 fins (a); temperature distribution and streamlines: 0 fins and t = 350 s (b); 0 fins and t = 1500 s (c); 3 fins and t = 900 s (d); 17 fins and t = 200 s (e).

3. Results

When no fins are present, the PCM is initially melted by conduction, and the temperature distribution within the enclosure exhibits a one-dimensional profile, linearly decreasing with the cavity height (see figure 1b). When convection becomes more effective in transferring heat upwards, Rayleigh–Bénard convection cells originate from the enclosure bottom (see figure 1c). Figure 2a shows the time-dependent trend of the melting front δ, evaluated at the enclosure center detecting the height at which the local liquid fraction equals 0.5 (middle of the melting range). In agreement with the analysis aimed at discovering the main scales of the problem [12], at the beginning (conduction regime) the melt layer thickness is proportional to the square root of time t (equation (1)), and then becomes linear in time in the convection regime (equation (2)):

$$\delta \sim \left[\frac{k\left(T_b - T_m\right)}{\rho L}\right]^{1/2} t^{1/2} \tag{1}$$

$$\delta \sim \frac{k\left(T_b - T_m\right)}{10\rho L}\left[\frac{g\beta\left(T_b - T_m\right)}{v\alpha}\right]^{1/3} t \tag{2}$$

where g is the gravitational acceleration, v is the PCM kinematic viscosity and α is the PCM thermal diffusivity. For the PCM properties and bottom wall temperature here considered, the transition from the conductive to the convective heat transfer predicted by the scale analysis, obtained matching equations (1) and (2), occurs at about 410 s, in accordance with the profile of figure 2a.

If fins are included within the cavity, but the number of fins is low, the one-dimensional vertical melting of the case without fins (conduction regime followed by Rayleigh–Bénard rolls) combines with the melting along the fins, where vertical convective cells develop, with a larger width at the fins top. In particular, as time goes by, the Rayleigh–Bénard cells that originated from the enclosure bottom become bigger, and the rolls positioned next to the fins merge with the convective cells along the fins (see figure 1d, referred to the case with 3 fins). Then also the adjacent Rayleigh–Bénard cells merge one after the other, becoming less numerous while the melting front spreads vertically from the enclosure bottom. At the same time, the melted layer propagates horizontally from the fins top, speeding up the phase change.

In contrast, if the number of fins is high, the PCM is melted entirely by conduction, since heat is transferred along the fins so fast that neither Rayleigh–Bénard cells along the cavity bottom nor convective cells along the fins have enough time to form (see figure 1e: case with 17 fins). In figure 2b, the average liquid fraction θ is plotted as a function of time for different fin numbers, showing the heat transfer enhancement yielded by the fins. In particular, going from 0 to 3 to 17 fins, the time needed to complete the PCM melting (θ equal to 1) decreases by 28 % and 90 %, respectively (from about 4770 s to 3430 s and 460 s). It should be noted that, due to the presence of the fins, the corresponding PCM volume within the enclosure decreases by 1.8 % and 14.4 %, respectively. In addition, with 17 fins the time-dependent trend of θ exhibits a final slope decrease (see the dotted curve in figure 2b). Indeed, when the melting front reaches the top of the fins, the PCM in the thin volume between the fins top and the enclosure top needs more time to melt.

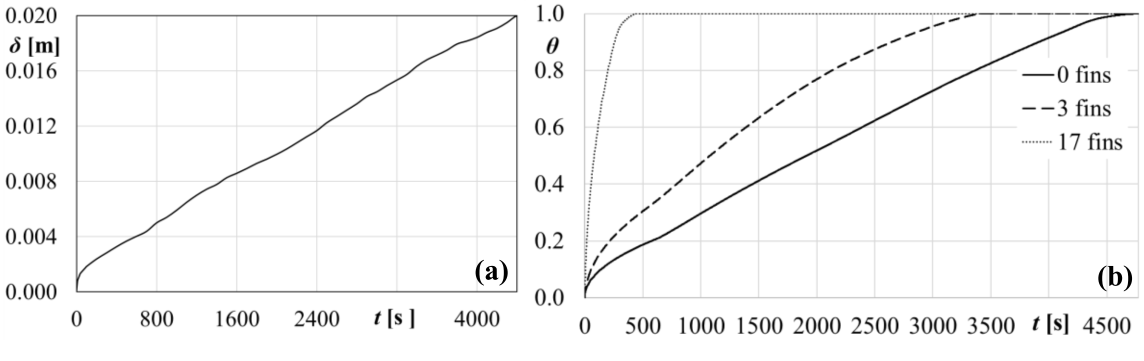

Figure 2. Melting front height as a function of time, 0 fins (a); average liquid fraction versus time with different fin numbers (b).

4. Conclusions

The melting of the PCM octadecane, placed in a bottom-heated enclosure, is numerically studied. The main outcomes obtained can be summarized as follows:

- Without fins, the phase change starts due to conduction, with the melted layer growing with the square root of time; then convection becomes more effective in transferring heat, and the melting front spreads linearly with time as Rayleigh–Bénard rolls develop.
- Adding metallic fins within the cavity speeds up the melting process. If the fin number is low, vertical convective cells form along the fins, and the phase change front propagates both vertically from the enclosure bottom and horizontally from the fin top.
- With a high number of fins, conduction is the only mechanism governing heat transfer and the rapid melting slows down when the phase change front reaches the top of the fins.
- Going from 0 to 17 fins means a 90 % reduction in the melting time.

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