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**Numerical study on energy and exergy performances of a
microencapsulated phase change material slurry based
photovoltaic/thermal module**

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21 **Abstract**

22 Microencapsulated phase change material (MPCM) slurry has proven to have potential
23 in elevating the overall performance of a photovoltaic/thermal (PV/T) module as a working
24 fluid. In order to make full use of the superiority of MPCM slurry and further improve energy
25 and exergy efficiencies of the PV/T module, the effects of MPCM concentration and melting
26 temperature under a wide inlet fluid velocity range were explored based on a three-
27 dimensional numerical model of coupled heat transfer in this study. The results show that
28 both the energy and exergy efficiencies increased with the concentration. A lower melting
29 temperature resulted in higher energy efficiency, whereas a higher melting temperature is
30 helpful for exergy efficiency improvement. The slurry with an excessively low melting
31 temperature (e.g. 27°C) even led to lower exergy efficiency than pure water. The melting
32 temperature needs to be precisely tailored to make a compromise between energy and exergy
33 efficiencies. In comparison with pure water, the improvement in energy efficiency provided
34 by the slurry was further enhanced at a lower inlet velocity, while the improvement in exergy
35 efficiency was optimized by adjusting the inlet velocity to a certain value. The maximum
36 improvement in energy efficiency provided by the slurry was 8.3%, whilst that in exergy
37 efficiency was 3.23% in this work. From the above, the superiority of MPCM slurry can be
38 further promoted by selecting suitable material properties and operating parameters.

39

40 *Keywords:* Photovoltaic/thermal module; Microencapsulated phase change material; Heat
41 transfer; Numerical simulation; Exergy efficiency.

42

Nomenclature

A	area, m ²	λ	thermal conductivity, W/m K
c	volumetric concentration	ΔT_r	melting temperature range, K
c_p	specific heat, J/kgK	<i>Subscripts</i>	
d	diameter, m	a	ambient or wind
e	shear rate, 1/s	AP	absorber plate
\dot{E}_x	exergy, W	b	bulk fluid
h	heat transfer coefficient, W/m ² K	c	convection
L_p	latent heat, kJ/kg	e	electrical
p	pressure, Pa	ex	exergy
P	packing factor	f	carrier fluid or flow
Pe_p	particle Peclet number	h	heat transfer
q	heat flux, W/m ²	in	inlet
Q_s	solar radiation intensity, W/m ²	l	liquid
\dot{S}_{gen}	volumetric entropy generation rate, W/m ³ K	m	melting
T	temperature, K	out	outlet
\vec{u}	velocity vector, m/s	p	particle
V	volume, m ³	PV	PV panel
<i>Greek</i>		ref	reference
α	absorptivity or thermal diffusivity, m ² /s	s	solid
β	temperature coefficient, 1/K	t	total or tube
ε	emissivity	th	thermal
η	efficiency	<i>Abbreviations</i>	
μ	viscosity, Pa·s	PV/T	photovoltaic/thermal
ρ	Density, kg/m ³	HTF	heat transfer fluid
σ_{sb}	Stefan-Boltzmann constant, W/m ² K ⁴	MPCM	microencapsulated phase change material

43 **1. Introduction**

44 The energy supply strategy is irreversibly shifting from conventional fossil fuels to
45 clean renewable energy sources to tackle energy shortage and environmental problems. Solar
46 energy, as one of the promising renewable energy sources, has had an increasing market
47 share in the last few years. The solar cell is currently the most prevalent solar energy power
48 conversion device since it can directly convert solar radiation into high-grade electrical
49 energy. However, a photovoltaic (PV) panel consisting of solar cells exhibits a notable
50 temperature rise as it is exposed to solar radiation [1], which causes PV efficiency
51 degradation and electrical power output loss [2]. Specifically, PV efficiency would decrease
52 by about 0.5% as the temperature of the crystalline silicon cells increased by 1°C [3]. In order
53 to prevent PV efficiency degradation, a cooling fluid is usually adopted to circulate at the
54 back of a PV panel, which could remove generated heat and make the PV panel operate at
55 lower temperatures [4]. The heat captured by the cooling fluid can also be further utilized.
56 Such a conversion system of solar energy, simultaneously producing electricity and heat from
57 solar radiation, is known as a photovoltaic/thermal (PV/T) system. PV/T systems have proven
58 to exhibit greater energy output per unit installation area and larger total energy efficiency,
59 compared to a PV panel or a conventional solar thermal collector [5].

60 Except for the geometrical configuration studied by Shan et al. [6], the type of heat
61 transfer fluid (HTF) or working fluid is another crucial factor in determining the performance
62 or efficiency of PV/T systems [7]. The HTFs used in PV/T systems which are widely
63 investigated in the literature mainly include air, water, and nanofluids [8]. Farshchimonfared
64 et al. [9] carried out optimum designs of an air-based PV/T collector connected to distribution
65 ducts of heated air. Solanki et al. [10] also explored the performance of an air-based PV/T
66 system. They demonstrated that maximum electrical and thermal efficiencies achieved by the
67 system were around 8% and 39%, respectively. Dimri et al. [11] integrated a thermoelectric

68 cooler into an air-based PV/T module, which obtained an increase by 7.3% in overall
69 electrical efficiency and an increase of 0.8%-2% in overall exergy efficiency compared with
70 conventional PV collector. Habibollahzade et al. [12] combined air-based PV/T panels and a
71 solar chimney to augment exergy efficiency and power generation. Their study indicated that
72 the proposed system exhibited higher exergy efficiency at a lower PV/T panel temperature
73 and a total exergy efficiency of 3.3% was obtained under a good balance with cost rate by
74 multi-objective optimization. The inferior heat removal ability of air becomes the major issue
75 of an air-based system, which is attributed to the weak thermal conductivity, small density
76 and low specific heat of air. Compared with air, water enhanced heat removal ability, and
77 thus in the water-based PV/T system, both the electrical and thermal efficiencies were
78 elevated. A typical water-based system proposed by Huang et al. [13] reached a thermal
79 efficiency of about 50% and an electrical efficiency of about 9.5%. Aste et al. [14] designed a
80 thin film PV/T collector using water as HTF and simulated its performance using a one-
81 dimensional mathematical model. They reported that the average annual overall efficiency of
82 the designed collector was about 42%. Kuo et al. [15] employed the Taguchi method to
83 optimize control parameters of a water-based PV/T collector for simultaneously improving
84 electrical and thermal efficiencies, which were 14.29% and 44.96% after optimization
85 respectively. Mousavi et al. [16] reported that integration of phase change materials in a
86 porous medium with a water-based PV/T collector could reach a highest thermal efficiency of
87 83% as well as an exergy efficiency of 16.7% under a solar irradiance of 600 W/m^2 .
88 Thinsurat et al. [17] proposed a water-based PV/T system integrated with thermal storage
89 units of thermochemical sorption, which could serve as a sole hot water supplier for a typical
90 household in an entire year. The proposed system could also achieve an electric efficiency of
91 13% and reduce the annual consumption of electricity to half at least. Introducing nanofluids
92 in PV/T systems can further improve energy efficiency due to the increased thermal

93 conductivity compared to pure water. Sardarabadi et al. [18] explored the role of SiO₂-water
94 nanofluid in a PV/T module and their study indicated that utilization of 3 wt.% nanoparticles
95 led to an increase by 7.9% in overall energy efficiency with respect to pure water. It should
96 be noted that energy efficiency does not always increase with the nanoparticle concentration
97 mainly due to the reduction of average specific heat of nanofluids [19]. Khanjari et al. [20]
98 comparatively analyzed the performances of tube-plate PV/T systems using pure water,
99 Al₂O₃-water nanofluid, and Ag-water nanofluid as HTFs. They concluded that the energy and
100 exergy efficiencies, as well as heat transfer coefficient, were all increased by introducing
101 nanofluids whilst the Ag-water nanofluid offered preferable improvement. Lari et al. [21]
102 designed an Ag-water nanofluid-based PV/T module to supply electricity and heat for
103 residential applications. Their economic analysis indicated that the proposed system reduced
104 the energy cost by 82% compared with the domestic electricity price in Saudi Arabia. Rahbar
105 et al. [22] established a 1-D model to study a novel concentrating PV/T collector with Ag-
106 water nanofluid as HTFs and triple-junction InGaP/InGaAs/Ge as PV cells. Their work
107 demonstrated that it outperformed a collector without nanofluid with a value of 5.1% in the
108 overall energy efficiency. They also proposed to couple it with organic Rankine cycle for
109 further increasing system performance. Bellos et al. [23] examined a PV/T collector with a
110 parabolic concentrator using pure oil or CuO-oil nanofluid as HTFs under various
111 combinations of inlet temperature and volumetric flow rate. They found that the nanofluid
112 provided enhancements of 2.08% and 3.05% in the total energy and exergy efficiencies,
113 respectively, compared to pure oil at a volumetric flow rate of 540 L/h with an inlet
114 temperature of 100°C.

115 Similar to nanofluids, a microencapsulated phase change material (MPCM) slurry can
116 be formed by uniformly dispersing small enough MPCM particles (i.e. PCM microcapsules)
117 and making them suspended in a carrier liquid (such as water) [24]. Because of MPCM latent

118 heat as well as the interaction among the MPCM particles, carrier liquid and tube wall, the
119 resulting MPCM slurry generally has large apparent specific heat and enhanced heat transfer
120 ability. The MPCM slurry thus has a strong ability to absorb and store large amounts of
121 thermal energy with a decent heat transfer coefficient [25]. Furthermore, the MPCM melting
122 temperature can be specified or selected to fit specific application [26]. In addition, the flow
123 rate of MPCM slurry can be easily regulated in light of its decent flowability. The above
124 advantages or features justify that the MPCM slurry seems to be a promising alternative for
125 conventional working fluids such as water to play a role in PV/T systems.

126 At a fundamental level, a volume of work has been conducted on the heat transfer
127 behavior of MPCM slurries in various channels and heat exchangers [27]. At the application
128 level, much work has also been carried out on the use of MPCM slurries in building heating
129 [28] and heat storage [29]. Recently, several researchers have explored the utilization of
130 MPCM slurries in PV/T systems. Qiu et al. theoretically [30] and experimentally [7]
131 examined the performance of a novel PV/T system with MPCM slurry as HTF but without
132 exergy analysis. Moreover, the theoretical analysis based on energy conservation and
133 experimental tests based on local monitoring cannot offer clear and deep insight into the
134 effects of heat transfer, flow and phase change behavior of MPCM slurries on the PV/T
135 system performance. Liu et al. [31] adopted a two-dimensional numerical model to analyze
136 the dynamic performance of a dual channel PV/T module with MPCM slurry and air as
137 HTFs. In their model, they did not take into account heat transfer enhancement caused by the
138 micro-convection of particles. The results showed that the designed collector with MPCM
139 slurry exhibited the highest overall energy efficiency of 80.57% at 13:00 while its overall
140 exergy efficiency achieved a maximum value of 11.4% in the morning. Liu et al. [32] also set
141 up a three-dimensional numerical model to evaluate the performance of a novel miniature
142 concentrating PV/T collector using MPCM slurry as HTF. They stated that lower solar

143 radiation intensity would result in higher electrical efficiency and higher thermal efficiency.
144 The above studies proved that the utilization of MPCM slurry simultaneously elevated the
145 electrical and thermal efficiencies of a PV/T collector compared to pure water.

146 However, the effect of MPCM melting temperature as a key parameter on the
147 performance of a PV/T module remains unaddressed in the literature, and thus it is unclear
148 how to select suitable MPCM. Furthermore, exergy analysis for the MPCM slurry based
149 PV/T module is scarce in the literature, whilst the phase change of MPCM leads to distinct
150 exergy characteristics. In addition, another two key parameters, MPCM volumetric
151 concentration and inlet slurry velocity, can both influence the melting region distribution of
152 MPCM slurry in tubes, which determine the effectiveness of slurry in performance
153 improvement of a PV/T module. Nevertheless, a study on the combined effects of the two
154 key parameters cannot be found in the literature, except that the effects of the two key
155 parameters have been separately explored [31]. The present study attempts to figure out the
156 above-mentioned issues to make full use of the superiority of MPCM slurry and further
157 improve the electrical, thermal and exergy efficiencies of a PV/T module. A three-
158 dimensional numerical model of coupled heat transfer including the forced convection of
159 slurry, convection of surrounding air, thermal radiation and thermal conduction, was
160 established to evaluate the performance of MPCM slurry based PV/T modules. The
161 numerical model was developed in commercial software, Fluent, and validated by comparing
162 the resulting data with previous experimental and numerical studies. A series of simulations
163 were performed on the basis of the validated model to predict the temperature distributions of
164 a PV/T module under different key parameter combinations, which were then used to discern
165 the role of MPCM in heat transfer. The pure water was also selected as a working fluid as a
166 baseline for comparison. On the basis of the simulation results, the comprehensive
167 performances of the module were calculated and compared, which included electrical,

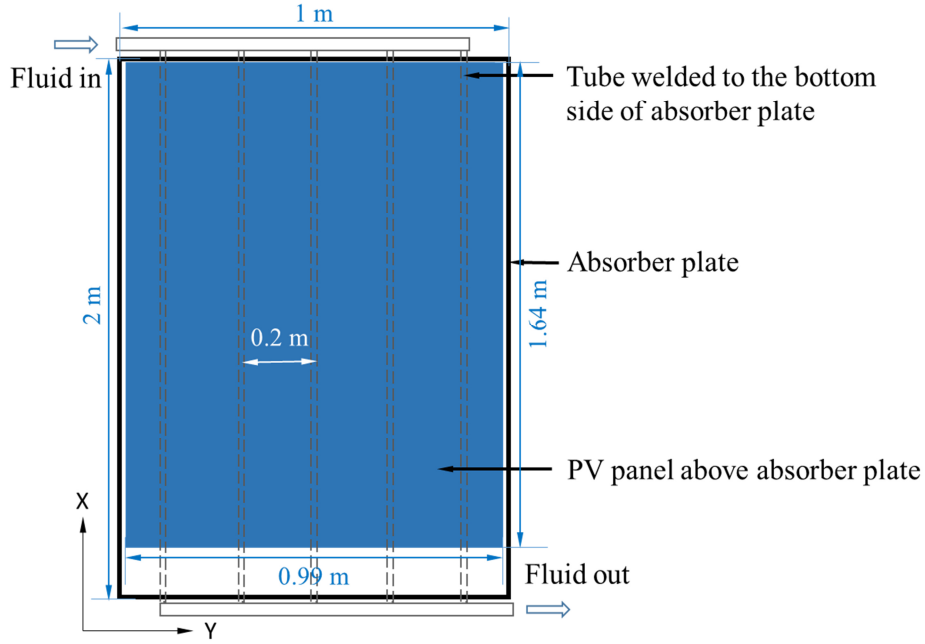
168 thermal and primary-energy saving efficiencies as well as exergy efficiency. The
169 comprehensive performance enhancements of the PV/T module were elaborated after
170 introducing the MPCM slurry compared with pure water. This study is helpful to understand
171 in depth the performance of MPCM slurry based PV/T modules.

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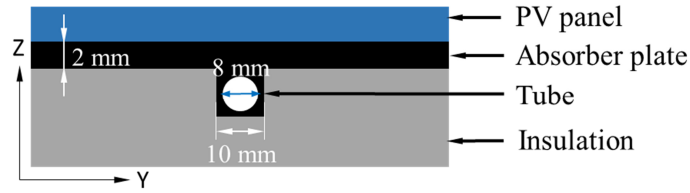
173 **2. Numerical model and solving procedure**

174 *2.1. Model geometry and main assumptions*

175 The proposed PV/T module in this study comprises a PV panel, an absorber plate, five
176 identical tubes and a thermal insulation layer, as shown in Fig. 1. The PV panel was placed
177 on the upper surface of the absorber plate while the five tubes were evenly welded on the
178 back surface of the absorber plate. All surfaces of the PV/T collector except the upper surface
179 were covered by the thermal insulation layer. In order to economize computational time and
180 resources, only 1/5 of the absorber plate and one tube were selected as the computational
181 domain [20]. The effects of the PV panel and thermal insulation layer were considered in the
182 boundary conditions. Dimensions and materials of the tubes, absorber plate and PV panel are
183 gathered in Table 1.



(a)



(b)

Fig. 1 Schematic of PV/T module: (a) front view and (b) local cross section (1/5).

Table 1 Dimensions, materials and properties for different components of the module [5].

Tubes	Absorber plate	PV panel
Number: 5	Length: 2 m	Length: 1.64 m
Length: 2 m	Width: 1 m	Width: 0.99 m
Outlet diameter: 0.01 m	Thickness: 0.002 m	$\alpha_{PV}=0.9$
Wall thickness: 0.001 m	Material: copper	$\varepsilon_{PV}=0.88$
Spacing between center of tubes: 0.2 m	$\alpha_{AP}=0.95$	$\eta_{ref}=12\%$ at $T_{ref}=25\text{ }^{\circ}\text{C}$
Material: copper ($\rho=8978\text{ kg/m}^3$, $\lambda=387.6\text{ W/m K}$, $c_p=381\text{ J/kg K}$)	$\varepsilon_{AP}=0.05$	$\beta=0.0045\text{ }^{\circ}\text{C}^{-1}$

The numerical model of coupled heat transfer was established on the basis of the following main assumptions: (a) because the MPCM particles are small enough and can

194 uniformly disperse in the carrier fluid, the MPCM slurry can be considered homogeneous and
 195 can be treated as a single phase fluid [27], which has been repeatedly adopted in the literature
 196 [33]; (b) the slurry shows Newtonian behavior as the MPCM volumetric concentration is less
 197 than 25% [34], which has also been proved by experimental measurements of the slurry
 198 viscosity [35]; (c) effective thermal conductivity is adopted for the micro-convection
 199 stemming from the interactions of particles with carrier fluid and tube wall [34]; (d) the
 200 melting process occurs over a temperature range with a width of ΔT_r across the melting
 201 temperature T_m , and the lower and upper melting temperature limits are assumed to be
 202 $T_L = T_m - \frac{1}{2}\Delta T_r$ and $T_H = T_m + \frac{1}{2}\Delta T_r$, respectively [36]; (e) the flow is laminar, steady-state,
 203 incompressible, and fully developed at the outlet; (f) the inlet velocities of all tubes are the
 204 same; (g) solar radiation is normal to the upper surface of the PV panel or the absorber plate;
 205 (h) all the surfaces of the absorber plate and tube contacting with the thermal insulation layer
 206 are considered adiabatic; (i) the back surface of the PV panel perfectly contacts with the
 207 upper surface of the absorber plate and thus the temperature distribution is regarded as the
 208 same in the two layers.

209 2.2. Governing equations and boundary conditions

210 The equations governing the laminar flow and thermal convection in the fluid region
 211 include continuity, momentum and energy equations, which can be expressed as

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

$$\nabla \cdot (\rho_b \vec{u} \vec{u}) = -\nabla p + \mu_b \nabla^2 \vec{u} + \rho_b \vec{g}, \quad (2)$$

$$\nabla \cdot (\rho_b \vec{u} c_{pb} T) = \nabla \cdot (\lambda_b \nabla T). \quad (3)$$

212 The governing equation for the thermal conduction in the solid region is

$$\nabla \cdot (\lambda_s \nabla T) = 0. \quad (4)$$

213 The solar radiation is captured to produce electricity and heat. The latter is then
 214 partially dissipated into the surroundings by ambient radiation and air convection while the
 215 rest is transferred into the HTF through the absorber plate. Therefore, the absorbed net heat
 216 flux on the upper surface of the absorber plate covered by the PV panel can be calculated by
 217 [1]

$$q_{AP} = Q_S(\alpha_{PV} - \eta_e) - \varepsilon_{PV}\sigma_{sb}(T_{PV}^4 - T_a^4) - h_c(T_{PV} - T_a), \quad (5)$$

218 where $\sigma_{sb} = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ and $h_c = 3u_a + 2.8$ [37]. In this study, the ambient
 219 conditions were set as $Q_S = 1000 \text{ W/m}^2$, $T_a = 273.15 \text{ K}$ and $u_a = 0.5 \text{ m/s}$ [5]. Similarly, the
 220 absorbed net heat flux on the upper surface of the absorber plate not covered by the PV panel
 221 can be calculated by

$$q_{AP} = Q_S\alpha_{AP} - \varepsilon_{AP}\sigma_{sb}(T_{AP}^4 - T_a^4) - h_c(T_{AP} - T_a). \quad (6)$$

222 All the surfaces contacting the thermal insulation are set to adiabatic boundaries. The two
 223 side surfaces of the segmental absorber plate are set to symmetric boundaries. The boundary
 224 conditions for the HTF flow are presented in Table 2.

225

226

Table 2 Boundary conditions for the HTF flow.

At the tube inlet	At the tube outlet	At the inner surface of the tube
$u_x = u_{in}$	$p = p_a$ (static pressure)	$u_x = u_y = u_z = 0$
$u_y = u_z = 0$		$q_f = q_t$
$T = T_{in} = T_a$		$T_f = T_t$

227

228 2.3. Properties of working fluids

229 The carrier fluid in this study was pure water. The temperature-dependent thermo-
 230 physical properties of pure water can be found in Reference [20]. The hydrocarbon n-
 231 eicosane was selected as PCM while the TiO_2 was selected as shell material in this study. The
 232 weight of PCM core accounted for about 78% of a microcapsule. The properties of PCM

233 microcapsules are summarized in Table 3 [38]. Based on the assumption (a), the bulk
 234 properties of the MPCM slurry can be calculated as a combination of the properties of the
 235 MPCM particles and carrier fluid by various theoretical homogeneous models and
 236 experimental correlations [36]. Based on the mass balance, the slurry density is expressed as

$$\rho_b = c\rho_p + (1 - c)\rho_f. \quad (7)$$

237

238 **Table 3** The properties of n-eicosane microcapsule in this study [38].

Density (kg/m ³)	Specific heat (J/kg K)	Latent heat (kJ/kg)	Thermal conductivity (W/m K)	Melting point (°C)	Particle Size (µm)
946.4	1973.1	192.66	0.749	37	10

239

240 The slurry dynamic viscosity can be calculated using the following correlation which
 241 has been validated for a particle concentration of up to 20% [39]:

$$\mu_b = (1 - c - 1.16c^2)^{-2.5}\mu_f. \quad (8)$$

242 The static thermal conductivity of the bulk slurry can be calculated based on the
 243 Maxwell model [36] as

$$\lambda_b = \lambda_f \frac{2 + \lambda_p/\lambda_f + 2c(\lambda_p/\lambda_f - 1)}{2 + \lambda_p/\lambda_f - c(\lambda_p/\lambda_f - 1)}. \quad (9)$$

244 When the slurry is flowing, the micro-convection mentioned in the assumption (c) will
 245 increase the effective thermal conductivity of the slurry, of which the calculated correlation
 246 can be found in Reference [34].

247 On the basis of the energy balance, the bulk specific heat of the slurry can be
 248 piecewise written as [36]

$$c_{pb} = \begin{cases} \left[c(\rho c_{p,s})_p + (1-c)(\rho c_p)_f \right] / \rho_b & \text{for } T < T_L \\ \left[c \left(\rho \left(\frac{c_{p,s} + c_{p,l}}{2} + \frac{L_p}{T_l - T_s} \right) \right)_p + (1-c)(\rho c_p)_f \right] / \rho_b & \text{for } T_L \leq T \leq T_H \\ \left[c(\rho c_{p,l})_p + (1-c)(\rho c_p)_f \right] / \rho_b & \text{for } T > T_H \end{cases} \quad (10)$$

249 This equation accounts for the phase change of the MPCM particles in the melting range
 250 between T_L and T_H as a step function. The melting temperature range ($\Delta T_r = T_H - T_L$) is set as
 251 1 K in this study [36].

252 2.4. Energy and exergy analysis

253 The gained thermal energy of the HTF equals the absorbed net heat on the upper
 254 surface of the absorber plate. Therefore, the thermal efficiency of the PV/T module according
 255 to the first thermodynamic law can be written as

$$\eta_{th} = \frac{\int_{A_{AP}} q_{AP} dA}{Q_S A_{AP}}, \quad (11)$$

256 The electrical efficiency of the PV panel depends on its temperature, which can be expressed
 257 as [3]

$$\eta_e = \eta_{ref} [1 - \beta(T_{PV} - T_{ref})]. \quad (12)$$

258 In order to reflect the high grade characteristics of electrical energy, primary-energy saving
 259 efficiency is proposed to indicate the overall energy performance of the PV/T module [40],
 260 which is defined as

$$\eta_p = \eta_{th} + P \eta_e / \eta_{power}. \quad (13)$$

261 Here P denotes the area ratio of the PV panel to the absorber plate; $\eta_{power} = 38\%$, denoting
 262 the general efficiency of a conventional thermal power plant;

263 The exergy efficiency of the PV/T module can be expressed as

$$\eta_{ex} = \dot{E}x_{gain} / \dot{E}x_{input} = (\dot{E}x_e + \dot{E}x_{th}) / \dot{E}x_{solar}, \quad (14)$$

264 The electrical exergy equals the produced electrical energy, which can be written as

$$\dot{E}x_e = \eta_e Q_S A_{PV}. \quad (15)$$

265 The thermal exergy obtained by the HTF can be calculated by

$$\dot{E}x_{th} = \int_{A_{AP}} q_{AP} \left(1 - \frac{T_a}{T}\right) dA - \int_{V_{fluid}} T_a (\dot{S}_{gen,h} + \dot{S}_{gen,f}) dV, \quad (16)$$

266 where $\dot{S}_{gen,h}$ and $\dot{S}_{gen,f}$ are the local volumetric entropy generation rates stemming from

267 irreversible heat transfer and flow friction in the HTF, which can be obtained by [41]

$$\dot{S}_{gen,h} = \frac{\lambda_b}{T^2} \left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2 \right], \quad (17)$$

$$\dot{S}_{gen,f} = \frac{\mu_b}{T} \left[2 \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2 \right]. \quad (18)$$

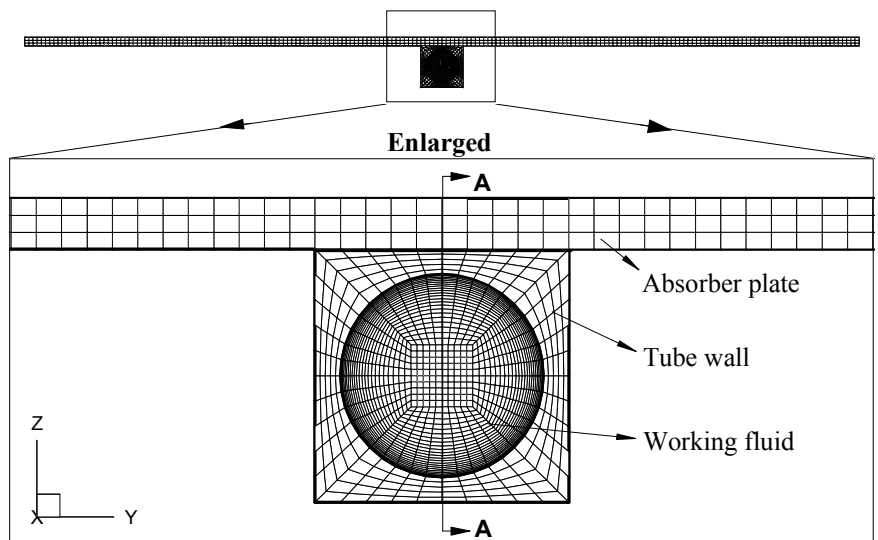
268 The calculation of the solar radiation exergy ($\dot{E}x_{solar}$) can be found in Reference [20].

269

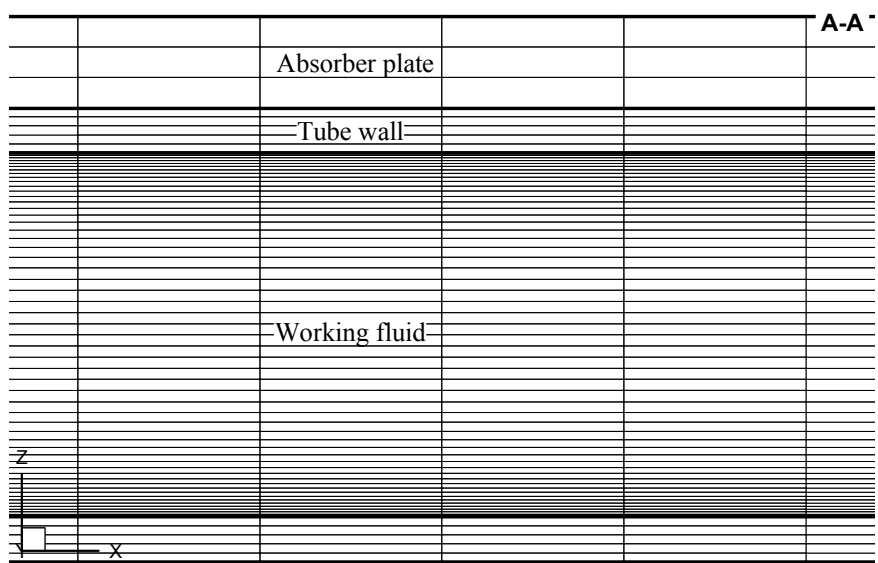
270 **3. Numerical method and model validation**

271 In this study, the governing equations mentioned in Section 2.2 were solved by the
 272 commercial software, Fluent, based on the finite volume method. The SIMPLE algorithm
 273 was selected to tackle the pressure-velocity coupling. The gradients of solved variables at the
 274 control volume center were calculated through the Green-Gauss cell-based method. The
 275 discretizing of convection and diffusion terms in momentum and energy equations was
 276 accomplished based on the QUICK scheme. As the residual values of continuity, momentum
 277 and energy equations reduced below 10^{-6} , 10^{-6} and 10^{-9} respectively, the numerical solution
 278 was regarded as convergent. The whole computational domain was discretized by structured
 279 hexahedral cells. The resulting grid from the Y-Z view with the locally enlarged image is
 280 illustrated in Fig. 2(a) while the grid on the local A-A section of the X-Z view is shown in
 281 Fig. 2(b). The grids are refined in the fluid region near the solid/fluid interfaces where
 282 velocity and temperature gradients are large. In order to carry out the test of grid

283 independence, simulation results on the basis of three different grid sets with 630,000,
 284 890,000 and 1,120,000 cells were comparatively analyzed. The predicted average absorber
 285 plate temperature, average tube outlet temperature and pressure drop in the tube under the
 286 three grid sets are summarized in Table 4. It can be found from this table that the differences
 287 in the average temperatures of the absorber plate and tube outlet are both less than ± 0.3 K
 288 and the percentage difference in the pressure drop is below 0.35% between the third and
 289 second grid sets. Hence, the following numerical simulations in this study were performed
 290 under the third grid set (i.e. 1,120,000 cells).



(a)



(b)

Fig. 2 Computational domains and grids: (a) Y-Z view and (b) Local A-A section of X-Z view.

296 **Table 4** Results of grid-independent test for the average absorber plate temperature (\bar{T}_{AP}), average
 297 tube outlet temperature (\bar{T}_{out}) and pressure drop (Δp) at a slurry with $c=10\%$ and $u_{in}=0.1$ m/s.

Grid number	\bar{T}_{AP} (K)	Difference (K)	\bar{T}_{out} (K)	Difference	Δp (Pa)	Difference (%)
630,000	315.11	-	308.72	-	98.41	-
890,000	316.23	1.02	309.55	0.83	102.95	4.6
1,120,000	316.49	0.26	309.76	0.21	103.32	0.35

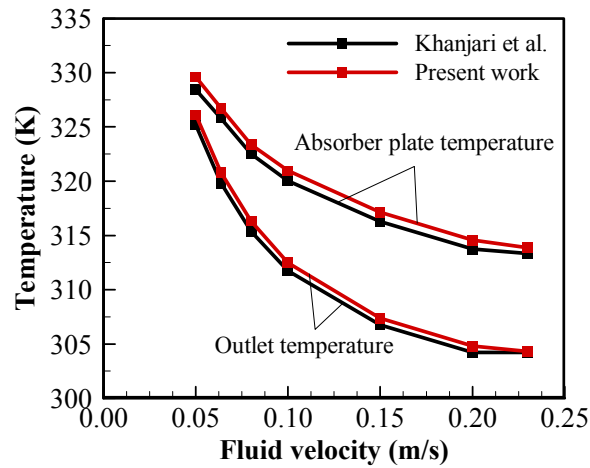
298

299 The established model was validated from two aspects. In the first aspect, the
 300 temperature data of a water-cooled PV/T system calculated by the established model was
 301 compared with one similar simulation work [20], as shown in Fig. 3(a). It can be seen that
 302 they have the same trend and little difference of less than 1 K at the same conditions, which
 303 shows a decent agreement. In the second aspect, the comparison was carried out with the
 304 experimental data on the convective heat transfer of MPCM slurry flow in a circular duct
 305 with a diameter of 3.14 mm [42] and 4 mm [35]. As presented in Fig. 3(b), the duct wall
 306 temperature predicted by the established model was compared with the experimental data for
 307 Stefan number of 3 ($Ste = 3$) [42]. It can be observed that the predicted wall temperatures
 308 coincide with the experimental data. Fig. 3(c) compares the Nusselt number predicted by this
 309 model with the experimental data [35] for two combinations of Reynolds number (Re) and
 310 Stefan number (Ste). It is obvious that the predicted Nusselt number agrees well with the
 311 experimental data at both two combinations. The heat transfer within a water-based PV/T
 312 module and the heat transfer of MPCM slurry in a duct involve all heat transfer processes in
 313 the MPCM slurry based PV/T module proposed in this paper. From the above, the established
 314 model proves to be reasonable and valid.

315

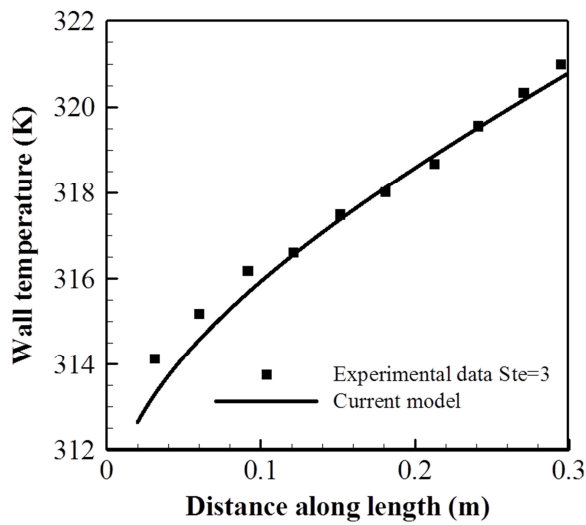
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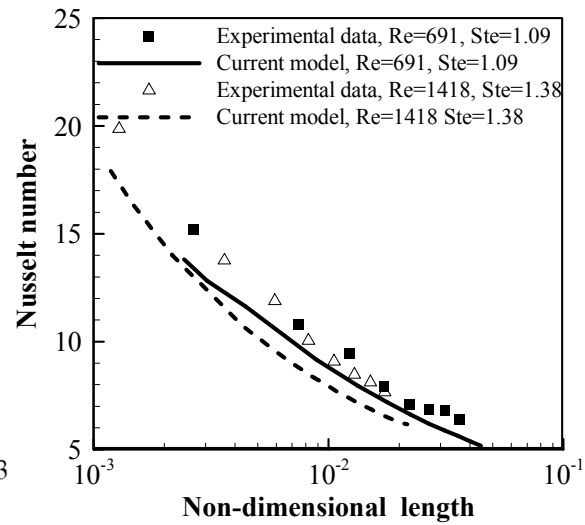
318
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(a)



320
321

(b)



322
323
324

(c)

Fig. 3 Comparison with references for model validation: (a) with the results of Khanjari et al. [20]; (b) with the experimental data of Goel et al. [42]; and (c) with the experimental data of Chen et al. [35].

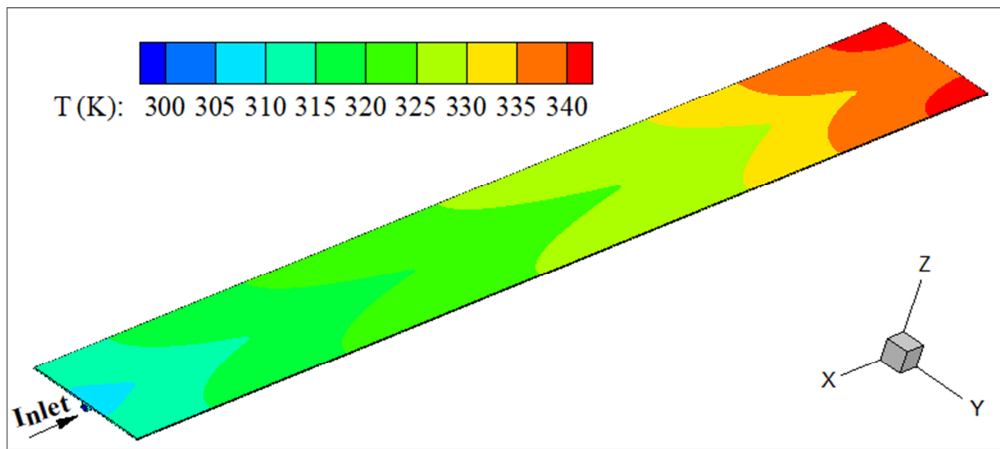
325 4. Results and discussions

326 4.1. Effects of MPCM volumetric concentration

327 To ascertain the effects of MPCM volumetric concentration in the slurry on the
 328 performance of the PV/T module under various tube inlet velocities, three different
 329 concentration values of 5%, 10% and 20% were selected for comparison while the inlet
 330 velocity varied from 0.04 m/s to 0.25 m/s. The comparisons among the three typical
 331 concentrations are enough to reveal the effects of concentration on the module performance.
 332 Therefore, only the results under the three concentrations were presented. With regards to

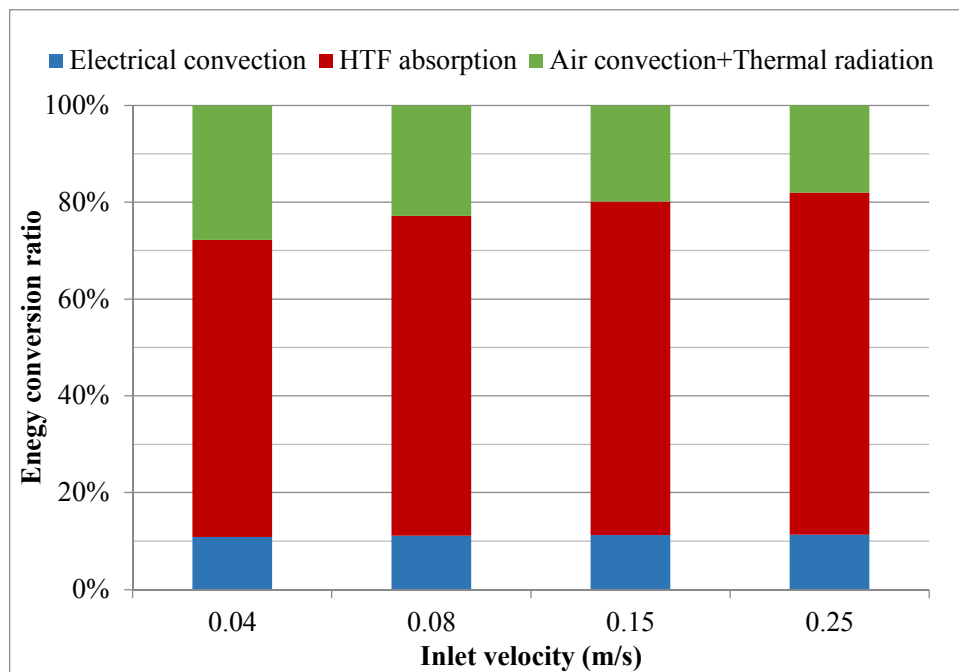
333 concentrations greater than 25%, the rheological behavior of the slurry is unknown, and the
334 viscosity could be too large to act as an effective working fluid. Hence, concentrations higher
335 than 25% were not considered in this paper. The pure water (i.e. the MPCM concentration is
336 0%) was also selected as a baseline. In order to ensure that the sizes of required HTF storage
337 tanks were the same under the same tube inlet conditions, the inlet velocity was selected
338 instead of the mass flow rate. Fig. 4(a) shows a typical temperature distribution of the
339 absorber plate when the slurry with $c=5\%$ enters the tube at $u_{in}=0.04$ m/s. It is easily
340 observed that the temperature increases both from the plate centre to the edge and from the
341 tube inlet to the outlet. This is because the edge of the absorber plate is far away from the
342 cooling tube and the temperature of HTF is gradually elevated along the flow direction
343 through continuous heat absorption. There is no sufficient cooling ability at the edge of the
344 absorber plate, especially near the outlet, which is the intrinsic disadvantage of the plate and
345 tube design [20]. Excess temperatures thus occur at the edge of the absorber plate near the
346 outlet. To avoid the overheating of the PV panel at this location, the PV panel is not paved
347 here, i.e. the PV panel is shorter than the absorber plate near the outlet as shown in Fig. 1(a).
348 More simulations indicate that other selected concentrations and inlet velocities also offered
349 the similar temperature distribution characteristics. The area-averaged temperature on the
350 absorber plate surface was used to represent the absorber plate temperature in the following.
351 Fig. 4(b) illustrates typical conversion ratios of solar radiation energy under various inlet
352 velocities at $c = 5\%$. The solar radiation energy is converted into three parts, which are
353 electricity, heat dissipated into the ambient by air convection and radiation, and heat absorbed
354 by the HTF. The ratio of solar radiation converted into electricity is the lowest among the
355 three manners and slightly increases with the inlet velocity. The ratio dissipated into the
356 ambient notably decreases with the increase of the inlet velocity. Therefore, the ratio
357 absorbed by the HTF increases with the inlet velocity, which is about 61%~71%. This

358 indicates that most solar radiation has been converted into useful heat and meanwhile the
 359 HTF plays a dominated role in the cooling.



360
 361

(a)



362
 363

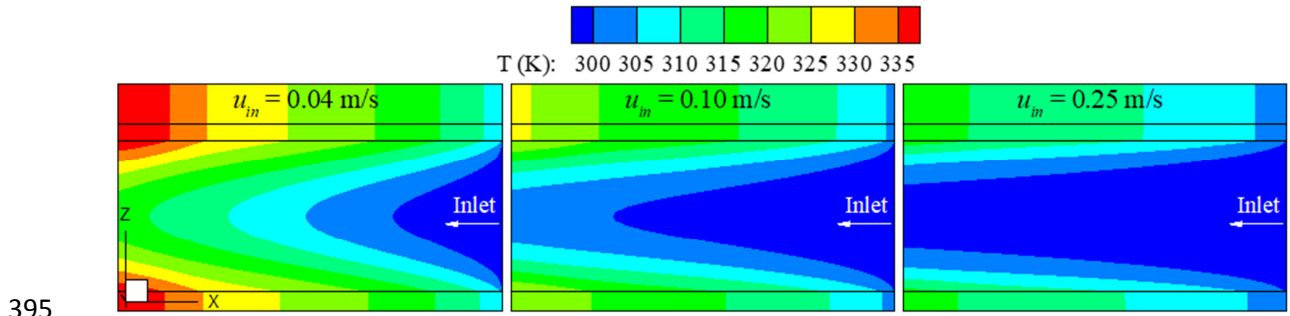
(b)

364 **Fig. 4** Temperature distribution of the absorber plate at $c=5\%$ and $u_{in}=0.04$ m/s (a) and conversion ratio of
 365 solar radiation energy in the PV/T module at $c=20\%$ (b).

366

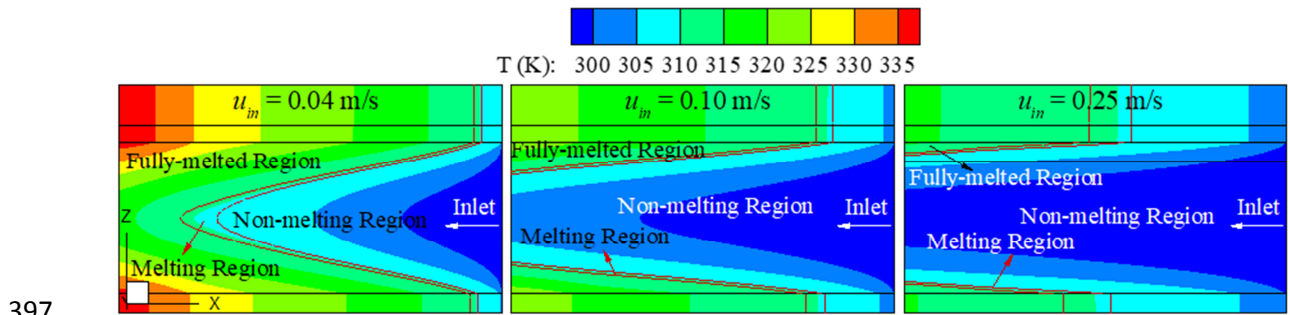
367 The temperature distributions of Section A-A under various MPCM concentrations
 368 and inlet velocities are summarized in Fig. 5. For the convenience of observation, the images
 369 are scaled by $X:Z=1:100$. It is obvious that the increase of inlet velocity or MPCM
 370 concentration is beneficial to obtaining a more uniform temperature distribution in the

371 absorber plate. Some of the MPCM particles were gradually melted along the flow direction
372 of slurry. The fluid region inside the tube can be divided into three regions: non-melting
373 region, melting region and fully-melted region. As the inlet velocity or the MPCM
374 concentration increases, the melting region inside the tube moves from the inlet to the outlet
375 and the fully-melted regions are diminished. The change can be explained as follows: On one
376 hand, as the inlet velocity increases at the same concentration, the heat absorption capacity of
377 the HTF augments under the same temperature rise. On the other hand, the increase of
378 MPCM concentration enhances the thermal conduction ability of the HTF, making the heat
379 from the absorber plate to be more easily transferred to the HTF near the tube centerline.
380 Both aspects lead to the decrease of the HTF temperature rise near the tube wall after the cold
381 HTF flows into the tube and thus the initiating position of melting moves downstream. The
382 changes of the melting region will lead to different melting ratios and absorbed amounts of
383 latent heat in the tube. At a small inlet velocity (e.g. 0.04 m/s), all of the MPCM particles are
384 fully melted in the tube at $c = 5\%$ and 10% , while a small part of the MPCM particles are not
385 fully melted in the tube at $c = 20\%$ because the high concentration of MPCM significantly
386 increases the latent heat absorption ability of the HTF. At a large inlet velocity (such as 0.10
387 m/s or 0.25 m/s), only a part of the MPCM particles for all concentrations can be totally
388 melted, because most heat from the absorber plate is absorbed in the form of sensible heat. It
389 can be inferred that the fully melted status for all MPCM particles can be achieved just at the
390 outlet by adjusting the inlet velocity. The required critical inlet velocity decreases as the
391 concentration increases. Since the absorbed amounts of latent heat and sensible heat are
392 markedly different under various combinations of the MPCM concentration and inlet velocity,
393 different temperature rises of fluids, cooling abilities for the PV plane, amounts of absorbed
394 energy and exergy are caused.



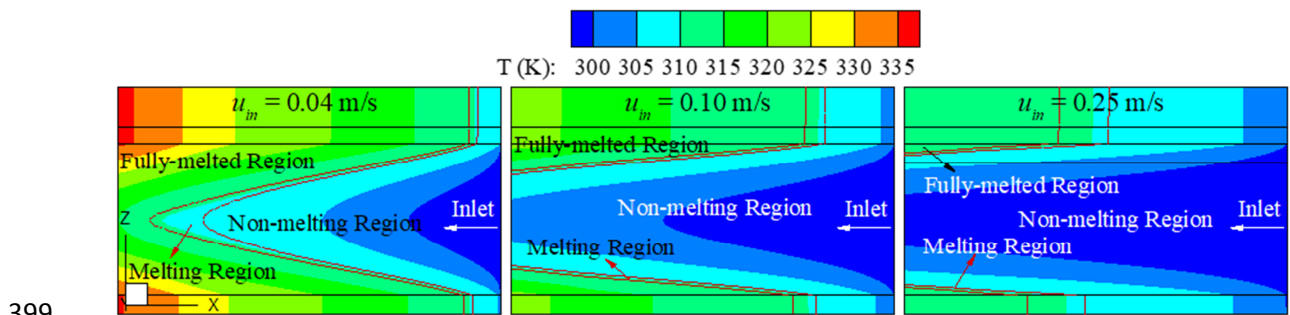
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(a)



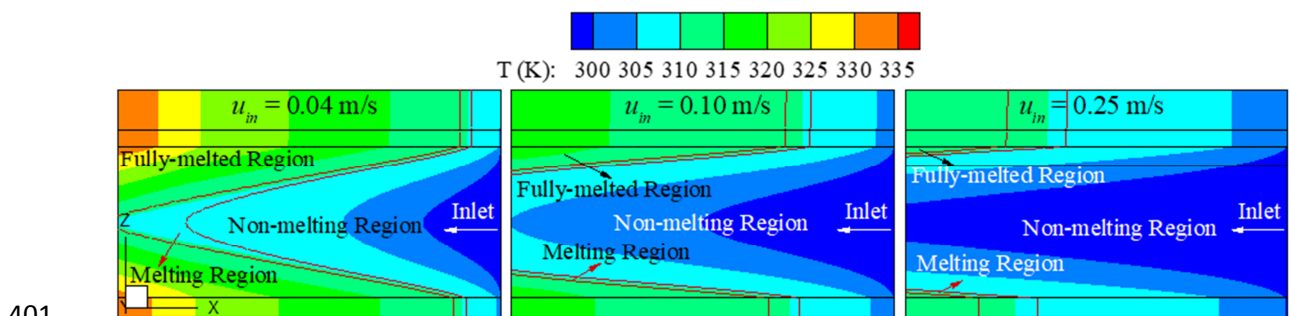
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(b)



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(c)



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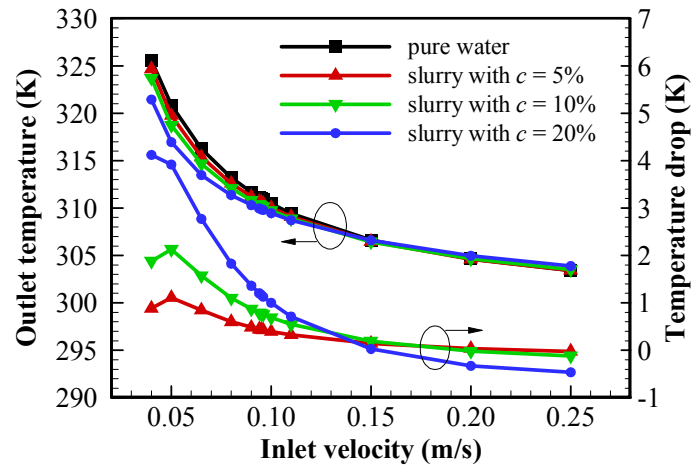
(d)

403 **Fig. 5** Temperature distribution of Section A-A ($X:Z=1:100$) with different HTFs: (a) pure water; (b) slurry
404 with $c=5\%$; (c) slurry with $c=10\%$; and (d) slurry with $c=20\%$.

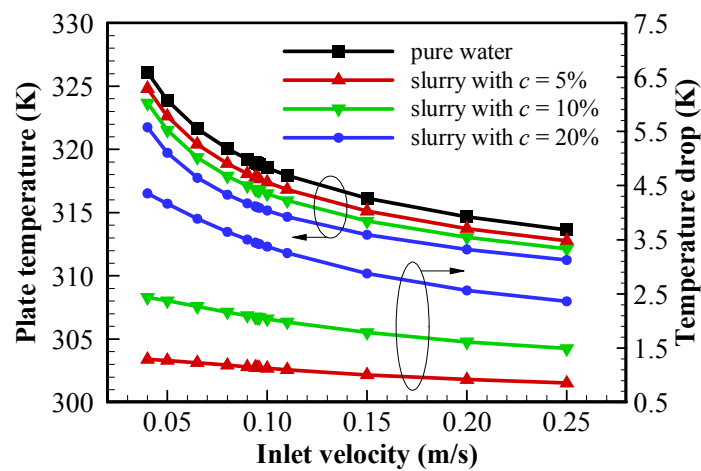
405

406 Fig. 6(a) displays the variations of outlet temperature with the inlet velocity under
407 various HTFs and the outlet temperature drop of slurry compared with pure water at the same

408 inlet velocity. For all volumetric concentrations, the outlet temperature decreases with the
409 increase in the inlet velocity. The inlet velocity should be well controlled to avoid component
410 damages or HTF evaporation caused by high temperature. Compared with pure water, the
411 outlet temperature of slurry is lower at a low inlet velocity (<0.15 m/s) but higher at a high
412 inlet velocity. This is because most of the MPCM particles can be melted at a small inlet
413 velocity and the absorption of latent heat prevents a temperature rise. On the contrary, most
414 of the MPCM particles are not melted at a large inlet velocity and they only play a role in
415 heat transfer enhancement. Similarly, at a small inlet velocity the outlet temperature
416 decreases with the increase of the MPCM concentration while the situation is inverse at a
417 large inlet velocity. For a small MPCM concentration (5% or 10%), the outlet temperature
418 drop of slurry compared with pure water has a maximum in the inlet velocity range of 0.04-
419 0.25 m/s. Combined with Fig. 5, it can be inferred that the maximum is achieved when the
420 MPCM particles reach the upper melting temperature at the tube outlet. In this condition, the
421 ratio of absorbed latent heat to sensible heat of the HTF in the tube is greatest. The variations
422 of average temperature of the absorber plate with the inlet velocity under various HTFs are
423 shown in Fig. 6(b). Obviously the higher inlet velocity and larger MPCM concentration
424 exhibit stronger cooling ability for the PV panel. The reason is that the HTF with a larger
425 MPCM concentration can absorb more heat in a small temperature rise via latent heat
426 absorption. Fig. 6(b) also illustrates the temperature drops of absorber plate under the slurries
427 with respect to pure water at the same inlet velocity. The slurry with the MPCM
428 concentration of 20% can lower the absorber plate temperature by 2.4 K~4.4 K compared to
429 the pure water in the selected inlet velocity range. The enhancement of cooling ability of
430 MPCM slurry compared to pure water decrease with the increasing inlet velocity, which is
431 due to the reduction in the ratio of absorbed latent heat to sensible heat of the HTF.



(a)



(b)

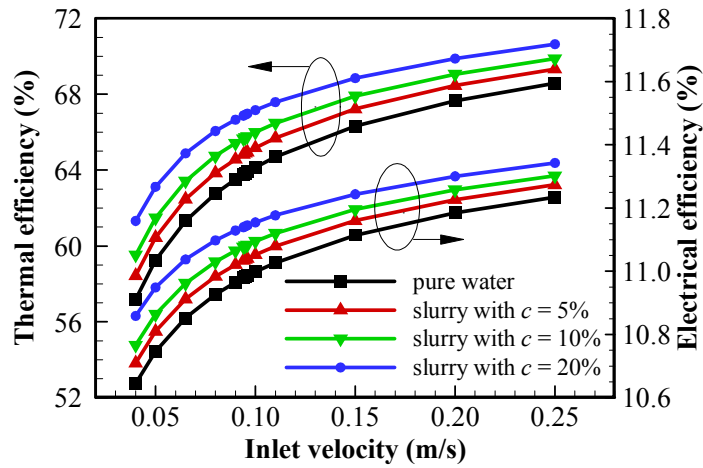
Fig. 6 Temperature variation with inlet velocity at different MPCM volumetric concentrations: (a) outlet; and (b) absorber plate. The temperature drop is calculated with respect to pure water at the same inlet velocity.

As previously described, the utilization of HTFs at the back of the PV panel is designed to simultaneously capture thermal energy for use and cool the PV panel for preventing electrical efficiency loss. Hence, the thermal and electrical efficiencies are two very crucial parameters to indicate the PV/T module performance. The variations in thermal and electrical efficiencies with the inlet velocity for different MPCM concentrations are demonstrated in Fig. 7(a). Increasing the inlet velocity or MPCM concentration can both augment the thermal efficiency. The thermal energy from solar radiation is partially captured by the HTF and partially dissipated to the environment by air convection and thermal

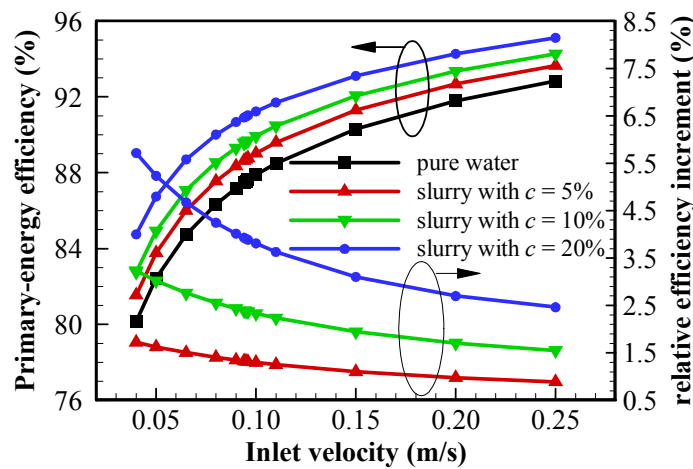
448 radiation. With the increase in inlet velocity or MPCM concentration, the temperature of the
449 absorber plate or PV panel decreases as demonstrated in Fig. 6(b). Subsequently, the thermal
450 energy dissipated to the environment decreases and more thermal energy is captured by the
451 HTF for use, as presented in Fig. 4(b). Therefore, the thermal efficiency increases. According
452 to Eq. (12), since the increase of the inlet velocity or MPCM concentration results in the
453 reduction of the PV panel temperature, the electrical efficiency accordingly increases. The
454 overall performance of the module is characterized by the primary-energy saving efficiency
455 defined in Eq. (13). The variations of the primary-energy saving efficiency for various HTFs
456 versus the inlet velocity are illustrated in Fig. 7(b). Since the thermal and electrical
457 efficiencies are both increased, the primary-energy saving efficiency increases with the
458 MPCM concentration or inlet velocity. The increasing rate of the efficiency progressively
459 decreases with the increasing inlet velocity for each HTF. The relative primary-energy saving
460 efficiency increments for the slurries with respect to the pure water at the same inlet velocity
461 are also illustrated in Fig. 7(b). It is apparent that the slurries provide larger efficiency
462 improvement at smaller inlet velocities with respect to the pure water. Specifically, the slurry
463 with $c = 20\%$ results in a relative increment of 2.5%~5.7% in the primary-energy saving
464 efficiency in the selected inlet velocity range.

465

466



(a)



(b)

Fig. 7 Variations with inlet velocity at different MPCM volumetric concentrations: (a) thermal efficiency and electrical efficiency; (b) primary-energy saving efficiency and relative efficiency increment with respect to pure water at the same inlet velocity.

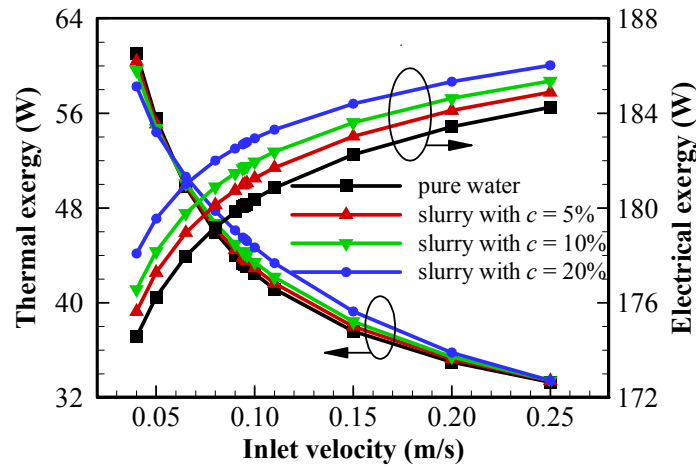
The quality of captured energy can be indicated by thermal exergy and electrical exergy. Fig. 8(a) presents the variations of thermal exergy and electrical exergy captured by the whole PV/T module for various HTFs with the inlet velocity. It can be found that the thermal exergy decreases with the increasing inlet velocity because more heat is absorbed at lower temperatures. For example, the thermal exergy for the slurry with $c = 20\%$ decreases from about 58 W to 33 W when the inlet velocity increases from 0.04 m/s to 0.25 m/s. At low inlet velocities, the thermal exergy of slurry is lower compared to pure water; when the inlet velocity increases over about 0.065 m/s the former becomes larger than the latter; with the

483 further increase in the inlet velocity, the difference between the two gradually diminishes.
484 Moreover, the thermal exergy increases with the MPCM concentration in the inlet velocity
485 range of 0.065~0.25 m/s, which is the same as the thermal efficiency. The trend can be
486 explained as follows: More sensible heat is absorbed at temperatures greater than the MPCM
487 melting temperature for pure water at small inlet velocities. On the contrary at large inlet
488 velocities, the heat absorption temperature of the pure water decreases and more latent heat is
489 absorbed near the relatively high MPCM melting temperature for the slurries; meanwhile, the
490 larger the MPCM concentration, the more the absorbed latent heat. Further increasing the
491 inlet velocity results in the notable decrease in the ratio of absorbed latent heat to sensible
492 heat, and thus the contribution of absorbed latent heat to the thermal exergy is reduced. The
493 electrical exergy increases with the inlet velocity or MPCM concentration, which is the same
494 as the change trend of the electrical efficiency. Specifically, the electrical exergy for the
495 slurry with $c = 20\%$ increases from about 178 W to 186 W when the inlet velocity increases
496 from 0.04 m/s to 0.25 m/s, which is notably greater than the thermal exergy at the same
497 conditions. Moreover, the improvement of electrical efficiency by increasing the MPCM
498 concentration is gradually weakened with the increase in the inlet velocity.

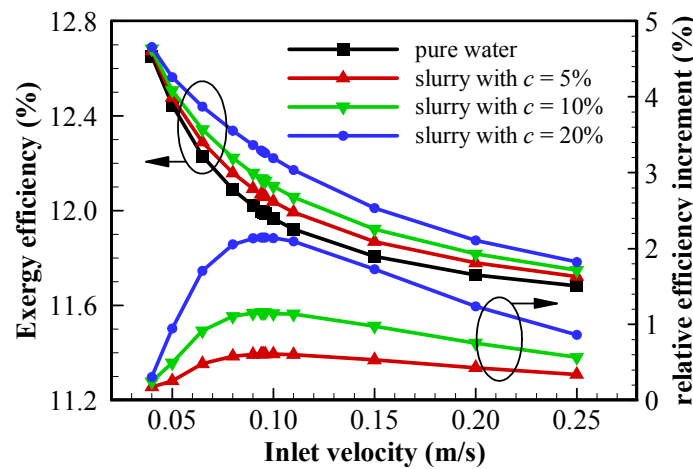
499 The ability to capture available energy of the PV/T module from the solar radiation is
500 indicated by the exergy efficiency. The variations of exergy efficiency with the inlet velocity
501 for different MPCM concentrations are presented in Fig. 8(b). The exergy efficiency
502 generally decreases with the increase of inlet velocity, which is opposite to the trend of
503 primary-energy saving efficiency as presented in Fig. 7(b). This is caused by the remarkable
504 reduction of the thermal exergy. Like the primary-energy saving efficiency, the increase of
505 MPCM concentration is still able to increase the exergy efficiency, which is mainly attributed
506 to the increase of electrical exergy. The variation rate of exergy efficiency for the slurries
507 with the inlet velocity is lower than the pure water. The relative exergy efficiency increment

508 of the slurry versus the pure water is also illustrated in Fig. 8(b). The slurries with different
509 MPCM concentrations exhibit similar variation characteristics of relative exergy efficiency
510 increment, which first increases and then decreases as the inlet velocity increases. The
511 maximum point becomes higher and the variation becomes more dramatic with the increase
512 in the concentration. The reason is that the higher the concentration, the larger the variations
513 in absorbed latent heat and entropy generation caused by flow friction for the same inlet
514 velocity change. The maximum exergy efficiency increments for the slurries with $c = 5\%$, 10%
515 and 20% are 0.61% , 1.16% and 2.14% , respectively. The corresponding inlet velocities are
516 0.01 m/s, 0.096 m/s and 0.095 m/s, respectively. This implies that the addition of MPCM
517 achieves the optimum enhancement in the PV/T module performance at these inlet velocities.

518 Compared to the work of Khanjari et al. [20], the exergy efficiency obtained in this
519 study is lower. The reasons are as follows: On one hand, Khanjari et al. [20] did not consider
520 the heat dissipation caused by the ambient air convection and ambient radiation in their
521 model, which is different from the present study; It means that all of the heat produced by
522 solar radiation was absorbed by the HTF in their simulations. On the other hand, the solar
523 radiation intensity was set as 800 W/m² in the work of Khanjari et al. [20], less than the set
524 value of 1000 W/m² in the present study; Liu et al. [32] indicated that a lower solar radiation
525 intensity gave rise to greater electrical and thermal efficiencies. Furthermore, the exergy
526 efficiency obtained in this study is higher compared with the work of Liu et al. [31], although
527 the solar radiation intensity was lower (589 - 852 W/m²) in their work.



(a)



(b)

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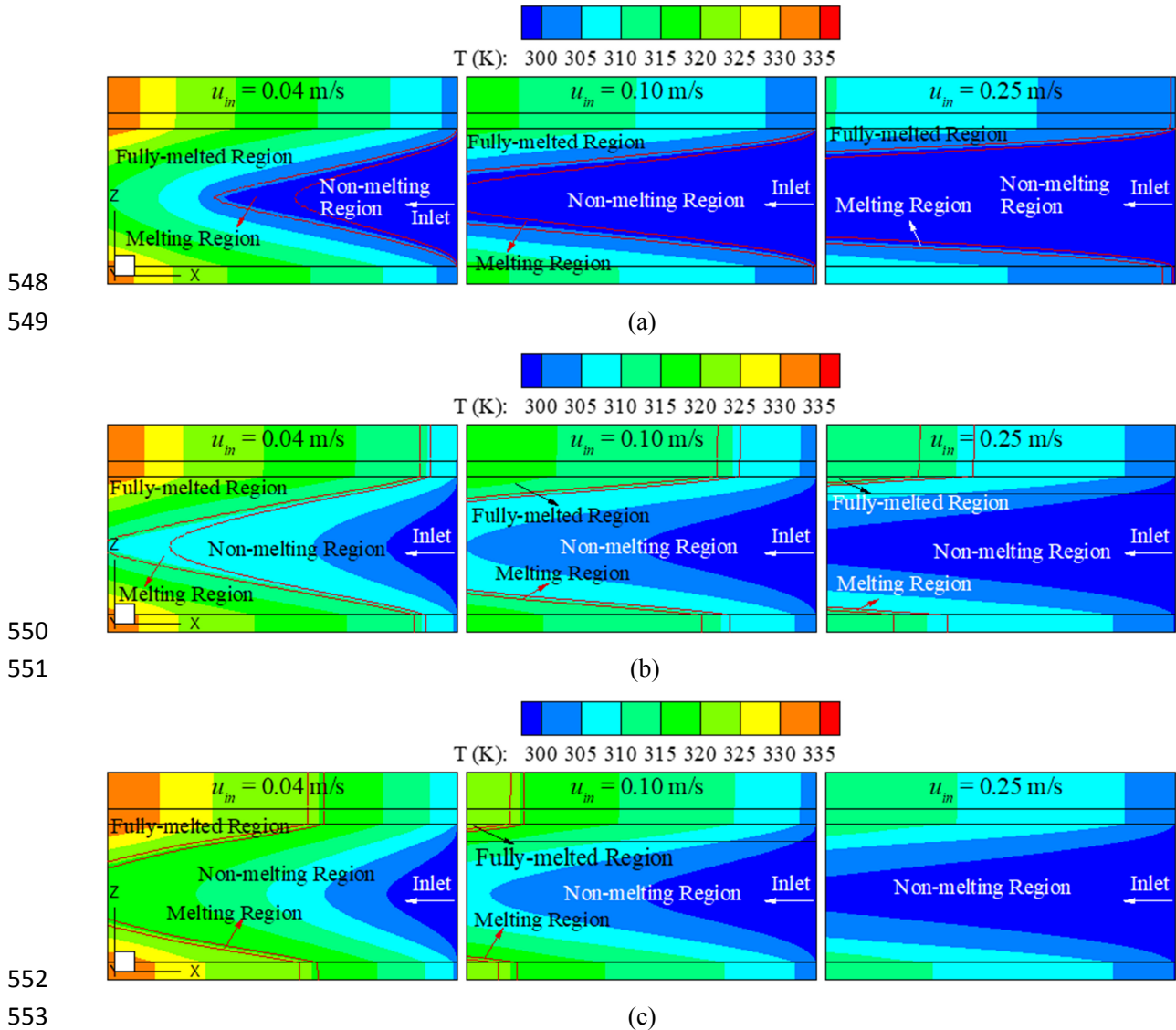
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Fig. 8 Variations with inlet velocity at different MPCM volumetric concentrations: (a) thermal exergy and electrical exergy; (b) exergy efficiency and increment compared to pure water at the same inlet velocity.

535 4.2. Effects of MPCM melting temperature

536 To ascertain the effects of MPCM melting temperature on the PV/T module
537 performance, three different melting temperatures, i.e. 27 °C, 37 °C and 47 °C, were selected
538 in the study for comparison, which are in the achievable operation temperature range of the
539 PV/T module. The MPCM concentration was set to 20% in this section. Fig. 9 summarizes
540 the temperature distributions of Section A-A under various melting temperatures with
541 different inlet velocities. With the increase of melting temperature, the melting region moves
542 from the tube inlet to the outlet and the absorber plate exhibits more uneven temperature

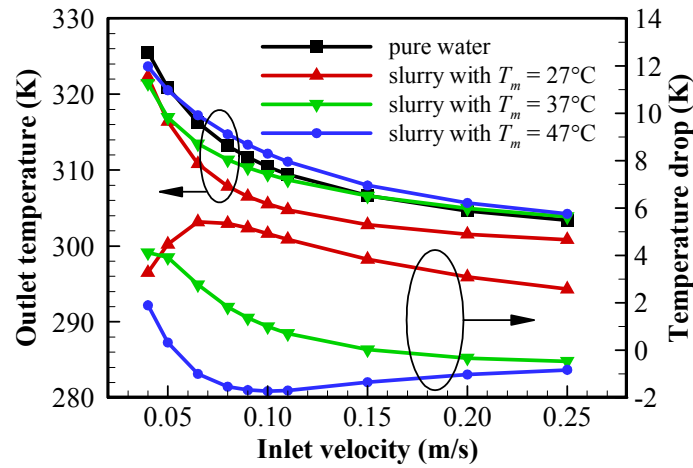
543 distribution at the same inlet velocity. Under the small inlet velocity (e.g. 0.04 m/s), only the
 544 melting temperature of 27°C ensures that all of the MPCM particles are fully melted in the
 545 tube. Lower inlet velocities are required to achieve this situation for the other two higher
 546 melting temperatures. Under the inlet velocity of 0.25 m/s, no melting of MPCM occurs in
 547 the tube for $T_m = 47^\circ\text{C}$.



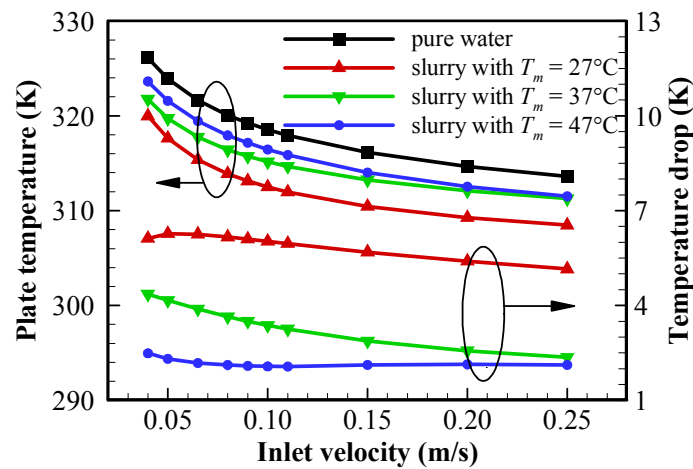
554 **Fig. 9** Temperature distribution of Section A-A ($X:Z=1:100$) using slurry with different melting
 555 temperatures: (a) 27 °C; (b) 37 °C; and (c) 47 °C.

557 Fig. 10(a) displays the variations of outlet temperature of slurries with various melting
 558 temperatures versus the inlet velocity. The outlet temperature of slurry with $T_m = 27^\circ\text{C}$ is

559 always lower compared to pure water in the whole selected range of inlet velocity, while this
560 situation is changed for the other two higher melting temperatures at high inlet velocities.
561 This is because the main role of the MPCM particles gradually shifts from absorbing latent
562 heat to enhancing heat transfer ability for the two higher melting temperatures with the
563 increase in inlet velocity. Fig. 10(a) also shows the outlet temperature drops of slurries with
564 respect to pure water at the same inlet velocity. Different melting temperatures lead to totally
565 different variation characteristics of the outlet temperature drop with the inlet velocity
566 compared to pure water. The temperature drop first increases and then decreases for $T_m = 27^\circ\text{C}$
567 while the change trend is inverse for $T_m = 47^\circ\text{C}$. The variations of average temperature of the
568 absorber plate with the inlet velocity under various MPCM melting temperatures are
569 demonstrated in Fig. 10(b). Obviously, the slurry with a lower MPCM melting temperature
570 leads to lower absorber plate temperatures, and thus shows stronger cooling ability for the PV
571 panel. This can be explained by the fact that a lower MPCM melting temperature ensures that
572 more heat is absorbed by the HTF at a lower temperature. Fig. 10(b) also shows the
573 temperature drops of the absorber plate for slurries compared with pure water. The
574 temperature drop of absorber plate exhibits a similar change trend to the outlet temperature
575 drop as presented in Fig. 10(a). The slurry with $T_m = 27^\circ\text{C}$ has highest the cooling ability
576 among the three melting temperatures, which can lower the absorber plate temperature by 5.2
577 K~6.3 K compared to pure water at the selected inlet velocity range. Its maximum cooling
578 ability enhancement occurs at the inlet velocity of about 0.06 m/s.



(a)



(b)

Fig. 10 Temperature variation with inlet velocity at different MPCM melting temperatures: (a) outlet; and (b) absorber plate. The temperature drop is calculated with respect to pure water at the same inlet velocity.

The variations of thermal and electrical efficiencies with the inlet velocity for various melting temperatures are demonstrated in Fig. 11(a). It is apparent that decreasing the MPCM melting temperature can augment both the thermal and electrical efficiencies. This is directly attributed to the lower absorber plate temperature at a lower melting temperature as shown in Fig. 10(b). The lower absorber plate leads to less heat dissipation into the ambient by air convection and radiation and more heat is absorbed by the HTF, which accordingly results in high thermal efficiency. Moreover, the lower absorber plate means lower PV panel temperature and thus higher electrical efficiency. The primary-energy saving efficiencies calculated based on thermal and electrical efficiencies for various melting temperatures are

595 illustrated in Fig. 11(b). Since the thermal and electrical efficiencies are both increased with
596 the decrease in melting temperature, a lower melting temperature results in a higher the
597 primary-energy saving efficiency. It is worth noting that the selected melting temperature
598 should be higher than the inlet HTF temperature. Moreover, all the slurries with the three
599 different melting temperatures offer higher primary-energy saving efficiency than the pure
600 water. The relative increment in the primary-energy saving efficiency for slurries with respect
601 to pure water is also presented in Fig. 11(b). The relative efficiency increment notably
602 decreases with the increase of the inlet velocity for $T_m = 27^\circ\text{C}$ and 37°C , whereas it keeps
603 relatively constant for the melting temperature of 47°C . Among the three melting
604 temperatures, the slurry with $T_m = 27^\circ\text{C}$ obtains the largest improvement in the primary-
605 energy saving efficiency versus the pure water, which results in a relative increment of
606 5.6%~8.3% at the selected inlet velocity range.

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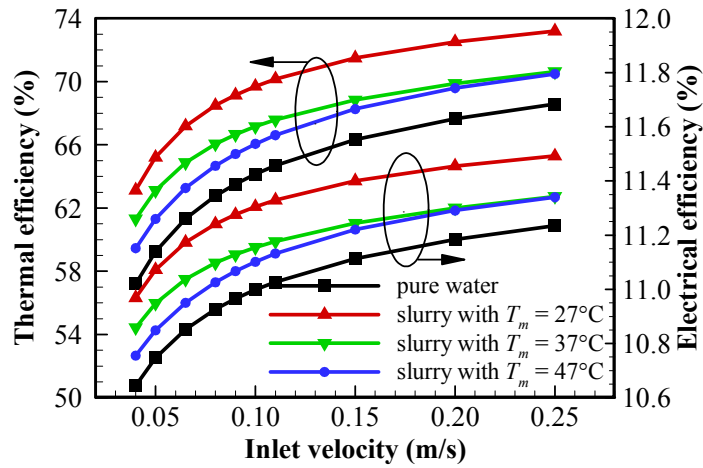
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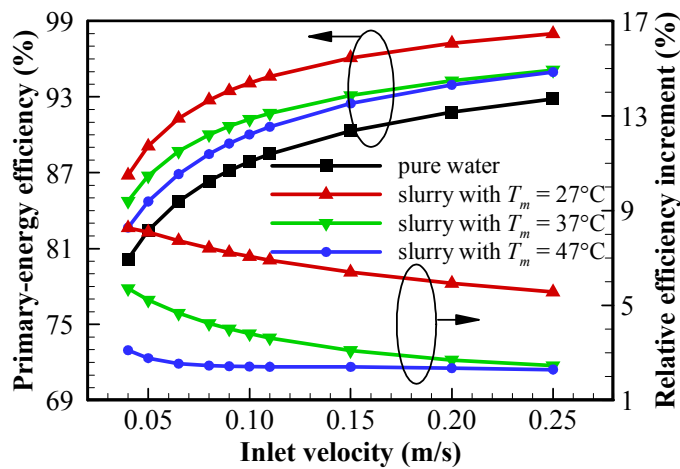
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(a)



(b)

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618 **Fig. 11** Variations with inlet velocity at different MPCM melting temperatures: (a) thermal efficiency and
619 electrical efficiency; (b) primary-energy saving efficiency and relative efficiency increment with respect to
620 pure water at the same inlet velocity.

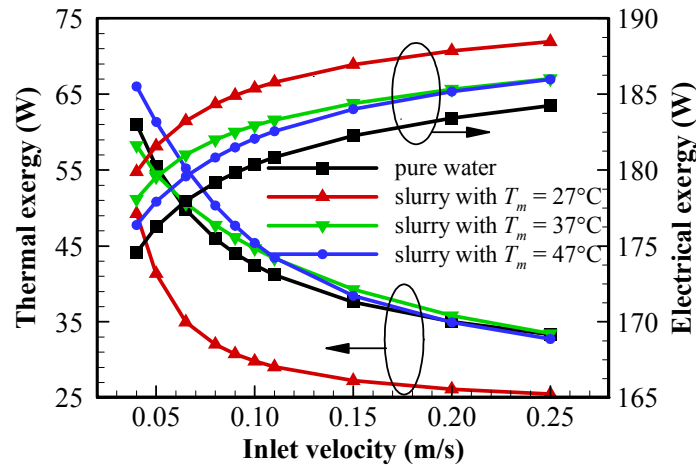
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622 The variations of thermal exergy and electrical exergy captured by the PV/T module
623 with the inlet velocity at various melting temperatures are presented in Fig. 12(a). Compared
624 to pure water at the same inlet velocity, the slurry with $T_m = 27^\circ\text{C}$ captures much less thermal
625 exergy because more heat is absorbed at such a low melting temperature, while the slurry
626 with $T_m = 47^\circ\text{C}$ captures more thermal exergy at small inlet velocities but the improvement
627 gradually diminishes until it vanishes with the increase of the inlet velocity. They are
628 different from the situation for the slurry with $T_m = 37^\circ\text{C}$. The slurry provides higher
629 electrical exergy than pure water at the same inlet velocity regardless of the melting

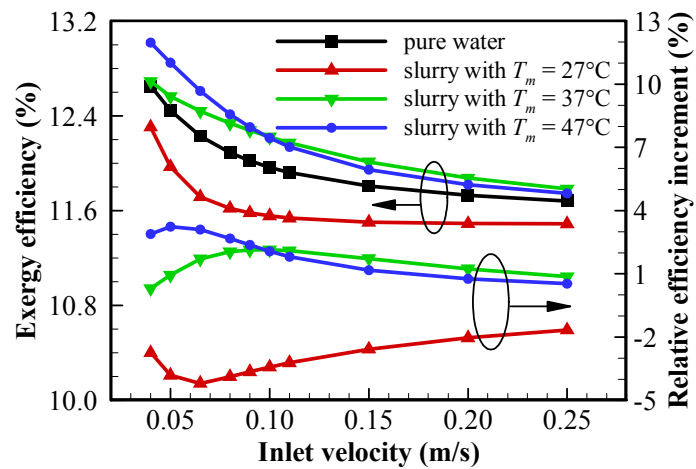
630 temperature, and the electrical exergy increases as the melting temperature decreases due to
631 the resulting lower absorber plate temperature.

632 The variations of exergy efficiency with the inlet velocity for various melting
633 temperatures are shown in Fig. 12(b). Compared to the pure water at the same inlet velocity,
634 the exergy efficiency for the slurry with $T_m = 27^\circ\text{C}$ is less, while those for the slurries with
635 $T_m = 37^\circ\text{C}$ and 47°C are higher. Although the electrical exergy is largest for the melting
636 temperature of 27°C , the thermal exergy is lowest and the sum of the two exergies is lowest,
637 which leads to the lowest exergy efficiency. Furthermore, the exergy efficiency for the slurry
638 with $T_m = 47^\circ\text{C}$ is larger than that for the slurry with $T_m = 37^\circ\text{C}$ at small inlet velocities, while
639 the former is less at large inlet velocities. The variations of the relative exergy efficiency
640 increment of the slurries with respect to the pure water are also illustrated in Fig. 12(b).
641 Likewise, the relative exergy efficiency increments for all the slurries with various melting
642 temperatures have extremums in the selected inlet velocity range. The maximum relative
643 exergy efficiency increments for the slurries with $T_m = 37^\circ\text{C}$ and 47°C are 2.14% and 3.23%,
644 respectively. They occur at the inlet velocities of 0.095 m/s and 0.05m/s, respectively. From
645 the above, adding the MPCM with $T_m = 47^\circ\text{C}$ into the pure water can achieve the largest
646 enhancement in the exergy efficiency of the module among the three melting temperatures,
647 while the exergy efficiency is largely weakened at $T_m = 27^\circ\text{C}$ instead.

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(a)



(b)

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Fig. 12 Variations with inlet velocity at different MPCM melting temperatures: (a) thermal exergy and electrical exergy; (b) exergy efficiency and increment compared to pure water at the same inlet velocity.

656 5. Conclusions

657 A numerical model of coupled heat transfer was established to examine the
658 performance of a MPCM slurry based PV/T module in this study. This model allowed for the
659 photoelectric conversion, HTF flow, air convection and ambient radiation. The effects of
660 MPCM volumetric concentration and melting temperature on the energy efficiency and
661 exergy efficiency of the module in a wide inlet velocity range were explored in detail. On the
662 basis of the simulation results, the main conclusions can be obtained as follows:

663 (1) The increase of volumetric concentration of MPCM particles simultaneously
664 elevated the electrical and thermal efficiencies as well as exergy efficiency under a relatively
665 high MPCM melting temperature.

666 (2) Both the electrical and thermal efficiencies increased with the decrease in MPCM
667 melting temperature, whereas higher melting temperatures (47°C) should be selected to obtain
668 preferable exergy efficiency. The slurry with an excessively low melting temperature (27°C)
669 even resulted in lower exergy efficiency than pure water due to lower thermal exergy.

670 (3) Compared with pure water, the slurry provided a greater improvement in energy
671 efficiency at a lower inlet velocity, whilst the maximum improvement in exergy efficiency
672 was achieved at a certain inlet velocity. The maximum improvements in energy and exergy
673 efficiencies were 8.3% and 3.23% among the selected parameter ranges, respectively.

674

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References

- [1] Y. Du, C.J. Fell, B. Duck, D. Chen, K. Liffman, Y. Zhang, et al. Evaluation of photovoltaic panel temperature in realistic scenarios. *Energy Convers Manage* 108 (2016) 60-7.
- [2] O. Dupré, R. Vaillon, M.A. Green. Physics of the temperature coefficients of solar cells. *Sol Energy Mater Sol Cells* 140 (2015) 92-100.
- [3] E. Skoplaki, J.A. Palyvos. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Sol Energy* 83 (2009) 614-24.
- [4] S. Singh, S. Agrawal, D.V. Avasthi. Design, modeling and performance analysis of dual channel semitransparent photovoltaic thermal hybrid module in the cold environment. *Energy Convers Manage* 114 (2016) 241-50.
- [5] S. Bhattarai, J.-H. Oh, S.-H. Euh, G. Krishna Kafle, D. Hyun Kim. Simulation and model validation of sheet and tube type photovoltaic thermal solar system and conventional solar collecting system in transient states. *Sol Energy Mater Sol Cells* 103 (2012) 184-93.
- [6] F. Shan, F. Tang, L. Cao, G. Fang. Comparative simulation analyses on dynamic performances of photovoltaic–thermal solar collectors with different configurations. *Energy Convers Manage* 87 (2014) 778-86.
- [7] Z. Qiu, X. Ma, X. Zhao, P. Li, S. Ali. Experimental investigation of the energy performance of a novel Micro-encapsulated Phase Change Material (MPCM) slurry based PV/T system. *Appl Energy* 165 (2016) 260-71.
- [8] X. Zhang, X. Zhao, S. Smith, J. Xu, X. Yu. Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. *Renew Sust Energy Rev.* 16 (2012) 599-617.
- [9] M. Farshchimofared, J.I. Bilbao, A.B. Sproul. Channel depth, air mass flow rate and air distribution duct diameter optimization of photovoltaic thermal (PV/T) air collectors linked to residential buildings. *Renew Energy.* 76 (2015) 27-35.
- [10] S.C. Solanki, S. Dubey, A. Tiwari. Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. *Appl Energy* 86 (2009) 2421-8.
- [11] N. Dimri, A. Tiwari, G.N. Tiwari. Thermal modelling of semitransparent photovoltaic thermal (PVT) with thermoelectric cooler (TEC) collector. *Energy Convers Manage* 146 (2017) 68-77.

- [12] A. Habibollahzade. Employing photovoltaic/thermal panels as a solar chimney roof: 3E analyses and multi-objective optimization. *Energy*. 166 (2019) 118-30.
- [13] J. Zhang, Y. Xuan, L. Yang. Performance estimation of photovoltaic–thermoelectric hybrid systems. *Energy*. 78 (2014) 895-903.
- [14] N. Aste, F. Leonforte, C. Del Pero. Design, modeling and performance monitoring of a photovoltaic–thermal (PVT) water collector. *Sol Energy* 112 (2015) 85-99.
- [15] C.-F.J. Kuo, J.-M. Liu, M.L. Umar, W.-L. Lan, C.-Y. Huang, S.-S. Syu. The photovoltaic-thermal system parameter optimization design and practical verification. *Energy Convers Manage* 180 (2019) 358-71.
- [16] S. Mousavi, A. Kasaeian, M.B. Shafii, M.H. Jahangir. Numerical investigation of the effects of a copper foam filled with phase change materials in a water-cooled photovoltaic/thermal system. *Energy Convers Manage* 163 (2018) 187-95.
- [17] K. Thinsurat, H. Bao, Z. Ma, A.P. Roskilly. Performance study of solar photovoltaic-thermal collector for domestic hot water use and thermochemical sorption seasonal storage. *Energy Convers Manage* 180 (2019) 1068-84.
- [18] M. Sardarabadi, M. Passandideh-Fard, S. Zeinali Heris. Experimental investigation of the effects of silica/water nanofluid on PV/T (photovoltaic thermal units). *Energy*. 66 (2014) 264-72.
- [19] A. Kasaeian, A.T. Eshghi, M. Sameti. A review on the applications of nanofluids in solar energy systems. *Renew Sust Energ Rev*. 43 (2015) 584-98.
- [20] Y. Khanjari, F. Pourfayaz, A.B. Kasaeian. Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system. *Energy Convers Manage* 122 (2016) 263-78.
- [21] M.O. Lari, A.Z. Sahin. Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications. *Energy Convers Manage* 149 (2017) 467-84.
- [22] K. Rahbar, A. Riasi, H. Khatam Bolouri Sangjoei, N. Razmjoo. Heat recovery of nano-fluid based concentrating Photovoltaic Thermal (CPV/T) Collector with Organic Rankine Cycle. *Energy Convers Manage* 179 (2019) 373-96.
- [23] E. Bellos, C. Tzivanidis. Investigation of a nanofluid-based concentrating thermal photovoltaic with a parabolic reflector. *Energy Convers Manage* 180 (2019) 171-82.

- [24] Q. Yu, F. Tchuente-Magaia, B. Al-Duri, Z. Zhang, Y. Ding, Y. Li. Thermo-mechanical analysis of microcapsules containing phase change materials for cold storage. *Appl Energy* 211 (2018) 1190-202.
- [25] G. Zhang, G. Cui, B. Dou, Z. Wang, M.A. Goula. An experimental investigation of forced convection heat transfer with novel microencapsulated phase change material slurries in a circular tube under constant heat flux. *Energy Convers Manage* 171 (2018) 699-709.
- [26] Y. Allouche, S. Varga, C. Bouden, A.C. Oliveira. Experimental determination of the heat transfer and cold storage characteristics of a microencapsulated phase change material in a horizontal tank. *Energy Convers Manage* 94 (2015) 275-85.
- [27] N.S. Roberts, R. Al-Shannaq, J. Kurdi, S.A. Al-Muhtaseb, M.M. Farid. Efficacy of using slurry of metal-coated microencapsulated PCM for cooling in a micro-channel heat exchanger. *Appl Therm Eng* 122 (2017) 11-8.
- [28] Z. Qiu, X. Ma, P. Li, X. Zhao, A. Wright. Micro-encapsulated phase change material (MPCM) slurries: Characterization and building applications. *Renew Sust Energy Rev.* 77 (2017) 246-62.
- [29] L. Liu, G. Alva, Y. Jia, X. Huang, G. Fang. Dynamic thermal characteristics analysis of microencapsulated phase change suspensions flowing through rectangular mini-channels for thermal energy storage. *Energy and Buildings.* 134 (2017) 37-51.
- [30] Z. Qiu, X. Zhao, P. Li, X. Zhang, S. Ali, J. Tan. Theoretical investigation of the energy performance of a novel MPCM (Microencapsulated Phase Change Material) slurry based PV/T module. *Energy.* 87 (2015) 686-98.
- [31] L. Liu, Y. Jia, Y. Lin, G. Alva, G. Fang. Performance evaluation of a novel solar photovoltaic–thermal collector with dual channel using microencapsulated phase change slurry as cooling fluid. *Energy Convers Manage* 145 (2017) 30-40.
- [32] L. Liu, Y. Jia, Y. Lin, G. Alva, G. Fang. Numerical study of a novel miniature compound parabolic concentrating photovoltaic/thermal collector with microencapsulated phase change slurry. *Energy Convers Manage* 153 (2017) 106-14.
- [33] F. Bai, M. Chen, W. Song, Q. Yu, Y. Li, Z. Feng, et al. Investigation of thermal management for lithium-ion pouch battery module based on phase change slurry and mini channel cooling plate. *Energy.* 167 (2019) 561-74.

- [34] P. Charunyakorn, S. Sengupta, S.K. Roy. Forced convection heat transfer in microencapsulated phase change material slurries: flow in circular ducts. *Int J Heat Mass Transf.* 34 (1991) 819-33.
- [35] B. Chen, X. Wang, R. Zeng, Y. Zhang, X. Wang, J. Niu, et al. An experimental study of convective heat transfer with microencapsulated phase change material suspension: Laminar flow in a circular tube under constant heat flux. *Experimental Thermal and Fluid Science.* 32 (2008) 1638-46.
- [36] A.B.S. Alqaity, S.A. Al-Dini, E.N. Wang, B.S. Yilbas. Numerical investigation of liquid flow with phase change nanoparticles in microchannels. *Int J Heat Fluid Flow* 38 (2012) 159-67.
- [37] S. Kumar, S.C. Mullick. Wind heat transfer coefficient in solar collectors in outdoor conditions. *Sol Energy* 84 (2010) 956-63.
- [38] L. Chai, X. Wang, D. Wu. Development of bifunctional microencapsulated phase change materials with crystalline titanium dioxide shell for latent-heat storage and photocatalytic effectiveness. *Appl Energy* 138 (2015) 661-74.
- [39] V. Vand. Theory of Viscosity of Concentrated Suspensions. *Nature.* 155 (1945) 364.
- [40] J. Ji, J.-P. Lu, T.-T. Chow, W. He, G. Pei. A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. *Appl Energy* 84 (2007) 222-37.
- [41] A. Bejan. Entropy generation through heat and fluid flow. Wiley 1982.
- [42] M. Goel, S. Roy, S. Sengupta. Laminar forced convection heat transfer in microencapsulated phase change material suspensions. *Int J Heat Mass Transf.* 37 (1994) 593-604.