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1 DESIGN OF FIN STRUCTURES FOR PHASE CHANGE MATERIAL (PCM) MELTING

2 PROCESS IN RECTANGULAR CAVITIES

3

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- 8

9 Abstract

10 The objective of this work is to analyze the lauric acid PCM melting process in a finned rectangular cavity, keeping both the PCM mass and the total fin area constant, thus changing only the fin aspect 11 ratio. The analysis was conducted through a parametric study of 78 different fin configurations. In 12 order to maintain the thermal capacity, the cavity and fin areas were kept constant while fin 13 dimensions were varied within a preset number of combinations of area fraction and width. The fins 14 tested were combinations of 9 fin aspect ratios (RA_f) and 9 fin-to-cavity area fractions (ϕ). A finite-15 volume numerical CFD method was used to obtain the results. Governing equations were the 16 conservation of mass, momentum and energy while phase change was governed by an enthalpy-17 porosity model. The mathematical model was validated against reference experimental results and 18 computational meshes were checked with GCI. For all tested cases, with an increase in the fin length 19 and a consequent reduction in RA_{f} , there was a reduction of the total time of the melting process. The 20 RA_{f} , which had shorter melting times, were defined as optimal aspect ratios (RA_{opt}). Thus, each ϕ 21 tested resulted in its own RA_{opt} . For $\phi = 0.005, 0.01, 0.02, 0.03, 0.04, 0.05, 0.1, 0.2$ and 0.3, $RA_{opt} =$ 22 0.013, 0.026, 0.052, 0.078, 0.104, 0.130, 0.260, 0.592 and 0.889, respectively. Future works could 23 contemplate a greater number of fins, with the same total area of this study, other PCM and other 24 25 temperature differences, for example.

26

27 Keywords: Phase Change Material (PCM). Melting process. Numerical simulation. Fin aspect

28 ratio, area fraction.

29 Nomenclature

30	A_c	cavity area, $A_c = H W$	[m ²]
31	A_f	fin area, $A_f = H_f / W_f$	[m ²]
32	С	porous zone constant	[kg m ⁻³ s ⁻¹]
33	C_p	specific heat	[J kg ⁻¹ K ⁻¹]
34	Fo	Fourier number, $Fo = \alpha t / L_c^2$	[-]
35	\vec{g}	gravity	[m s ⁻²]
36	Н	cavity height	[mm]
37	h	heat transfer coefficient	[W m ⁻² K]

38	k	thermal conductivity	$[W m^{-1} K^{-1}]$
39	L	latent heat	[J kg ⁻¹]
40	L_c	characteristic length, $(L_c = A_c^{1/2})$	[mm]
41	Nu	Nusselt number, $Nu = h L_c / k$	[-]
42	р	pressure	[Pa]
43	<i>q</i> "	heat flux	[W m ⁻²]
44	RA	aspect ratio, $AR = H / W$	[-]
45	Ŝ	momentum equation source term	[Pa m ⁻¹]
46	Т	temperature	[K]
47	t	time	[s]
48	$ec{V}$	velocity vector	[m s ⁻¹]
49	W	cavity width	[mm]
50	W_{f}	fin width	[mm]
51			
52	Greek symb	pols	
53	β	liquid fraction	[-]
54	ε	computational constant	[0,001]
55	λ	specific enthalpy	[J kg ⁻¹]
56	μ	dynamic viscosity	[kg m ⁻¹ s ⁻¹]
57	ρ	density	[kg m ⁻³]
58	ϕ	area fraction, $\phi = A_f / A_c$	[-]
59			
60	Subscripts		
61	С	cavity	
62	f	fin	
63	i	initial	
64	L	phase change	
65	l	liquid	
66	т	melting	
67	opt	optimal	
68	ref	reference	

69	S	solid
70	se	sensible
71	W	wall

72 **1. INTRODUCTION**

The increase in energy demand, air pollution, energy prices, partial unavailability of fossil 73 fuels and environmental concerns are driving causes of studies on alternative methods of energy 74 production (Reddy, Mudgal, and Mallick 2018). As an extension, the development and application of 75 76 energy storage techniques has become a crucial part of this area. Among the different forms of energy 77 storage, thermal storage through sensible, latent or thermochemical heat (Zhang et al. 2016) has 78 become one of the most used in several applications (Hasnain 1998; Dabiri, Mehrpooya and Nezhad 79 2018; Zhu, Ma, and Wang 2009). The latent heat technique has become more attractive due to its high energy storage capacity and the ability to provide heat at a constant temperature equal to the 80 material transition temperature. The materials used in latent heat energy storage are called Phase 81 82 Change Materials (PCM) (Ibrahim et al. 2017). These are classified according to their chemical composition into organic (paraffin and non-paraffin), inorganic (salt and metal hydrates), and eutectic 83 84 (metal alloys) (Jamil et al., 2019, Ibrahim et al., 2017). As for the phase change temperature classification, three groups are universally accepted: low, medium, and high temperature, Ehms et 85 86 al., 2019. According to Pielichowska et al., (2014), PCM is considered low temperature when the 87 phase change occurs at up to 15 °C, medium temperature when the phase change should occur between 15 °C and 90 °C, and high temperature when the phase change occurs above 90 °C. 88

The selection of a PCM depends on its thermal properties, applications, stability and cost 89 90 (Aslfattahi et al., 2020). Their application can occur in many areas such as biomedicine, textile, automotive (Jaguemont et al., 2018) and construction (Pielichowska and Pielichowski 2014, 91 92 Souayfane et al. 2016), solar power plants (Zhang et al. 2016, Khan et al. 2017) and electronic components (Baby e Balaji 2012, Kalbasi and Salimpour, 2015). In buildings, PCM can be used for 93 cooling in passive or active systems (Souayfane et al. 2016). For example, one way of using PCM in 94 buildings is through the inclusion of micro-encapsuleted PCM in the materials used in construction 95 96 (Kalnaes et al., 2015). Another interesting application of PCM is in the temperature control of electric 97 car batteries. In this case, according to Jaguemont et al. (2018), PCM should have a melting point 98 between 45 °C and 50 °C to obtain greater efficiency. Solar absorption refrigeration systems can also 99 use PCM adapted to the working temperature, mass rate and loading and unloading time (Khan et al. 100 2017). Another interesting application refers to the use of PCM as thermal protection for food

products sensitive to thermal variations (Leducq et al. 2015). In terms of cooling electronic components, Baby e Balaji (2012) studied experimentally the application of PCM with different types of fins and at different power levels. It was found that, by including PCM in the finned cavity, the electronic device showed a significant improvement in operating time.

PCMs have several advantages: small volumetric variation during phase change processes, 105 high specific heat and latent melting heat (Baby and Balaji 2012) as well as thermal stability 106 107 (Jaguemont et al. 2018). On the other hand, these materials have characteristic low thermal conductivities which result in low charge and discharge rates (Akeiber et al. 2016; Pizzolato et al. 108 2017). Therefore, it is necessary to incorporate additional techniques to improve heat transfer between 109 the cavity and PCM. Among these techniques there are: multiple PCM usage (Ibrahim et al. 2017), 110 high thermal conductivity particle dispersion in the PCM (Wu et al. 2020), microencapsulation (Sun 111 et al. 2019) and fins. According to Kean et al. (2018), the inclusion of nanoparticles can reduce the 112 time of the melting or solidification processes. But, if nanoparticle concentration is in excess, a 113 negative effect may occur due to the agglomeration of material. In terms of thermal and enthalpic 114 115 stability with nanoparticle PCM, Aslfattahi et al. (2019) found an increase in thermal stability as well as a decrease in melting point, compared to pure material. 116

117 Baby and Balaji (2012) studied experimentally the application of PCM to cool electronic components. Different types of fins were investigated at different power levels. It was found that, by 118 119 including PCM in the finned cavity, the electronic device showed a significant improvement in 120 operating time. In general, fins result in an increase in active area and promote natural convection and associated thermal processes such as phase change. Consequently, the natural convection process is 121 a defining parameter in the efficiency of finned systems. Fin geometry and positioning are also 122 123 important to the phase change process (Kazemi et al. 2018; Pu et al. 2020; Abdulateef et al. 2017). In tubular systems, longitudinal fins placed at the bottom of the cavity allowed the formation of 124 recirculation zones which decreased PCM melting time (Kazemi et al. 2018). In comparison, tubular 125 systems with radial fins were also studied with variations in height and number of fins while keeping 126 the volume fraction and thickness constant (Pu et al. 2020). In this case it was determined that 127 configurations with longer fins decreased natural convection, reduced fin interactions and increased 128 129 melting time but an intermediate length was deemed the most adequate. Triple tube cavities were studied with different configurations of rectangular and triangular fins (Abdulateef et al. 2017). 130 131 Results showed that placement of the fins affected substantially natural convection and could reduce total melting times. 132

Several different fin geometric characteristics can be varied to evaluate their effect in PCM 133 melting. In the case of varying fin thickness in rectangular cavities, an optimum ratio of fin thickness 134 to combined fin + PCM volume which increased heat transfer rate through the fin but did not reduce 135 considerably heat transferred from the wall to the PCM was determined (Mostafavi, Parhizi, and Jain 136 2019). Fin thickness was also found to be directly proportional to heat transfer through it and inversely 137 proportional to temperature at its base, which improved cooling in the system (Arshad et al. 2020). 138 139 Fins of different geometries were also examined in the melting process of paraffin PCM with or without nanoparticles (Kok 2020). In this case, fin geometries that probed into regions of un-melted 140 PCM resulted in more satisfactory results than conventional fins despite having less heat transfer 141 surface area. Melting lauric acid PCM was studied in rectangular cavities with 3 fins of different 142 143 widths and placement (Joshi and Rathod 2019). It was determined that reducing the width of upper fins did not affect melting time but increased thermal storage capacity. Melting RT42 PCM was 144 145 studied numerically in rectangular cavities with two fins with varying lengths placed at different heights while maintaining a constant total length (Ji et. al., 2018). It was proven that placement of 146 147 shorter fins higher and longer fins lower reduced total melting time when compared to two fins of equal length. However, there was a limit to the length of the shorter fin, below which there were no 148 149 changes to melting time. Of these, fins are the most attractive due to ease of construction and low 150 manufacturing cost (Agyenim et al. 2010).

There are several studies in the literature on PCM melting/solidification in finned cavities. However, studies of this type that maintain constant total fin area and PCM mass have not been found in the literature. Thus, the objective of this study is to analyze the PCM melting process in a finned rectangular cavity keeping both the PCM mass and the total fin area constant, thus changing only the fin aspect ratio. With this, it becomes possible to determine the optimal aspect ratio to minimize the total melting time for different fractions of the area between fin and cavity.

157

158 2.1 Physical Domain

The studied physical domain, depicted in Fig. 1, consisted of a two-dimensional rectangular cavity with a width (W) of 50 mm and height (H) of 120 mm filled with lauric acid PCM initially in a solid-state. A "negative fin", i.e. a morphing lateral intrusion, was positioned horizontally at the center of the right wall with specified width (W_f) and height (H_f). A 2 mm opening was located in the upper wall near the right side to simulate the loss of PCM from the cavity during the melting process. While classical fin problems with a fixed temperature at its base do result in variations of temperature

along the length of the fin, the physical scale of the problem results in essentially a constant-165 temperature fin. This was observed in the experimental study of Kamkari and Shokouhmand 2014; 166 and used to validate the numerical results of Joshi and Rathod 2019. So, it also was incorporated as a 167 boundary condition in this work. The upper, lower, left side, front and rear walls were considered 168 thermally insulated. This condition guaranteed null heat flow through these walls. Furthermore, with 169 this condition, there was no temperature difference between the front and rear walls. Consequently, 170 no considerable flow or circulation was expected to develop along this direction and the physical 171 problem can be considered two-dimensional. 172

173





Figure 1 - 2D cavity domain with a morphing lateral intrusion shaped as a fin.

The constraints of the parametric study were the cavity area ($A_c = HW$) and the fin area 177 $(A_f = H_f W_f)$. Area A_c was kept constant and equal to 6,000 mm² while A_f was obtained from the area 178 fraction $(\phi = A_f/A_c)$. Nine values of ϕ (0.005, 0.01, 0.02, 0.03, 0.04, 0.05, 0.1, 0.2 and 0.3) as well 179 as nine values of W_f (10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm and 48 mm) 180 were selected. Through combinations of A_c , ϕ , and W_f , values of A_f and H_f were obtained and it was 181 possible to calculate the fin aspect ratio $(RA_f = H_f/W_f)$. The selected values of ϕ and W_f resulted, 182 ideally, in 81 geometric configurations. Of these, 3 of them could not be simulated as they exceeded 183 the cavity dimensions and were discarded. Table 1 shows the dimensions of the remaining 78 fins. 184

						W_f [mm]			
		10	15	20	25	30	35	40	45	48
$\phi = 0.005$		3.00	2.00	1.50	1.20	1.00	0.86	0.75	0.67	0.63
$\phi = 0.01$		6.00	4.00	3.00	2.40	2.00	1.71	1.50	1.33	1.25
$\phi = 0.02$		12.00	8.00	6.00	4.80	4.00	3.43	3.00	2.66	2.50
$\phi = 0.03$	H_f [mm]	18.00	12.00	9.00	7.20	6.00	5.14	4.50	4.00	3.75
$\phi = 0.04$		24.00	16.00	12.00	9.60	8.00	6.86	6.00	5.33	5.00
$\phi = 0.05$		30.00	20.00	15.00	12.00	10.00	8.57	7.50	6.66	6.25
$\phi = 0.10$		60.00	40.00	30.00	24.00	20.00	17.14	15.00	13.33	12.50
$\phi = 0.20$			80.00	60.00	48.00	40.00	34.29	30.00	26.66	25.00
<i>φ</i> = 0.30				90.00	72.00	60.00	51.43	45.00	40.00	37.50

187 The properties of lauric acid are shown in Tab. 2, Tab. 3 and Tab. 4. Table 2 presents the 188 values of specific heat (c_p) , density (ρ) , temperature (T), and latent heat (L).

189 Table 2 - Properties of lauric acid (Adapted of Kamkari and Shokouhmand 2014).

Specific heat capacity solid/liquid [J/(kg K)]	2,180/2,390
Density solid/liquid [kg/m ³]	940/885
Melting temperature range [K]	316.65/321.35
Latent heat [J/kg]	187,210

190

Thermal conductivity (k) and dynamic viscosity (μ) of lauric acid as a function of temperature 191 were obtained by linear interpolation and are presented in Tab. 3 and 4, respectively. It is worth 192 mentioning that regarding the nonmetallic PCMs, heat conduction mainly relies on the vibration of 193 194 the crystal lattice, as addressed by Wu et al. (2020). The lattice component of thermal conductivity strongly depends on the way the molecules are arranged. More specifically, the temperature increase 195 leads to a weakening of the atomic bonds, which in turn causes heat transfer inhibition. Thus, the 196 mechanism mentioned above justifies the feeble reduction of thermal conductivity with the 197 198 augmentation of temperature illustrated in Tab. 3.

- 199
- 200

201

<i>T</i> [K]	293	303	313	323	328	333	338	343
<i>k</i> [W/(m K)]	0.161	0.159	0.158	0.145	0.143	0.142	0.139	0.138

Table 4 - Dynamic viscosity of lauric acid (Valeri and Meirelles 1997).

<i>T</i> [K]	321.2	322	333	344	355	372	383
μ [kg/(m s)]	0.00760	0.00747	0.00542	0.00428	0.00338	0.00250	0.00210

204 2.2 Mathematical Model

The mathematical model used to represent the melting process consisted of the equations of conservation of mass, momentum and energy shown in Eq. (1-3), respectively:

$$207 \qquad \frac{\partial \rho}{\partial t} + \nabla \left(\rho \vec{V} \right) = 0 \tag{1}$$

$$208 \quad \frac{\partial}{\partial t} (\rho \vec{V}) + \nabla (\rho \vec{V} \vec{V}) = \nabla (\mu \nabla \vec{V}) - \nabla p + \rho \vec{g} + \vec{S}$$
⁽²⁾

209
$$\frac{\partial}{\partial t}(\rho\lambda) + \nabla(\rho\vec{V}\lambda) = \nabla(k\nabla T)$$
 (3)

where \vec{V} represents the velocity vector, *t* is the time, *p* is the pressure, \vec{g} is the acceleration of gravity, \vec{S} is the source term, and λ is the total enthalpy. The total enthalpy is obtained by adding the change in enthalpy associated with phase change (λ_L) and sensible enthalpy (λ_{se}), obtained through Eq. (4):

213
$$\lambda_{se} = \lambda_{ref} + \int_{T_{ref}}^{T} c_p dT$$
(4)

where λ_{ref} is the enthalpy at the reference temperature ($T_{ref} = 298$ K). The enthalpy in phase change is calculated as $\lambda_L = \beta L$.

For the PCM melting process, an enthalpy porosity model (Voller and Prakash 1987) was used. The model treated the solid-liquid interface zone (mushy zone) as a porous zone with the source term obtained from Eq. (5):

219
$$\vec{S} = \frac{(1-\beta)^2}{(\beta^3+\varepsilon)} C \vec{V}$$
(5)

where β is the liquid fraction, ε is a constant with value of 0.001 used to prevent division by zero and C is the porous zone constant. This constant depends on the morphology of the porous zone (Voller and Prakash 1987). The net fraction of PCM within the phase change range is calculated from Eq.(6):

224
$$\beta = \begin{cases} 0 & se \quad T < T_s \\ 1 & se \quad T > T_l \\ T - T_s / T_l - T_s & se \quad T_s < T < T_l \end{cases}$$
(6)

The boundary conditions adopted were of adiabatic left, lower and upper walls of the domain, shown in Eq. (7-9), respectively:

227
$$-k\frac{\partial T}{\partial x}\Big|_{\substack{x=0\\y=0-H}} = 0$$
(7)

228
$$-k\frac{\partial T}{\partial y}\Big|_{\substack{x=0-W\\y=0}} = 0$$
(8)

229
$$-k\frac{\partial T}{\partial y}\Big|_{\substack{x=W-opening\\y=0}} = 0$$
(9)

while a prescribed temperature condition was applied on the right vertical wall, all fin surfaces andthe opening, as shown in Eq. (10, 11), respectively:

232
$$T|_{\substack{x=W\\y=0-H}} = T_W$$
 (10)

233
$$T|_{\substack{x=opening\\y=H}} = T_a$$
(11)

234 **3 Numerical Model**

Numerical simulations were performed on ANSYS FLUENT[®] and the computational meshes 235 were created on ANSYS ICEM[®] version 18.2. In the reference experimental work of Kamkari and 236 Shokouhmand (2014), the liquid PCM was removed manually. In the present numerical work, this 237 PCM removal was modeled through the "pressure-outlet" boundary condition imposed on the 238 opening, with gauge pressure of 0 Pa and temperature of 343 K. For the pressure correction and 239 pressure-velocity coupling, the "presto" and "simple" criteria were adopted, respectively. The flow 240 241 was considered laminar transient with a time step of 0.1 s. In the energy and momentum equations, a "*first-order upwind*" scheme was used. Absolute convergence criteria of 10^{-8} for the energy equation 242 and 10⁻⁵ for the velocity and continuity equations were adopted. Relaxation coefficients used were: 243

0.15 for pressure and momentum, 0.3 for density, field forces and energy and 0.2 for the liquid 244 fraction. Intermediate values of $k \in \mu$ were obtained by linear interpolation of the data of Tab. 3 and 245 Tab. 4. The value of ρ_s was considered constant as of Tab. 2; however, values of ρ_l were pre-set from 246 reference (Chuah et al. 2006) according to temperature: 885 kg/m³ at 321.35 K (Tab. 1), 870 kg/m³ 247 at 323 K and 862 kg/m³ at 333 K. The lower, upper, and left walls of the cavity were defined as 248 adiabatic. The right wall and the fin surfaces were kept at the heating temperature $T_w = 343$ K. The 249 no-slip condition was applied in all walls and the fin surfaces, except for the opening, which was 250 considered free flow at $T_a = 343$ K. In addition, the PCM was subjected to an initial temperature of T_i 251 =298 K. 252

253

254 3.1 Model Validation and Mesh Test Sensitivity

255 3.1.1 Model Validation

Numerical validation was performed with comparisons to reference experimental data 256 (Kamkari and Shokouhmand 2014) in two ways: through liquid fraction field and with the liquid 257 258 fraction profile over time. The reference study consisted of the melting process of lauric acid PCM in 259 a similar physical domain. The experimental rectangular cavity measured 50 mm in width, 120 mm in height and 120 mm in thickness, with a fin 25 mm in width and 4 mm in height. The fin and the 260 261 right wall were subjected to a constant temperature of 343 K while the remaining walls were thermally insulated. The PCM was initially at a temperature of 298 K, i.e., solid-state (Kamkari and 262 263 Shokouhmand 2014).

Figure 2 shows a comparison of liquid fraction fields (β) from the reference experimental study (Kamkari and Shokouhmand 2014) and the present numerical study at 10 min, 30 min and 50 min of the melting process. Figures 2(a, c, e) contain the experimental results and Figs. 2(b, d, f) the numerical results. In the numerical results, white and blue colors represent the solid-state PCM, while black and red colors represent the liquid state. As seen in Fig. 2, there is good visual agreement in the liquid fraction between both sets of results for all melting times.



Figure 2 - β distribution at time t = 10 min, 30 min and 50 min: (a), (c) and (e) experimental results (Kamkari and Shokouhmand 2014); (b), (d) and (f) present numerical results.

Furthermore, Fig. 3 shows transient profiles of β obtained experimentally (Kamkari and Shokouhmand 2014) and numerically (present study). The values of β range from 0 to 1, with 0 representing the solid-state PCM and 1 representing the liquid state. Coherent agreement can be clearly observed between the numerical and experimental results. The average difference was approximately 5.4%, while the maximum difference was approximately 6.3% at t = 110 min with $\beta = 0.856$.

279

270



280Figure 3 – Liquid fraction β as function of time t: comparison between experimental results (Kamkari and281Shokouhmand 2014) and present numerical results.

282

Considering the good agreement between the numerical results of the present study and reference experimental results (Kamkari and Shokouhmand 2014), both qualitative (Fig. (2)) and quantitative (Fig. (3)), as well as the constant value assigned to C (seen in Section 3.1.3), the
numerical model used in this study was considered validated.

287

288 3.1.2 Mesh Test Sensitivity

For the present numerical study, three computational meshes were created, as seen in Fig. 4, with increasing number of elements. Meshes (a), (b) and (c) contained 10,118, 14,520 and 28,457 elements, respectively. Mesh independence analysis was performed using the GCI (Grid Convergence Method) procedure (Celik et al. 2008) by comparing the most refined mesh (c) with the intermediate mesh (b) and the least refined mesh (a). The calculated percentage rates were 1.9% and 5.5%, respectively. Thus, with a GCI of 1.9%, mesh (c) with 28,457 elements mesh was considered suitable for numerical simulations.



296

297

298

Figure 4 – Grid convergence study meshes: (a) 10,118, (b) 14,520 and (c) 28,457 elements.

299 3.1.3 Adjustment of porous zone constant "C"

The porous zone constant (C) of Eq. (5) indicated the material velocity damping to zero in the solid phase and its value had to be adjusted according to the problem analyzed. By definition, the value of C should be sufficient to allow flow in the transition region while at the same time suppressing velocity in the solid phase (Voller and Prakash 1987). For the present study, a range of several orders of magnitude of C values were tested. It was observed that a value of $C = 10^{11}$ more satisfactorily reproduced the PCM merging process and, consequently, was kept for all the numerical results presented in this study.

307

308 4. RESULTS AND DISCUSSIONS

The objective of this study was to analyze the influence of fin aspect ratio $(RA_f = H_f/W_f)$, and obtain the optimal aspect ratio (RA_{opt}) , thereby minimizing the melting process time for each ϕ . For clarity, each parameter affecting optimization was analyzed individually.

312

313 **4.1 Effects of Buoyancy on the Melting Process**

Figures 5(a, b) show the velocity fields for $RA_f = 0.288$ and $\phi = 0.03$ at times t = 20 min and 314 40 min, respectively. In the figures, PCM is represented with gray color in the solid phase and black 315 316 color in the liquid phase, with the velocity field at the same instant of time superimposed. It can be seen in both figures that, due to the buoyancy force generated by the variation of temperature within 317 the liquid phase, an upward flow is present close to the heated wall (right) and in the region above 318 the fin. Downward flow can also be observed at the solid-liquid interface, thus ensuring the principle 319 320 of mass conservation. In between these two convective currents and their velocity profile, it is possible to observe a shear region captured by the proper refinement of the computational mesh 321 throughout the domain. Heating occurs along the upper side of the fin and beyond the reach of the 322 vertical wall. In this region, a large recirculation zone is observed and can be classified as Rayleigh-323 324 Bénard convection. A similar flow can also be observed between the base of the cavity and the base 325 of the fin, producing another recirculation zone in this region but with different characteristics.



Figure 5 – Velocity distribution for $RA_f = 0.288$ and $\phi = 0.03$ at: (a) t = 20 min, (b) t = 40 min.

329

Figures 6(a, b) show temperature fields for $RA_f = 0.450$ and 0.078 with $\phi = 0.03$ at times t = 330 10 min and 50 min, respectively. In the figures, for all presented results, a robust thermal gradient 331 near the right vertical wall and the entire perimeter of the fin can be initially observed. Strong thermal 332 stratification is detected in the cavity at the final t = 50 min moment and especially in the region 333 above and below the fin. Buoyant forces arising from the change in density near the active vertical 334 wall form an upward convective current seen in Fig. 5(b). This current stratifies thermally the liquid 335 336 PCM in the upper part of the cavity. A similar condition is observed below the fin for both tested values of RA_{f} , which contributes to the formation of a curved melting front. However, at t = 10 min 337 and t = 50 min, there is an increase in thermal stratification in the region below the fin with decreasing 338 RAf. This behavior is related to the increase in fin perimeter, which limits the movement of the upward 339 340 convective currents to the top of the cavity and contributes to accelerate the melting process. Slight temperature variations at the top of the fin at t = 10 min for both tested values of RA_f have also been 341 342 detected. These characteristics fused layer instabilities are associated with Rayleigh-Bénard convection formation. Finally, it is worth mentioning that, for the others tested values of area fraction 343 344 ϕ , this behavior is also observed.





347 **4.2 Area Fraction Effect**

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Figures 7(a-d) show the liquid fraction (β) fields at time t = 50 min for W_f = 20 mm and 48 348 349 mm and area fractions of $\phi = 0.01, 0.05, 0.2$ and 0.3, respectively. In the figures, the first and third columns present β fields with respect to the case $W_f = 20$ mm; similarly, the second and fourth columns 350 351 are with respect to $W_f = 48$ mm. As observed in Fig. 7(a-d), there is a reduction of the total time of the melting process for any ϕ with an increase in the fin width W_f , which also corresponds to a 352 353 reduction in the value of RAf. In addition, it can be seen that the liquid fraction fields near the right vertical wall are similar to each other for both $W_f = 20$ mm and $W_f = 48$ mm, featuring a thin layer of 354 molten PCM for different RA_f and ϕ values. It is also noted that at t = 50 min and for ϕ = 0.01 to 0.05, 355 within different values of RA_f, the solid-liquid interface profiles are similar to each other, differing 356 only in the region to the left of the fin between $W_f = 20$ mm and $W_f = 48$ mm. 357



359

Figure 7 – β field at t = 50 min, W_f = 20 and 48 mm: (a) ϕ = 0.01; (b) ϕ = 0.05; (c) ϕ = 0.2 and (d) ϕ = 0.3. 361

362 **4.3 Effect of Fin Aspect Ratio** (RA_f)

The different heat transfer mechanisms in a melting process can be identified by varying the Nusselt number $(Nu = h L_c/k_l)$ as a function of Fourier number $(Fo = \alpha_l t/L_c^2)$, where L_c is the characteristic length $(L_c = A_c^{1/2})$, A_c is the cavity area, h is the heat transfer coefficient $(h = q^r/(T_w - T_l))$, q^r is the heat flux on the right sidewall and fin perimeter, T_w (343 K) is the wall temperature, T_l is the PCM liquid temperature and α_l $(\alpha_l = k_l/\rho_l c_{pl})$ is the liquid thermal diffusivity. The heat flux (q^r) was obtained on CFX-Post from the results obtained from Fluent.

Figure 8(a-f) shows Nu profiles as a function of Fo for different RA_f and $\phi = 0.01, 0.03, 0.05, 0.05$ 369 0.1, 0.2, and 0.3, respectively. As seen in the figure, regardless of the values of RA_f and ϕ , all results 370 show 3 different regions: I – with a marked reduction of Nu in the initial moments; II - with Nu values 371 without large variations, despite fluctuations in most of the melting process and III – a sharp reduction 372 of Nu in the final moments. More specifically, the low thermal resistance of the thin wall-melted 373 374 PCM layer in the initial moments allows the characterization of region I as conductive. With the 375 beginning of the melting process, still in region I, there is an increase in the size of the liquid layer. This behavior induces a change in the heat transfer mechanism from conductive to convective 376 represented by region II. In region II, Nu continues to decrease but more slowly. This behavior is in 377 accordance with reference work (Ji et al. 2018) and corroborates with the observations on the velocity 378 379 fields (Fig. 5): heating at the fin tip produces recirculation of the Rayleigh-Bénard liquid PCM which generates, in turn, fluctuations in the local temperature. Consequently, Nu also has fluctuations as 380 seen in region II of Fig. 8(a-f). These oscillations decrease as the solid-liquid interface moves away 381 from the fin in accordance with known experimental behavior (Kamkari and Shokouhmand 2014). 382 383 In addition, regarding Fig. 8(a-f), it can be observed that smaller values of RA_f ($RA_f = H_f / W_f$) are associated with longer periods of Nu fluctuations. This behavior is due to the increase of W_{f} . 384 385 Moreover, it is observed that increasing the value of ϕ reduces the amplitude of the instabilities, which is visually evident in a comparison of Fig. 8(a) and 8(f). This fact justifies the reduction of the time 386 387 difference of the melting process with increasing of ϕ seen in the analysis of the liquid fraction 388 profiles. In region III, at the final moments, Nu number again decreases more sharply due to the reduction of the heat transfer rate resulting from weakening convection currents. In this figure it can 389 also be observed that, for all values ϕ and near Fo = 0.05, there is a small increase in Nu for the 390 highest *RA_f* values. This behavior occurs due to the greater length of the solid-liquid PCM interface, 391 as seen in Fig. 7(a-d). For example, in Fig. 7(a) for ϕ =0.01, the length of the solid-liquid interface for 392 $RA_f = 0.15$ is greater than for $RA_f = 0.026$, resulting in a larger Nu seen in Fig. 8(a). As a final point, 393 it should be mentioned that for all tested ϕ values, the cases with the lowest Nu are those that presented 394 395 the fastest melting processes.



398 Figure 8 – Nu vs. Fo, for several values of RA_f and: (a) $\phi = 0.01$; (b) $\phi = 0.03$; (c) $\phi = 0.05$; (d) $\phi = 0.1$; 399 (e) $\phi = 0.2$ and (f) $\phi = 0.3$.

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Figures 9(a-c) show β fields for $\phi = 0.005$ at times t = 1 min, 10 min, 30 min, 50 min, 70 min 401 and 90 min and $RA_f = 0.300$, 0.033 and 0.013, respectively. As in Fig. 7, blue color represents the 402 solid phase and red color represents the liquid phase. Initially, it is observed that at t = 1 min, 403 regardless of the values of RAf, the fused PCM layer in the vicinity of the heated wall is very thin. At 404 this time, the PCM is almost entirely in the solid phase and the heat transfer process is predominantly 405 conductive. As t increases, the thickness of the molten layer increases and buoyant forces become 406 predominant in relation to viscous ones; therefore, a change in the heat transfer mechanism occurs, 407 becoming convective. As a result, solid-phase erosion occurs in the upper cavity at the solid-liquid 408 interface, forming a curvature of the melting front. This can be observed in Fig 9 for all values of RA_f 409

410 at t = 30 min, 50 min and 70 min. Additionally, it is noted that RA_f also influences the melting rate. 411 For example, after the initial moments, there is a tendency to accelerate the PCM merger process with 412 reduced RA_f . This is mainly identified at t = 50 min, where it can be observed that the melting rate for 413 $RA_f = 0.013$ is much larger than for $RA_f = 0.3$. This behavior is due to the augmented perimeter of the

fin inserted in the PCM, which increases the heat transfer area between the fin and the PCM.



416 Figure 9 – β field for $\phi = 0.005$, t = 1 min, 10 min, 30 min, 50 min, 70 min and 90 min, and: (a) $RA_f = 0.300$; 417 (b) $RA_f = 0.033$ and (c) $RA_f = 0.013$.

418

In quantitative terms, the influence of RA_f (H_f/W_f) over β is shown in Fig. 10(a-f) which 419 highlights the variations of β as a function of time for different *RA_f* and $\phi = 0.01, 0.03, 0.05, 0.1, 0.2$ 420 and 0.3, respectively. Overall, higher values of RA_f are associated with longer complete PCM melting 421 times ($\beta = 1$) independent of the area fraction ϕ . Moreover, since the increase in RA_f leads to fins with 422 smaller heat exchange area, the heat removal (per unit time) process ends up being penalized. 423 Conversely, it can be demonstrated that there is a gradual tendency of acceleration of the melting 424 process with the gradual reduction of the aspect ratio RA_f for all tested values of ϕ , even if it is not 425 evident which were the smallest calculated RA_f values. 426



428 Figure $10 - \beta$ vs. t for several values of *RA_f* and: (a) $\phi = 0.01$; (b) $\phi = 0.03$; (c) $\phi = 0.05$; (d) $\phi = 0.1$; (e) $\phi = 0.2$ and (f) $\phi = 0.3$.

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A deeper understanding of how the total melting time is affected by the various parameters can be obtained from Fig. 11: it shows the maximum time of the melting process ($\beta = 1$) as a function of *RA_f* for all the simulated values of ϕ of all 78 configurations. It can be immediately observed that increases of ϕ are associated with decreases in the time required for the PCM to completely melt. For example, at *RA_f* = 1 and for $\phi = 0.02$ and 0.2, the maximum melting times were approximately 165 min and 127 min, respectively. Therefore, the increase of an order of magnitude in the ϕ value led to a reduction of approximately 38 min in the melting process.



439 Figure 11 – Maximum melting time of each fin configuration as function of RA_f and several values of ϕ . 440

441 For this study the optimum aspect ratio (RA_{opt}) was defined as the one with the lowest melting rate, i.e. the shortest time to reach complete melting for each ϕ . For ϕ ranging from 0.005 to 0.1, the 442 443 shortest melting times were obtained with the lowest RA_f . However, for $\phi = 0.2$ and 0.3, the shortest time occurred in the "second lowest" RA_{f} , which were designated the proper RA_{opt} . The total trend of 444 445 the *RA*_{opt} values is plotted in Figure 12 as a dashed line. Similar behavior was observed for this configuration in other studies (Biserni, Rocha, and Bejan 2004) in which the optimal geometries 446 proved to be the ones which permitted, as far as possible, the morphing "inverted fins" to penetrate 447 the cavity. The optimal values of aspect ratios found in this study are shown in Table 5 with respect 448 to tested values of ϕ . 449

450

451

Table 5 - RA_{opt} at corresponding values of ϕ .

ϕ	0.005	0.01	0.02	0.03	0.04	0.05	0.1	0.2	0.3
<i>RA</i> _{opt}	0.013	0.026	0.052	0.078	0.104	0.130	0.260	0.592	0.889

452

Further work was conducted with the investigation of the absorbed energy. Since the cavity 453 area (A_c) was constant, the fin area (A_f) obviously increased with increases of the area fraction ($\phi =$ 454 $A_{\not l}/A_c$). Under these conditions, increasing ϕ implied a reduction in the amount of mass contained in 455 the cavity and the resulting variation in the energy absorbed by it. This behavior can be observed in 456 Fig. 12, which shows the total energy absorbed by the cavity as a function of time for the optimal 457 aspect ratios RA_{opt} with respect to all tested area fractions ϕ . It can be noticed that, as ϕ increases, 458 there is a reduction in absorbed energy as predicted. For example, between $\phi = 0.1$ and $\phi = 0.3$ at t =459 460 100 min, the energy absorbed is approximately 861 kJ and 690 kJ, respectively. This represents a reduction of around 20% in terms of absorbed energy. However, for a variation of 10% in area fraction 461

462 $(\phi = 0.005 \text{ and } \phi = 0.05) \text{ at } t = 100 \text{ min}$, the absorbed energy is around 935 kJ and 902 kJ, respectively. 463 These values represent a decrease of only approximately 3% of absorbed energy. Based on these 464 results, it can be concluded that the reduction of the absorbed energy should be significant only for 465 values of ϕ greater than a threshold value of 0.05.





467 Figure 12 – Cavity absorbed energy over time with respect to the optimal aspect ratios, RA_{opt} and several ϕ 468 values.

469 Finally, Fig. 13 shows the variation of the energy absorbed in the cavity as a function of time with respect to the cases $RA_f = 1.33$ and $\phi = 0.05$ and 0.2. Figure 13 shows a clear inversion in trend 470 471 at a time of approximately 80 min. For times shorter than 80 min, an increase in ϕ results in an increase in absorbed energy. For example, at t = 60 min and ϕ = 0.05 and ϕ = 0.2, approximately 549 kJ and 472 473 625 kJ were absorbed, respectively. This represents an increase of 12% in absorbed energy when ϕ is increased from 0.05 to 0.2. This behavior may be of great interest in applications that require a high 474 storage rate in shorter times. In contrast, for times longer than 80 min, the opposite behavior is 475 observed with a decrease in ϕ resulting in an increase in absorbed energy. For example, at t = 120 476 min, for $\phi = 0.05$ and 0.2, approximately 890 kJ and 790 kJ were absorbed, respectively. This 477 demonstrates that a 15% increase in area fraction resulted in approximately an 11% reduction in total 478 energy absorption. 479



483 **5.** Conclusions

The present work was concerned with the effect of the aspect ratio of an "inverted fin", i.e. an intrusion placed in a rectangular cavity, in the melting process of lauric acid PCM. Results were obtained by means of a computational model based on the equations of conservation of mass, momentum, energy and an enthalpy-porosity model representing the PCM melting process. The main conclusions were:

- a shear region between two convective currents was observed. This was a result of a buoyant upward flow in the region above the fin and a downward flow at the solid-liquid interface.
 Another region with great recirculation was observed between the base of the cavity and the base of the fin. In addition, the existing circulation along the top of the fin was classified as Rayleigh-Bénard convection.
- for all tested values of area fraction (ϕ), there was a reduction in total time of the melting process with a reduction of the value of the fin aspect ratio RA_f , caused by the increase of the fin width W_f . It was also noted that at t = 50 min for ϕ ranging from 0.01 to 0.05, with different values of RA_f , the solid-liquid interface profiles were similar to each other, differing only in the region to the left of the fin between $W_f = 20$ mm and $W_f = 48$ mm.
- *Nu* profiles as a function of *Fo* for different RA_f and $\phi = 0.01, 0.03, 0.05, 0.1, 0.2$ and 0.3 showed 3 distinct regions. Region I presented a marked reduction of *Nu* in the initial moments (mostly due to conduction). Region II presented *Nu* values without large variations but with fluctuations in most of the melting process (mostly due to convection). Region III presented sharp reductions of *Nu* in the final moments, due to the weakening of convection currents.
- The various parameters affecting the total melting time were investigated with reference to the 505 78 simulated configurations. The increase of ϕ was associated with decreasing times required

for the PCM to completely melt. For example, for $RA_f = 1$ and $\phi = 0.02$ and 0.2, the maximum melting times were approximately 165 min and 127 min, respectively. Therefore, the increase of an order of magnitude in the value of ϕ led to a reduction of approximately 38 min in the melting process.

510 Finally, an investigation regarding the amount of absorbed energy with respect to RA_{opt} was carried out. It was noticed that there was a reduction in absorbed energy as ϕ increased. For 511 512 example, at t = 100 min for ϕ = 0.1 and ϕ = 0.3, the energy absorbed was approximately 861 kJ and 690 kJ, respectively. This represented a reduction of around 20% in terms of absorbed 513 514 energy. However, for an increase of 10% of area fraction ($\phi = 0.005$ to $\phi = 0.05$) at t = 100 min, the absorbed energy was around 935 kJ and 902 kJ, respectively. These values represented a 515 516 decrease of 3% of absorbed energy. With these results, it was concluded that the reduction of the absorbed energy was significant only for ϕ greater than a threshold value of 0.05. 517

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