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Numerical study of the nanocomposite phase change material-based heat sink for passive cooling of electronic components.

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Abstract

The current two-dimensional (2D) numerical study presents the melting phenomenon and heat transfer performance of the nanocomposite phase change material (NCPCM) based heat sink. Metallic nanoparticles (copper: Cu) of different volume fractions of 0.00, 0.01, 0.03, and 0.05 were dispersed in RT-28HC, used as a PCM. Transient simulations with conjugate heat transfer and melting/solidification schemes were formulated using finite-volume-method (FVM). The thermal performance and melting process of the NCPCM filled heat sink were evaluated through melting time, heat storage capacity, heat storage density, rate of heat transfer and rate of heat transfer density. The results showed that with the addition of Cu nanoparticles, the rate of heat transfer was increased and melting time was reduced. The reduction in melting time was obtained of -1.36% , -1.81% , and -2.56% at 0.01, 0.03, and 0.05, respectively, compared with 0.00 NCPCM based heat sink. The higher heat storage capacity enhancement of 1.87% and lower reduction of -7.23% in heat storage density was obtained with 0.01 volume fraction. The enhancement in rate of heat transfer was obtained of 2.86% , 2.19% and 1.63% ; and reduction in rate of heat transfer density was obtained of -6.33% , -21.05% and -31.82% with 0.01, 0.03, and 0.05 volume fraction of Cu nanoparticles, respectively. The results suggest that Cu nanoparticles of 0.01

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volume fraction has the lower melting rate, higher heat storage capacity and heat transfer rate, lower heat storage density and heat transfer rate density which is preferable for passive cooling electronic components.

Keywords: Nanocomposite phase change material; Copper nanoparticles; Heat sink; Electronics cooling

Nomenclature

Abbreviations

Al_2O_3	Aluminum oxide
Cu	Copper
FVM	Finite volume method
HS	Heat sink
ICs	Integrated circuits
NCPCM	Nanocomposite phase change material
PCM	Phase change material
PRESTO	PREssure STaggering Option
QUICK	Quadratic Upstream Interpolation for Convective Kinematics
SIMPLE	Semi-Implicit Pressure-Linked Equation
UDF	User-defined function

Symbols

A_m	Mushy zone
B	Boltzman constant (J/K)
ρc_p	Volumetric heat capacity ($J/m^3.K$)
f_l	Liquid fraction
g	Gravitational acceleration (m/s^2)
H	Height (mm)
Q	Heat storage capacity (J)
q	heat storage density (J/kg)
k	Thermal conductivity ($W/m.K$)
L	Latent heat of fusion ($J/kg.K$)
m	Mass (Kg)
p	Pressure (Pa)

\dot{Q}	Rate of heat transfer (W)
\dot{q}	Rate of heat transfer density (W/kg)
S	Source term in momentum equation
T	Temperature (K)
t	Time (sec)
u	Velocity component in x -axis (m/s)
v	Velocity component in y -axis (m/s)
W	Width (mm)
c_p	Specific heat capacity ($J/kg.K$)
ΔH	Fractional latent-heat ($J/kg.K$)
$2D$	Two dimensional

Greek letters

φ	Volume fraction
μ	Viscosity ($Pa.s$)
β	Thermal expansion coefficient ($1/K$)

Subscripts

HS	Heat sink
hs	Heat source
ini	Initial
l	Liquidus
m	Melting
$ncpcm$	Nanocomposite phase change material
np	Nanoparticles
ref	Reference
x	x -axis
y	y -axis

1. Introduction

The recent advancement of technology in electronics industries and communication has led to the miniaturization and more power for electronic chips. As a result of this, the operating temperature has been recognized as critical factor which deteriorates the performance

5 and efficiency of integrated circuits (ICs) [1]. Therefore, the design and cooling performance
6 of cooling devices are crucial to remove the excessive heat flux. An effective and efficient
7 thermal management has become vital to maintain or lower the electronic components tem-
8 perature lower than their maximum allowable operating temperature to increase the lifespan
9 and reliability of electronic components and to avoid the major breakdown [2].

10 Passive cooling technology of electronics presents an efficient and clean technology with zero
11 emission energy, when it is integrated to a phase-change phenomenon. Phase change mate-
12 rials (PCMs) can be widely used in heat sinks for practical electronic cooling applications
13 due to high storage capacity and providing an almost constant temperature on the surface of
14 the electronic device during the phase change process. In addition to the electronic cooling,
15 due to the advantages of latent heat storage compared with sensible heat storage, PCMs
16 has been widely engaged with space heating [3], photovoltaic panel cooling [4], waste heat
17 recovery [5], low temperature district heating [6, 7], ground source heat pumps integration
18 [8], etc. Solid-liquid phase-change process exhibits by the PCM absorb the heat rejected by
19 electronic device when integrated with a heat sink at constant and intermittent heat fluxes
20 [9, 10]. Due to the intrinsic lower thermal conductivity of PCM causes to delay the heat
21 dissipation rate from electronic devices. Therefore, to enhance the thermal conductivity
22 of PCM, nanoparticles of higher thermal conductivity is dispersed in PCM to improve the
23 heat transfer rate [11, 12]. Several studies have been reported based on nanoparticles en-
24 hanced PCM for thermal energy storage [13, 14]. Lin and Al-Kayiem [15, 16] examined the
25 thermophysical properties of Cu nanoparticles dispersed in paraffin wax of various weight
26 percentages. The authors found that by adding the Cu nanoparticles, the thermal conduc-
27 tivity was increased and melting temperature and latent-heat of fusion were reduced. The
28 enhancement in thermal conductivity was reported of 14.0%, 23.9%, 42.5% and 46.3% by
29 adding 0.5%, 1.0%, 1.5% and 2.0% weight percentages of Cu nanoparticles. Colla et al. [17]
30 studied the thermophysical and heat transfer performance of nano-PCM in a square cavity.
31 The results showed that nano-PCM delayed the melting process compare to the pure PCM.
32 Bondareva et al. [18] investigated the heat transfer performance of NCPCM filled cooling
33 system and found the increase in melting rate with increase of nanoparticles concentration.
34 Authors reported that melting phenomenon accelerated by adding nanoparticles initially
35 due to heat conduction in solid and liquid PCM layers. Further, the authors investigated
36 the 2D numerical study to formulate the melting process of paraffin enhanced with Al_2O_3
37 nanoparticles in a heat sink oriented at different angles [19]. Authors carried out the distri-

38 bution of velocity and temperature as a function of time and concentration of nanoparticles.
39 It was found that adding nanoparticles accelerated the heat exchange within the system and
40 reduced the melting time of PCM at any inclination angle. More further, authors reported
41 that optimal volume fraction of nanoparticles was the function of volumetric heat generation
42 and fins height. Mahdi and Nsofor [20] proposed a numerical study on solidification process
43 of Al_2O_3 nanoparticles based NCPCM inside a triplex-tube thermal energy storage system.
44 The volume concentration of nanoparticles was varied from 0 – 8% and solidification time
45 was reduced from 8% to 20% with 3% and 8% loading of Al_2O_3 nanoparticles. Moreover,
46 it was found that with the addition of nanoparticles did not show the significant change
47 in solidification process. However, as time elapsed and loading was increase, the rate of
48 solidification was increased. Ebrahimi and Dadvand [21] studied numerically the melting
49 process of NCPCM by using Al_2O_3 nanoparticles in a rectangular enclosure by using four
50 different arrangements of heat source. The effect of different nanoparticles volume fraction
51 was analysed. The results showed that the loading content of 2% Al_2O_3 nanoparticles had
52 the highest melting rate and better heat transfer rate. Hosseinizadeh et al. [22] numerically
53 investigated the melting of NCPCM using RT-27 and copper nanoparticles in a spherical
54 container. Three different concentrations of nanoparticles were changed and results were
55 obtained that increasing the concentration of copper nanoparticles increased the effective
56 thermal conductivity and lowered the latent-heat of fusion. Arshad et al. [23, 24, 25, 26]
57 conducted the numerical and experimental studies to explore the fin thickness of finned heat
58 sink at constant volume fraction of 9% by different PCMs, volumetric fractions of PCM and
59 different power levels. The results reported that 3 mm fin thickness had the better thermal
60 performance by lowering the average heat sink temperature. Recently, Faraji et al. [27, 28]
61 reported the results of a numerical study of the natural convection induced by NCPCM
62 melting in a inclined rectangular enclosure. The objective of the study was to reveal the ef-
63 fect of the insertion of metallic nanoparticles by quantifying their contribution to the overall
64 thermal response of the heat sink. The results showed that the addition of nanoparticles
65 contributes to efficient cooling of the electronic component by decreasing the average oper-
66 ating temperature.

67 The present study explore the thermal performance and melting phenomenon of NCPCM
68 based heat sink by using copper (Cu) nanoparticles of four different volume fractions of 0.00,
69 0.01, 0.03, and 0.05 dispersed in RT-28HC, used as a PCM, at a constant power level of 5 W
70 applied at heat sink base. The key novelty of the current study is to study the heat flow and

71 melting interface of NCPCM filled in heat sink specially used for portable electronic devices
72 which has been rarely discussed in the literature. The transient simulations are carried out
73 through control volume approach to study the solid-liquid phase field, heat flow field and
74 temperature variations. The thermal enhancement performance of the NCPCM filled heat
75 sink is evaluated through different thermal performance evaluation indicators such melting
76 time, heat storage capacity, heat storage density, rate of heat transfer, and rate of heat
77 transfer density for the solution of efficient passive cooling of electronic components.

78 **2. Geometric and Mathematical description**

79 *2.1. Physical model*

80 The cross-sectional isometric view of a three-dimensional heat sink filled with NCPCM
81 and other components, used for passive cooling of electronics devices, is shown in 1a which
82 has been employed in previous experimental studies by Arshad et al. [24, 25, 26]. The
83 physical domain of the NCPCM based heat sink considered in current study is shown in
84 Figure 1b. Since the heat flow is symmetrical along the axis, thus two-dimensional (2D)
85 heat flow simulations are carried out. A 2D rectangular heat sink with width ($W = 70$
86 mm) and height ($H = 25$ mm) is heated with a heat source of volumetric heat generation
87 (q''') with sizes of $l = 50$ mm and $t = 2$ mm. All the sides of heat sink are adiabatic
88 except top surface which undergoes with natural convection. The internal cavity of the heat
89 sink having width ($w = 60$ mm) and height ($h = 20$ mm) is filled with different volume
90 fractions ($\varphi = 0.00, 0.01, 0.03, \text{ and } 0.05$) of nanoparticles. The heat sink made of copper
91 is numerically modelled to investigate the thermal performance and melting phenomenon
92 of NCPCM at a constant power input of 5 W. The thermophysical properties of RT-28HC
93 which is used PCM and copper (Cu) nanoparticles are listed in Table 1. The current system
94 is designed to investigate passive thermal performance NCPCM based heat sink of portable
95 electronic components.

96 *2.2. Numerical model*

97 The numerical model is developed based the physical domain presented in the Figure
98 1. The conduction heat transfer mode is considered for the heat sink while conduction
99 and convection heat transfer are considered for NCPCM (mixture of PCM and nanoparti-
100 cles). Following assumptions are the necessary taken to model the NCPCM based heat sink
101 problem presented in this work:

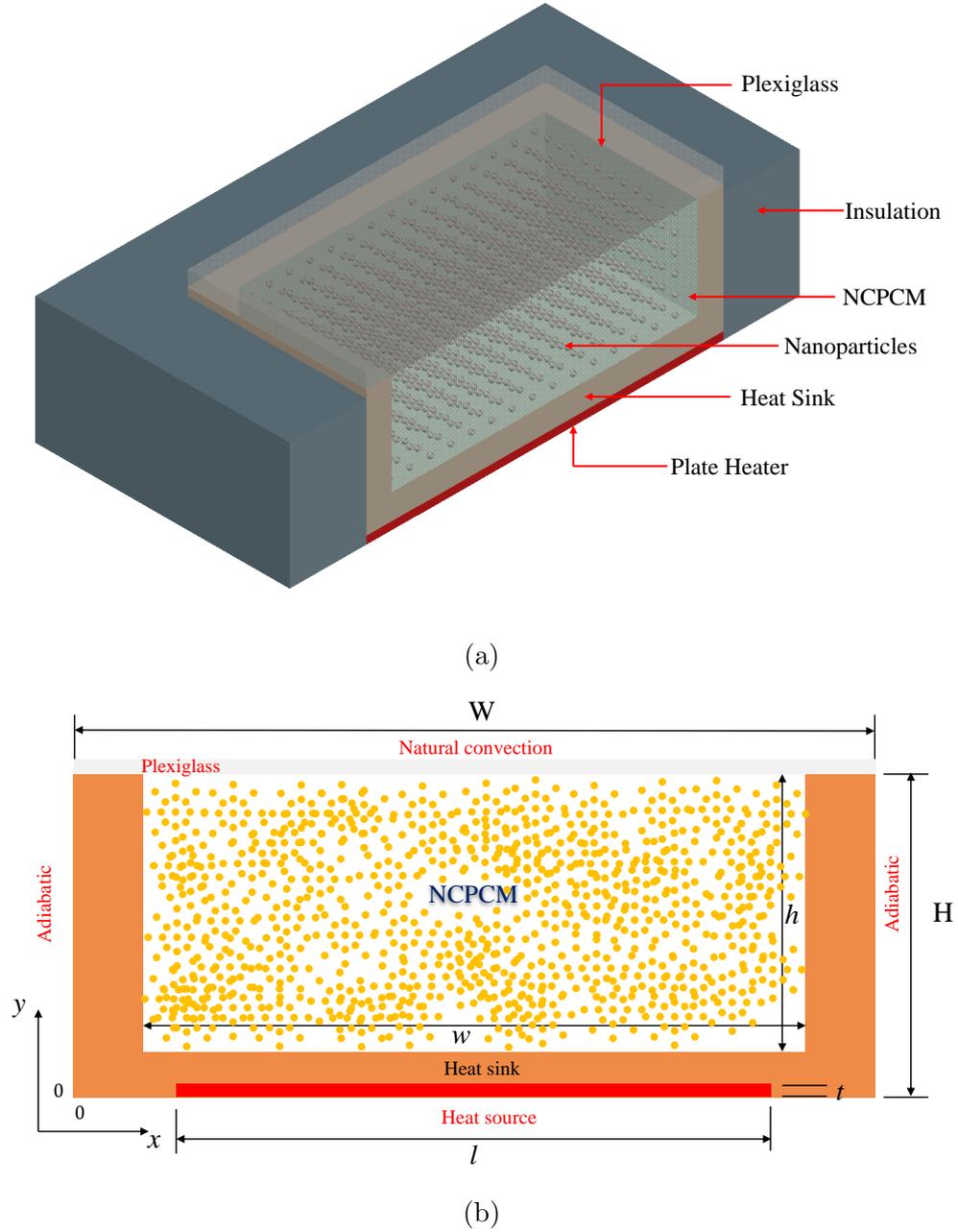


Figure 1: (a) A 3D isometric view of NCPCM filled heat sink assembly and (b) physical domain used in current study.

- 102 • The initial temperature of heat sink and NCPCM are the same temperature.
- 103 • The thermophysical properties of heat sink, PCM and nanoparticles are constant.
- 104 • The NCPCM is considered as colloid suspension which exhibits as a Newtonian fluid.
- 105 The liquid NCPCM flow regime is $2D$, laminar, unsteady and incompressible.
- 106 • The dispersion of nanoparticles in PCM is assumed homogeneous, no agglomeration
- 107 is considered.

Table 1: Thermophysical properties of PCM and nanoparticles.

Property	RT-28HC	Cu
T_m (K)	301	–
T_s (K)	302	–
T_l (K)	300	–
L (J/kg)	250,000	–
c_p (J/kg.K)	2000	380
ρ (kg/m ³)	825	8920
k (W/m.K)	0.2	400
μ (Pa.s)	0.0235	–
β (1/K)	0.0006	–

- 108 • The nanoparticles and PCM are in local thermal equilibrium and there is no-slip
109 between them.
- 110 • The heat sink is considered as solid-state with homogeneous and isotropic properties
111 and thermal conduction heat transfer exists.
- 112 • Viscous dissipations are considered negligible.
- 113 • Volume change in NCPCM is negligible during phase-change process.
- 114 • The Boussinesq approximation is used to model the buoyancy driven force under
115 natural convection as $\rho = \rho_m/\beta(T - T_m) + 1$, where $T_m = (T_s + T_l)/2$.
- 116 • No-slip boundary conditions are considered for velocities at the boundaries.
- 117 • Adiabatic boundary conditions are assumed from the surroundings.

118 Based on the above assumptions, the governing equations to model the NCPCM flow
119 motion and temperature variation inside the heat sink are governed by the standard Navier-
120 Stokes and energy equations:

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Momentum in x-direction:

$$\rho_{ncpcm} \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu_{ncpcm} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + S_x \quad (2)$$

Momentum in y-direction:

$$\rho_{ncpcm} \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu_{ncpcm} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + (\rho\beta)_{ncpcm} g(T - T_{ref}) + S_y \quad (3)$$

121 where:

$$S_x = A_m \frac{(1 - f_l)^2}{f_l^3 - 0.001} \cdot u \quad S_y = A_m \frac{(1 - f_l)^2}{f_l^3 - 0.001} \cdot v \quad (4)$$

122 where, the ρ_{ncpcm} , μ_{ncpcm} , β_{ncpcm} are the density, dynamic viscosity, and thermal ex-
 123 pansion coefficient of the NCPDM, respectively; p and g are the pressure and gravita-
 124 tional acceleration, respectively. The S_x and S_y are source terms, defined by Carman-
 125 Kozeny relation for flow in porous media, in x and y directions, respectively. The
 126 source terms represent a gradual reduction in velocities from a finite value in liquid
 127 to zero in solid, over the computational cell that undergoes the phase-change phe-
 128 nomenon. This means that each cell behaves like a porous media whose porosity is
 129 equal to liquid-fraction. The A_m is the mush-zone constant which reflecting the mor-
 130 phology of melting front. The value of A_m is chosen of 10^5 present study [23, 29].
 131 Additionally, f_l is the liquid-fraction during the phase-change in temperature interval
 132 of $T_s < T < T_l$ and it varies between 0 (solid) to 1 (liquid), which is defined as:

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

Energy (liquid-phase):

$$(\rho c_p)_{ncpcm} \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k_{ncpcm} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - \frac{\partial(\rho \Delta H)_{ncpcm}}{\partial t} \quad (6)$$

Energy (solid-phase):

$$(\rho c_p)_{ncpcm} \left(\frac{\partial T}{\partial t} \right) = k_{ncpcm} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (7)$$

133 where, $(\rho c_p)_{ncpcm}$ is the volumetric heat capacity and ΔH_{ncpcm} is the fractional latent-
 134 heat of the NCPCM which is expressed in terms of latent-heat of fusion L_{ncpcm} as follows:

$$\Delta H_{ncpcm} = f_l L_{ncpcm} \quad (8)$$

135 Where

$$\Delta H_{ncpcm} = \begin{cases} 0 & \text{if } T < T_m \\ f_l L_{ncpcm} & \text{if } T \geq T_m \end{cases} \quad (9)$$

136 Since, the only heat conduction heat transfer mode is considered for heat sink and heat
 137 source. Thus, the corresponding governing equations can be written as follow:

Energy (heat sink):

$$(\rho c_p)_{HS} \left(\frac{\partial T}{\partial t} \right) = k_{HS} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (10)$$

Energy (heat source):

$$(\rho c_p)_{hs} \left(\frac{\partial T}{\partial t} \right) = k_{hs} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + q''' \quad (11)$$

138 where, $(\rho c_p)_{HS}$, k_{HS} , $(\rho c_p)_{hs}$, and k_{hs} are the volumetric heat capacity and thermal con-
 139 ductivities of heat sink and heat source, respectively.

140 2.3. Thermophysical properties of NCPCM

141 The thermophysical properties of NCPCM are changed with the addition of nanoparticles
 142 of varying volume fractions. The provided thermophysical properties of pure PCM (RT-
 143 28HC) and Cu nanoparticles are listed in Table 1. All the effective properties of NCPCM
 144 are constant except thermal conductivity and calculated based on the volume fraction of
 145 nanoparticles. The effective density (ρ_{ncpcm}) , specific heat capacity $(c_{p_{ncpcm}})$, latent-heat
 146 (L_{ncpcm}) , and thermal expansion coefficient (β_{ncpcm}) of the NCPCM can be calculated using
 147 simple theoretical models of mixtures as follows [18, 19, 20, 30, 31]:

$$\rho_{ncpcm} = \varphi \rho_{np} + (1 - \varphi) \rho_{pcm} \quad (12)$$

$$c_{p_{ncpcm}} = \frac{\varphi (\rho c_p)_{np} + (1 - \varphi) (\rho c_p)_{pcm}}{\rho_{ncpcm}} \quad (13)$$

$$L_{ncpcm} = \frac{(1 - \varphi)(\rho L)_{pcm}}{\rho_{ncpcm}} \quad (14)$$

$$\beta_{ncpcm} = \frac{\varphi(\rho\beta)_{np} + (1 - \varphi)(\rho\beta)_{pcm}}{\rho_{ncpcm}} \quad (15)$$

$$\mu_{ncpcm} = 0.983e^{(12.959\varphi)}\mu_{pcm} \quad (16)$$

148 In above Equations 12–16, φ is the volume fraction of nanoparticles, the subscripts
 149 $ncpcm$, np and pcm refer to the NCPCM, nanoparticles, and PCM, respectively. **The tran-**
 150 **sient modifications of k_{ncpcm} of NCPCM are evaluated as function of operating temperature,**
 151 **volume fraction and particle size of Cu nanoparticles using a empirical correlations proposed**
 152 **by Vajjha and Das [32], as follows:**

$$k_{ncpcm} = \frac{k_{np} + 2k_{pcm} - 2(k_{pcm} - k_{np})\varphi}{k_{np} + 2k_{pcm} + (k_{pcm} - k_{np})\varphi} k_{pcm} + 5 \times 10^4 \beta_k \zeta \varphi \rho_{pcm} c_{p_{pcm}} \sqrt{\frac{BT}{\rho_{np} d_{np}}} f(T, \varphi) \quad (17)$$

153 where, B is Boltzmann constant which is equal to 1.381×10^{-23} J/K, $\beta_k = 8.4407(100\varphi)^{-1.07304}$,
 154 and function ($f(T, \varphi)$) is defined as follows:

$$f(T, \varphi) = (2.8217 \times 10^{-2}\varphi + 3.917 \times 10^{-3}) \frac{T}{T_{ref}} + (-3.0669 \times 10^{-2}\varphi - 3.91123 \times 10^{-3}) \quad (18)$$

155 where, T_{ref} is the reference temperature which is equal to 273.15 K. The first part of
 156 Equation 18 relates with Maxwell model to determine the thermal conductivity of solid
 157 PCM while second part of Equation 18 accounts the effects of Brownian motion of nanopar-
 158 ticles, nanoparticles size, volume fraction and temperature dependence. Additionally, ζ
 159 is a correction factor which comes in Brownian motion term, because there is no Brown-
 160 ian motion in solid-phase. Therefore, the value of ζ is defined as the same as for f_l [33].
 161 **The theoretical models have been widely employed to calculate the effective thermophysical**
 162 **properties of nano-PCM or nanocomposite PCM which has been verified in several papers**
 163 **in the literature for nanofluids as well as nano-PCMs. As approved in the experimental**
 164 **study of Vajjha and Das [32], the employed formulation for the effective thermal conductiv-**
 165 **ity fits very well with the valid experimental study with the maximum deviation of 2.8%.**

166 Vajjha and Das [32] experimentally measured the thermal conductivity of nanofluids and
 167 developed a model accounts for the effects of nanoparticles size, volume fraction, temper-
 168 ature, nanoparticles and base fluid thermophysical properties and Brownian motion effect
 169 of nano-particles which provides a more comprehensive model compared with the earlier
 170 models proposed by Maxwell [34], Bruggeman [35], Hamilton and Crosser [36] and Xuan et
 171 al. [37] which were significantly a function of nanoparticle volume fraction. Therefore, to
 172 have accurate results, the model of Vajjha and Das was employed which were validated with
 173 experimental thermal conductivity values. They also compared their experimental results
 174 with those of several existing models showing good agreement [38]. This equation is also
 175 widely used after its development in different numerical studies in the literature showing
 176 the accuracy of this equation [29, 39, 40, 41]. For the viscosity, the experimental model
 177 Vajjha et al. [42] was employed which is determined based on the experimental data and
 178 also validated with previous models. Vajjha suggested that the model for the viscosity is
 179 practical within the range of 20-90 °C and suitable for the proposed model in this study
 180 [43]. Other formulations have already been employed in several published numerical studies
 181 in the literature in highly reputation journals such as [18, 20, 31, 44]. It should also be
 182 noted that in different review papers on Nano-enhanced phase change material, the models
 183 of Vajjha et al. for the thermophysical properties of NePCM are approved and verified and
 184 thus they were employed in this study.

185 2.4. Initial and boundary conditions

186 The initial and boundary conditions applied in current study are labelled in Figure 1.
 187 The side walls of the heat sink are defined as an adiabatic boundary condition except the
 188 top surface which is undergoes the natural convection effect. Following are the initial and
 189 boundary conditions applied in this work to solve the governing equations as follows:

190 1. Initial conditions

$$191 \quad t = 0, T = T_{ini} = 288.15 \text{ K}, f_l = 0$$

192 2. Boundary conditions

193 • No-slip condition at walls: $u = v = 0$

194 • Adiabatic walls:

$$195 \quad -k \frac{\partial T}{\partial x} \Big|_{x=0-W} = 0 \quad \text{Along vertical walls}$$

$$196 \quad -k \frac{\partial T}{\partial y} \Big|_{\substack{x=0-10,60-70 \\ y=0}} = 0 \quad \text{For bottom}$$

197 • Natural convection:

$$198 \quad -k \frac{\partial T}{\partial y} \Big|_{y=H} = h(T - T_\infty) \quad \text{Natural convection}$$

199 • Volumetric heat generation provided from heat source:

$$200 \quad -k \frac{\partial T}{\partial y} \Big|_{\substack{x=10-60mm \\ y=0-2mm}} = \dot{q}'''$$

201 2.5. Performance evaluation parameters

202 To estimate the thermal performance of NCPCM based heat sink, four different perfor-
 203 mance evaluation parameters such as heat storage capacity (Q), heat storage density (q),
 204 rate of heat transfer (\dot{Q}), and rate of heat transfer density (\dot{q}) along with the total melting
 205 time (t_{melt}). The total Q is defined as the total thermal energy storage capacity during the
 206 pre-sensible heating, latent-heat of fusion, and post-sensible heating of NCPCM. Whereas,
 207 q indicates the total thermal energy storage capacity per unit mass of the NCPCM. Since,
 208 the pre-sensible heating and latent-heat are the most significant parameters to determine
 209 the Q of NCPCM based heat sink whiling charging mode. Therefore, Q and q can be defined
 210 by Equations 19 and 20, respectively, as follows [45]:

$$Q = m_{ncpcm} \left(\int_{solid} c_{p_{ncpcm}} dT + f_l L_{ncpcm} + \int_{liquid} c_{p_{ncpcm}} dT \right) \\ \approx m_{ncpcm} [c_{p_{ncpcm}} (T_m - T_i) + f_l L_{ncpcm}] \quad (19)$$

211 and

$$q = \frac{Q}{m_{ncpcm}} = \frac{m_{ncpcm} \left(\int_{solid} c_{p_{ncpcm}} dT + f_l L_{ncpcm} + \int_{liquid} c_{p_{ncpcm}} dT \right)}{m_{ncpcm}} \\ \approx \frac{m_{ncpcm} [c_{p_{ncpcm}} (T_m - T_i) + f_l L_{ncpcm}]}{m_{ncpcm}} \quad (20)$$

212 Since, the Q and q can only evaluate the storage capacity of NCPCM based heat sink
 213 relative to the mass of NCPCM. However, there is no relationship of total t_{melt} of NCPCM
 214 with Q and q . Thus, the overall thermal performance of heat sink cannot be evaluate only
 215 with Q and q . Therefore, the effect of t_{melt} , m_{ncpcm} , and Q are combined together to define
 216 the rate of heat transfer (\dot{Q}) and rate of heat transfer density (\dot{q}). The \dot{Q} indicates the total
 217 thermal energy storage capacity per unit melting time and \dot{q} is defined as total thermal

218 energy storage capacity per unit melting time and per unit mass of NCPCM, by Equations
 219 21 and 22, respectively, as follows:

$$\dot{Q} = \frac{Q}{t_{melt}} = \frac{m_{ncpcm} \left(\int_{solid} c_{p_{ncpcm}} dT + f_l L_{ncpcm} + \int_{liquid} c_{p_{ncpcm}} dT \right)}{t_{melt}} \approx \frac{m_{ncpcm} [c_{p_{ncpcm}} (T_m - T_i) + f_l L_{ncpcm}]}{t_{melt}} \quad (21)$$

220 and

$$\dot{q} = \frac{Q}{t_{melt} \cdot m_{ncpcm}} = \frac{m_{ncpcm} \left(\int_{solid} c_{p_{ncpcm}} dT + f_l L_{ncpcm} + \int_{liquid} c_{p_{ncpcm}} dT \right)}{t_{melt} \cdot m_{ncpcm}} \approx \frac{m_{ncpcm} [c_{p_{ncpcm}} (T_m - T_i) + f_l L_{ncpcm}]}{t_{melt} \cdot m_{ncpcm}} \quad (22)$$

221 2.6. Numerical procedure and model validation

222 In current study, the developed governing equations were solved using a commercial com-
 223 putational fluid dynamics (CFD) package ANSYS-FLUENT 19.1. The enthalpy-porosity
 224 method was adopted to model the effect of phase-change process in NCPCM based heat
 225 sink. In this method, a fixed grid is considered while solution of the governing equations
 226 which are varied for both solid and liquids phases. Finite volume method (FVM) scheme
 227 was considered to discretize the conservation equations of continuity, momentum and en-
 228 ergy with double precision. The mushy zone is modelled as a "pseudo" porous medium
 229 which exhibits the porosity equal to the liquid-fraction. The porosity increases from 0 to 1
 230 respecting the solid to liquid phases, respectively; as the PCM melts and velocities develops
 231 from zero. The PRESSURE-BASED method is select to discretize the governing equations
 232 from Eq. 1-11 which is recommended for incompressible flow with high-order Quadratic
 233 Upstream Interpolation for Convective Kinematics (QUICK) differencing scheme presented
 234 by Leonard [46]. The Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm was
 235 adopted for pressure-velocity coupling by Patanker [47]. The PRESTO (PREssure STag-
 236 gering Option) scheme was adopted for pressure correction equation. The User-defined
 237 function (UFD) was written in C++ language to account the effective thermal conductivity
 238 of NCPCM because of the dispersion of Cu nanoparticles. The gravity effects were also
 239 considered and second-order upwind difference scheme was adopted to discretize convective

240 terms in momentum and energy equations. A optimum mesh size and time-step of 54087
241 elements and 0.1s were considered and in the current study [23]. The under-relaxation
242 factors were set as 0.3, 0.6, 0.9 and 1.0 for pressure, velocity, liquid-fraction and thermal
243 energy, respectively. The convergence criteria are set to 10^{-4} , 10^{-4} and 10^{-6} for continuity,
244 momentum and energy equations, respectively.

245 The numerical model adopted in current study is validated with experimental results using
246 an unfinned heat sink filled with PCM at $\varphi = 0.00$. The similar initial conditions, boundary
247 conditions and thermophysical properties of materials are adopted in this work to validate
248 the results. The RT-35HC is selected as a PCM with melting temperature of 35 °C and a
249 input power level of 5 W is applied at the base of heat sink. The results of average heat sink
250 temperature are compared of both and numerical studies as shown in Figure 2. It can be seen
251 that an acceptable agreement is achieved between the experimental results and the present
252 study. A few discrepancies are observed before the melting and later in phase-change phase
253 which are due to achieving perfectly adiabatic boundary conditions while experimentation
254 and presence impurities in RT-35HC compared with the ideal thermophysical properties
255 provided in numerical study.

256 To validate the code related to the use of nanoparticles, the results of Mahdi and Nsofore [30]
257 are used for comparison. They simulated the melting process inside a horizontal triple-tube
258 LHS unit using RT82 and 2% Al_2O_3 nanoparticles where the temperatures of the inner and
259 outer tubes are considered 90 °C. As shown in Figure 4, the present results are in excellent
260 agreement with Ref. [30].

261 **3. Results and discussion**

262 *3.1. Evaluation of isotherms*

263 The instantaneous variations of average heat sink temperature (T_{HS}) is shown in Figure
264 4 for different volume fractions ($\varphi = 0.00, 0.01, 0.03, \text{ and } 0.05$) of Cu nanoparticles. The
265 isotherms of NCPCM heat sink are grouped at every 600 s of melting process for each φ as
266 follows:

- 267 • At $t = 1500\text{s}$, the variation in T_{HS} can be see from lower to higher temperature over
268 the surface of the heat sink which is due to the conduction and convection heat transfer
269 modes. The conduction heat transfer process can be seen clearly at the boundaries
270 of PCM and heat sink interaction because of the higher temperature gradient. A

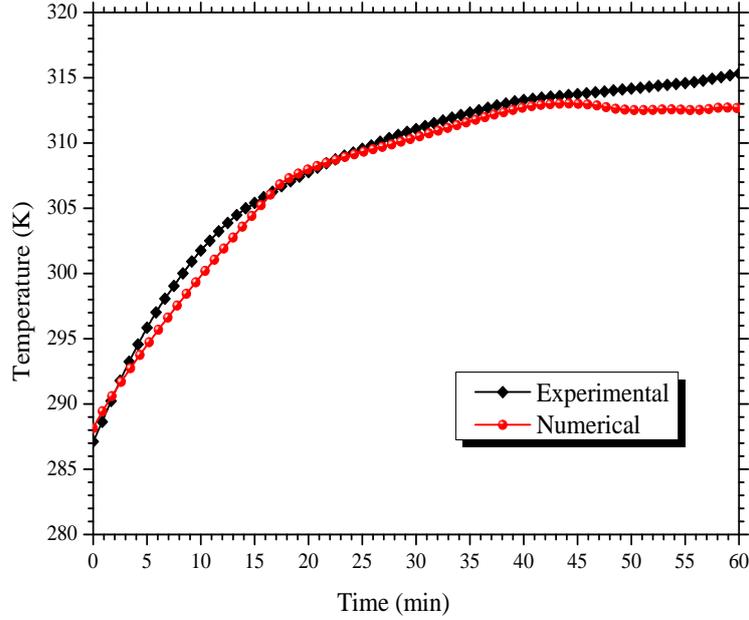


Figure 2: Validation of present study with experimental results of an unfinned heat sink filled with PCM at $\varphi = 0.00$.

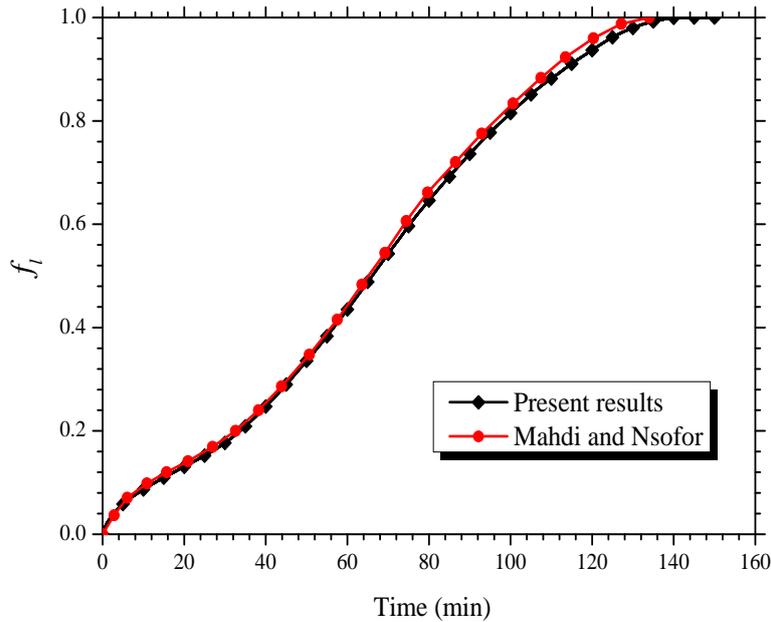


Figure 3: Validation of present results of NCPCM simulation compared with Mahdi and Nsofor at $\varphi = 0.02$ [30].

271 uniform isotherms distribution can be seen between the solid and liquid PCM zones
 272 specially at $\varphi = 0.05$. However, the dominant heat transfer process is because of
 273 pure conduction. Since, the addition of different nanoparticles φ do not show the a
 274 noticeable distribution of isotherms inside the heat sink which indicates that presence
 275 of nanoparticles are just to enhance the heat transfer rate by conduction.

- 276 • At $t = 2100s$, the both conduction and convection heat transfer modes can be seen

277 in isotherms and PCM tend to depart the uniformity in shape which is the initiating
278 of natural convection heat transfer of NCPCM inside the heat sink. At the bottom
279 of heat sink, the circular pattern of isotherms can be observed which is due to the
280 buoyancy force which are developed by the temperature gradient across the heat sink
281 base and gravity force.

282 • At $t = 2700s$, the more dominant convection patterns of isotherms can be seen while
283 heat transfer process of NCPCM heat sink. The more deformed and circular patterns
284 are increased in size because of the growing role of convection heat transfer in melt
285 zone. The relatively cold PCM at the upper part of heat sink moves downward under
286 the gravity effect while melting which is replaced by a melted PCM moving upward
287 under the effect of buoyancy force. At this stage the PCM temperature is affected by
288 both conduction and natural convection heat transfer modes, however, heat conduction
289 mode is dominant until the isotherms do not keep a unified colour.

290 • At $t = 3300s$, the more uniform isotherms are observed in shape and colour become of
291 increasing effect natural convection inside the PCM melt zone. It can be observed that
292 increasing the φ while PCM melting process, the isotherms show there is no significant
293 influence of circulating patterns. This is because of increase of the effective thermal
294 conductivity of NCPCM by adding the nanoparticles which enhance the conduction
295 phenomenon and PCM melting. However, by the adding the nanoparticles, the viscos-
296 ity of the PCM is increased which tend to reduce the movement of liquid PCM inside
297 the heat sink resulting in weakens the natural convection heat transfer contribution.
298 A closer look reveals that upper part of the heat sink has the higher temperature zone
299 as compared to the central zone which show that PCM melt is dominant because of
300 exceeding effect to buoyancy force rather than gravity force. In general, it can be seen
301 that nanoparticles improves the thermal conduction heat transfer with the less effect
302 of natural convection inside the heat sink.

303 3.2. Evaluation of liquid-fraction

304 The solid-liquid interface of NCPCM heat sink is illustrated though f_l contours presented
305 in 5. The melting phenomenon of PCM at different φ of 0.00, 0.01, 0.03, and 0.05 of
306 Cu nanoparticles is presented at different time stages to better understand influence of
307 nanoparticles in PCM as follows:

- 308 • At $t = 1500$ s, the solid liquid zones of PCM can be seen clearly representing in blue
309 and red colours, respectively. The PCM melting layers at the bottom and sides walls
310 can be observed and circulating patterns of liquid PCM are found at the bottom of
311 the heat sink due the effect of buoyancy and gravity forces. Since the heat transfer
312 occurs from bottom and sides of heat sink which is mainly due to conduction heat
313 transfer between solids walls and solid PCM layers.

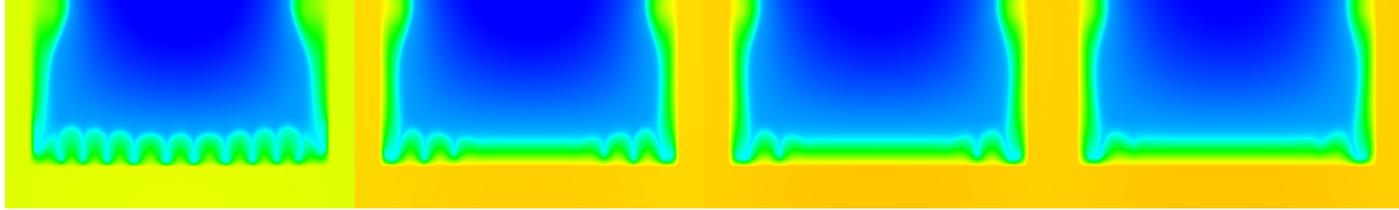
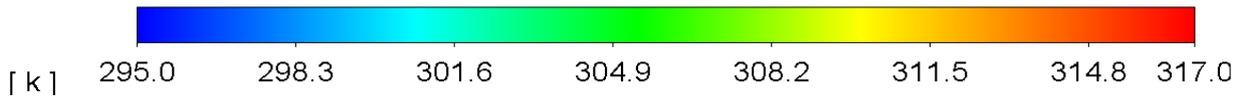
- 314 • At $t = 2100$ s, the increasing tend of circulating patterns of liquid PCM are observed
315 which is because of the increasing effect of buoyancy force developed as a result of
316 temperature gradient. Since, the addition of nanoparticles enhance the thermal con-
317 ductivity of NCPCM as the well as the viscosity of NCPCM which enhance the heat
318 transfer rate and also affects the melt movement of PCM. Therefore, conduction heat
319 transfer mode dominates over convection mode.

- 320 • At $t = 2700$ s, the significance of natural convection is noticeable by appearing the
321 more deformation and size of rotating circles of melted PCM during melting process of
322 NCPCM. In addition, a regular melting patterns of solid–liquid PCM can be seen with
323 the increase of nanoparticles volume fraction. A closer look reveals that relative cold
324 PCM moves downward from solid–liquid interface because of gravitational effect which
325 improves the complete melting of PCM. This movement of melted PCM enhances the
326 rate of PCM melting at the bottom half of the heat sink compared to the upper half.

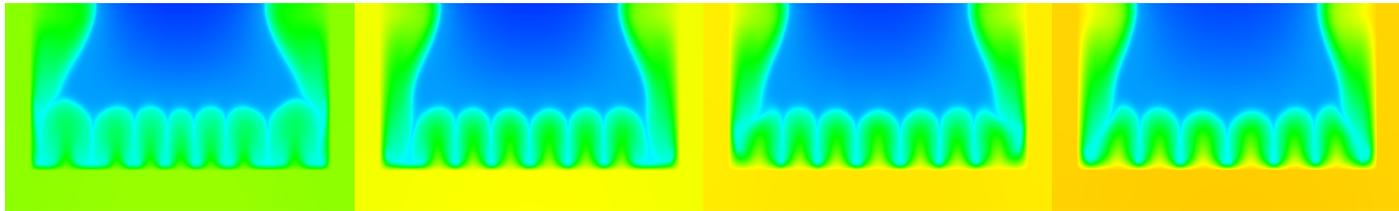
- 327 • At $t = 3300$ s, the higher rate of f_l of NCPCM is obtained in most of the part of
328 heat sink domain which shows the dominant contribution of natural convection heat
329 transfer because of the influence of buoyancy effects. There is still movement of cold or
330 relative less melted PCM towards the bottom because of gravity effects, however, there
331 is a absence of circulating patterns of melted PCM and uniform melting is observed
332 specially at $\varphi = 0.05$. It can be observed that the increasing the φ of nanoparticles
333 increases the size of melted NCPCM and more symmetrical melting patten is observed
334 because of viscous effects.

- 335 • At $t = 3600$ s, the complete melting of NCPCM is obtained for 0.01, 0.03, and 0.05
336 φ because of conduction and natural convection contribution. Since, the addition of
337 nanoparticles improves the thermal conductivity of PCM, thus, it improves the con-
338 ductive heat transfer rate within the PCM and faster melting is achieved. Contrarily,

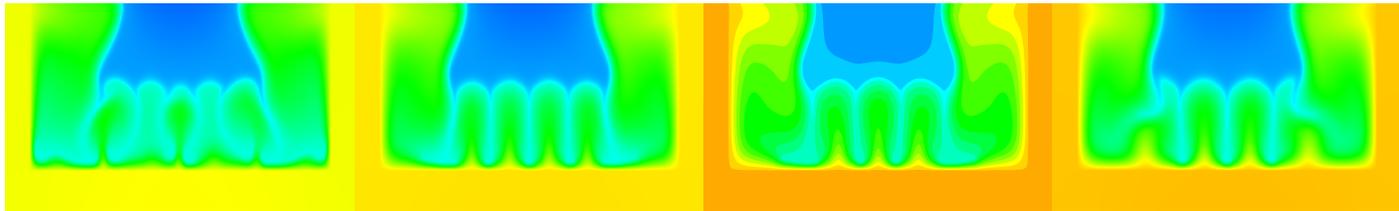
Static Temperature



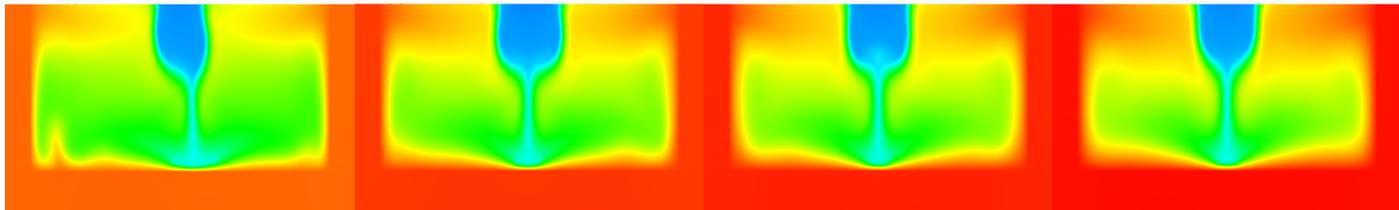
(a) 1500s, $\varphi = 0.00$ (b) 1500s, $\varphi = 0.01$ (c) 1500s, $\varphi = 0.03$ (d) 1500s, $\varphi = 0.05$



(e) 2100s, $\varphi = 0.00$ (f) 2100s, $\varphi = 0.01$ (g) 2100s, $\varphi = 0.03$ (h) 2100s, $\varphi = 0.05$



(i) 2700s, $\varphi = 0.00$ (j) 2700s, $\varphi = 0.01$ (k) 2700s, $\varphi = 0.03$ (l) 2700s, $\varphi = 0.05$

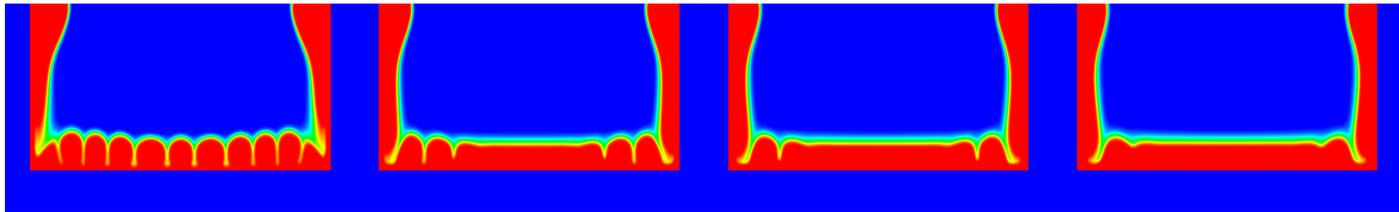


(m) 3300s, $\varphi = 0.00$ (n) 3300s, $\varphi = 0.01$ (o) 3300s, $\varphi = 0.03$ (p) 3300s, $\varphi = 0.05$

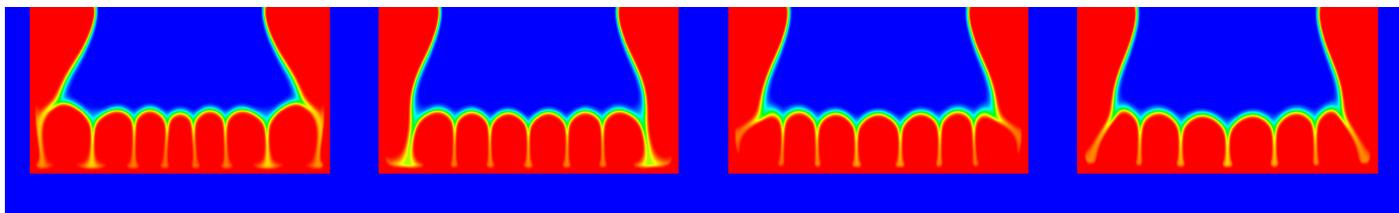
Figure 4: Variation of isotherms contours at various t and φ of NCPCM based heat sink.

339 at $\varphi = 0.00$, there is a still little portion of unmelted PCM which results in to decrease
 340 the heat sink temperature suddenly. In short, the effect of nanoparticles appear more
 341 significantly as the φ of nanoparticles increases and time progresses while the melting
 342 process of NCPCM based heat sink.

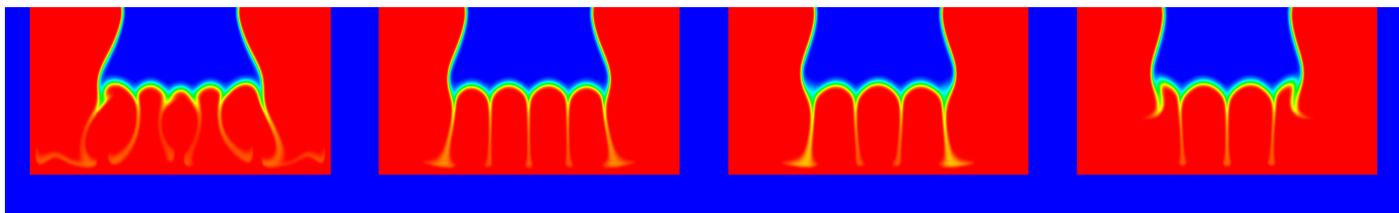
Liquid Fraction



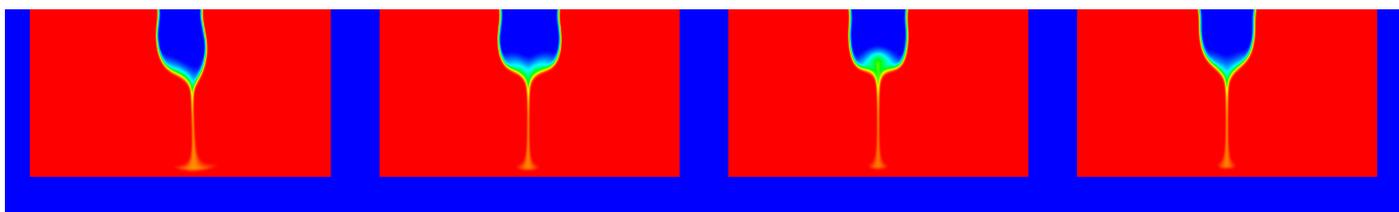
(a) 1500s, $\varphi = 0.00$ (b) 1500s, $\varphi = 0.01$ (c) 1500s, $\varphi = 0.03$ (d) 1500s, $\varphi = 0.05$



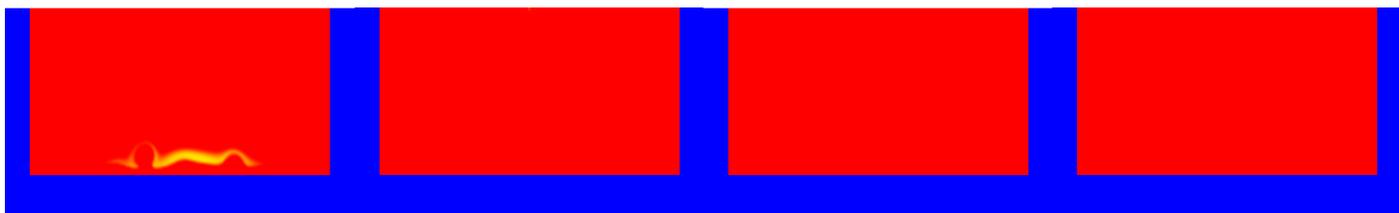
(e) 2100s, $\varphi = 0.00$ (f) 2100s, $\varphi = 0.01$ (g) 2100s, $\varphi = 0.03$ (h) 2100s, $\varphi = 0.05$



(i) 2700s, $\varphi = 0.00$ (j) 2700s, $\varphi = 0.01$ (k) 2700s, $\varphi = 0.03$ (l) 2700s, $\varphi = 0.05$



(m) 3300s, $\varphi = 0.00$ (n) 3300s, $\varphi = 0.01$ (o) 3300s, $\varphi = 0.03$ (p) 3300s, $\varphi = 0.05$



(q) 3600s, $\varphi = 0.00$ (r) 3600s, $\varphi = 0.01$ (s) 3600s, $\varphi = 0.03$ (t) 3600s, $\varphi = 0.05$

Figure 5: Variation of f_l at various t and φ of NCPCM based heat sink.

3.3. Evaluation of average T_{HS} and T_{ncpcm} of NCPCM based heat sink.

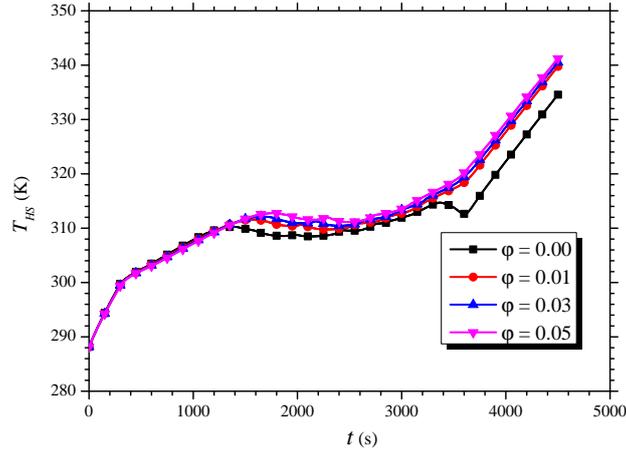
The distribution of average T_{HS} and T_{ncpcm} for different φ of nanoparticles are presented in Figure 6a and 6b, respectively, at a constant input power level. A higher temperature rise is observed with the increase of φ at the end of melting after 3600 s for both T_{HS} and T_{ncpcm} . Additionally, it can be seen that the lower T_{HS} and T_{ncpcm} are observed as φ increases from 0.01 to 0.05, however, these are higher than at $\varphi = 0.00$. The T_{HS} of 334.5, 339.77, 340.54, and 341.23 K at φ of 0.00, 0.01, 0.03, and 0.05, respectively. Similarly, the T_{ncpcm} of 329.51, 334.61, 335.14, and 335.69 K at φ of 0.00, 0.01, 0.03, and 0.05, respectively. The higher temperature rise at φ of 0.01, 0.03, and 0.05 is because of the increase of effective ρ_{ncpcm} , $\rho_{ncpcm}c_{ncpcm}$ and decrease of L_{ncpcm} . Moreover, the k_{ncpcm} increases with the increase of time and temperature as φ increases from 0.01 to 0.05. This result in increase of the T_{HS} and T_{ncpcm} and decrease of L_{ncpcm} with the increase of time. Figure 6 also illustrates that a uniform melting is observed during phase-change process with the increase of φ . The results suggest that a heat sink with NCPCM filling is more effective than the pure PCM which can be more efficient for passive cooling electronic components.

3.4. Evaluation of f_l and t_{melt} of NCPCM based heat sink

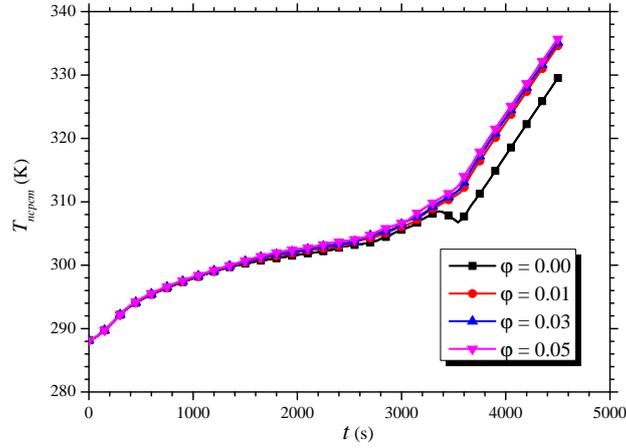
The results of f_l and t_{melt} are presented in 7a and 7b, respectively, at constant power level. It can be seen that the higher f_l is observed with the increase of φ which results in reduce the t_{melt} of NCPCM. The complete t_{melt} of NCPCM is obtained of 3625, 3590, 3575, 3555 s for φ of 0.00, 0.01, 0.03, and 0.05, respectively, a shown in Figure 7a. The comparison t_{melt} of NCPCM at φ of 0.00, 0.01, 0.03, and 0.05 is shown in Figure 7b. The t_{melt} of 3320, 3275, 3260, 3235 s is obtained for φ of 0.00, 0.01, 0.03, and 0.05, respectively. This illustrates that with the increase of φ , the t_{melt} reduces, as expected. The reduction in t_{melt} of NCPCM based heat sink is obtained of -1.36% , -1.81% , and -2.56% at $\varphi = 0.01$, 0.03, and 0.05, respectively, compared with pure PCM based heat sink.

3.5. Evaluation of Q and q of NCPCM based heat sink

The comparison of Q and q of NCPCM based heat sink at different φ is shown in Figure 8. The heat storage analysis presents the amount of heat absorbed by the NCPCM heat sink generated by a electronic component during operation. It can be seen that heat storage capacity increases at $\varphi = 0.01$ and 0.03, however, a slight decrease is obtained at 0.05 of Cu nanoparticles. This variation in results is because of the change in total mass of the PCM by adding the nanoparticles. The Q is composed of the total heat stored energy during



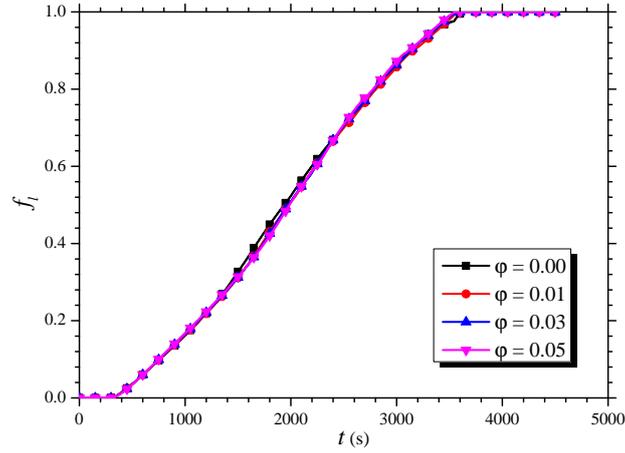
(a)



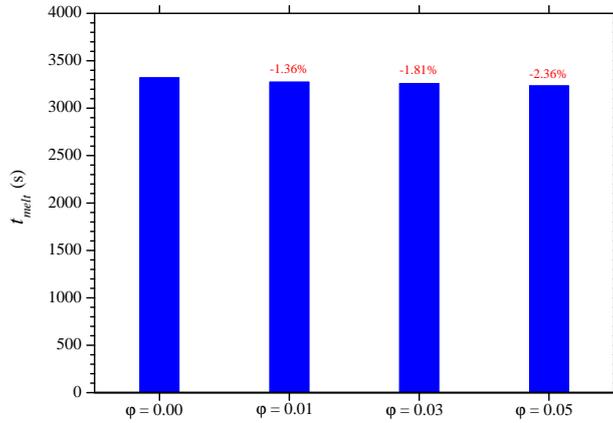
(b)

Figure 6: Variation of average (a) T_{HS} and (b) T_{ncpcm} of NCPCM based heat sink.

375 sensible heating and latent–heating of the NCPCM, as mentioned in Equation 19. The total
 376 Q is calculated of 287.28, 292.66, 289.53, and 286.33 kJ of corresponding φ of 0.00, 0.01,
 377 0.03, and 0.05. The variations for 0.01, 0.03, and 0.05 φ of Cu nanoparticles are obtained
 378 of 1.87%, 0.78%, and -0.33% , respectively, compared with 0.00 or pure PCM based heat
 379 sink. Since, the variations in Q is very small, however, the increasing effect of NCPCM
 380 mass cannot be ignored due the increase of the effective ρ_{ncpcm} with the addition of Cu
 381 nanoparticles. Compared with pure PCM, the mass of PCM increases by 9.81%, 29.44%,
 382 and 49.06% by adding the φ of 0.01, 0.03, and 0.05, respectively. Therefore, the results q ,
 383 defined by Equation 20, are shown in Figure 8 for different φ . The q reduces significantly
 384 with the addition of Cu nanoparticles and depends on the amount of φ . The q is reduced
 385 290.19, 269.20, 225.95, and 194.03 kJ/kg of corresponding φ of 0.00, 0.01, 0.03, and 0.05.
 386 For 0.01, 0.03, and 0.05 φ of Cu nanoparticles, the q is dropped of -7.23% , -22.14% , and
 387 -33.14% , respectively, compared with 0.00 or pure PCM based heat sink. The results are



(a)



(b)

Figure 7: Variation of (a) f_l and (b) t_{melt} of NCPCM based heat sink.

388 attributed to the product of effective ρ_{ncpcm} and c_{ncpcm} , $\rho_{ncpcm}c_{ncpcm}$. The results of Q and
 389 q indicate that even though the addition of nanoparticles increases the mass of PCM and
 390 reduces the effective c_{ncpcm} of NCPCM, however, the effect of ρ_{ncpcm} is more than the c_{ncpcm} .
 391 Therefore, it is suggested to use the $\varphi = 0.01$ of Cu nanoparticles for NCPCM heat sink for
 392 passive cooling application of electronic component.

393 3.6. Evaluation of \dot{Q} and \dot{q} of NCPCM based heat sink.

394 The comparison of \dot{Q} and \dot{q} is presented in Figure 9. The \dot{Q} and \dot{q} are calculated
 395 using Equations 21 and 22, respectively, to evaluate the rate of cooling performance or
 396 enhancement in heat transfer of a NCPCM based heat sink. It can be seen that rate of heat
 397 transfer increases with the addition of Cu nanoparticles. However, it decreases slightly from
 398 0.01 to 0.05 due to the decrease of effective c_{ncpcm} of NCPCM. The \dot{Q} is obtained of 79.25,
 399 81.52, 80.99, and 80.54 W for φ of 0.00, 0.01, 0.03, and 0.05, respectively. The enhancement
 400 in \dot{Q} is obtained of 2.86%, 2.19%, and 1.63% for 0.01, 0.03, and 0.05, respectively, of φ of Cu

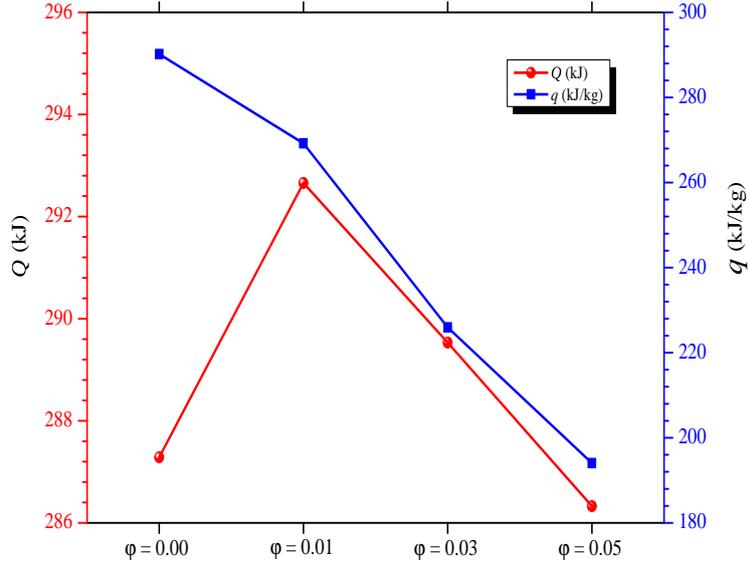


Figure 8: *Comparison of Q and q of a NCPCM based heat sink.*

401 nanoparticles. In addition, the effect of \dot{q} with different PCM masses, defined by Equation
 402 22, is proposed and assessed for different φ . Since, PCM mass increases with the increase of
 403 φ , therefore, the \dot{q} decreases. The amount of \dot{q} is obtained of 80.05, 74.99, 63.20, and 54.58
 404 W for φ of 0.00, 0.01, 0.03, and 0.05, respectively. With the addition of 0.01, 0.03, and
 405 0.05 Cu nanoparticles, the \dot{q} is dropped of -6.33% , -21.05% , and -31.82% , respectively, as
 406 expected, as shown in Figure 9. The results indicate that, at $\varphi = 0.01$ of Cu nanoparticles,
 407 higher and lower trend is obtained between \dot{Q} and \dot{q} , respectively, which is preferable for
 408 passive cooling electronic device in practical applications.

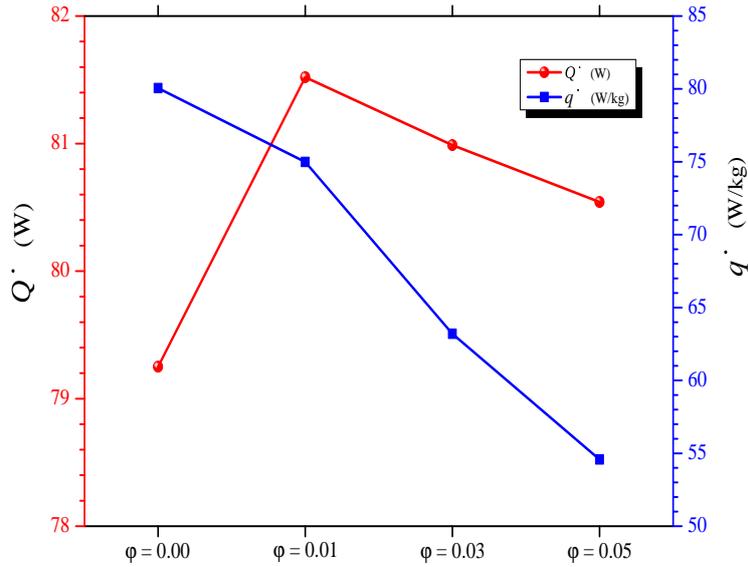


Figure 9: *Comparison of \dot{Q} and \dot{q} of a NCPCM based heat sink.*

409 4. Conclusions

410 A transient 2D numerical study is conducted to investigate the influence of nanopar-
411 ticles in PCM based heat sink to evaluate the thermal cooling performance of electronic
412 components. Different volume fractions of 0.00, 0.01, 0.03, and 0.05 of Cu nanoparticles
413 are varied with at a constant power level of 5 W. The contours of isotherms and transient
414 liquid–fraction are presented for different time intervals and volume fractions of nanoparti-
415 cles. Different thermal performance evaluation indicators such melting time, heat storage
416 capacity, heat storage density, rate of heat transfer, and rate of heat transfer density were
417 evaluated. Following are the key findings drawn from the results:

- 418 • The addition of nanoparticles enhanced the melting rate and thermal conduction mode
419 of PCM with the increase of volume fraction because of the enhancement in effective
420 thermal conductivity and viscous effects of NCPCM. Addition of nanoparticles im-
421 proved the uniformity in melting process.
- 422 • A temperature rise was observed with the increase of φ at the end of melting process
423 for both heat sink and NCPCM cases. The lower heat sink and NCPCM temperatures
424 were achieved with the increase of volume fraction of nanoparticles.
- 425 • The melting time was reduced with the increase of nanoparticles volume fraction and
426 the reduction in melting time was obtained of -1.36% , -1.81% , and -2.56% at 0.01,
427 0.03, and 0.05, respectively, compared with pure PCM based heat sink.
- 428 • The higher heat storage capacity was obtained with 0.01 volume fraction and enhance-
429 ment of 1.87% was achieved compared with pure PCM. The heat storage capacity den-
430 sity was decreased with addition of nanoparticles and minimum reduction of -7.23%
431 was obtained with 0.01 volume fraction.
- 432 • The enhancement in rate of heat transfer was obtained of 2.86% , 2.19% and 1.63% ;
433 and reduction in rate of heat transfer density was obtained of -6.33% , -21.05% and
434 -31.82% with 0.01, 0.03, and 0.05 volume fraction of Cu nanoparticles, respectively.
435 The results suggest that Cu nanoparticles of 0.01, the rate of heat transfer is higher
436 and rate heat transfer density is lower which is preferable for passive cooling electronic
437 device in practical application.

438 To sum up, it is revealed that the addition of Cu nanoparticles in PCM improve the heat
439 flow and solid-liquid melting transformation with more uniformly. The lower heat sink base

440 temperature can be achieved with NCPCM based heat sink, however, this variation is not so
441 significant with only the addition of nanoparticles. Thus, it is suggested to combine metallic
442 fins and/or metal-foams along with the nanoparticles. Moreover, the better enhancement in
443 conjugate heat transfer rate is obtained with NCPCM based heat sink compared with pure
444 PCM based heat sink. Thus, this paper provide guidelines toward the usage of PCM-based
445 electronic cooling applications by providing an in-depth system level performance analysis.

446

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451 research program.

452 **Conflict of interest**

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

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