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Design of fin structures for phase change material (PCM) melting process in rectangular cavities

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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
11 cavity, keeping both the PCM mass and the total fin area constant, thus changing only the fin aspect
12 ratio. The analysis was conducted through a parametric study of 78 different fin configurations. In
13 order to maintain the thermal capacity, the cavity and fin areas were kept constant while fin
14 dimensions were varied within a preset number of combinations of area fraction and width. The fins
15 tested were combinations of 9 fin aspect ratios (RA_f) and 9 fin-to-cavity area fractions (ϕ). A finite-
16 volume numerical CFD method was used to obtain the results. Governing equations were the
17 conservation of mass, momentum and energy while phase change was governed by an enthalpy-
18 porosity model. The mathematical model was validated against reference experimental results and
19 computational meshes were checked with GCI. For all tested cases, with an increase in the fin length
20 and a consequent reduction in RA_f , there was a reduction of the total time of the melting process. The
21 RA_f , which had shorter melting times, were defined as optimal aspect ratios (RA_{opt}). Thus, each ϕ
22 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 , $RA_{opt} =$
23 $0.013, 0.026, 0.052, 0.078, 0.104, 0.130, 0.260, 0.592$ and 0.889 , respectively. Future works could
24 contemplate a greater number of fins, with the same total area of this study, other PCM and other
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	C	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	\bar{g}	gravity	[m s ⁻²]
36	H	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	p	pressure	[Pa]
43	q''	heat flux	[W m ⁻²]
44	RA	aspect ratio, $AR = H / W$	[-]
45	\vec{S}	momentum equation source term	[Pa m ⁻¹]
46	T	temperature	[K]
47	t	time	[s]
48	\vec{V}	velocity vector	[m s ⁻¹]
49	W	cavity width	[mm]
50	W_f	fin width	[mm]
51			
52	<i>Greek symbols</i>		
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	<i>Subscripts</i>		
61	c	cavity	
62	f	fin	
63	i	initial	
64	L	phase change	
65	l	liquid	
66	m	melting	
67	opt	optimal	
68	ref	reference	

69	<i>s</i>	solid
70	<i>se</i>	sensible
71	<i>w</i>	wall

72 **1. INTRODUCTION**

73 The increase in energy demand, air pollution, energy prices, partial unavailability of fossil
74 fuels and environmental concerns are driving causes of studies on alternative methods of energy
75 production (Reddy, Mudgal, and Mallick 2018). As an extension, the development and application of
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
80 high energy storage capacity and the ability to provide heat at a constant temperature equal to the
81 material transition temperature. The materials used in latent heat energy storage are called Phase
82 Change Materials (PCM) (Ibrahim et al. 2017). These are classified according to their chemical
83 composition into organic (paraffin and non-paraffin), inorganic (salt and metal hydrates), and eutectic
84 (metal alloys) (Jamil et al., 2019, Ibrahim et al., 2017). As for the phase change temperature
85 classification, three groups are universally accepted: low, medium, and high temperature, Ehms et
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
88 between 15 °C and 90 °C, and high temperature when the phase change occurs above 90 °C.

89 The selection of a PCM depends on its thermal properties, applications, stability and cost
90 (Aslfattahi et al., 2020). Their application can occur in many areas such as biomedicine, textile,
91 automotive (Jaguemont et al., 2018) and construction (Pielichowska and Pielichowski 2014,
92 Souayfane et al. 2016), solar power plants (Zhang et al. 2016, Khan et al. 2017) and electronic
93 components (Baby e Balaji 2012, Kalbasi and Salimpour, 2015). In buildings, PCM can be used for
94 cooling in passive or active systems (Souayfane et al. 2016). For example, one way of using PCM in
95 buildings is through the inclusion of micro-encapsuled PCM in the materials used in construction
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

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

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

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

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

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

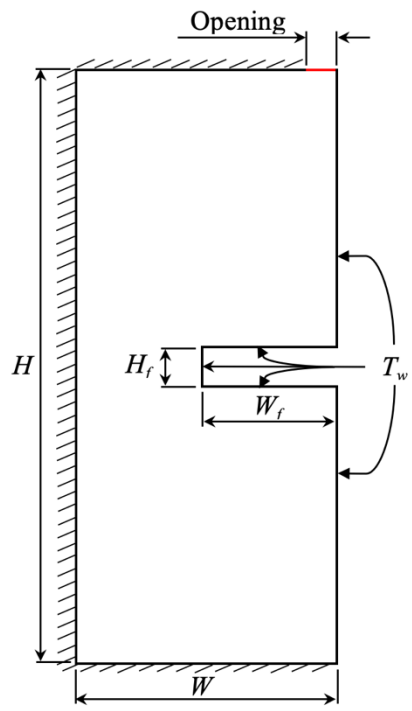
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158 **2.1 Physical Domain**

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

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

173



174

175

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

176

177 The constraints of the parametric study were the cavity area ($A_c = HW$) and the fin area
 178 ($A_f = H_f W_f$). Area A_c was kept constant and equal to $6,000 \text{ mm}^2$ while A_f was obtained from the area
 179 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
 180 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)
 181 were selected. Through combinations of A_c , ϕ , and W_f , values of A_f and H_f were obtained and it was
 182 possible to calculate the fin aspect ratio ($RA_f = H_f/W_f$). The selected values of ϕ and W_f resulted,
 183 ideally, in 81 geometric configurations. Of these, 3 of them could not be simulated as they exceeded
 184 the cavity dimensions and were discarded. Table 1 shows the dimensions of the remaining 78 fins.

185

Table 1 – Range of dimensions of fins tested.

		W_f [mm]								
		10	15	20	25	30	35	40	45	48
$\phi = 0.005$	H_f [mm]	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
$\phi = 0.03$		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
$\phi = 0.30$				90.00	72.00	60.00	51.43	45.00	40.00	37.50

186

187

188

The properties of lauric acid are shown in Tab. 2, Tab. 3 and Tab. 4. Table 2 presents the 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

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Table 3 - Thermal conductivity of lauric acid (Shokouhmand and Kamkari 2013).

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

202

203

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

T [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

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

$$207 \frac{\partial \rho}{\partial t} + \nabla(\rho \vec{V}) = 0 \quad (1)$$

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

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

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

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

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

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

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

220 where β is the liquid fraction, ε is a constant with value of 0.001 used to prevent division by zero and
 221 C is the porous zone constant. This constant depends on the morphology of the porous zone (Voller

222 and Prakash 1987). The net fraction of PCM within the phase change range is calculated from Eq.
 223 (6):

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

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

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

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

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

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

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

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

234 **3 Numerical Model**

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

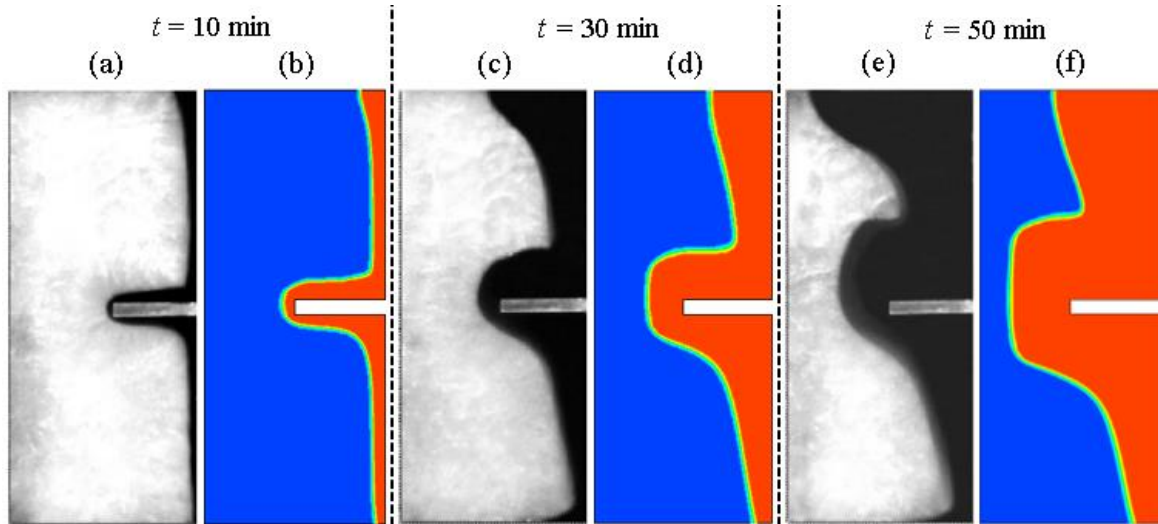
244 0.15 for pressure and momentum, 0.3 for density, field forces and energy and 0.2 for the liquid
245 fraction. Intermediate values of k e μ were obtained by linear interpolation of the data of Tab. 3 and
246 Tab. 4. The value of ρ_s was considered constant as of Tab. 2; however, values of ρ_l were pre-set from
247 reference (Chuah et al. 2006) according to temperature: 885 kg/m³ at 321.35 K (Tab. 1), 870 kg/m³
248 at 323 K and 862 kg/m³ at 333 K. The lower, upper, and left walls of the cavity were defined as
249 adiabatic. The right wall and the fin surfaces were kept at the heating temperature $T_w = 343$ K. The
250 no-slip condition was applied in all walls and the fin surfaces, except for the opening, which was
251 considered free flow at $T_a = 343$ K. In addition, the PCM was subjected to an initial temperature of T_i
252 =298 K.
253

254 **3.1 Model Validation and Mesh Test Sensitivity**

255 **3.1.1 Model Validation**

256 Numerical validation was performed with comparisons to reference experimental data
257 (Kamkari and Shokouhmand 2014) in two ways: through liquid fraction field and with the liquid
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
260 in height and 120 mm in thickness, with a fin 25 mm in width and 4 mm in height. The fin and the
261 right wall were subjected to a constant temperature of 343 K while the remaining walls were thermally
262 insulated. The PCM was initially at a temperature of 298 K, i.e., solid-state (Kamkari and
263 Shokouhmand 2014).

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



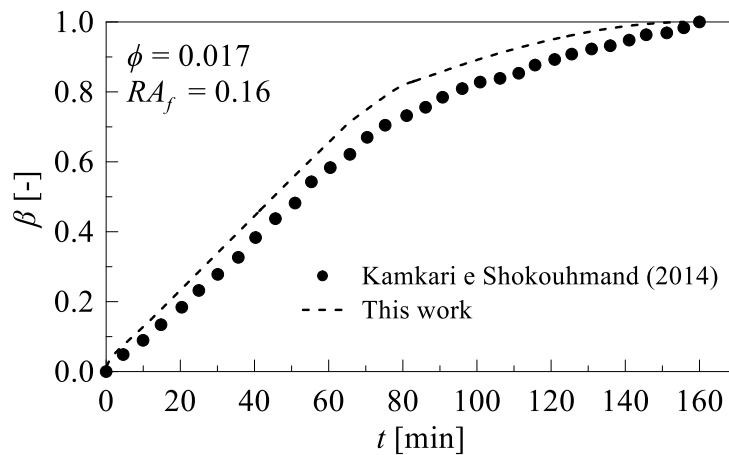
270

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

273

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

279



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

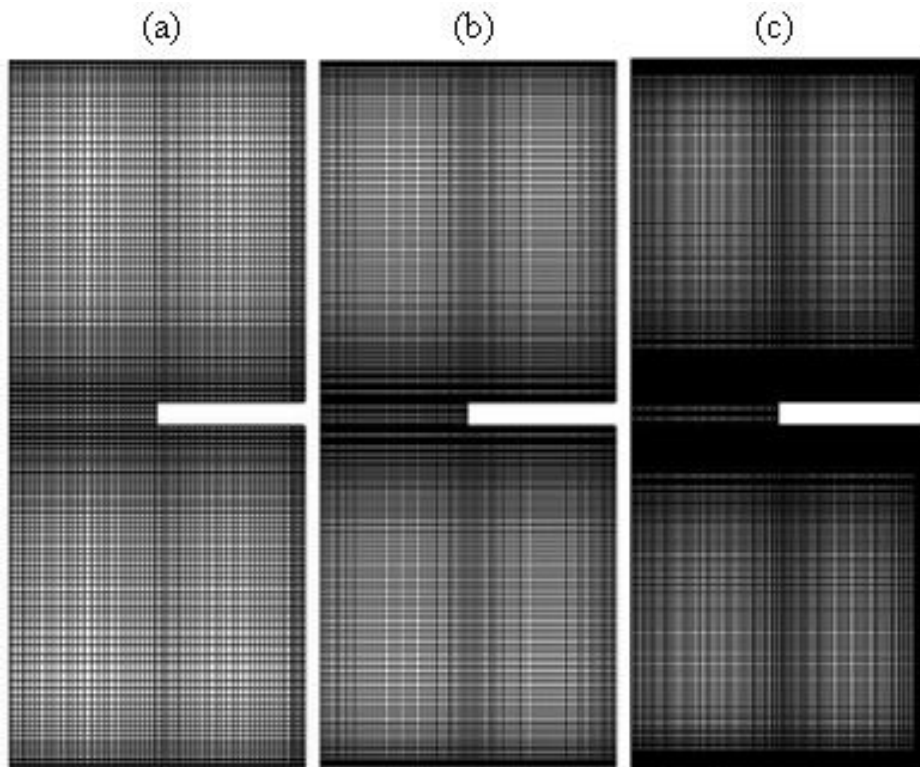
Considering the good agreement between the numerical results of the present study and
reference experimental results (Kamkari and Shokouhmand 2014), both qualitative (Fig. (2)) and

285 quantitative (Fig. (3)), as well as the constant value assigned to C (seen in Section 3.1.3), the
286 numerical model used in this study was considered validated.

287

288 3.1.2 Mesh Test Sensitivity

289 For the present numerical study, three computational meshes were created, as seen in Fig. 4,
290 with increasing number of elements. Meshes (a), (b) and (c) contained 10,118, 14,520 and 28,457
291 elements, respectively. Mesh independence analysis was performed using the GCI (Grid
292 Convergence Method) procedure (Celik et al. 2008) by comparing the most refined mesh (c) with the
293 intermediate mesh (b) and the least refined mesh (a). The calculated percentage rates were 1.9% and
294 5.5%, respectively. Thus, with a GCI of 1.9%, mesh (c) with 28,457 elements mesh was considered
295 suitable for numerical simulations.



296

297

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

298

299 3.1.3 Adjustment of porous zone constant “C”

300 The porous zone constant (C) of Eq. (5) indicated the material velocity damping to zero in the
301 solid phase and its value had to be adjusted according to the problem analyzed. By definition, the
302 value of C should be sufficient to allow flow in the transition region while at the same time

303 suppressing velocity in the solid phase (Voller and Prakash 1987). For the present study, a range of
304 several orders of magnitude of C values were tested. It was observed that a value of $C = 10^{11}$ more
305 satisfactorily reproduced the PCM merging process and, consequently, was kept for all the numerical
306 results presented in this study.

307

308 **4. RESULTS AND DISCUSSIONS**

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

312

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

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

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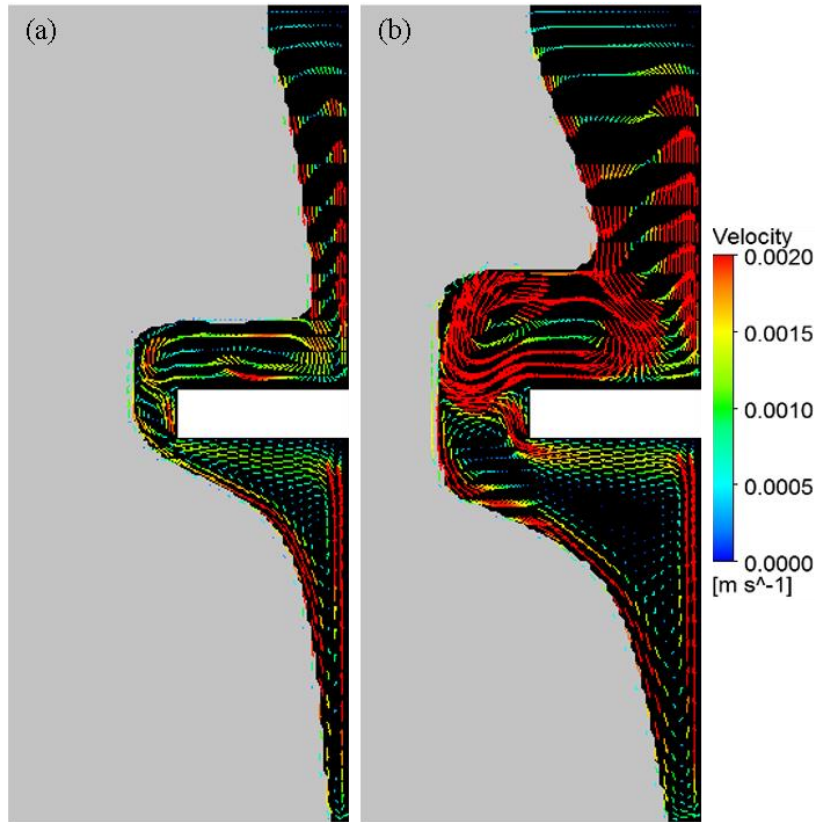


Figure 5 – Velocity distribution for $RA_f = 0.288$ and $\phi = 0.03$ at: (a) $t = 20$ min, (b) $t = 40$ min.

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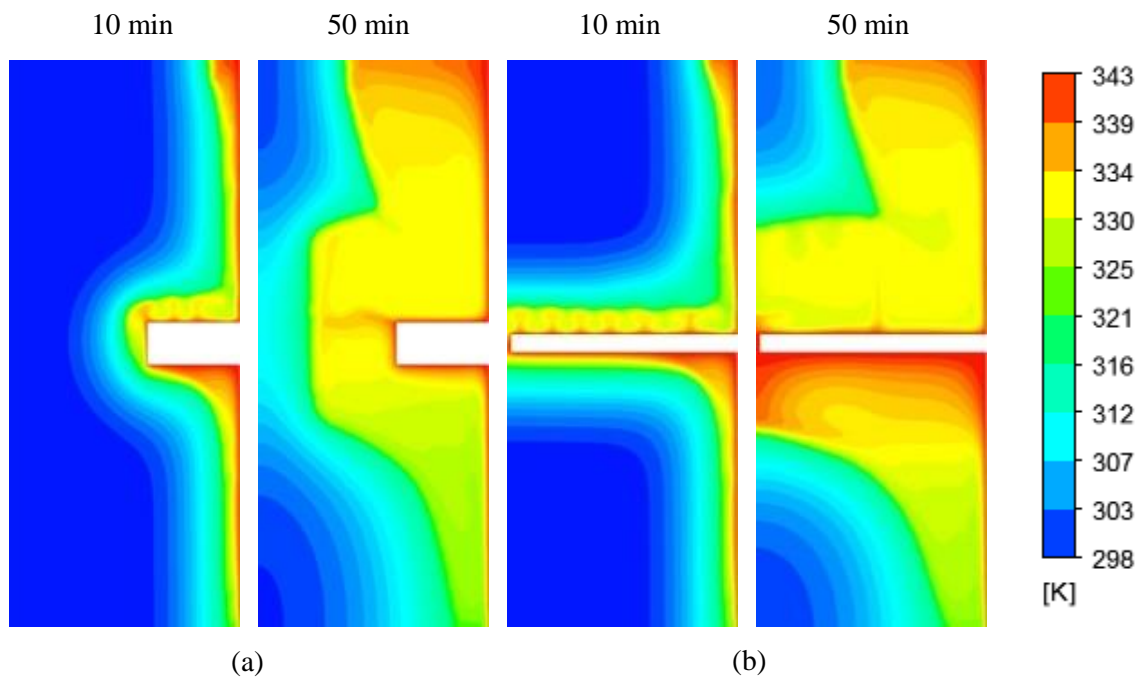
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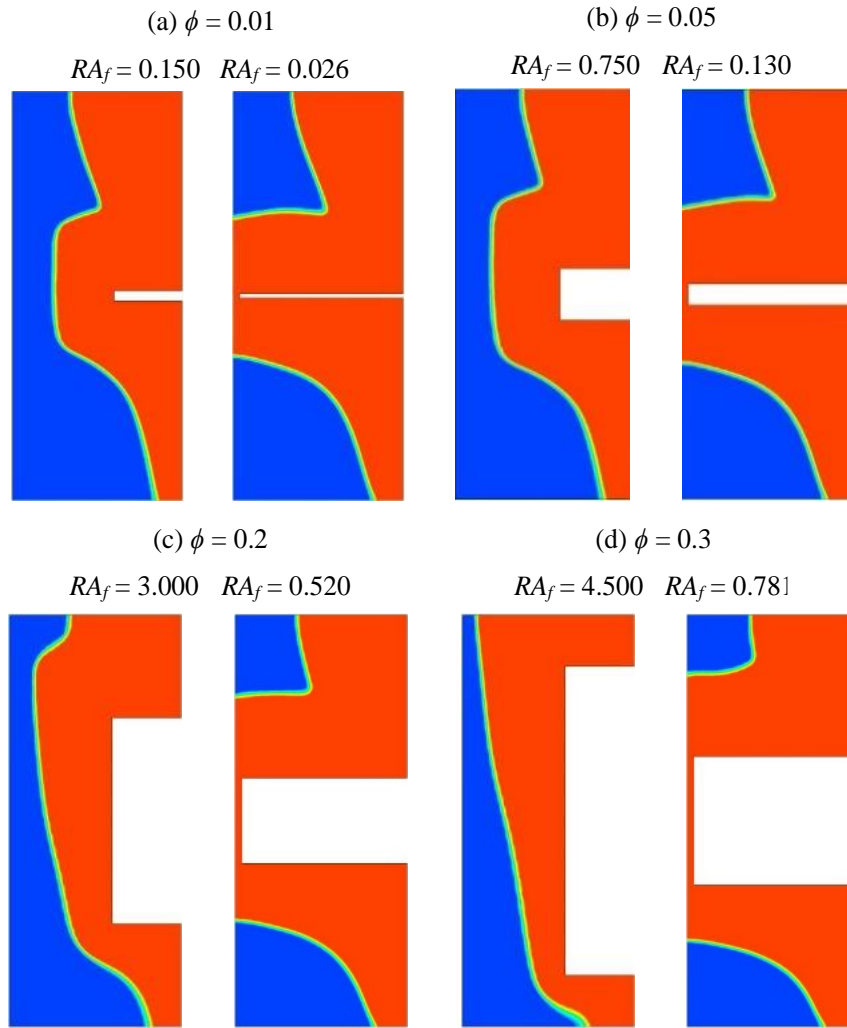
Figures 6(a, b) show temperature fields for $RA_f = 0.450$ and 0.078 with $\phi = 0.03$ at times $t = 10$ min and 50 min, respectively. In the figures, for all presented results, a robust thermal gradient near the right vertical wall and the entire perimeter of the fin can be initially observed. Strong thermal stratification is detected in the cavity at the final $t = 50$ min moment and especially in the region above and below the fin. Buoyant forces arising from the change in density near the active vertical wall form an upward convective current seen in Fig. 5(b). This current stratifies thermally the liquid 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 and $t = 50$ min, there is an increase in thermal stratification in the region below the fin with decreasing RA_f . This behavior is related to the increase in fin perimeter, which limits the movement of the upward 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 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 ϕ , this behavior is also observed.



345
 346 Figure 6 – Temperature distribution at $t = 10$ and 50 min, $\phi = 0.03$ and: (a) $RA_f = 0.450$ and (b) $RA_f = 0.078$.

347 4.2 Area Fraction Effect

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



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

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4.3 Effect of Fin Aspect Ratio (RA_f)

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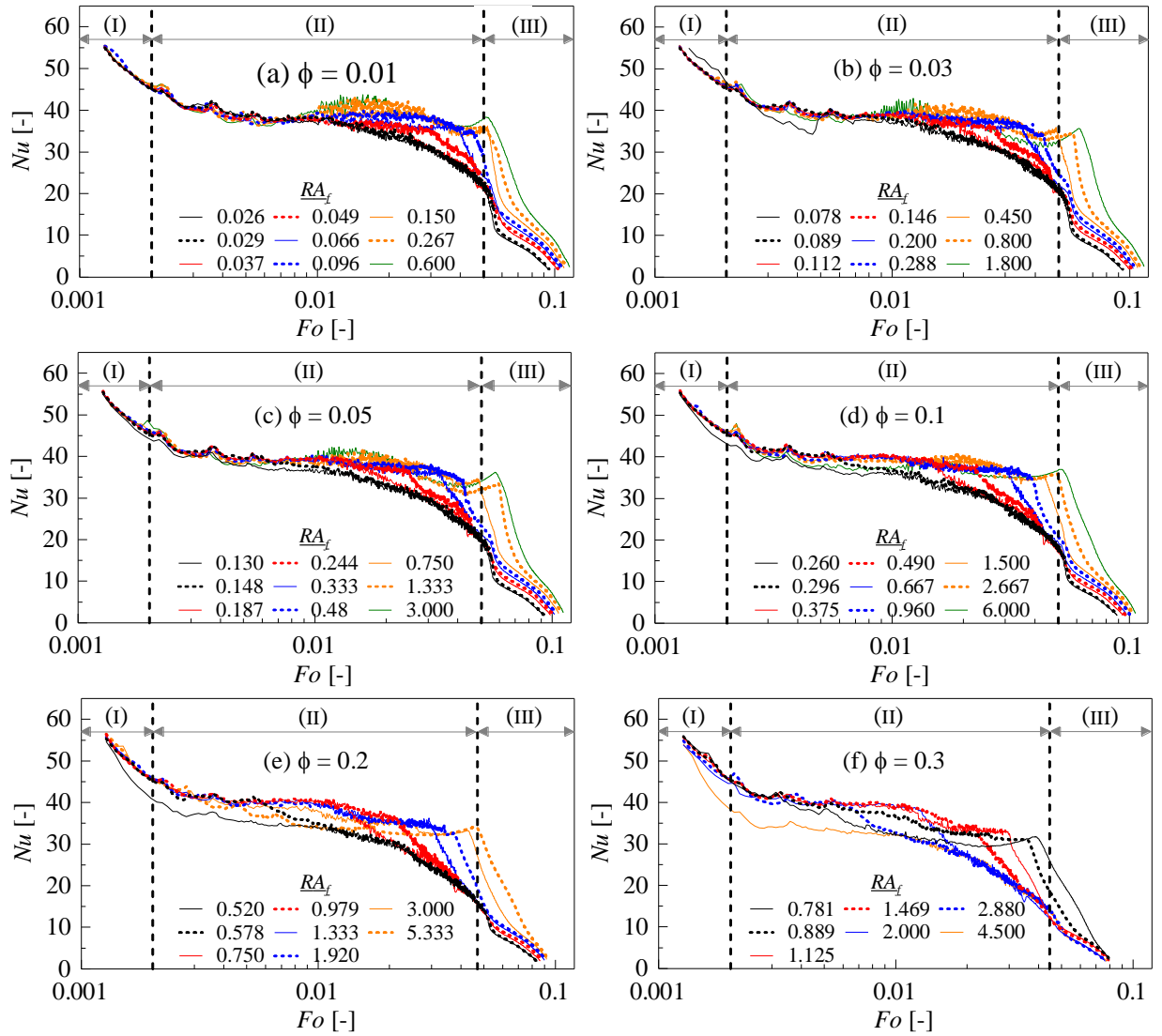
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The different heat transfer mechanisms in a melting process can be identified by varying the Nusselt number ($Nu = h L_c / k_l$) as a function of Fourier number ($Fo = \alpha_l t / L_c^2$), where L_c is the characteristic length ($L_c = A_c^{1/2}$), A_c is the cavity area, h is the heat transfer coefficient ($h = q'' / (T_w - T_l)$), q'' 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 ($\alpha_l = k_l / \rho_l c_{p_l}$) is the liquid thermal diffusivity. The heat flux (q'') was obtained on CFX-Post from the results obtained from Fluent.

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

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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) $\phi = 0.1$;

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(e) $\phi = 0.2$ and (f) $\phi = 0.3$.

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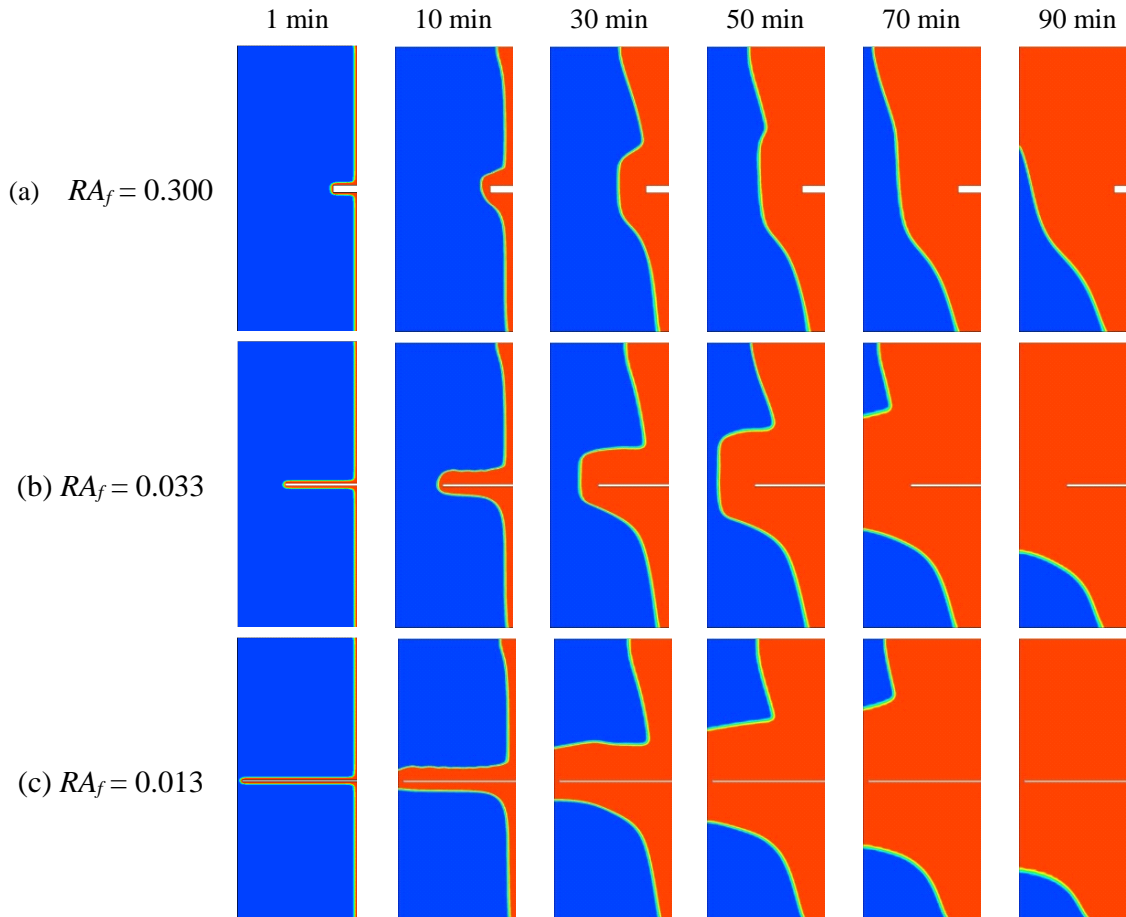
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Figures 9(a-c) show β fields for $\phi = 0.005$ at times $t = 1$ min, 10 min, 30 min, 50 min, 70 min and 90 min and $RA_f = 0.300, 0.033$ and 0.013 , respectively. As in Fig. 7, blue color represents the solid phase and red color represents the liquid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

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

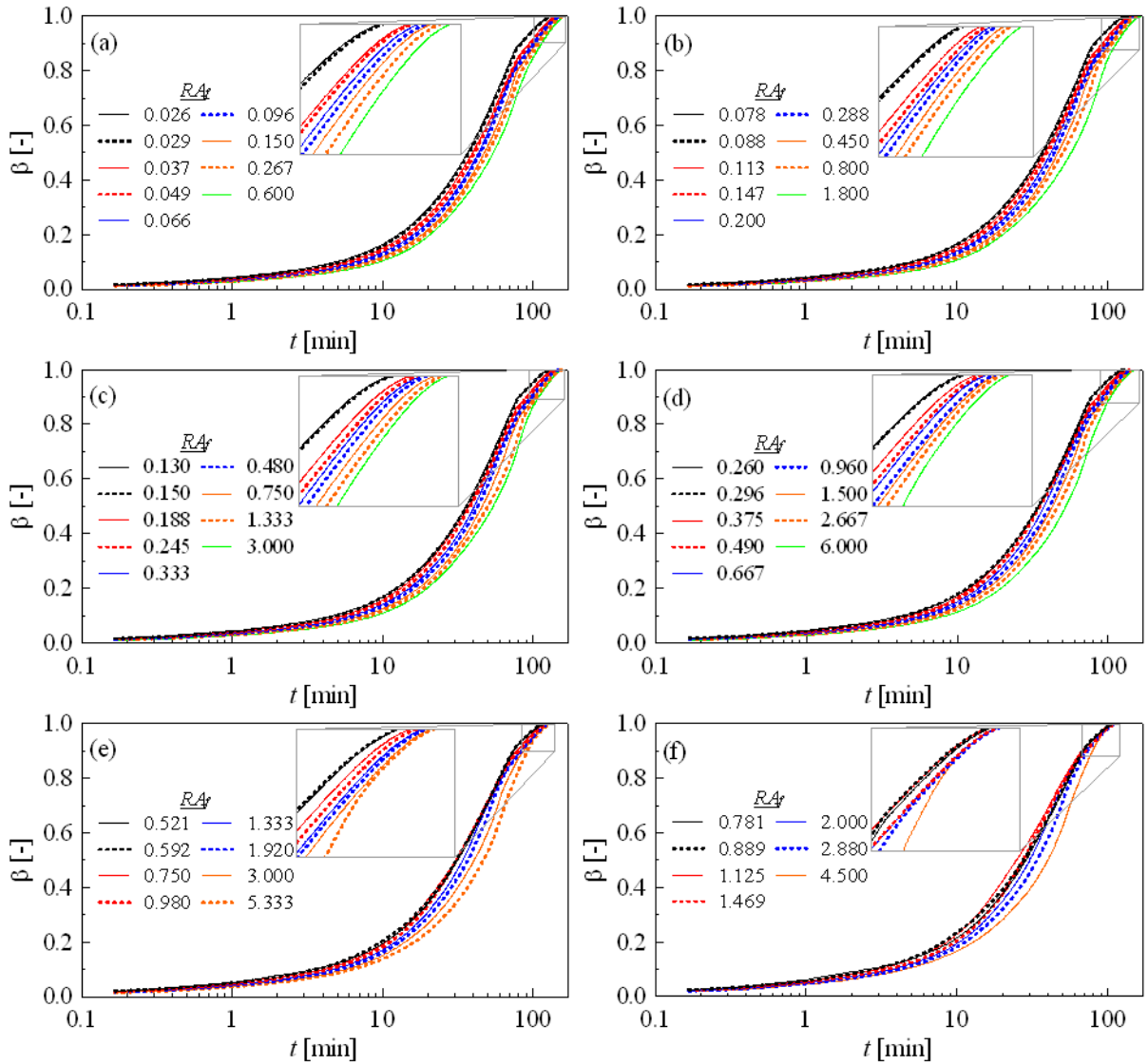


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416 Figure 9 – β field for $\phi = 0.005$, $t = 1$ min, 10 min, 30 min, 50 min, 70 min and 90 min, and: (a) $RA_f = 0.300$;
 417 (b) $RA_f = 0.033$ and (c) $RA_f = 0.013$.

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



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428 Figure 10 – β 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) $\phi =$
 429 0.2 and (f) $\phi = 0.3$.

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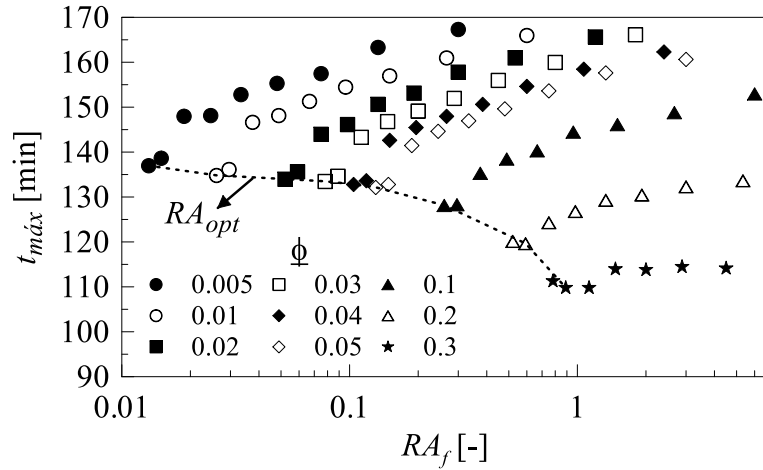
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A deeper understanding of how the total melting time is affected by the various parameters can be obtained from Fig. 11: it shows the maximum time of the melting process ($\beta = 1$) as a function of RA_f for all the simulated values of ϕ of all 78 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.



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

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

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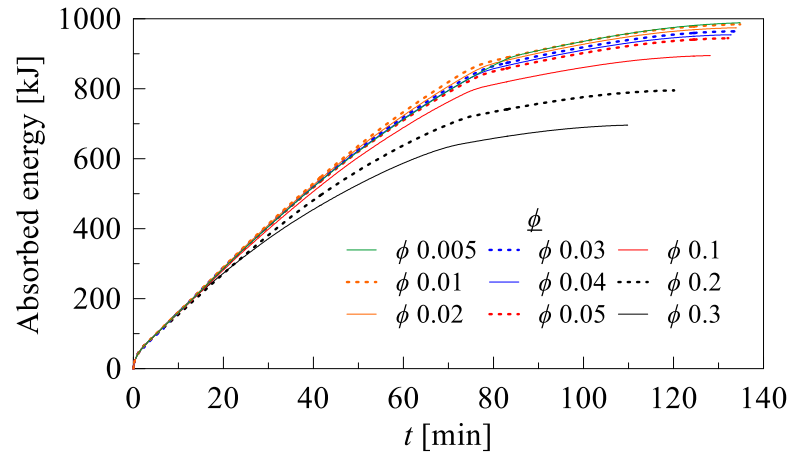
Table 5 - RA_{opt} at corresponding values of ϕ .

ϕ	0.005	0.01	0.02	0.03	0.04	0.05	0.1	0.2	0.3
RA_{opt}	0.013	0.026	0.052	0.078	0.104	0.130	0.260	0.592	0.889

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453 Further work was conducted with the investigation of the absorbed energy. Since the cavity
 454 area (A_c) was constant, the fin area (A_f) obviously increased with increases of the area fraction ($\phi =$
 455 A_f/A_c). Under these conditions, increasing ϕ implied a reduction in the amount of mass contained in
 456 the cavity and the resulting variation in the energy absorbed by it. This behavior can be observed in
 457 Fig. 12, which shows the total energy absorbed by the cavity as a function of time for the optimal
 458 aspect ratios RA_{opt} with respect to all tested area fractions ϕ . It can be noticed that, as ϕ increases,
 459 there is a reduction in absorbed energy as predicted. For example, between $\phi = 0.1$ and $\phi = 0.3$ at $t =$
 460 100 min, the energy absorbed is approximately 861 kJ and 690 kJ, respectively. This represents a
 461 reduction of around 20% in terms of absorbed energy. However, for a variation of 10% in area fraction

462 ($\phi = 0.005$ and $\phi = 0.05$) at $t = 100$ 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.



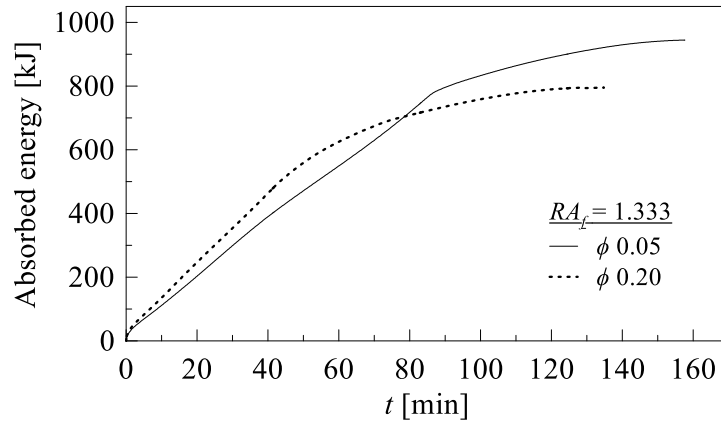
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467 Figure 12 – Cavity absorbed energy over time with respect to the optimal aspect ratios, RA_{opt} and several ϕ
 468 values.

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

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Figure 13 – Absorbed energy over time for $RA_f = 1.33$ and $\phi = 0.05$ and 0.2 .

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5. Conclusions

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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:

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- 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 78 simulated configurations. The increase of ϕ was associated with decreasing times required

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

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

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