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Cooling performance of an active-passive hybrid composite phase change material (HcPCM) finned heat sink: Constant operating mode

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Abstract

The present study explores a hybrid thermal management technology based on air cooling and hybrid composite phase change material (HcPCM) filled finned heat sink for cooling performance of lower to medium heat flux dissipating electronic devices. Two-dimensional numerical simulations are conducted to study the conjugate heat transfer effects of three types of finned heat sink: air-cooled finned heat sink, HcPCM-cooled finned heat sink, and hybrid (air-HcPCM) cooled finned heat sink. A heat sink with a constant volume fraction of plate-fins is designed in all cases and simultaneous effects of hybrid nanoparticles and air are investigated to keep the heat sink temperature at safe operating conditions between 40 – 60 °C. The effect of air is incorporated into the heat sink by applying the convective heat transfer coefficient of $h_c = 10 - 100 \text{ W/m}^2\cdot\text{K}$ which tends to create the natural convection and forced convection heat transfer characteristics. The heat flux is varied from 25 – 40 kW/m² in the current study. The hybrid nanoparticles of carbon additives (GO and MWCNTs) are dispersed into the RT-35HC, used as a PCM, with a volume fraction of 0% to 6%. Transient simulations are carried out using COMSOL Multiphysics to solve the governing equations for PCM based conjugate heat transfer model. The results showed that forced convection heat transfer improved the cooling performance of the hybrid heat

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sink compared to natural convection heat transfer. The addition of nanoparticles further enhanced thermal enhancement and uniform melting distribution of PCM inside the finned heat sink. The h_c between 30 to 50 W/m².K shows optimized values for forced convection heat transfer operating conditions. The volume fraction of 2% of GO+MWCNTs nanoparticles is recommended or optimum concentration for uniform melting of PCM inside the finned heat sink.

Keywords: Hybrid composite phase change material; HcPCM-based Finned heat sink; Hybrid (air-HcPCM) Finned heat sink; Carbon-additives; Electronics devices

Nomenclature

Abbreviations

GO	Graphite oxide
MWCNTs	Multi-walled carbon nanotubes
FEM	Finite Element method
HS	Heat sink
TM	Thermal management
HcPCM	Hybrid composite phase change material
PCM	Phase change material
BDF	Backward Differentiation Formula
PARDISO	Parallel Direct Sparse Solver Interface

Symbols

A_m	Mushy zone
B	Boltzman constant (J/K)
ρc_p	Volumetric heat capacity ($J/m^3.K$)
g	Gravitational acceleration (m/s^2)
F	Force (N)
H	Height (mm)
k	Thermal conductivity ($W/m.K$)
L	Latent heat of fusion ($J/kg.K$)
m	Mass (kg)
p	Pressure (Pa)
S	Source term in momentum equation
V	Volume (m^3)
T	Temperature (K)
t	Time (sec)
V	Velocity (m/s)

W	Width (mm)
c_p	Specific heat capacity ($J/kg.K$)
h_c	Convective heat transfer coefficient ($W/m^2.K$)
ΔH	Fractional latent-heat ($J/kg.K$)
$2D$	Two dimensional

Greek letters

φ	Volume fraction
μ	Viscosity ($Pa.s$)
β	Thermal expansion coefficient ($1/K$)
f_l	Liquid fraction
φ	Volume fraction of TCE
q	Heat flux
sf	Shape factor

Subscripts

ini	Initial
l	Liquidus
s	Solidus
m	Melting
$cpcm$	Composite phase change material
$hcpcm$	Hybrid composite phase change material
np	Nanoparticles
eff	effective
ref	Reference
x	x -axis
y	y -axis

1. Introduction

The growing development and advancement in nanotechnology, the integration and miniaturization of integrated circuits (ICs) has shifted to high-density, smarter and faster with high local heat generation during operation. According to Moore's law, the number of transistors in microprocessors are growing exponentially because of the advancement in

6 semiconductor manufacturing technologies [1, 2]. The heat source (i.e., chip) is considered
7 highly intensive in miniaturized ICs. Thus, local heat dissipation is expected to vary between
8 600 to 1000 W/cm² in the next decades [3]. As a consequence, the technical performance
9 of ICs are diminished or even sometimes totally shut down if that internal heat generated
10 is not properly dissipated to the atmosphere. Therefore, for a safe, effective, and reliable
11 operation of micro ICs, the chip temperature or junction temperature (the temperature at
12 the silicon die) should be lower than the threshold value of 85 – 125 °C, depending on the
13 type of circuit board [4, 5]. For this purpose, an efficient and reliable thermal management
14 technology has become a must-have challenge beforehand. With the conventional solutions
15 for thermal management of electronics devices including natural convection and forced con-
16 vection, single/multi-phase active and passive cooling systems [6]. According to the contact
17 of cooling fluid, the cooling methods are classified as (i) direct contact and (ii) indirect
18 contact [7, 8], as shown in Fig. 1. Among different cooling methods, the air cooling with
19 forced convection is commonly used because of its simple assembly and low-cost advantages
20 compared to the liquid cooling with forced convection. In the last decade, the indirect
21 cooling method based on phase change materials (PCMs) filled heat sink has introduced a
22 new direction of heat dissipation from ICs as a passive cooling technique. With excellent
23 inherent thermophysical properties such as high specific heat, high latent heat, constant
24 phase-change temperature and good chemical stability of PCMs have proved a promising
25 passive cooling medium for the eat dissipation of electronic equipment [9]. However, the
26 lower thermal conductivities, paraffin-based PCMs, reduce the heat transfer rate during the
27 charging and discharging modes of PCMs.

28 To enhance the heat transfer rate through the PCM, the researchers and scientists have
29 adopted several approaches including extended surfaces [10–12], porous medium [13–15], and
30 high thermal conductive nanomaterials, called as thermal conductivity enhancers (TCEs)
31 [16–18]. The researchers further explored the effect of different geometric parameters of
32 these TCEs individually. For instance Kandasamy et al. [19] conducted an experimental
33 and numerical study for transient thermal management of plastic quad flat package (QFP)
34 electronic devices using PCM based heat sink of 6, 10 and 33 plate-fins. The lower heat sink
35 temperature was obtained with 33 plate-fin case. The higher discharging time was reported
36 compared with the charging time at input power of 2, 3, and 4 W. Fok et al. [20] conducted
37 an experimental study of plate-fins having 0, 3 and 6 number of fins of a PCM-filled heat
38 sinks under different operation modes such as frequent, heavy and light usages. The lower

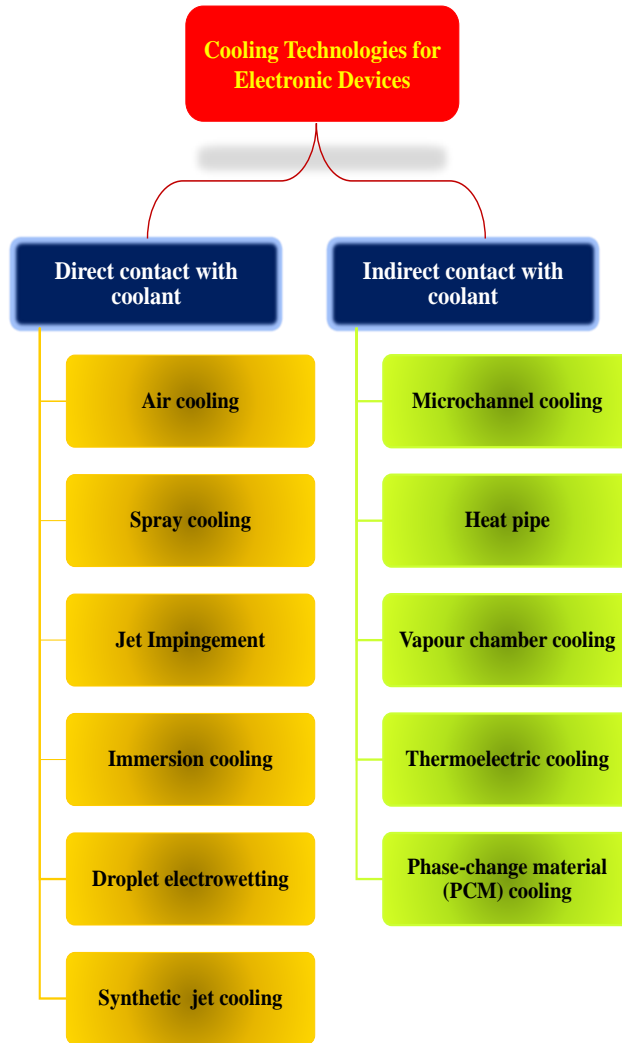


Figure 1: *Classification of commonly used thermal management methods [7, 8].*

39 heat sink base temperature and higher latent-heating phase completion duration were ob-
 40 tained with 6 number of plate-fin case. For all cases of usage, the less charging time of PCM
 41 was observed compared with the discharging time at different input power levels. Further,
 42 in another experimental study [21], they reported the charging time took approximately 120
 43 mins whereas, partial solidification phase was achieved even after 250 mins of a PCM-filled
 44 heat sink at 5 W. Yang and Wang [22, 23] conducted a numerical study to validate the
 45 experimental results of [20, 21]. A good agreement in validation results with experimental
 46 data was achieved and only the results of the charging mode were presented. Baby and Bal-
 47 aji [24] investigated the PCM filled plate-fin and pin-fin configurations of constant volume
 48 fraction of 9% and found that pin-fin heat sink had better thermal performance compared
 49 with plate-fin heat sink filled with PCM. Further, they investigated the different number of

50 fins of 33, 72 and 120 of PCM-based pin-fin heat sink [25]. The authors found the highest
51 enhancement factor of 24 with 72 pin-fin heat sink filled with n-eicosane compared with a
52 heat sink without fins at 7 W. The authors reported a charging time of 160 mins, whereas
53 the discharging phase did not complete even after 270 mins. Mahmoud et al. [26] conducted
54 an experimental study using 3, 6, 9, 36 and honeycomb cavities configuration PCM filled
55 plate-fin heat sinks. The higher heat transfer performance was obtained with honeycomb
56 configured PCM based heat sink during melting and cooling processes. The charging phase
57 duration was reported as 60 mins at 3, 4 and 5 W, whereas the discharging phase took 160
58 mins to reach the ambient temperature at a 3 W power level. Arshad et al. [27] analyzed the
59 impact of fin thickness on PCMs. According to the results, with the change of fin height, the
60 volume fraction was also varied. The best cooling performance was obtained using 2 mm fin
61 thickness at 1.0 volume fraction of PCM and also, number of fins have great impact on the
62 effectiveness of PCM heat sinks. Further, they investigated the thickness of 2 mm square
63 and 3 mm circular fins PCM heat sinks and found that 3 mm circular pin-fin PCM filled
64 heat sink had the better thermal cooling performance [28, 29]. Ali et al. [30] experimentally
65 investigated the different configurations such as triangular, rectangular and circular pin-fins
66 heat sink filled with paraffin wax and n-eicosane filled. The authors revealed that triangular
67 pin-fin configuration was the most effective compared with rectangular and circular pin-fins
68 because of higher number fins and lower surface area ratio. Debich et al. [31] conducted a
69 numerical study of a circular pin-fin heat sink filled with paraffin wax at a constant heat
70 flux. The results of baseline and optimum designs are compared for both charging and
71 discharging cases. It was found that the charging phase was completed after 120 min and
72 discharging phase did not complete even after 140 mins. Deng et al.[32] conducted a com-
73 prehensive experimental study using plate-fin heats sink having 2, 4 and 6 number of fins at
74 different heat fluxes. The authors found the complete charging and discharging in 90 and
75 410 mins, respectively. Mozafari and Lee [33] numerically studied the thermal cooling per-
76 formance of a dual-PCM based heat sink. The n-eicosane and RT-44 were filled inside the
77 plate-fin heat sink and results of charging and discharging were presented at constant heat
78 flux. The complete charging of PCMs was reported after 64 mins whereas discharging time
79 was reported of around 124 mins. Sivashankar and Selvam [34] conducted an experimental
80 study based on different configurations of pin-fins such as circular, square, hexagonal and
81 triangular and PCMs of different melting point temperatures namely, OM35 and OM46. It
82 was reported that OM35 took 60 mins for charging duration, however, more than 200 mins

83 were taken in discharging phase and it did not completely solidify. Kalbasi [35] conducted
84 a numerical study to investigate the three different types of PCM-based plate-fin heat sinks
85 under varying input power levels and different heat transfer coefficients. The author found
86 that the performance of hybrid heat sink was acceptable. During the pre-melting phase, the
87 heat rejection and heat storage were 54.55% and 45.45%, respectively.

88 Recently, the integration of nanoparticles, metal foams, and pin-fins with PCM were re-
89 ported by different researchers under constant charging and discharging operations. Praveen
90 et al. [36] conducted an experimental study to study the heat transfer performance of mi-
91 croencapsulated PCM (MEPCM) based graphene nano-platelets and paraffin in a finned
92 heat sink. The authors found the charging durations of PCM and MEPCM of around 70
93 and 90 mins, respectively. However, there was no complete discharging achieved till at 180
94 mins for both PCM and MEPCM. Arshad et al. [37, 38] conducted a numerical study to
95 investigate the combine effect of metal-foam, nanoparticles and PCM. The detailed natural
96 convection heat transfer and melting phenomenon of Cu nanoparticles of different volume
97 fraction of 1%, 3% and 5% dispersed into PCM were studied. A heat transfer enhancement
98 of 2.86%, 2.19% and 1.63% with 1%, 3% and 5% volume fraction of Cu nanoparticles, re-
99 spectively. Further, the authors found that Cu metal-foam and fully filled heat sink with
100 PCM showed the better heat transfer rate. The Cu nanoparticles of 1% volume fraction
101 exhibited the optimum volume fraction in comparison with 3% and 5% with metal-foam and
102 PCM. A lower melting time reduction of 18.10% and higher rate of heat transfer of 8.12%
103 were obtained with 1% Cu nanoparticles. Hassan et al. [39] used the graphene nanoplatelets
104 (GNPs) and magnesium oxide (MgO) nanoparticles with PT-58, used as a PCM to develop
105 the cPCM, and filled into copper foam having a porosity of 97%. It was concluded that
106 GNPs/PCM based nano-PCM effectively reduced heat sink base temperature. The max-
107 imum reduction was obtained of 16% and 13.1% in case of GNPs/PCM/copper-foam and
108 MgO/PCM/copper-foam, respectively at 0.02 wt.% nanoparticles loading and 1.54 kW/m²
109 input heat flux. The authors reported that charging phase of PCM and nano-PCM com-
110 pleted after 90 mins, whereas there was no complete solidification occurred even after 100
111 mins. Fayyaz et al. [40] used the multi-walled carbon nanotubes (MWCNTs) as nanoparti-
112 cles and dispersed in RT-42, used as a PCM, and filled in circular, square, and triangular-
113 shaped pin-fin heat sinks. The results revealed that circular pin-fin heat sink showed the
114 best thermal performance with based temperature reduction of 20.40% and 25.83% at 3 wt%
115 and 6 wt% of MWCNTs in PCM, respectively. The charging phase duration was reported

116 at 167 mins, whereas the discharging phase duration was longer than 250 mins. Zahid et al.
117 [41] worked on the analysis of thermal behavior on different heat fluxes using square pin-fin,
118 metal-foam and empty heat sink with Al_2O_3 and RT-54HC. They concluded that there was
119 a significant drop in base temperature with increase in mass fraction of Al_2O_3 nanoparticles
120 with Cu metal-foam heat sink. At input heat fluxes, the maximum enhancement in the
121 working time of Cu metal-foam heat sink against 0.25 wt.% of NPs was 288%, 223.81%, and
122 202.56%, respectively.

123 A clear reflection from previous literature can be revealed that authors only conducted the
124 passive cooling scheme by using fins, extended surfaces, porous medium, and nanomaterials
125 either separately or collectively. To the best of the author's knowledge, no single study has
126 been reported which explores the effects of fins, hybrid nanoparticles and external forced
127 convection, cumulatively. In the current study, a combination of active and passive cooling
128 technologies is presented by combining the air-cooled and PCM-cooled thermal management
129 systems, as shown in Fig. 1. A numerical study is presented to combine air, nanoparticles,
130 fins and PCM under natural and forced convection operating conditions to study the con-
131 ventional air cooling and novel hybrid composite PCMs (HcPCMs) cooling techniques under
132 constant heating loads. In addition, this study explores a combined effect of active-passive
133 novel cooling technology based on the idea of latent heat thermal energy storage system for
134 the efficient cooling of electronic devices.

135 **2. Theoretical Methodology**

136 *2.1. Problem description*

137 A conventional finned heat sink is used in the current study, adopted for the cooling
138 of electronic components, and three different cases: (i) air-cooled, (ii) HcPCM-cooled, and
139 (iii) hybrid (air-HcPCM) cooled finned heat sinks, as shown in Figure 2, are investigated
140 numerically to explore the effect of natural and forced convection heat transfer performance
141 at constant heating. A heat sink made of aluminium and a constant volume fraction of fins is
142 chosen having high thermal conductivity and is lighter in weight. The hybrid nanoparticles
143 of carbon additives, graphene oxide (GO), and multi-walled carbon nanotubes (MWCNTs)
144 are selected because of their higher thermal conductivity and also these nanoparticles belong
145 to carbon family as the selected PCM, RT-35HC, which makes a more stable and uniform
146 mixture of cPCMs practically compared to the metallic or metallic-oxide nanoparticles with

147 paraffin based PCMs [18]. The volume fraction (φ) of graphene oxide (GO) and multi-
 148 walled carbon nanotubes (MWCNTs) are chosen of 0%, 2%, 4%, and 6%. The heat flux (q)
 149 is varied from 25, 30, 35, and 40 kW/m² at the base of the heat sink. The thermophysical
 150 properties of aluminium, RT-35HC, GO and MWCNTs are provided in Table 1. The overall
 151 dimensions of the heat sink are 70 × 70 × 25 mm³ with walls and fin thickness of 5 and 2
 152 mm, respectively, and the base of 5 mm where the constant heat flux is provided. Figure 3
 153 shows the physical domain used with all boundary constraints to achieve the core objective
 154 of the current study.

Table 1: Thermophysical properties of RT-35HC, Aluminum, GO and MWCNTs [42, 43].

Property	RT-35HC	Aluminum	GO	MWCNTs
T_m (K)	308.15	-	-	-
T_l (K)	309.5	-	-	-
T_s (K)	306.5	-	-	-
L (J/kg)	240,000	-	-	-
ρ (kg/m ³)	825	2719	1800	2100
c_p (J/kg.K)	2000	871	717	630
k (W/m.K)	0.2	202.37	5000	3000
β (1/K)	0.0006	-	-	-
μ (Pa.s)	0.0235	-	-	-

155 2.2. Mathematical modeling

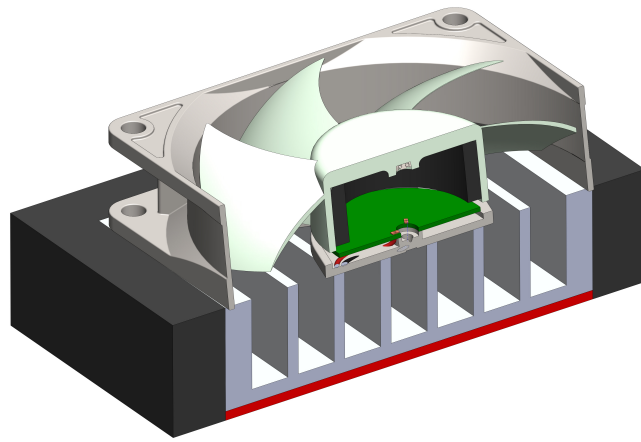
156 The conjugate heat transfer is considered to model the current phase-change heat trans-
 157 fer inside the heat sink between the PCM and hybrid nanoparticles. The heat transfer
 158 purely conduction through the finned heat sink. The thermophysical properties of the heat
 159 sink, HcPCM and nanoparticles remained constant. The liquid HcPCM is assumed as lam-
 160 inar, transient, and incompressible. The melting/solidification phenomenon of HcPCM is
 161 modeled as enthalpy-porosity formulation. The following governing equations are used to
 162 solve the continuity, momentum, and energy equations for the proposed problem [44, 45]:

Continuity:

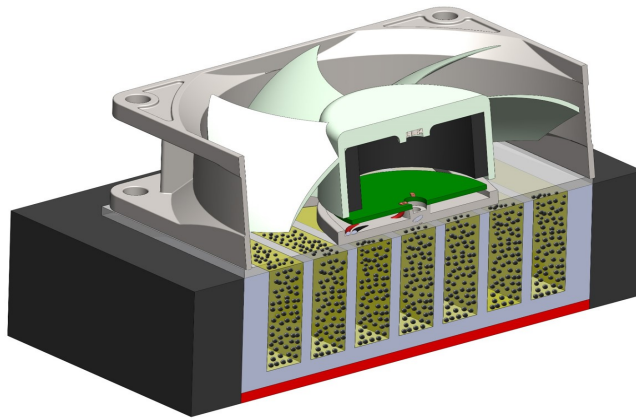
$$\nabla \cdot \vec{V} = 0 \quad (1)$$

Momentum:

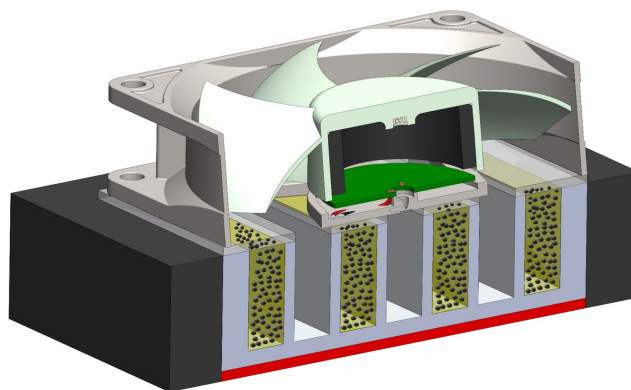
$$\rho_{hcpcm} \frac{D\vec{V}}{Dt} = -\nabla p + \mu_{hcpcm} \nabla^2 \vec{V} + \vec{S} + \vec{F}_b \quad (2)$$



(a)



(b)



(c)

Figure 2: An isometric cross-sectional view of (a) air-cooled finned heat sink, (b) HcPCM cooled finned heat sink and (c) hybrid (air-HcPCM) finned heat sink assembly.

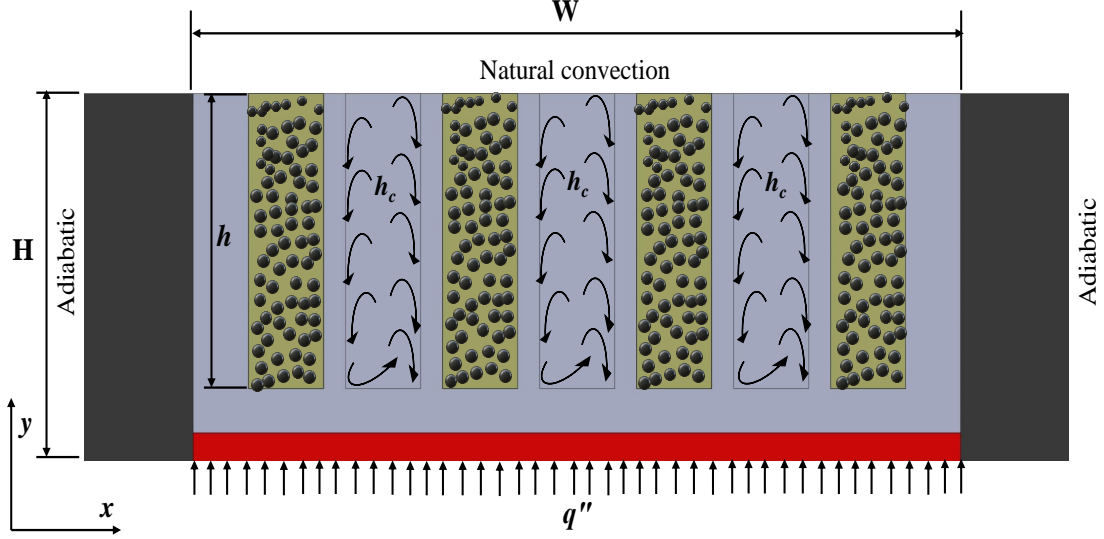


Figure 3: Schematic diagram of the physical domain.

Energy:

$$(\rho C_p)_{hcpcm} \frac{DT}{Dt} = \nabla \cdot (k_{hcpcm} \nabla T) \quad (3)$$

Here, ρ_{hcpcm} is the density, t is the time, p is the pressure, μ_{hcpcm} is the dynamic viscosity, $(\rho C_p)_{hcpcm}$ is the thermal capacitance and k_{hcpcm} is the thermal conductivity of HcPCM. The \vec{S} is Darcy's momentum mentioned in Equation 2, which can be defined as follows:

$$\vec{S} = -A_{mush} \frac{(1 - l_f)^2}{l_f^3 - \varepsilon} \cdot \vec{V} \quad (4)$$

Where, A_{mush} is a constant number (10^5) that illustrates the morphology of the mushy zone [46] and $\varepsilon = 0.001$ is only a constant value applied to avoid dividing by zero. Moreover, l_f is the liquid fraction of the PCM in the mushy region, and can be defined as:

$$l_f = \begin{cases} 0 & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s} & \text{if } T_s < T < T_l \\ 1 & \text{if } T > T_l \end{cases} \quad (5)$$

The \vec{F}_b in Equation 2 is the body force which is defined as follows:

$$\vec{F}_b = F_{bx} \vec{i} + F_{by} \vec{j} \quad (6)$$

Here,

$$F_{bx} = 0 \quad F_{by} = -\rho_{ref} g \beta (T - T_{ref}) \quad (7)$$

Where, g is the gravitational body acceleration, T_{ref} is the reference temperature, and β is the thermal expansion coefficient has a value of $\beta = 0.0006 \text{ K}^{-1}$ [47, 48]. The term $-\rho_{ref} g \beta (T - T_{ref})$ is the Boussinesq approximation.

The specific heat (c_{phcpcm}) of HcPCM in Equation 3 can be defined as follow:

$$c_{phcpcm} = \begin{cases} c_{phcpcm_s} & \text{if } T < T_s \\ c_{peff} = c_{phcpcm_s} (1 - l_f) + c_{phcpcm_l} (l_f) + \frac{\Delta H_{hcpcm}}{T_l - T_s} & \text{if } T_s < T < T_l \\ c_{phcpcm_l} & \text{if } T > T_l \end{cases} \quad (8)$$

Here, c_{phcpcm_s} , c_{phcpcm_l} , T , T_s , T_l , and ΔH_{hcpcm} are the solid specific heat, liquid specific heat, average temperature, solidus temperature, and liquids temperature, and fractional latent-heat of the HcPCM, respectively.

The addition of hybrid carbon additives (GO+MWCNTs) into the PCM (RT-35HC) vary its thermophysical properties as the volume fraction of GO+MWCNTs is increased from 0% to 6%. The effective properties such as density (ρ_{hcpcm}), specific heat capacity (c_{phcpcm}), latent-heat of fusion (L_{hcpcm}), thermal expansion coefficient (β_{hcpcm}), dynamics viscosity (μ_{hcpcm}), and thermal conductivity (k_{hcpcm}) of HcPCMs are calculated using theoretical models of mixtures as follows [43, 49]:

$$\rho_{hcpcm} = \varphi_2 \rho_{np_2} + [(1 - \varphi_2) \{ \varphi_1 \rho_{np_1} + (1 - \varphi_1) \rho_{pcm} \}] \quad (9)$$

$$(\rho c_p)_{hcpcm} = \varphi_2 (\rho c_p)_{np_2} + [(1 - \varphi_2) \{ \varphi_1 (\rho c_p)_{np_1} + (1 - \varphi_1) (\rho c_p)_{pcm} \}] \quad (10)$$

$$(\rho L)_{hcpcm} = (1 - \varphi_1) (1 - \varphi_2) (\rho L)_{pcm} \quad (11)$$

$$(\rho \beta)_{hcpcm} = \varphi_2 (\rho \beta)_{np_2} + [(1 - \varphi_2) \{ \varphi_1 (\rho \beta)_{np_1} + (1 - \varphi_1) (\rho \beta)_{pcm} \}] \quad (12)$$

$$\mu_{hcpcm} = \frac{\mu_{pcm}}{(1 - \varphi_1)^{2.5} (1 - \varphi_2)^{2.5}} \quad (13)$$

$$\frac{k_{hcpcm}}{k_{pcm}} = \frac{k_{np_2} + (sf - 1)k_{pcm} - (sf - 1)(k_{pcm} - k_{np_2})\varphi_2}{k_{np_2} + (sf - 1)k_{pcm} + (k_{pcm} - k_{np_2})\varphi_2} \quad (14)$$

where:

$$\frac{k_{cpcm}}{k_{pcm}} = \frac{k_{np_1} + (sf - 1)k_{pcm} - (sf - 1)(k_{pcm} - k_{np_1})\varphi_1}{k_{np_1} + (sf - 1)k_{pcm} + (k_{pcm} - k_{np_1})\varphi_1} \quad (15)$$

163 In above Equations 9–15, φ_1 and φ_2 represent the volume fractions of nanoparticles of type
 164 1 and nanoparticles of type 2, respectively. The subscripts $hcpcm$, np , pcm , np_1 and np_2
 165 refer to the HcPCM, nanoparticles, PCM, nanoparticles of type 1 and nanoparticles of type
 166 2, respectively.

167 2.3. Mesh independency

168 The grid independence test has been conducted to find the optimum mesh size of the
 169 heat sink to avoid the effects of numerical accuracy and to reduce the computational cost.
 170 The four different mesh categories such as normal, fine, finer, and extra finer of element
 171 sizes of 4643, 6636, 10111 and 19004, respectively, of a PCM-cooled heat sink to consider
 172 the effects of both air and PCM, cumulatively. The results of average heat sink temperature
 173 and liquid fraction for selected meshes sizes are presented in Figures 4a and 4b, respectively.
 174 From Figure 4, it can be seen that there is no significant difference between normal to extra
 175 finer meshes in average heat sink temperature and liquid fraction. This is because of the low
 176 PCM upfront velocity and thermal front movement which reflects a low Peclet number and
 177 Courant number situation. Since, the deviation between extra finer and finer mesh sizes is
 178 minimum, thus the finer mesh with element size 10111 is chosen for further simulation in
 179 current study. In similar pattern, the optimum mesh size is considered for air-cooled and
 180 hybrid cooled finned heat sinks.

181 2.4. Numerical method and validation

182 The governing equations Eqs. 1–8 are solved using a finite element method (FEM)
 183 based computational tool, COMSOL Multiphysics. The problem is computed for a linear
 184 set of equations with Parallel Direct Sparse Solver Interface (PARDISO) in fully-coupled
 185 automated reordering algorithm mode. Implicit backward differentiation formula (BDF)
 186 is used for time-stepping with automatic step size selection between BDF order 1-2. The
 187 tolerance termination technique is adapted where custom relative tolerance value 10^{-4} is
 188 used for all outcome variables. A backward Euler method with 10^{-3} fraction for initial step
 189 is used for consistent initialization of the algebraic variables.

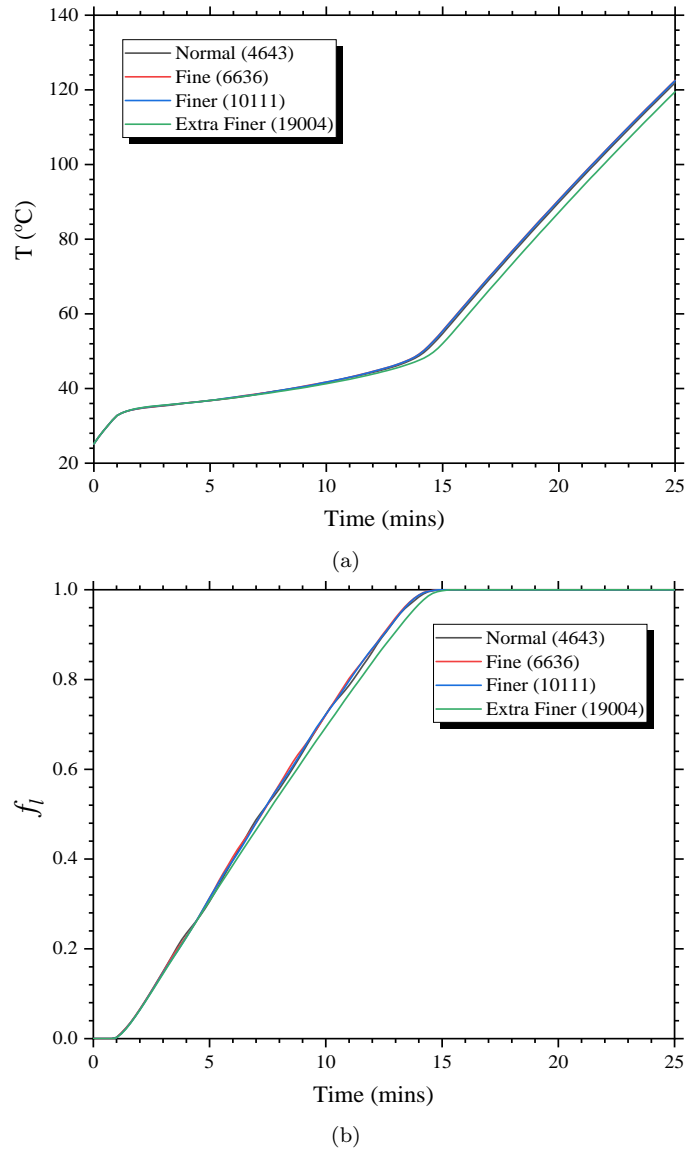


Figure 4: Mesh independence results of (a) average heat sink temperature (b) liquid fraction with time, for different meshes.

190 The present results of liquid fraction, to validate the current developed governing model,
 191 are validated a comparison to the results of with Sunku Prasad et al. [44]. Figure 5 presents
 192 the results of f_l against the time at power level of 12 W and RT-35HC is used as PCM,
 193 filled in a plate-fin heat sink. A good agreement can be seen between current numerical
 194 and reported results of PCM melting process. The present results of f_l is validated with
 195 experimental results of the PCM (lauric acid) and fin combination reported by Kamkari
 196 and Shokouhmand [48], as shown in Fig. 6. A rectangular domain with 3 fins at 90° is
 197 considered with an interior of 50 mm in width, 120 mm in height and 120 mm in depth.
 198 An input wall temperature of 70°C is applied and the results of the melting processes are
 199 compared. A good agreement is obtained between the numerical and experiment results

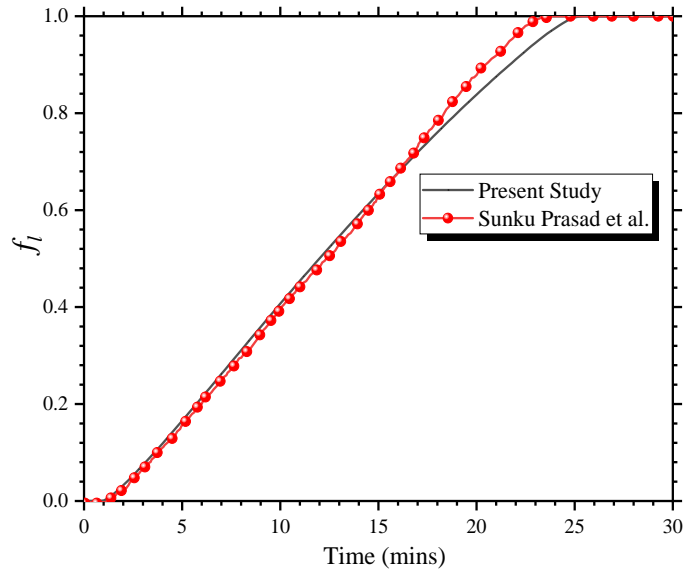


Figure 5: Validation of present numerical results of the liquid fraction compared with Sunku Prasad, et al. [44].

200 of lauric acid f_l . The variations in results may be due to radiation and conduction heat transfer and PCM properties varying in experimentation with temperature and time.

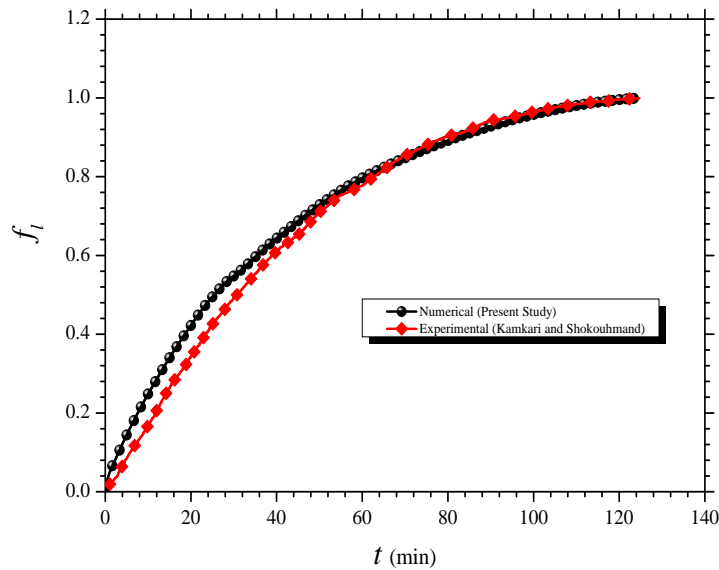


Figure 6: Validation of present numerical results with experimental results by Kamkari and Shokouhmand [48].

201

202 3. Results and discussion

203 3.1. Performance of air-cooled finned heat sink

204 The cooling performance of an air-cooled finned heat sink is presented in Figure 7 by
 205 varying the different heat fluxes (q) and convective heat transfer coefficient (h_c). The values
 206 of q are varied as 25, 30, 35, and 40 kW/m² as shown in Figures 7a, 7b, 7c, and 7d,

207 respectively, at different h_c of 10, 20, 30, 40, 50, and 100 W/m².K. As expected, the effect of
 208 h_c for each heat flux clearly shows that the increasing h_c reduces the overall temperature of
 209 the heat sink. This shows that the effects of forced convection heat transfer mode ($h_c > 10$)
 210 are more predominant on the cooling performance of the heat sink compared with the natural
 211 convective heat transfer mode ($h_c \leq 10$). During the natural convective heat transfer, the
 212 heat sink cools or dissipates the excessive heat generated by the electronic components under
 213 natural convection effects i.e. without the effect of external force and air motion is caused
 214 by buoyancy. As a result of this, the temperature of the heat sink rises dramatically initially
 215 and remains constant around 15 min till the end. Whereas, during the forced convective
 216 heat transfer, in case of $h_c > 10$, the heat sink transfers the internal heat due to the effect
 217 of external forced flow of air. Thus, the external flow of air flowing through the heat sink
 218 fins reduce the heat sink base temperature that can be clearly seen in all cases presented in
 219 Figures 7a-7d as the h_c varies from 10 to 100 W/m².K. Furthermore, it can be revealed from
 220 Figures 7a-7d that the lowest heat sink temperature is obtained in case of $h_c = 100$ W/m².K
 221 which is as expected. However, it also reveals clearly that at $h_c = 40$ and $h_c = 50$ W/m².K,
 222 the heat sink temperature lies between $\approx 30 - 40^\circ\text{C}$, which is the optimum average body
 223 temperature range for a human [50]. The effect of temperature distribution at different
 224 heat fluxes of q 25, 30, 35, and 40 kW/m² under natural convection heat transfer coefficient
 225 ($h_c = 10$ W/m².K) is shown in Figure 7e. Temperature distribution clearly shows that with
 226 the increase of q the heat sink temperature increases, as expected. There is a sharp increase
 227 in the heat sink temperature initially because of higher heat capacity. However, it reaches
 228 a contact level because of thermal inertia, since at this point, the heat sink stores the heat
 229 rather than to transfer it.

230 3.2. Performance of HcPCM-cooled finned heat sink

231 The temperature variations at different volume fractions ($\varphi = 0\%$, 2%, 4%, and 6%) of
 232 hybrid nanoparticles (GO+MWCNTs), different h_c of 10, 20, 30, 40, 50, and 100 W/m².K
 233 and $q = 40$ kW/m² are shown in Figure 8a-8d. Two major significances occurred during
 234 the melting of HcPCM inside the finned heat sink as the h_c is applied at the top surface
 235 of the heat sink. Firstly, it can be seen clearly that with the increase of h_c the heat sink
 236 temperature decreases and minimum temperature is achieved at $h_c = 100$ W/m².K, as
 237 expected. Secondly, the latent heating phase is also increased as the h_c increases from 10 to
 238 100 W/m².K. This is because of higher heat transfer from the heat sink base towards the

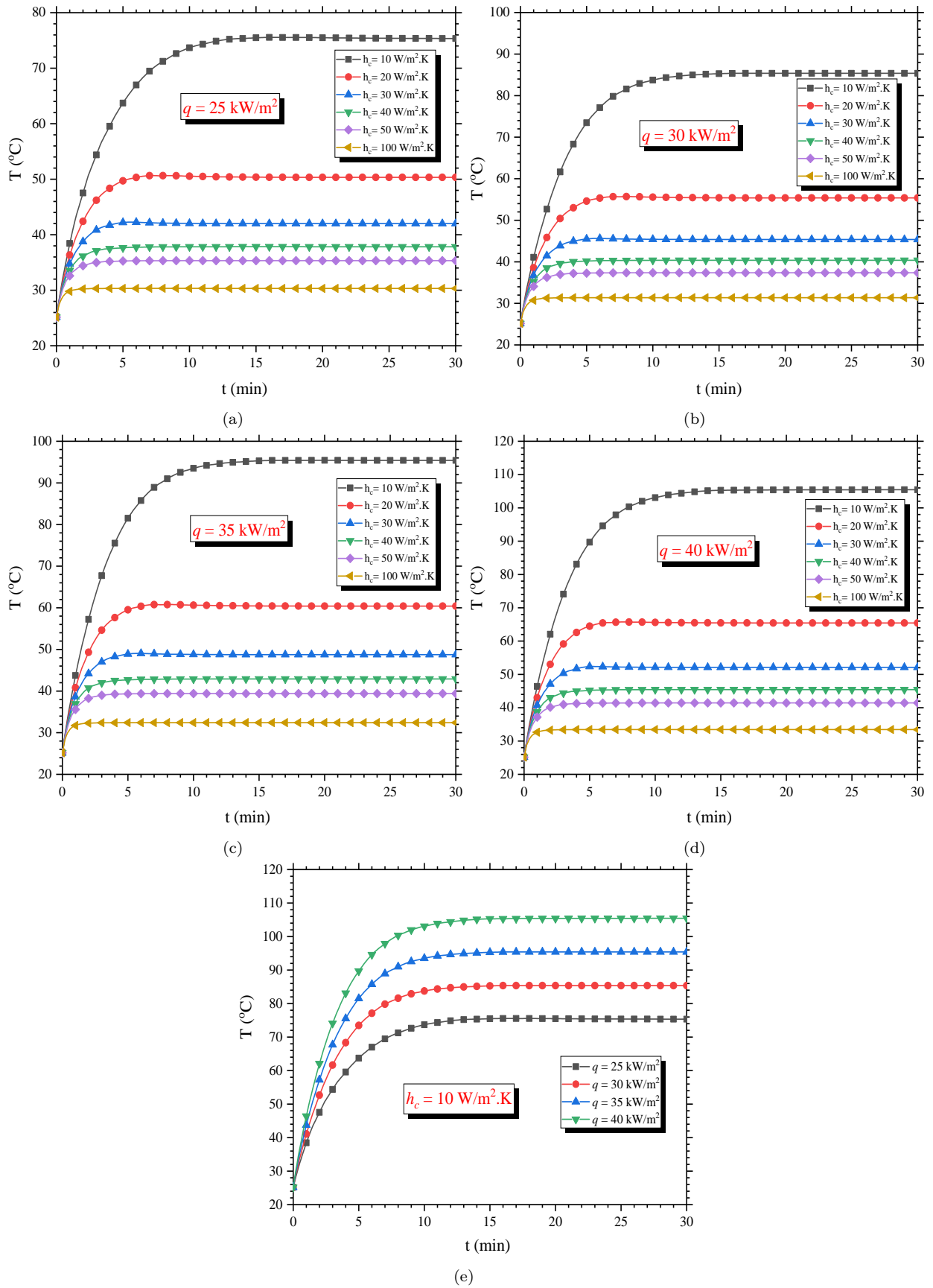


Figure 7: Temperature-Time variations of air-cooled finned heat sink under various q and h_c : (a) $q = 25 \text{ kW/m}^2$, (b) $q = 30 \text{ kW/m}^2$, (c) $q = 35 \text{ kW/m}^2$, (d) $q = 40 \text{ kW/m}^2$ and (e) $h_c = 10 \text{ W/m}^2.K$.

239 ambient due to the effect of forced convective heat transfer coefficient ($h_c > 10 \text{ W/m}^2\text{.K}$)
 240 compared to the natural convective heat transfer coefficient ($h_c \leq 10 \text{ W/m}^2\text{.K}$). The melt
 241 fraction (l_f) distribution of HcPCM based finned heat sink of hybrid nanoparticles dispersion
 242 at different $\varphi =$ is presented in Figure 9 under natural and forced heat transfer heating
 243 environments. It can be seen from Figures 9a-9d that in all cases of φ , l_f is decreased
 244 with the increase of h_c from natural to forced convection heat transfer conditions. This
 245 shows that the melting time (t_m) of HcPCM is enhanced resulting in extended the latent
 246 heating phase duration. There is no significant variation in l_f during before and after
 247 sensible heating mode, however, the HcPCM melting variation becomes significance while
 248 the HcPCM reaches the phase of complete melting. The effect of forced convection heat
 249 transfer mode shows that melting of the HcPCM is delayed and increases the heat transfer
 250 rate resulting in it reducing the heat sink base temperature. The comparison of all cases of
 251 $\varphi = 0\%$, 2% , 4% , and 6% at $h_c = 10 \text{ W/m}^2\text{.K}$ and constant heating is presented in Figure 10a
 252 and 10b for heat sink base temperature and melting performance, respectively. From Figure
 253 10a, it can be revealed that the addition of GO+MWCNTs hybrid nanoparticles reduces the
 254 heat sink base temperature. Although, that reduction in heat sink temperature is not so
 255 significant, however, nanoparticles enhanced the temperature distribution and uniformity of
 256 HcPCM melting. Furthermore, it can also be seen that as the φ is increased from 0% to 6%
 257 the latent heating phase is shortened and heat sink base temperature is increased during the
 258 post-sensible melting phase. The comparison of φ represented in Figure 10b shows that l_f
 259 is increased as the φ increases from 0% to 6% resulting in a reduction of the t_m of HcPCM.

260 3.3. Performance of hybrid HcPCM cooled finned heat sink

261 The cooling performance of a hybrid (air-HcPCM) finned heat sink (as shown in Figure
 262 2c) operating under different h_c and φ at constant heating of $q = 40 \text{ kW/m}^2$ is presented
 263 in Figure 11. A clear evidence can be seen that the thermal performance of a hybrid heat
 264 sink integrated with HcPCM and forced flow through the fins immensely is improved in
 265 terms of reduction of the heat sink base temperature. A clear difference in the drop of heat
 266 sink temperature can be seen in each case shown in Figures 11a-11d due the effect of h_c .
 267 In addition to this, there is less or no significant phase change effect observed at $h_c = 100$
 268 $\text{W/m}^2\text{.K}$ of HcPCM which means the amount of heat energy that the hybrid heat sink is
 269 absorbing from the electronic component is releasing approximately equal to that amount
 270 of heat energy towards the ambient. This is eventually maintaining the heat sink base tem-

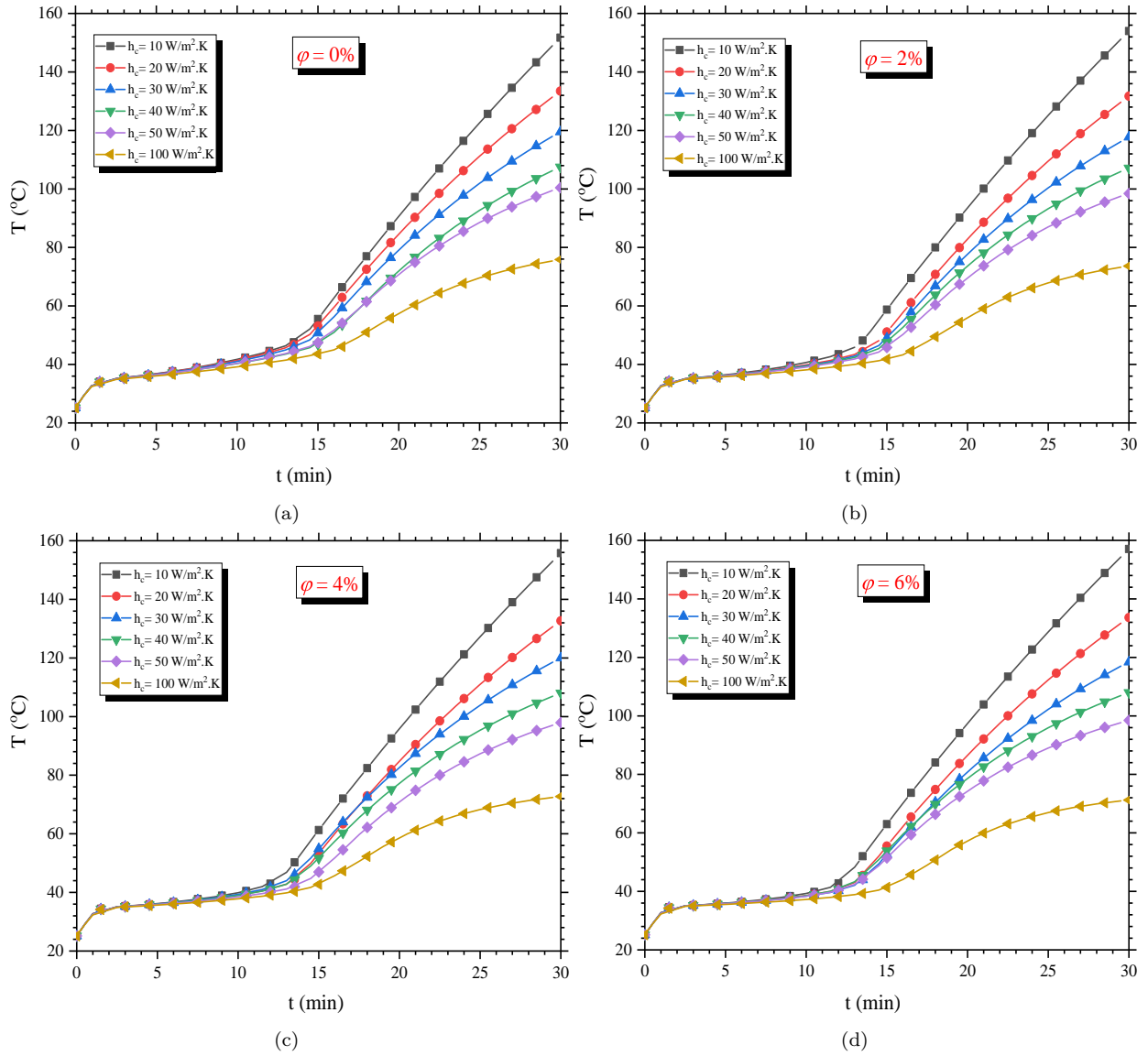


Figure 8: Temperature-Time variations of HcPCM cooled finned heat sink under various $\phi =$ (a) 0%, (b) 2%, (c) 4%, and (d) 6%.

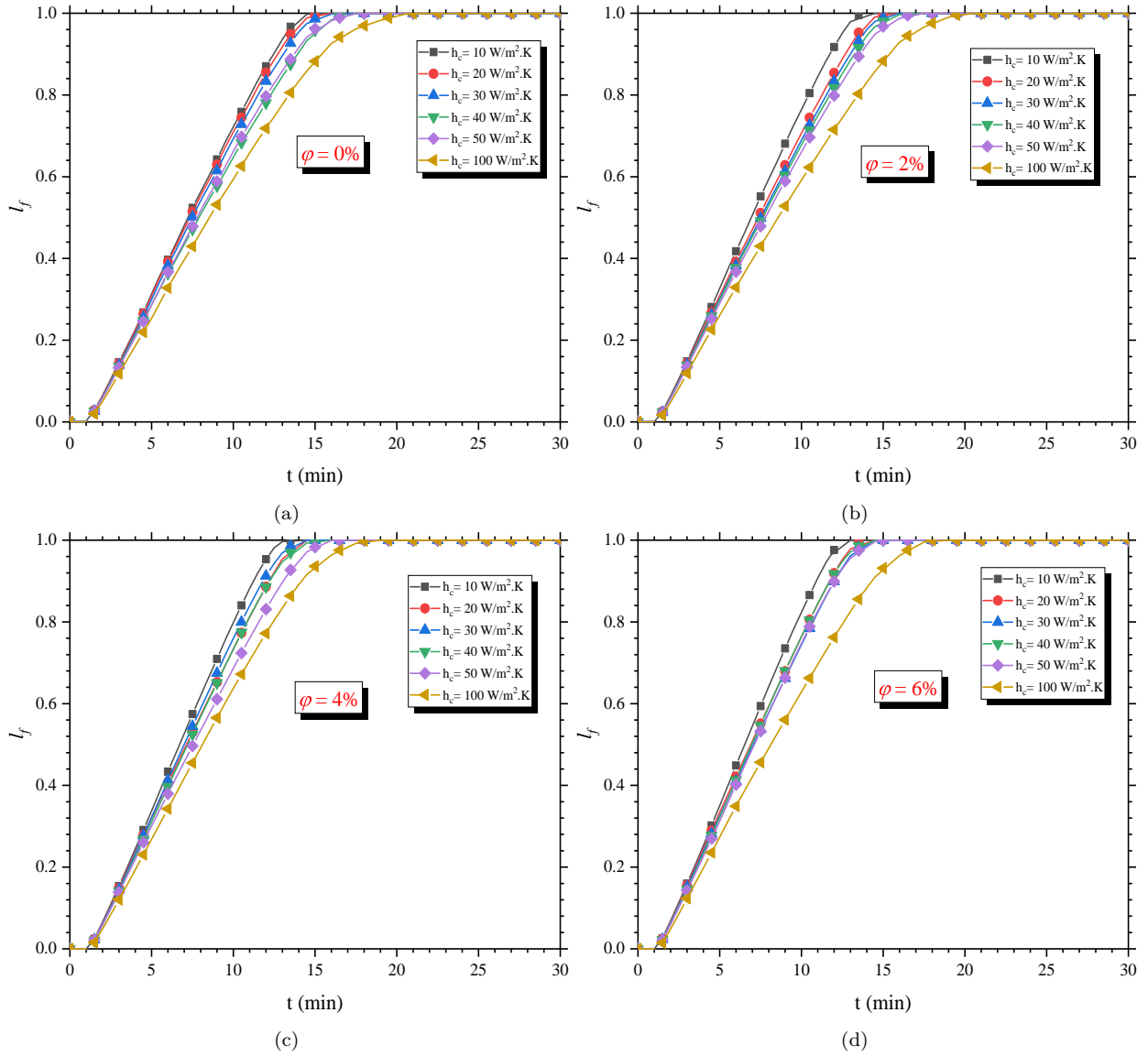


Figure 9: The l_f variations of HcPCM cooled finned heat sink under various $\varphi =$ (a) 0%, (b) 2%, (c) 4%, and (d) 6%.

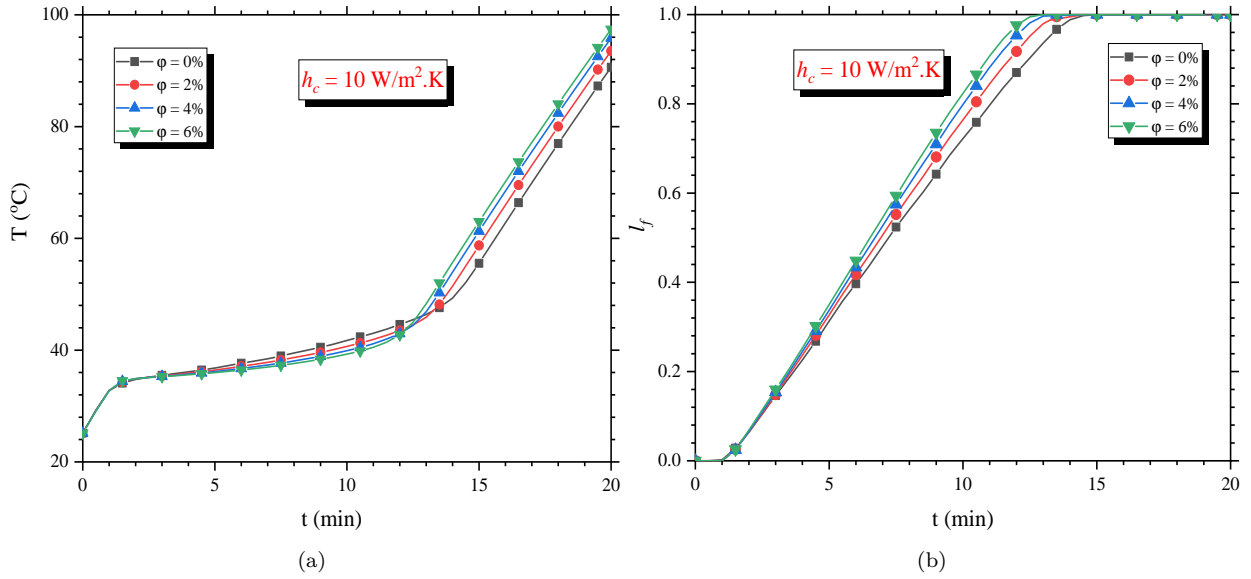


Figure 10: (a) Time histories and (b) l_f of HcPCM cooled finned heat sink temperature under various φ at $h_c = 10 \text{ W/m}^2.\text{K}$.

271 perature within a safe operating limit and provides the highest cooling performance. The
 272 latent heating phase of HcPCM filled in finned heat sink is extended with the increase of
 273 h_c due to a higher heat transfer rate at each φ . At $\varphi = 0\%$, the slight change in the latent
 274 heating phase around 26 mins which is showing the starting of a post-sensible heating phase.
 275 However, at $\varphi = 2\%$, 4% , and 6% , there is no post-sensible heating phase is revealed till 30
 276 mins of operation and only latent heating phase continues. This shows the effect of forced
 277 convection heat transfer by applying an additional cooling media such as air in the present
 278 case shows the more efficient and higher thermal cooling enhancement. The melting distri-
 279 bution of HcPCM in hybrid heat sink in terms of l_f is presented in Figure 12 at different
 280 h_c and φ . It is shown in Figures 12a-12d that l_f is decreasing and t_m is increasing with the
 281 increase of h_c from 10 to $100 \text{ W/m}^2.\text{K}$. Furthermore, it is revealed that only in the case of
 282 $\varphi = 0\%$ l_f reaches to the value of 1, means HcPCM completely melts at $h_c = 100 \text{ W/m}^2.\text{K}$.
 283 However, in case of $\varphi = 2\%$, 4% , and 6% , l_f does not reaches to $l_f = 1$ at $h_c = 100 \text{ W/m}^2.\text{K}$
 284 which shows that there is no complete melting of HcPCM even after 30 min of heating.
 285 The comparison of $\varphi = 0\%$, 2% , 4% , and 6% of heat sink temperature and l_f at $h_c = 10$
 286 $\text{W/m}^2.\text{K}$ is shown in Figures 13a and 13b, respectively. There is a slight variation in heat
 287 sink temperature observed at $\varphi = 2\%$, 4% , and 6% during latent heating and post-sensible
 288 phases, however, the heat sink temperature is lower than $\varphi = 0\%$ in all cases. Similarly, the
 289 l_f variations show that l_f increases with the increase of φ at $h_c = 10 \text{ W/m}^2.\text{K}$. This shows
 290 that the latent heating phase duration or t_m is reduced with the addition of hybrid nanopar-

291 ticles of GO+MWCNTs. The presence of hybrid nanoparticles into the pure PCM reveal no
292 significance impact on the thermal performance. However, the addition of hybrid nanopar-
293 ticles especially carbon-additives improve the thermal conductivity, specific heat capacity,
294 reduce the latent heat capacity and enhance the uniformity while melting/solidification
295 phase transformation [18, 51].

296 This isotherm and streamline contours of temperature distribution of hybrid finned heat sink
297 integrated with HcPCM at $\varphi = 6\%$ are shown in Figure 14. The temperature distribution
298 at different time steps of 3, 6, 9, and 12 mins are presented for h_c of 10, 20, 30, 40, 50, and
299 100 W/m².K. A dominant effect of conduction heat transfer can be seen at the initial stage
300 of the heating. The higher temperature can be seen at the base of heat sink towards the
301 top side and lower temperature distribution is revealed between the fins filled with HcPCM.
302 The lower temperature is because of the absorption of heat by the HcPCM, supplied at the
303 base of heat sink, because of its latent heat of fusion. Additionally, the lower temperature
304 distribution can be seen on surface of fins subjected to the air flow through the fins. The
305 additional force flow of air, which acts as a act cooling, further increase the heat transfer
306 rate from the heat sink base and HPCM and fins network to towards the ambient. The
307 melting phenomenon of hybrid HcPCM finned heat sink is presented in Figure 15 subjected
308 of natural and forced convective heat transfer modes with h_c of 10, 20, 30, 40, 50, and 100
309 W/m².K. The hybrid nanoparticles of GO+MWCNTs of $\varphi = 6\%$ enhances the melting rate
310 over time during constant heating, however, the external effect of airflow reduces the melt-
311 ing rate which can be seen from Figure 15a-15d at $h_c = 10$ W/m².K and Figures 15u-15x at
312 $h_c = 100$ W/m².K. There is no complete melting of HcPCM at $h_c = 100$ W/m².K even at
313 12min of heating, whereas, HcPCM completely melts at 12min in case of $h_c = 10, 20, 30,$
314 and 40 W/m².K.

315 The isotherm and streamline contours of hybrid HcPCM finned heat sink filled at different
316 $\varphi = 0\%, 2\%, 4\%,$ and 6% subject to natural effect of $h_c = 10$ W/m².K are shown in Figure
317 16 at various time periods. Similarly, the melt fraction contours of hybrid HcPCM finned
318 heat sink filled at different $\varphi = 0\%, 2\%, 4\%,$ and 6% subject to natural effect of $h_c = 10$
319 W/m².K are shown in Figure 17 at various periods. The isotherm and streamlines contours
320 show the higher heat sink temperature at fins surfaces and lower temperature between the
321 cPCM filled fins. Moreover, with the increase of heating duration e.g. 3, 6, 9, and 12 mins
322 at a specific φ , the heat sink temperature increases and conduction heat transfer is the
323 dominant to transfer the heat inside the heat sink. However, the convection heat transfer is

324 the predominant mode to transfer the heat between the fins due to the external flow of air.
 325 Higher melt fraction of HcPCM is revealed with the increase of heating operation for each
 326 φ . Also, at a specific time period, with the increase of φ from 0% to 6%, the melt fraction is
 327 also increases at constant heating because of absorption of heat and showing the complete
 328 phase transformation process.

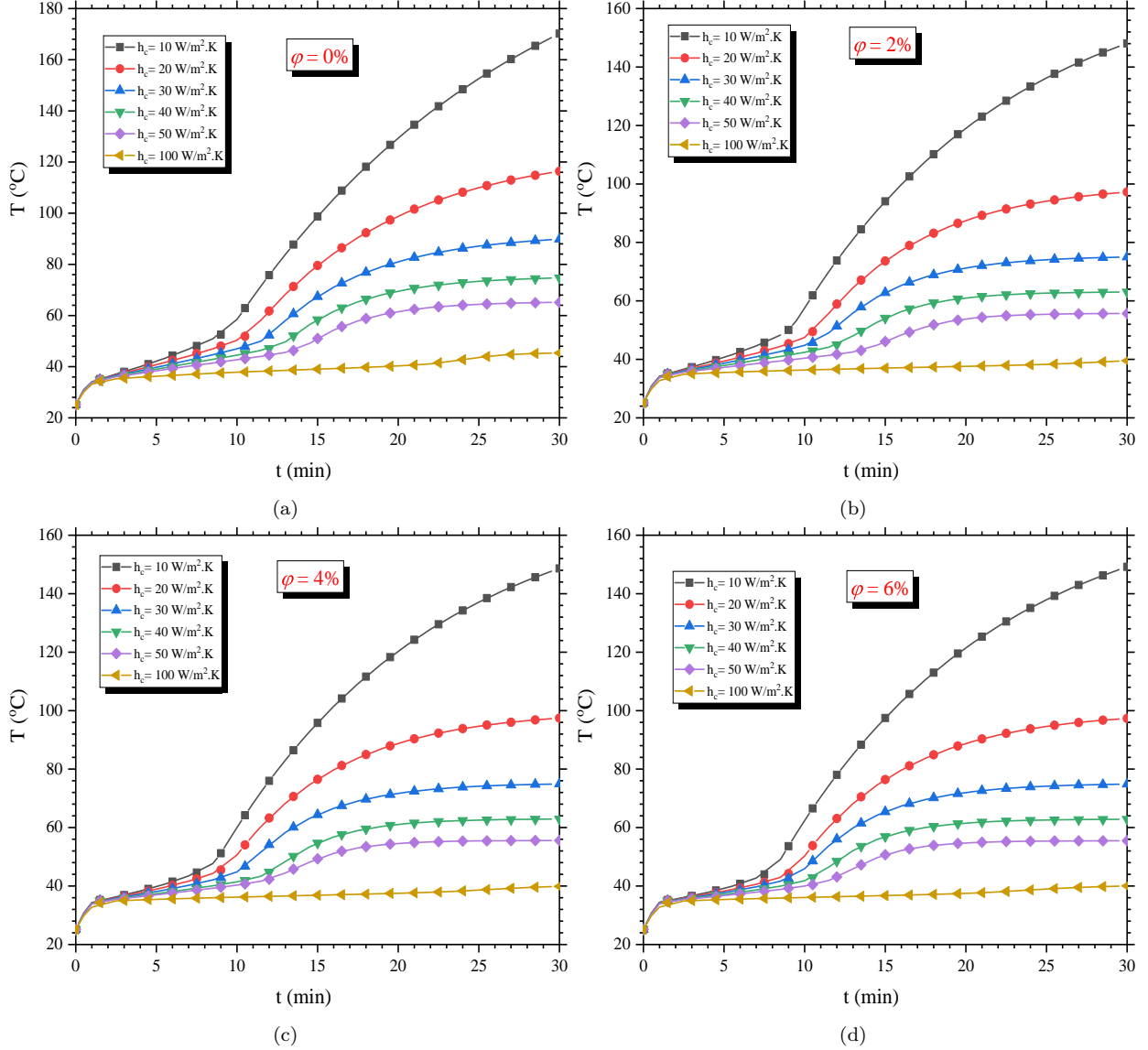


Figure 11: *Temperature-Time variations of hybrid HcPCM cooled finned heat sink under various $\varphi =$ (a) 0%, (b) 2%, (c) 4%, and (d) 6%..*

329 4. Conclusion

330 A transient two-dimensional numerical study is carried out with the idea of to integrate
 331 the active and passive cooling method in a novel thermal management technology for lower
 332 to medium heat flux dissipating electronic devices. The current study presents conventional

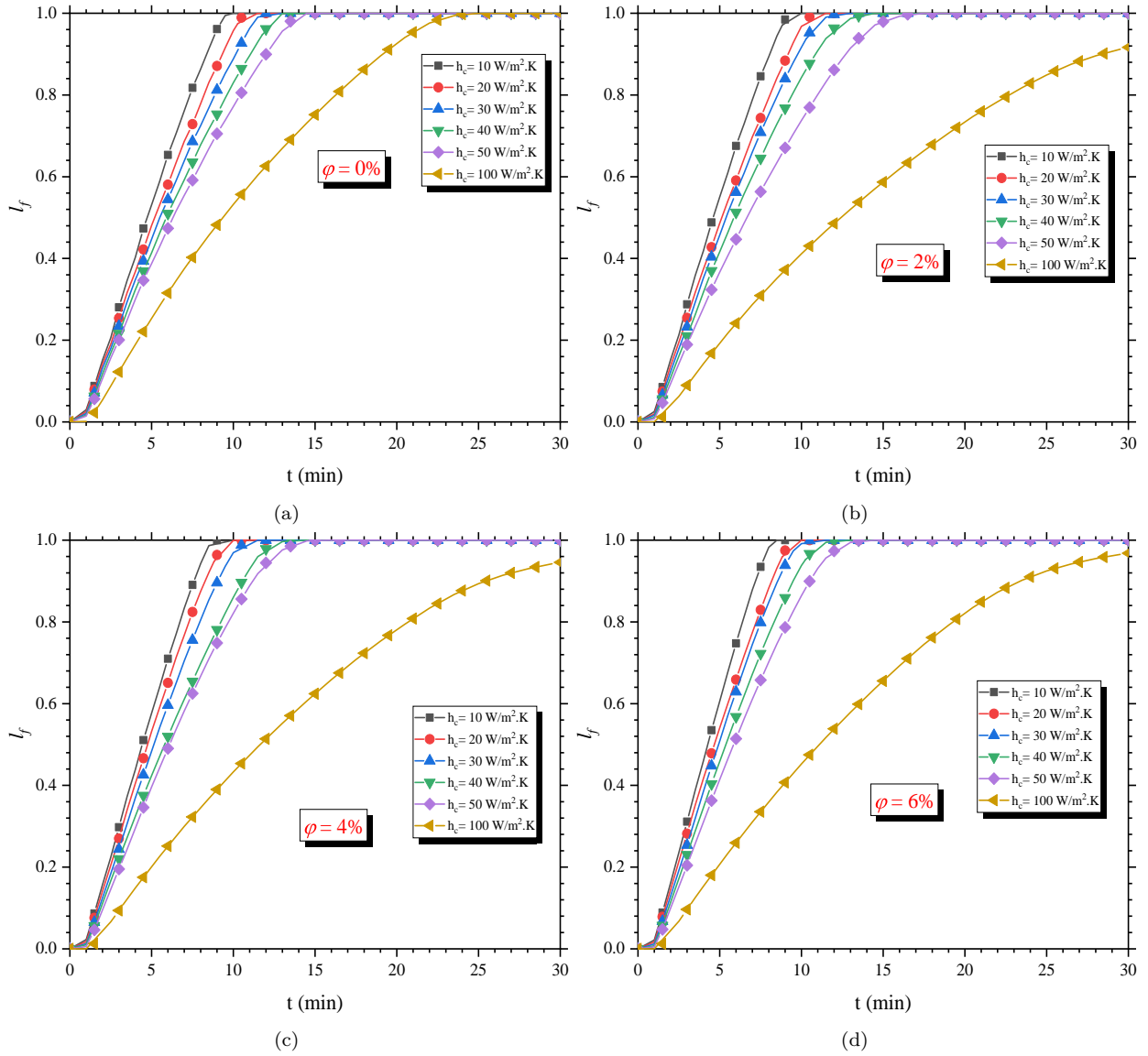


Figure 12: The l_f variations of hybrid HcPCM cooled finned heat sink under various $\varphi =$ (a) 0%, (b) 2%, (c) 4%, and (d) 6%

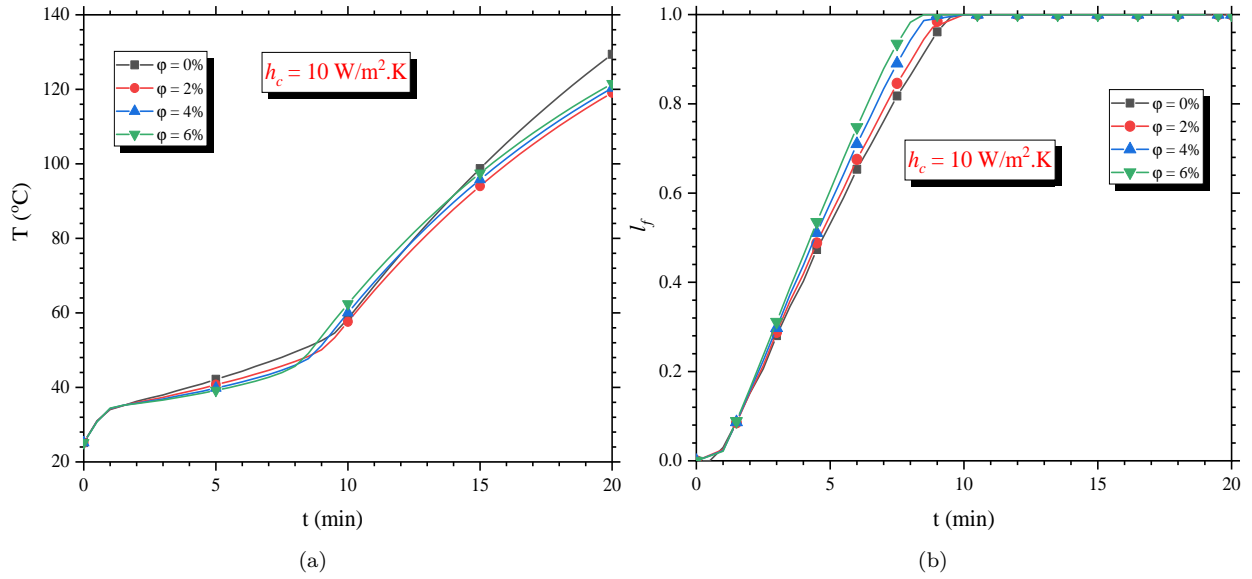


Figure 13: (a) Time histories and (b) l_f of hybrid HcPCM cooled finned heat sink temperature under various $\varphi =$ at $h_c = 10 \text{ W/m}^2.\text{K}$

333 air cooling method as an active cooling method and PCM-based heat sink as a passive
 334 cooling method. The hybrid composite PCM (HcPCM) is designed by dispersing the hybrid
 335 nanoparticles of GO and MWCNTs with volume fractions of 0%, 2%, 4%, and 6% in RT-
 336 35HC. The convective heat transfer coefficient (h_c) is varied from 10 – 100 $\text{W/m}^2.\text{K}$ and
 337 heat flux (q) is varied from 25, 30, 35, and 40 kW/m^2 . A plate-fin heat sink of constant
 338 volume fractions, made of aluminium, is selected and three different finned heat sinks such
 339 as air-cooled, HcPCM cooled and hybrid HcPCM cooled configurations are investigated
 340 numerically. The following main key outcomes are revealed in present study:

- 341 • The effect of $h_c = 10 \text{ W/m}^2.\text{K}$ on an air-cooled heat sink did not reduce the heat
 342 sink base temperature and a higher temperature rise is observed with the increase of
 343 q . However, when the h_c is between 30 to 50 $\text{W/m}^2.\text{K}$, the base temperature reduces
 344 within the human comfortable temperature range at $q = 25 \text{ kW/m}^2$.
- 345 • The HcPCM based finned heat sinks reveal that the addition of GO+MWCNTs in
 346 RT-35HC reduces the heat sink base temperature with increase of hybrid nanoparti-
 347 cles concentration from 0% to 6%. Meanwhile, the effect of h_c further reduces base
 348 temperature and keeps the heat sink in safe temperature operating limit. This shows
 349 that the combined effects of hybrid nanoparticles and h_c reduces the average heat sink
 350 temperature significantly and uniformed the melting process of PCM.
- 351 • In the case of a hybrid HcPCM finned heat sink, the h_c significantly improves the heat

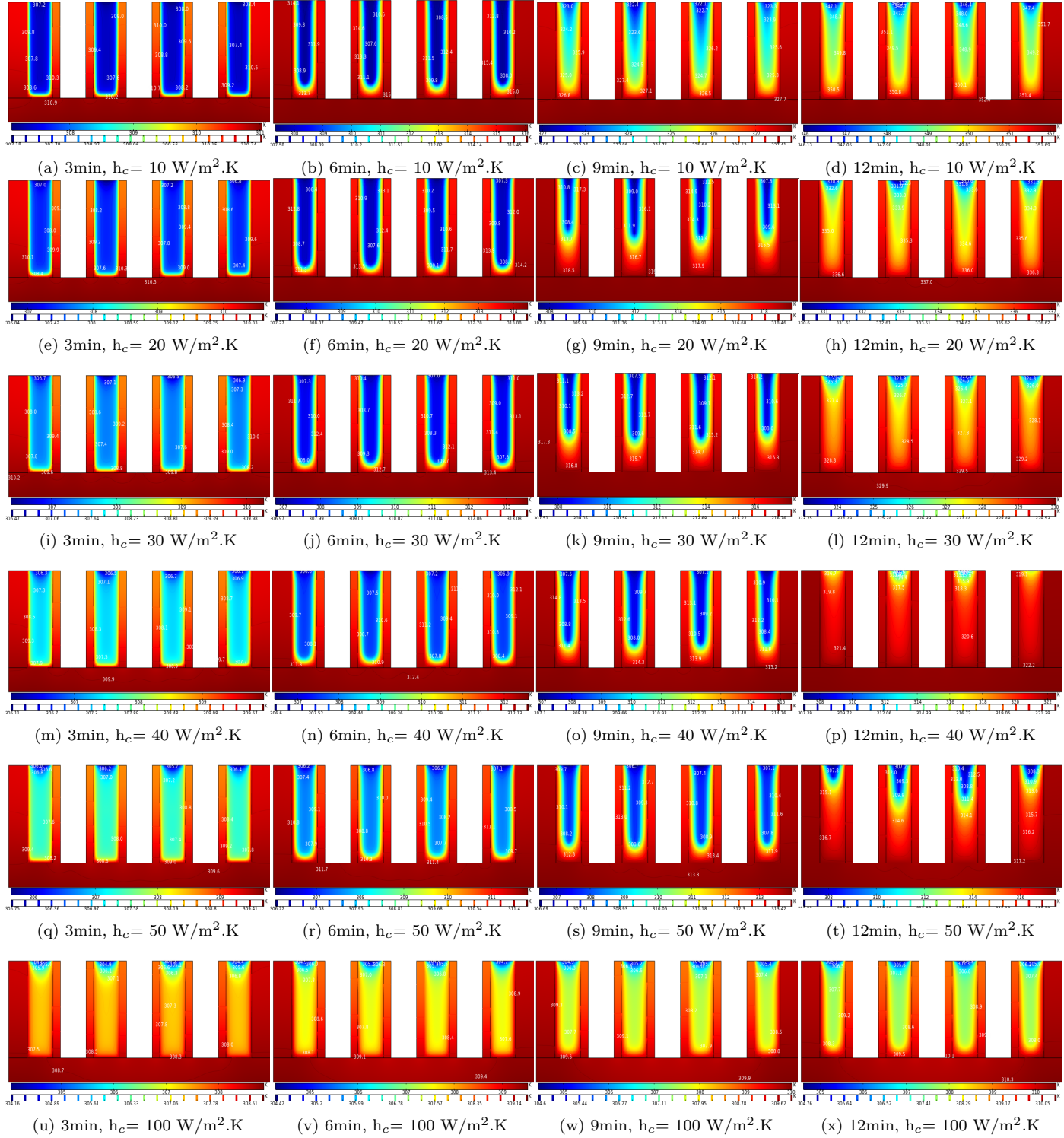


Figure 14: Comparison of isotherms contours of hybrid HcPCM filled finned heat sink at $\varphi = 6\%$ and $h_c = 10, 20, 30, 40, 50,$ and $100 \text{ W/m}^2.\text{K}$ at various time-steps.

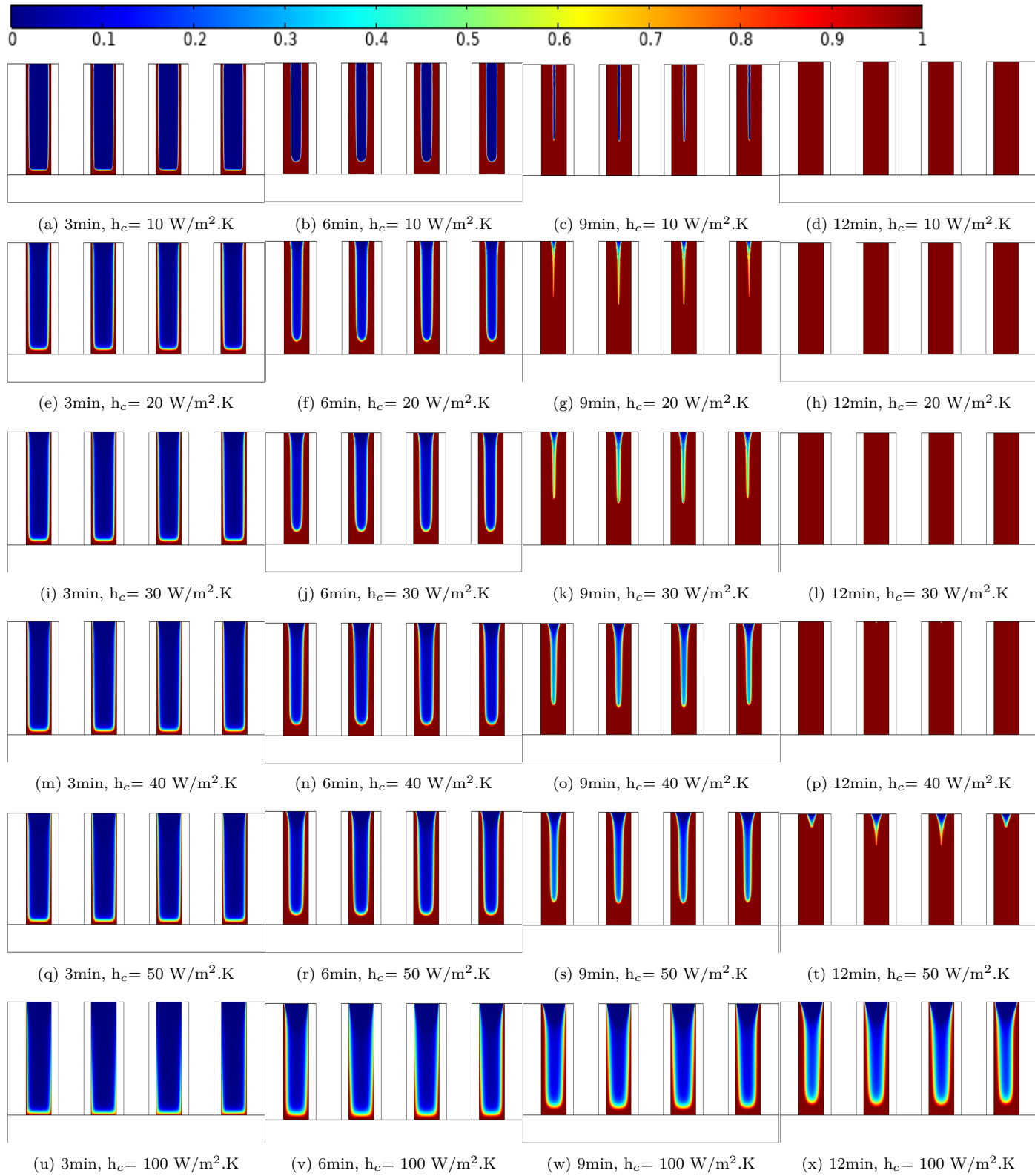


Figure 15: Comparison of liquid fraction contours of hybrid HcPCM filled finned heat sink at $\varphi = 6\%$ and $h_c = 10, 20, 30, 40, 50,$ and $100 \text{ W/m}^2 \cdot \text{K}$ at various time-steps.

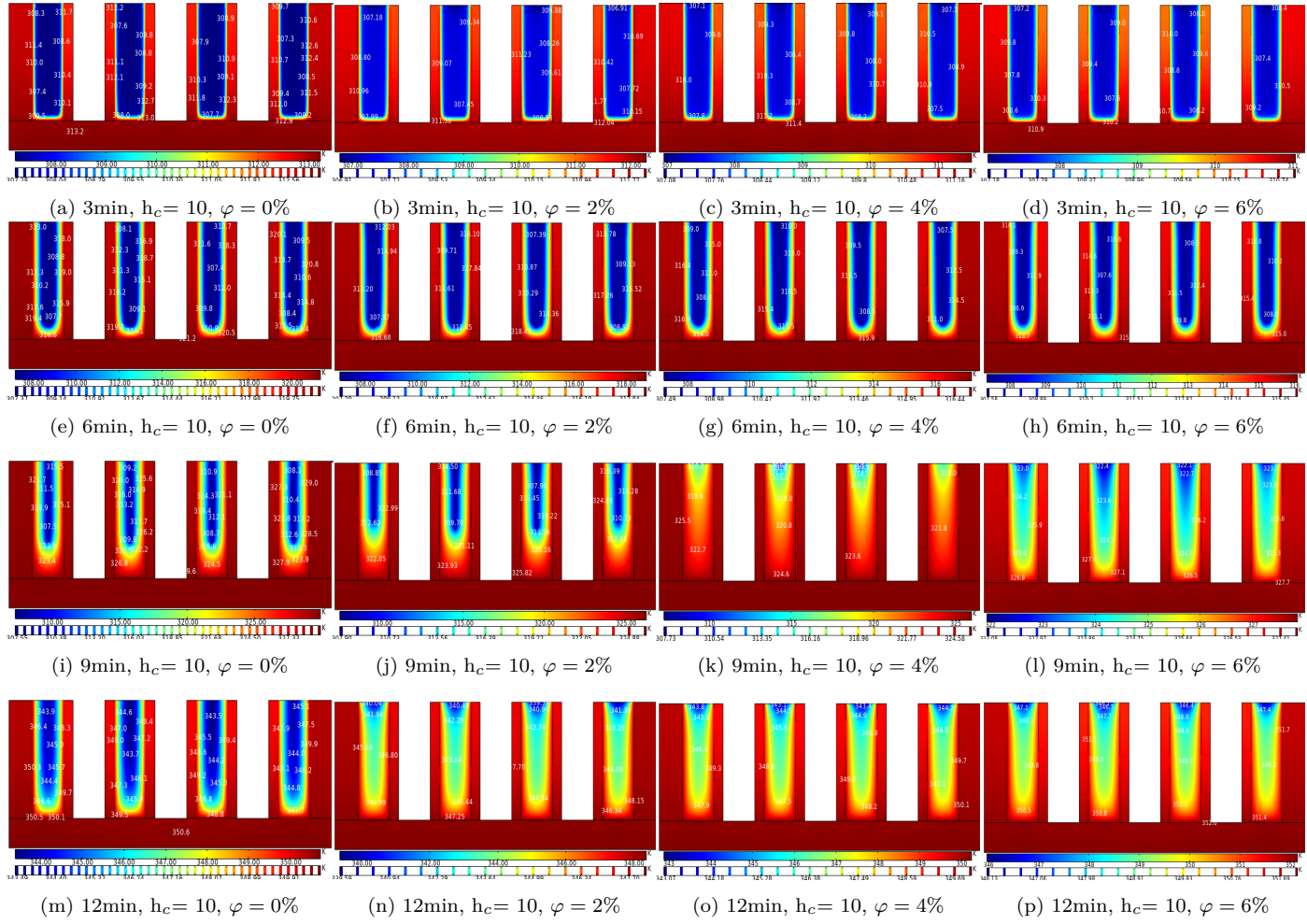


Figure 16: Comparison of isotherms contours of hybrid HcPCM filled finned heat sink at $\varphi = 0\%$, 2% , 4% and 6% and $h_c = 10 \text{ W/m}^2 \cdot \text{K}$ at various time-steps.

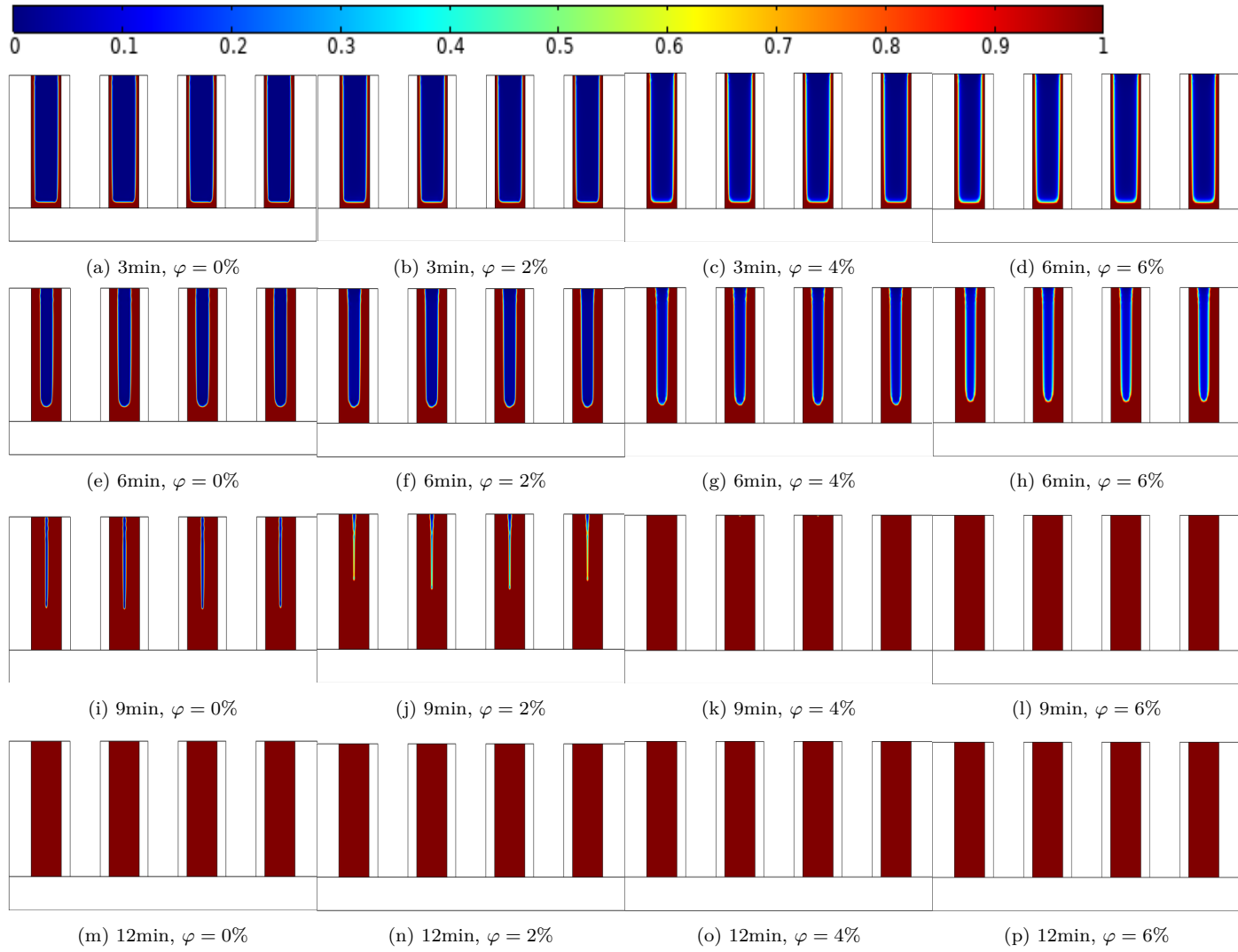


Figure 17: Comparison of liquid fraction contours of hybrid HcPCM filled finned heat sink at $\varphi = 0\%$, 2% , 4% and 6% and $h_c = 10 \text{ W/m}^2 \cdot \text{K}$ at various time-steps.

352 transfer from the heat sink base to ambient and extends the latent heating phase of
 353 HcPCM due to the effective transfer rate. At $h_c = 100 \text{ kW/m}^2$, there is no complete
 354 melting is achieved and heat sink temperature remains at ambient temperature even
 355 after 30 mins.

- 356 • The liquid fraction of HcPCM and Hybrid HcPCM heat sinks is increased with increase
 357 of volume fraction from 0% to 6% . Similarly, with $h_c = 10 - 100 \text{ W/m}^2 \cdot \text{K}$, the higher
 358 liquid fraction is obtained from 100 to $10 \text{ W/m}^2 \cdot \text{K}$ which means PCM does not melt
 359 fully.

360 It is concluded that the forced convection heat transfer improved the cooling performance of
 361 hybrid HcPCM finned heat sink compared to natural convection heat transfer in case of air-
 362 cooled and HcPCM finned-based heat sink. The addition of nanoparticles further enhanced

363 thermal enhancement and uniform melting distribution of PCM inside the finned heat sink.
364 The h_c between 30 to 50 W/m².K shows the optimized values for forced convection heat
365 transfer operating conditions. The volume fraction of 2% of GO+MWCNTs nanoparticles
366 is recommended as an optimum concentration for uniform melting of PCM inside the finned
367 heat sinks both for hybrid and non-hybrid cases.

368 **Conflict of interest**

369 The authors declare no conflict of interest regarding this research article.

370 **References**

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