Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: CUE2020-D-061

Effect of heat exchanger configurations on energy and exergy of photovoltaic thermal system using coolant

Mingmin Kong[1], Qi Xia[1], Shuaiming Feng[1], Chen Chen[1,2*],ShuiQing Zhou[1,2],Zengliang Gao[1,2]
1 Institute of Process Equipment and Control Engineering, Zhejiang University of Technology, Hangzhou, Zhejiang 310032, China
2 Zhejiang University of Technology Innovation Research Institute, Shengzhou, Zhejiang 312451, China
E-mail: chen89@zjut.edu.cn

ABSTRACT

In order to study the effect of different configurations of photovoltaic thermal system on its performance, this paper analyzes the energy and exergy of photovoltaic thermal system with different coolant and heat exchanger configurations with numerical simulation methods. Basically, the heat transfer process between the PV panel and coolant in two different configurations, i.e., the straight tube and the wave tube. Furthermore, the temperature, energy and exergy efficiencies of the two configurations based on pure water cooling photovoltaic thermal system are compared. The results show that the wave tube has the best performance with the maximum thermal efficiency of 58.38% and the electrical efficiency of 11.41%, which are 4.37% and 3.56% higher than the straight tube respectively. In addition, the corresponding exergy efficiency is increased by 4% at the same condition. A lower concentration of CNT/water nanofluid has better performance in practical applications. When the volume concentration is 0.15%, the photovoltaic thermal system has a maximum thermal efficiency of 57.99%, and an electrical efficiency of 11.39%, the exergy efficiency is 11.95%. It is very important to configure the structure of the photovoltaic thermal system and select the appropriate nanofluid.

Keywords: Photovoltaic-thermal module, Heat exchanger configuration, Nanofluid, Energy, Exergy

NONMENCLATURE

Abbreviations	
PVT	Photovoltaic-thermal
Ab	Absorber plate
PV	Photovoltaic
elc	electrical
th	thermal
ex	exergy
a	ambient
in	inlet
out	outlet
f	fluid
t	tube
ref	reference temperature
sun	Sun temperature(K)
HTF	Heat transfer fluid tube
CNT	Carbon nanotubes
Symbols	

A	Area(m^2)
q	Energy(W/m^2)
G	Solar radiation(W/m^2)
T	Temperature(K)
P	Pressure
u	Velocity(m/s)
ρ	Density(kg/m^3)
C_p	Specific heat capacity(J/kg.K)
k	Thermal conductivity(W/m^2.K)
μ	Dynamic viscosity (Pa.s)
β	Impact factor
L	Length(m)
W	Width(m)
D	Diameter(m)
Th	Thickness(m)
S	Space(m)
H	Height(m)
α	Absorptivity
σ	Stefan-boltzmann constant
ε	Emissitvity
η	Efficiency (%)
$\dot{m}$	Mass flow rate(kg/s)
$\dot{E}x$	Exergy

1. INTRODUCTION

With the dramatic increase of carbon dioxide emissions, human-beings pay more attention to the renewable energy. Solar energy as the most abundant renewable resource is of great significance to the future of the mankind. Research on photovoltaic power generation cells shows that the surface operating temperature plays a vital role in the photovoltaic energy conversion process. For every 1 K rise in the surface temperature of the photovoltaic panel, the power generation efficiency decreases by about 0.5% [1]. In order to reduce the temperature of the photovoltaic panel surface, active cooling and passive cooling methods are commonly used. Compared with passive cooling, active cooling is generally more efficient. For the active cooling, optimizing the suitable geometries, configurations of the heat exchanger and the coolant are very important [2-4].

Much research has been conducted to investigate the performance of different types of nanofluids in enhancing the performance of photovoltaic thermal system e.g., non-metal/metal oxide nanofluid, metal elemental nanofluid [5-8], and inorganic carbon-based nanofluid [6, 7, 9-12]. In addition, some researches have been conducted to optimize the heat exchanger structure on the back of the photovoltaic panel in using nanofluid/phase change material/ microcapsule phase change nanofluid, in order to improve the efficiency of the PVT system [3, 4, 13-15].

To authors' best knowledge, the investigations on the effect of different heat exchanger configurations, e.g., straight tubes and wave tubes, on the performance of PVT systems is limited. In this paper, two heat exchanger configurations, i.e., the straight tube and the wave tubes, with pure water and CNT/water nanofluid as the coolant for the photovoltaic heating system are analysed. A three -dimensional CFD model is developed and verified by comparing with research results in other references. Furthermore, the effects of heat exchanger configurations on the PV cell temperature and efficiency are analysed. In addition, the application performance of CNT/water nanofluid in photovoltaic thermal systems has also been further studied.

2. MODELING AND VADIDATION PROCEDURES

The schematics of the photovoltaic thermal system is shown in Figure 1. The tubes for heat transfer are evenly arranged on the back of the photovoltaic panel. Within the tube, the coolant takes away the waste heat, improving the power generation efficiency of the photovoltaic panel. Figure 2 shows the structure model of the photovoltaic panel, with 5 heat exchange tubes symmetrically distributed on the back of the photovoltaic panel. Considering the symmetric structure of the photovoltaic panel, the 1/5 structure of the central part is selected for model. Furthermore, Figure 3 presents the structural components of a photovoltaic panel with a heat exchange tube. Figure 4 shows a schematic the heat exchange structure with the straight tube and the wave tube. In this study, the diameter of tube is fixed to be 8mm and the manufacturing material is the same as the reference [16].

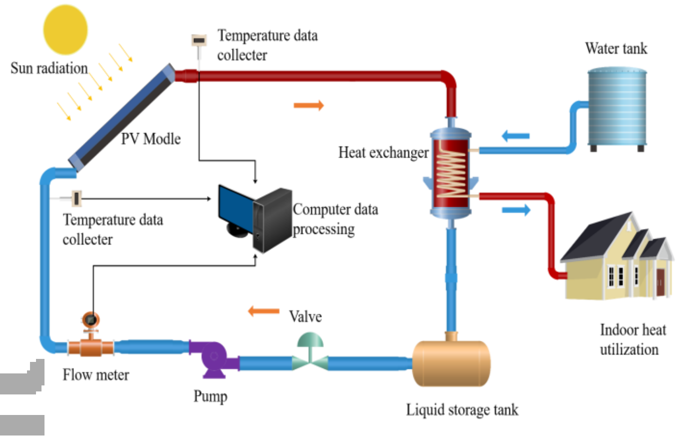


Figure 1 PVT system schematic diagram

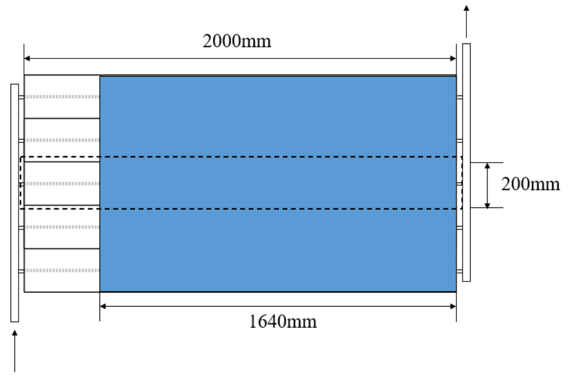


Figure 2 Photovoltaic panel structure model

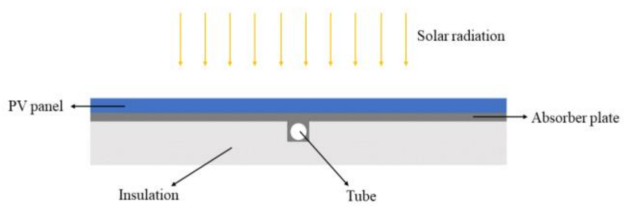


Figure 3 The structural components of a photovoltaic panel with a heat exchange tube

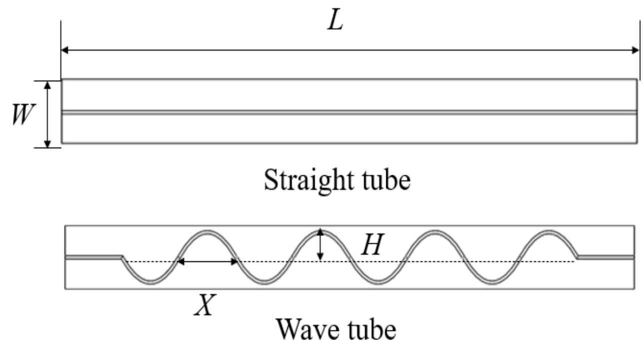


Figure 4 Schematic diagram of heat exchange structure with the straight tube and the wave tube

2.1 Governing equation and boundary conditions

A three dimensional model is developed to simulate steady state heat transfer of incompressible laminar nanofluid flow with the commercial software Fluent [8]. The mass conservation is calculated as

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

The momentum equation is calculated as

$$\nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g} \qquad (2)$$

The energy equation is calculated as

$$\nabla \cdot (\rho \vec{u} C_p T) = \nabla \cdot (\kappa \cdot \nabla T) \qquad (3)$$

For the heat-absorbing plate covered by photovoltaic panels, there are radiation and convection to the ambient. Hence, the net heat flow obtained by the heat-absorbing plate q_{cover} can be calculated as [13]:

$$q_{cover} = G(\alpha_{PV} - \eta_{elc}) - \varepsilon_{PV}\sigma(T_{PV}^4 - T_a^4) - h_c(T_{PV} - T_a) \qquad (4)$$

Where σ=5.67×10^{-8} W/m^2.K^4, T_a=298.15K, u_a=0.5m/s, G=1000W/m^2 and h_c=3u_a+2.8.

For the other part not covered by photovoltaic panels, the net heat flux density can be calculated as:

$$q_{uncover} = G\alpha_{PV} - \varepsilon_{PV}\sigma(T_{PV}^4 - T_a^4) - h_c(T_{PV} - T_a) \qquad (5)$$

The temperature at the tube inlet is set to be 303.15 K. Table 1 presents the values of relevant parameters in Equations (4) and (5). The boundary conditions for the HTF flow are depicted in Table 2.

Table 1 The parameters of the absorber plate and PV panel

Absorber plate	PV panel
$\alpha_{Ab}=0.95$	$\alpha_{PV}=0.95$; $\varepsilon_{PV}=0.88$; $\beta=0.00451$
$\varepsilon_{Ab}=0.05$	η_{ref} =0.12 at $T_{ref}=298.15$K

Table 2 Boundary conditions for the HTF flow

Inlet conditions of the tube	Outlet conditions of the tube	Inner surface conditions of the tube
$u_x=u_{in}$	$P=P_a$	$u_x=u_y=u_z=0$
$u_y=u_z=0$		$T_f=T_t$
$T=T_{in}=T_a$		$q_f=q_t$

2.2 Properties of working fliuds

In this study, The ground state fluid is selected as pure water, and its thermophysical parameters are found in reference[6]. As we all know, CNT/water nanofluid as a coolant with excellent thermophysical properties, We obtained the physical properties of CNT/water nanofluid with different volume fractions in Literature[17]. According to the pseudo-homogeneous model and related theoretical expressions, CNT nanoparticles are uniformly dispersed in pure water, which can be regarded as forming a stable single-phase fluid and Newtonian fluid, the physical properties of different coolants are recorded in Table 3.

Table 3 Thermophysical parameters of different coolants at 298.15K

Fliud&Nanofliud	ρ (kg/m^3)	C_p (J/kg.K)	k (W/m.K)	μ (pa.s)
Pure water	998.2	4182	0.6	0.001
CNT/water(0.15 vol%)	1034.02	3834.68	0.667	0.00281
CNT/water(0.45 vol%)	1043.57	3634.05	0.698	0.00632

2.3 Energy and exergy analysis

The thermal efficiency calculation formula of the photovoltaic thermal system is [18]:

$$\eta_{th}=\frac{\int_{Ab} q_{Ab}dA}{GA_{Ab}}=\frac{\dot{m}C_p(T_{out}-T_{in})}{GA_{Ab}} \tag{6}$$

Considering that the photovoltaic panel power generation efficiency is mainly determined by the photovoltaic panel temperature T_{PV} and the reference ambient temperature T_{ref} , the electric efficiency calculation formula is [19]:

$$\eta_{elc}=\eta_{ref}\left[1-\beta(T_{PV}-T_{ref})\right] \tag{7}$$

The total energy utilization efficiency η_{total} of the photovoltaic thermal system is:

$$\eta_{total}=\eta_{th}+\eta_{elc} \tag{8}$$

The exergy efficiency of photovoltaic thermal system is:

$$\eta_{ex}=\frac{\dot{E}x_{out}}{\dot{E}x_{in}}=\frac{\dot{E}x_{elc}+\dot{E}x_{th}}{\dot{E}x_{solar}} \tag{9}$$

Where electrical exergy is given as:

$$\dot{E}x_{elc}=\eta_{elc}GA_{PV} \tag{10}$$

The exergy efficiency $\dot{E}x_{th}$ is computed as:

$$\dot{E}x_{th}=\dot{m}C_p(T_{out}-T_{in})(1-\frac{T_a}{T_{out}}) \tag{11}$$

The exergy of solar radiation $\dot{E}x_{solar}$, given T_{sun} =5774 K, is computed as:

$$\dot{E}x_{solar}=GA_{Ab}\left[1-\frac{4}{3}(\frac{T_a}{T_{sun}})+\frac{1}{3}(\frac{T_a}{T_{sun}})^4\right] \tag{12}$$

2.4 Numercial method and model vadidation

In this study, The SIMPLE algorithm was adopted to solve pressure-velocity coupling in the commercial software FLUENT 19.0. The gradients of solved variables at the control volume were settled by the Green-Gauss cell-based method. The discretizing of convection and diffusion terms in momentum and energy equations was finished based on QUICK scheme. When the residual values of continuity, momentum and energy equations decreased below 10^{-8}, 10^{-8}, 10^{-9} respectively, the numerical solution was regarded as convergent. In order to verify the grid independence of the numerical simulation process, the three different numbers of grids with 600000,800000,1530000 cells were used for comparative analysis. In the three different types of grids, the average PV temperature, the average tube outlet temperature simulation prediction results were recorded in Table 4. As the number of grids increases, the temperature difference gradually decreases. It is more appropriate to choose a grid number of 1530000 as the numerical simulation result. Figure 5 shows the computational area and grids of the model. Our model-generated results have been compared to the results of Yu et al with the same properties[13]. Table 5 presents the properties of different types of photovoltaic panels for model inputs. Figure 6 shows the comparison of our model-generated and established PV panel temperatures for different fluid inlet temperatures. Figure 7 shows the comparisons of the thermal efficiency and electric efficiency from our model and other references. As shown in Figures 6 and 7, the results similar, which validates our model.

Table 4 Results of grid-independent test for the average PV temperature, the average tube outlet temperature and the pressure drop at CNT/water nanofluid(0.15vol%) with u_{in} =0.1m/s

Grid number	T_{PV} (K)	Difference(K)	T_{out}	Difference(K)
850000	320.99	-	313.316	-
1180000	321.02	0.03	313.379	0.063
1530000	321.036	0.016	313.397	0.0018

Table 5 Structural physical parameters of different types of photovoltaic panels

Types	Photovoltaic panel structure		
	PV	Straight tube	Wave tube
Length, L(m)	1.64	2	2
Width, W(m)	1	-	-
Diameter, D(m)	-	0.008	0.008
Thickness, Th(m)	0.002	0.001	0.001
Space, S(m)	-	-	0.2
Height, H(m)	-	-	0.08

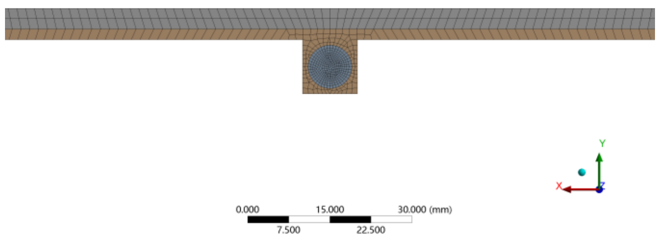


Figure 5 The computational domains and grids of the model

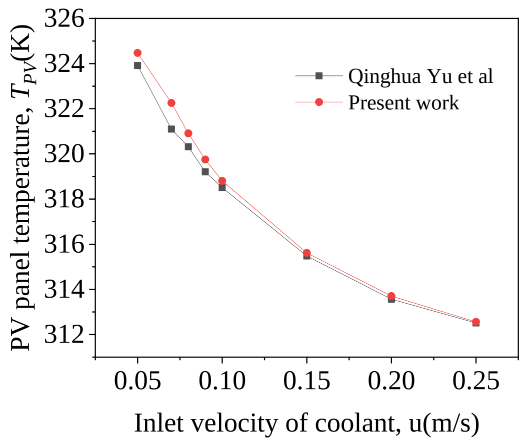


Figure 6 The average PV panel surface temperature validation study of PVT system compared with Yu et al

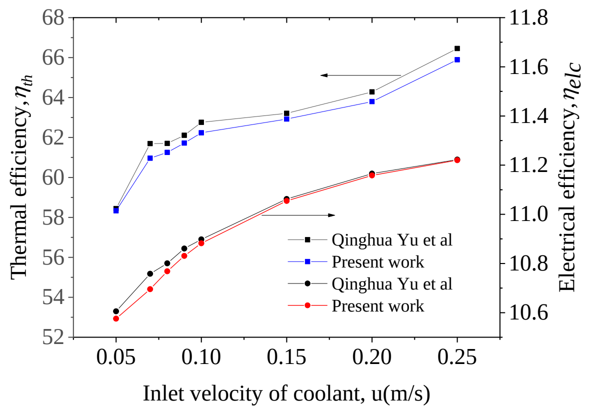


Figure 7 The thermal and electrical efficiency validation study of PVT system compared with Yu et al

3. RESULTS AND DISCUSSIONS

3.1 Effect on PV panel temperature

With the validated model, the effects of the two configurations on the PV panel temperature are investigated. The fluid inlet velocity range set by the research object in this paper is 0.05m/s-0.25m/s, and the inlet temperature is 303.15K. Figure 8 shows the change of the average surface temperature of photovoltaic panels with the two configurations using pure water for cooling. As the fluid inlet velocity increases, the temperature of the photovoltaic panels is gradually reduced. Wave tube has a lower photovoltaic panel temperature. When the fluid inlet velocity is 0.25m/s, it has the lowest photovoltaic panel temperature of 309.05K.

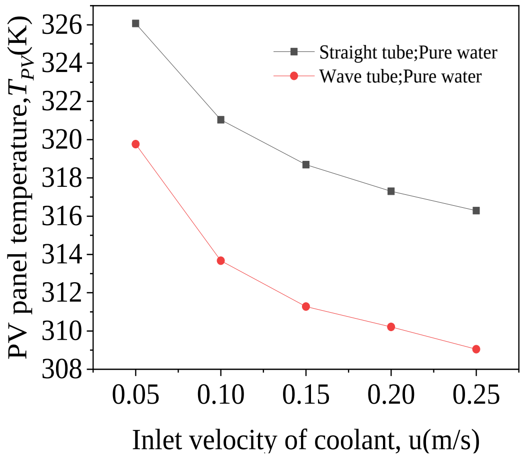


Figure 8 The influence of different heat exchanger configurations on the average temperature of PV panel for pure water

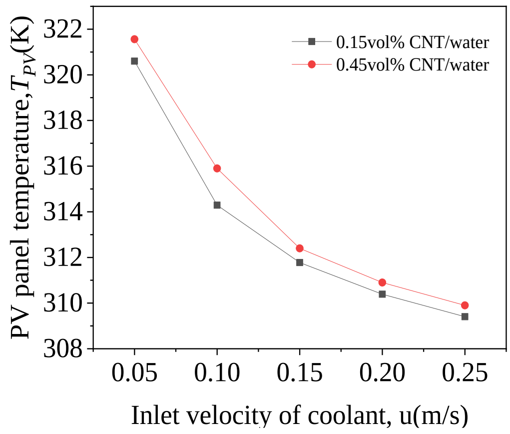


Figure 9 The average surface temperature of the photovoltaic panel uses different volume fractions of CNT/water nanofluid

Furthermore, we choose a wave tube configurations as the research object. Figure 9 shows that the average surface temperature of the photovoltaic panel uses different volume fractions of CNT/water nanofluid along with the speed range of 0.05m/s-0.25m/s. The cooling efficiency of CNT/water nanofluid with a volume fraction of 0.15% is better than that of CNT/water nanofluid with a volume fraction of 0.45%, making the average temperature of the photovoltaic panel surface lower.

3.2 Effect on thermal and electrical efficiency

The effects of the two configurations on the thermal and electrical efficiency are investigated. Figure 10 shows the thermal and electrical efficiency of PV panels as functions of the fluid inlet velocity with the two configurations. Along with the increase of inlet velocity, both the thermal efficiency and electrical efficiency of the two configurations gradually increase. The wave configuration has better performance. At a speed of 0.25m/s, the wave tube has a thermal and electrical efficiency of 58.38% and 11.41%. Compared to the straight tube, the thermal efficiency increases by 4.37%, and the electrical efficiency increases by 3.56%.

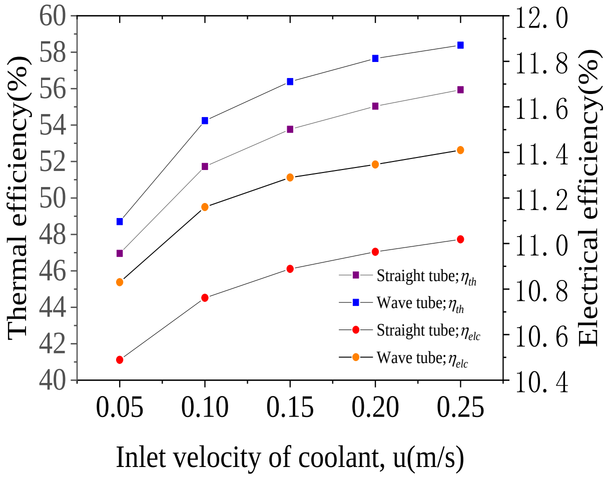


Figure 10 Thermal and electrical efficiency of PV panels with the two configurations

Figure 11 shows the thermal efficiency and electrical efficiency of CNT/water nanofluid with different volume fractions in a photovoltaic thermal system with wave tube configurations. As the fluid inlet velocity increases, the total efficiency of the photovoltaic thermal system continues to increase. Furthermore, the CNT/water nanofluid with a volume fraction of 0.15% has the highest thermal efficiency and electrical efficiency of 57.9% and 11.39% when the velocity is 0.25m/s. Figure 12 depicts the distribution of electrical conversion, HTF thermal absorption and thermal radiation and air conversion rate with the 0.15% volume fraction of CNT/water nanofluid under different speed conditions. Higher mass flow rate can reduce thermal radiation and air conversion loss, and improve the total efficiency of photovoltaic thermal system.

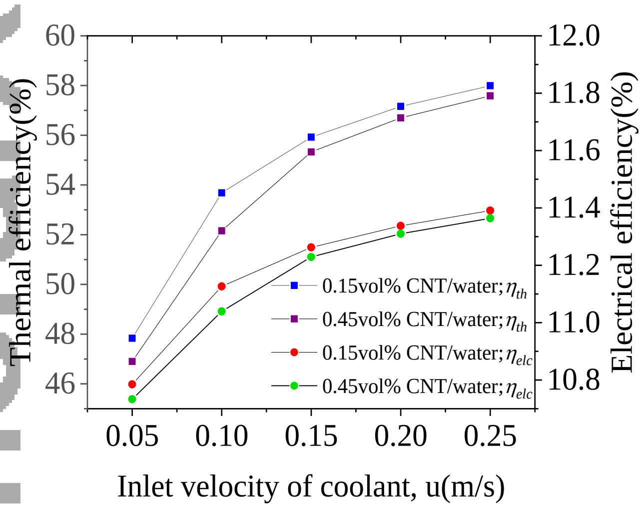
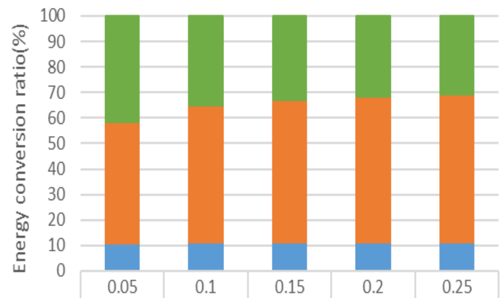


Figure 11 The thermal and electrical efficiency performance of different volume fractions of CNT/water nanofluids in a photovoltaic thermal system with wave tube configurations



	0.05	0.1	0.15	0.2	0.25
Thermal radiation and air convection	41.38	35.1885	32.813	31.4999	30.61535
HTF thermal absorption	47.835	53.685	55.925	57.1625	57.99375
Electrical convection	10.785	11.1265	11.262	11.3376	11.3909

Inlet velocity,u(m/s)

Figure 12 The distribution of electrical conversion, HTF thermal absorption and thermal radiation and air conversion rate with the 0.15% volume fraction of CNT/water nanofluid

3.3 Effect on exergy efficiency

According to the second law of thermodynamics, exergy efficiency is more meaningful to analyze the work available. Figure 13 shows the exergy efficiency of PVT system as a function of the fluid inlet velocity. As shown in Figure 13, the wave tube has a higher exergy efficiency. When the velocity is 0.25m/s, the exergy efficiency of the straight tube and the wave tube is 11.44% and 11.9%, respectively.

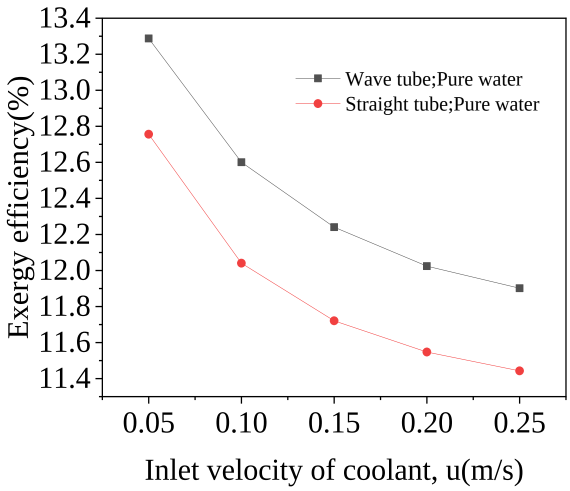


Figure 13 Exergy efficiency of PV panels under different configurations

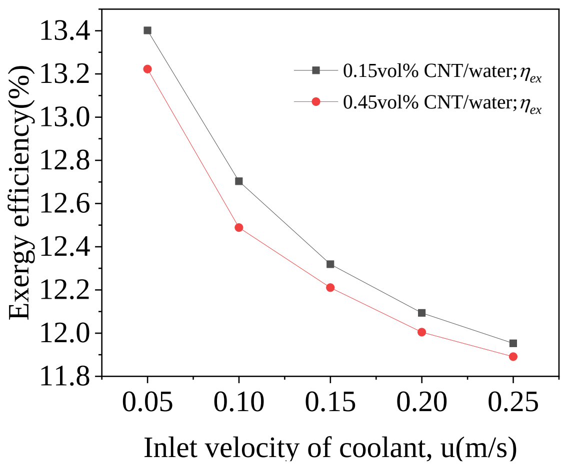


Figure 14 Exergy efficiency of PV panels under wave tube configurations for CNT/water nanofluid

Figure 14 shows the exergy efficiency of photovoltaic thermal system with different volume fractions under wave tube configurations for CNT/water nanofluid. With the increase of the flow rate, the exergy efficiency of CNT/water nanofluid with a low concentration of 0.15% volume fraction is higher than the performance of 0.45% volume fraction of CNT/water nanofluid. When the inlet flow rate is 0.25m/s, the exergy efficiency of 0.15% volume fraction of CNT/water nanofluid and 0.45% volume fraction of CNT/water nanofluid is 11.95% and 11.9%. Therefore, the application of lower concentration of CNT/water nanofluid in photovoltaic thermal systems has better exergy efficiency.

4. CONCLUSION

In this paper, the effect of the heat exchanger configurations on the PV cell temperature change, energy and exergy performance of photovoltaic panels are discussed. Based on the results, the thermal efficiency, electrical efficiency and the exergy efficiency of the PVT system with the wave tube are 4.37%, 3.56%, and 4% higher than that with the straight tube. Therefore, it is worthy to improving the heat exchanger configuration with the wave tube. Furthermore, the use of lower concentration of CNT/water nanofluid has better performance in photovoltaic thermal system applications.

DECLARATION OF COMPETING INTEREST

The authors declared that there is no conflict of interest.

ACKNOWLEDGEMENT

The information, data, or work presented herein was supported by Natural Science Foundation of Zhejiang Province (No. LY20E060007). The authors gratefully acknowledge the support.

REFERENCE

[1] Singh GK. Solar power generation by PV (photovoltaic) technology: A review. Energy. 2013;53:1-13.

[2] Ogbonnaya C, Turan A, Abeykoon C. Numerical integration of solar, electrical and thermal exergies of photovoltaic module: A novel thermophotovoltaic model. Solar Energy. 2019;185:298-306.

[3] Radwan A, Ahmed M. Thermal management of concentrator photovoltaic systems using microchannel heat sink with nanofluids. Solar Energy. 2018;171:229-46.

[4] Khanna S, Reddy KS, Mallick TK. Effect of climate on electrical performance of finned phase change material integrated solar photovoltaic. Solar Energy. 2018;174:593-605.

[5] Javadi FS, Saidur R, Kamalisarvestani M. Investigating performance improvement of solar collectors by using nanofluids. Renewable and Sustainable Energy Reviews. 2013;28:232-45.

[6] Al-Waeli AHA, Sopian K, Chaichan MT, Kazem HA, Hasan HA, Al-Shamani AN. An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system. Energy Conversion and Management. 2017;142:547-58.

[7] Al-Waeli AHA, Chaichan MT, Kazem HA, Sopian K. Comparative study to use nano-(Al 2 O 3 , CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors. Energy Conversion and Management. 2017;148:963-73.

[8] Khanjari Y, Pourfayaz F, Kasaeian AB. Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system. Energy Conversion and Management. 2016;122:263-78.

[9] Borode A, Ahmed N, Olubambi P. A review of solar collectors using carbon-based nanofluids. Journal of Cleaner Production. 2019;241.

[10] Rahmanian S, Hamzavi A. Effects of pump power on performance analysis of photovoltaic thermal system using CNT nanofluid. Solar Energy. 2020;201:787-97.

[11] Nasrin R, Rahim NA, Fayaz H, Hasanuzzaman M. Water/MWCNT nanofluid based cooling system of PVT: Experimental and numerical research. Renewable Energy. 2018;121:286-300.

[12] Al-Waeli AHA, Chaichan MT, Kazem HA, Sopian K, Ibrahim A, Mat S, et al. Comparison study of indoor/outdoor experiments of a photovoltaic thermal PV/T system containing SiC nanofluid as a coolant. Energy. 2018;151:33-44.
[13] Yu Q, Romagnoli A, Yang R, Xie D, Liu C, Ding Y, et al. Numerical study on energy and exergy performances of a microencapsulated phase change material slurry based photovoltaic/thermal module. Energy Conversion and Management. 2019;183:708-20.
[14] Rejeb O, Sardarabadi M, Ménézo C, Passandideh-Fard M, Dhaou MH, Jemni A. Numerical and model validation of uncovered nanofluid sheet and tube type photovoltaic thermal solar system. Energy Conversion and Management. 2016;110:367-77.
[15] Xu H, Zhang C, Wang N, Qu Z, Zhang S. Experimental study on the performance of a solar photovoltaic/thermal system combined with phase change material. Solar Energy. 2020;198:202-11.
[16] Fayaz H, Nasrin R, Rahim NA, Hasanuzzaman M. Energy and exergy analysis of the PVT system: Effect of nanofluid flow rate. Solar Energy. 2018;169:217-30.
[17] Halelfadl S, Maré T, Estellé P. Efficiency of carbon nanotubes water based nanofluids as coolants. Experimental Thermal and Fluid Science. 2014;53:104-10.
[18] Eisapour M, Eisapour AH, Hosseini MJ, Talebizadehsardari P. Exergy and energy analysis of wavy tubes photovoltaic-thermal systems using microencapsulated PCM nano-slurry coolant fluid. Applied Energy. 2020;266.
[19] Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy. 2009;83:614-24.