International Journal of Engineering & Technology, 7 (3.20) (2018) 599-611

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Nanofluids Used in Photovoltaic Thermal (PV/T) Systems: a Review

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Abstract

Solar energy has attracted increasing research attention, particularly to improve and develop new small-sized devices with high energy efficiency or to establish appropriate techniques to produce such devices. These materials should be effectively utilised to enhance solar energy system performance. Nanofluids exhibit potential for heat transfer and absorption. This paper reviews studies on nanofluids used in solar energy systems, specifically photovoltaic thermal (PV/T) systems. The implementation of solar collector and PV/T system variables without or with nanofluids is also discussed. This paper is divided into two sections. The first part reports theoretical and experimental outcomes of analyses on thermal conductivity, density, specific heat and heat transfer coefficientof nanofluids. Thermophysical characteristics of nanofluids have been widely investigated to study the influence of these materials on the performance of solar collector and PV/T systems. The second part discusses nanofluid applications in photovoltaic thermal PV/T solar systems and solar collector. Nanofluids can be utilised to improve the performance of different solar thermal systems, particularly photovoltaic thermal systems, and thus increase the overall solar energy yield.

Keywords: Solar Energy;Nanofluids; PV/T Systems

1. .Introduction

Conventional fluids, such as ethylene glycol, motor oil and water, are commonly used for transferring heat. Heat transfer using conventional fluids restricts upgrade and minimises heat exchangers. It can be improved by applying solid particles as the attachment material or substance pendent in base fluids and by increasing thermal conductivity in conventional fluids. However, the thermal conductivity of basic fluid is lower than that of solid metals; thus, suspension of solid particles from base metal is required to enhance the thermal conductivity of fluid. This limitation can be addressed using materials made from nano-sized solid particles. Nanofluids contain solid particles and nano-sized materials. Pendent or suspended nanoparticles can change the thermal and transfer characteristics of the base fluids. Generally, nanoparticles exhibit unique characteristics. For example, the size ratio and characteristics of these particles confer them with a suitable physical dimension and low kinetic energy. Corcione[1] reported that nanoparticles with a large surface are stable when dispersed in a base fluid.

Nanofluids are apparently two-phase systems obtained by the dispersion of nano-sized solid materials in conventional exchange fluids. Thus, when compared with base fluids, nanofluids present better characteristics, such as specific heat and especially thermal conductivity [2]. In addition to enhanced performance in transferring heat, nanofluids possess mechanical, optical, magnetic and electrical properties superior to those of base fluids. For these reasons, nanofluids have potential for applications in transfer and storage of energy, mass transfer and even in mechanical or biomechanical fields [2]. Nanofluids can also be used in cooling and heating systems, especially in solar energy systems.

The utilisation of solar energy as the provider of electric power and in fluid heating guarantees several environmental, economic and even maintenance benefits. With these benefits, investment in this type of energy tends to grow because of the concern for the environment and climate change that has been occurring worldwide. Solar energy can be used, among others, for lighting, heating environments, obtaining hot water by using solar thermal collectors and producing electricity by using photovoltaic, thereby reducing the use of conventional energy sources. The use of solar energy has great importance worldwide. The increase in the installed capacity of solar water heaters and photovoltaic panels is due to the great concerns of saving energy, protecting the environment and developing technical advancements. Therefore, a combination of thermal energy and photovoltaic technology in one model, called a photovoltaic thermal collector system (PV/T), is introduced. The main components of the PV/T include photovoltaic panel, absorber plate and insulation material. The photovoltaic solar panel is used for electricity production, and the absorber plate is used for extracting the heat from solar radiation and transferring it to the circulating fluid. In this case, circulating fluid can be water or air in photovoltaic solar thermal collector system for cooling photovoltaic panels, which enhances the electrical efficiency of the solar cell [3],[4]. Replacing the working fluid in the photovoltaic thermal system with nanofluid can enhance solar cell cooling due to the improved thermal behaviour of nanofluid and solar energy conversion in solar energy collectors.

In this work, we focus on the use of nanofluids in solar collectors, solar energy systems and PV/T systems. The use of nanofluids in PV/T is given particular research attention.

2. Preparation of Nanofluids

In the production of nanofluids, the main aspects to consider are the nanoparticle materials and base liquids, although this process presupposes the close control of a set of important parameters in order to obtain functional thermal fluids [5]. The nanoparticles must exhibit high dispersion and chemical compatibility with the selected base fluid to obtain stable, uniform and long-lasting suspension, without clumps or chemical alteration of the fluid [6]. Different processes, which are usually distinguished between two-step and single-step methods, can be adopted to produce nanofluids,

2.1 Single-Step Methods

In the single-step methods, direct synthesis of nanoparticles within the base fluid occurs, that is, the nanoparticles are produced followed by dispersion in the fluid. In 1978 [7], a single-step technique called direct evaporation at vacuum [vacuum evaporation onto a running oil substrate (VEROS)], which involves evaporation of nanoparticles in a vacuum chamber through a beam of electrons with the aid of the rotation of a disk covered by oil, was proposed. Later, in 1997, a modified VEROS technique was proposed, in which cathodic spray was used at high pressure in the preparation of suspensions with metal particles [8]. In the same field, in 2005, [9] applied a method known as submerged arc nanoparticle synthesis. Vacuum-submerged arc nanoparticle synthesis system has been applied as part of the synthesis of nanofluids with copper particles and dielectric base fluids to decrease of agglomeration of nanoparticles [9],[2]. Although, single-step methods provide improved dispersion and blend stability, they are rarely used due to their high complexity [10]. The drying, storage and transport of nanoparticles are not practiced to reduce its agglomeration and improve its stability within the fluid [11]. On the other hand, single-step techniques rely on physical high. However, the major disadvantage of these methods is that incomplete reactions result in the formation of impurities in nanofluids [12],[2]. Thus, given the particularities of these methods, their industrial scale application is not feasible [11].

2.2 Two-Step Methods

In two-step methods, the nanoparticles are first produced in the form of dry powders and subsequently dispersed in a fluid. These are the most commonly used methods given that the nanoparticle synthesis processes are established at the industrial level, allowing economic production on a large scale [2]. A posterior dispersion of the nanoparticles within the base fluid is generally achieved with the aid of or induced by magnetic forces [5]. The dispersion of nanoparticles within the base fluid is an extremely important procedure that will compromise the thermophysical characteristics of the final nanofluid and the stability of the mixture.

3. Thermophysical Characteristics of Nanofluids

Most of the investigations on the thermophysical characteristics of nanofluid have focused on the characterisation of the nanofluids' capacity for to heat transfer and thermal conductivity. However, to allow the correct sizing of nanofluid exchange systems, characterisation of all the thermophysical aspects of these systems is necessary. The subsequent paragraphs highlight the results of some investigations on the thermophysical characteristics that have direct impact on the heat transfer performance of nanofluids.

3.1 Density

Density is the mass per unit volume of a given substance. This parameter is important to consider because an excessive increase in density strongly influences the pumping capacity and efficiency in a forced convection heat exchanger.

[13] studied the thermophysical properties of nanofluids composed of water and ethylene glycol containing a suspension of multilayer carbon nanotubes (MWCNTs). Based on their experimental data, the density of the nanofluids increases with the concentration of MWCNTs and deviates relative to the values predicted by the correlation of [14]. This deviation increases with the concentration of MWCNTs. The fluid filled inside of the MWCNTs increased the mass of the nanofluid to a certain volume, resulting in an increase in density. [15] measured the density of three nanofluids, which contained nanoparticles of zinc oxide (ZnO), antimony oxide ($Sb_2O_3SnO_2$) and aluminium oxide (Al_2O_3) dispersed in a (60:40) ethylene glycol/water base fluid. Experimental results for density agreed with those calculated theoretically. [16] studied the variation of the density of nanofluids with temperature. They found that the density decreased with increasing temperature. Similarly, [17] measured the density of composite nanofluids at different concentrations (1% to 4%) of dispersed Al_2O_3 nanoparticles in water. The results show that the density of base fluid is lower than that of nanofluids, tending to increase with the increase in the volume fraction of the nanoparticles. These experimental results show that the density of nanofluids tends to increase with the concentration of nanoparticles and is inversely correlated with the temperature.

3.2 Specific Heat

The physical aspect that defines the thermal variation of a particular substance upon accepting a certain amount of heat is known as specific heat. This aspect is extremely important because it provides the amount of energy that a body can transmit to another body. One of the first studies of the specific heat in nanofluids was conducted by [14] who used Eq. 1 to determine the specific heat of the fluids.

$$Cp_{nf}=(1-\phi)\,Cp_{fb}+\phi Cp_p \tag{1}$$

Where Cp_{nf} is the specific heat of the nanofluid, ϕ is the volume fraction and Cp_{fb} and Cp_p is the specific heat of the base fluid and the specific heat of the nanoparticles, respectively.

Based on the assumptions of thermal equilibrium between the nanoparticles and base fluids, [18] determined a correlation for the specific heat of nanofluids, as shown in Eq. 2:

$$Cp_{nf} = \frac{\emptyset Cp_p + (1-\emptyset)\rho_{fb} Cp_{fb}}{\rho_{nf}} \tag{2}$$

Where ρ_{fb} is the density of the base fluid and ρ_{nf} is the density of the nanofluid.

[19] used a calorimeter to measure the specific heat of a suspension at different concentrations (0.3% to 0.6%) of graphite nanoparticles in a lubricant (polyalphaolefin). They verified that a rise in temperature and in the concentration of nanoparticles result in an increase of the specific heat of the nanofluid. [20] showed that the base fluid, as well as the size and concentration of nanoparticles affect the specific heat of the nanofluids.

[21] assessed the specific heat of three nanofluids containing ZnO, SiO_2 and Al_2O_3 nanoparticles. SiO_2 and Al_2O_3 were dispersed in a base fluid with an ethylene and water ratio of 60:40, while the ZnO nanoparticles were dispersed within distilled water. The specific heats at different concentrations of nanoparticles and temperatures were characterised. The following correlation for specific heat, following the experimental results, was developed:

$$Cp_{nf} = \frac{((A\frac{T}{T_o}) + (B\frac{Cp_p}{Cp_{fb}}))}{(c+\emptyset)} \times Cp_{fb} \tag{3}$$

Since T is the temperature of the fluid, T_0 is the reference temperature (273K) and A, B and Care the adjustment coefficients for the different test fluids.

Compared with studies on other thermophysical characteristics, research works on the specific heat of nanofluids are limited. Based on the available literature, the following factors influence the specific heat of the nanofluid: temperature, volume concentration of nanoparticles and specific heat of the base fluid. Literature suggests that the specific heat of nanofluids increases with temperature and reduces with higher volume concentration [22].

3.3 Thermal Conductivity of Nanofluids

Several works verified that many factors influence the thermal conductivity of the nanofluids. Several researchers performed experimental works and reviews on the thermal conductivity of desirable nanofluids. The results highlighted that nanofluids contain small nanoparticles with greater thermal conductivity compared with that of the base fluid. The following section highlights some studies and main conclusions regarding the thermal conductivity of nanofluids.

In order to identify the factors that influence thermal conductivity, nanofluid composed of SiO_2/water with SiO_2 concentrations of (1% to 4%) was studied in terms of its thermal conductivity [23]. They used the transient hot wire approach and verified that the thermal conductivity increased linearly with the increase in nanoparticle concentration. Using the same method, [24] observed an increase in thermal conductivity with nanoparticle concentration, verifying that the decrease of the average nanoparticle size also increases thermal conductivity. Likewise, [25] verified that in Cu/ethylene glycol nanofluids, temperature influences the increase in thermal conductivity. [26] assessed the way in which thermal conductivity and pH value are affected by temperature and found that for SnO_2/water nanofluids with low nanoparticle concentrations, the temperature and pH value influence the increase in thermal conductivity.

[27] studied different nanofluids composed of different nanoparticles in an attempt to verify the importance of nanoparticles in enhancing thermal conductivity. They used SiO_2, CuO and MWCNT in different base fluids. These materials were utilised to assess how thermal conductivity was affected by base fluid, such as mineral oil, ethylene glycol and water. The results showed that MWCNT presents a higher thermal conductivity increase than those in other nanoparticles.Recently, [28] used the transient hot wire method to study the thermal conductivity variation as a function of temperature for nanofluids composed of MWCNT and ethylene glycol/water. The results of the study show that the thermal conductivity increased by approximately 7% for nanofluid with 1.5 vol% of MWCNT. They also predicted that the Brownian motion is not the only mechanism that causes an improvement in thermal conductivity. Table 1 presents some empirical results pertaining to the thermal conductivity of nanofluids based on different nanoparticles, base fluids and concentrations.

Table 1:. Summary of some empirical results of the thermal conductivity of nanofluids.

Ref No.	Type of nanofluid/Base fluid	Concentration %	Increase in thermal conductivity %
[29]	Al-Cu/EG	1.5	200
[21]	ZnO / EG-water	10	17
[21]	Al_2O_3 / EG-water	10	35
[21]	CuO / EG-water	10	32
[30]	Fe_3O_4/querosene	1	34
[25]	Cu/EG	0.3	0.5
[25]	Cu/EG	5	8
[25]	Cu/EG	11	16
[25]	Cu/EG	33	46
[24]	Au/water	0.00026	48
[23]	SiO_2/water	4	23
[23]	SiO_2/water	1	3.23
[26]	SnO_2/water	0.024	7
[28]	MWCNT/EG	1.5	17
[31]	MWCNT/water	3	13
[13]	MWCNT/water	0.45	19.73

At the end of the 19th century, [32] proposed the first link to determine the thermal conductivity of the suspension. Despite plenty empirical and theoretical studies on the thermal conductivity of nanofluids, no model is widely adopted by the academic community. Many mechanisms were presented to illustrate the rise in the thermal conductivity of nanofluids. For example, the valid Hamilton model was established in [33], following the Maxwell model [32] and considers the volume fraction and geometry. Several studies presented the following four vital mechanisms of nanofluids in increasing thermal conductivity: (1) fluid layering at the liquid/molecule interface, (2) Brownian movement of nanoparticles, (3) nanoparticle assembly in nanofluids, and (4) nature of heat transport particles despite being ballistic. Several models can be utilised to estimate theoretically the thermal conductivity values of the nanofluids. [34] provided a good review of these models. Table 2 summarizes some correlations developed to quantify the thermal conductivity of nanofluids.

Table 2:. Summary of some existing correlations for determination of thermal conductivity of nanofluids.

Ref No	Correlations
[32]	$k_{nf} = k_{fb}\frac{k_p + 2k_{fb} + 2\emptyset(k_p + k_{fb})}{k_p + (n-1)k_{fb} - \emptyset(k_p - k_{fb})}$
[33]	$k_{nf} = k_{fb}\frac{k_p + (n-1)k_{fb} + (n-1)\emptyset(k_p - k_{fb})}{k_p + (n-1)k_{fb} - \emptyset(k_p - k_{fb})}$
[35]	$k_{nf} = k_{fb}\frac{k_{pe} + 2k_{fb} + 2\emptyset(k_{pe} - k_{fb})(1+\beta)^3}{k_{pe} + k_{fb} - \emptyset(k_{pe} - k_{fb})(1+\beta)^3}$ $k_{pe} = k_p\frac{[2(1-\gamma) + (1+\beta)^3(1+2\gamma)]\gamma}{-1(1-\gamma) + (1+\beta)^3(1+2\gamma)}$
[36]	$k_{nf} = \emptyset k_p + (1-\emptyset)k_{fb}$
[37]	$k_{nf} = k_{fb}\frac{1 - \emptyset + 2\emptyset\frac{k_p}{k_p - k_{fb}}ln\frac{k_p + k_{fb}}{2k_{fb}}}{1 - \emptyset + 2\emptyset\frac{k_{fb}}{k_p - k_{fb}}ln\frac{k_p + k_{fb}}{2k_{fb}}}$
[38]	$k_{nf} = \frac{(k_p - k_{lr})\emptyset k_{lr}(2\beta 1^3 - \beta^3 + 1) + (k_p + 2k_{lr})\beta 1^3[\emptyset\beta^3(k_{lr} - k_{fb}) + k_{fb}]}{\beta 1^3(k_p + 2k_{lr}) - (k_p - k_{lr})\emptyset(\beta 1^3 + \beta^3 - 1)}$
[39]	$k_{nf} = \frac{(k_p - k_{lr})\emptyset k_{lr}(2\beta 1^2 - \beta^2 + 1) + (k_p + 2k_{lr})\beta 1^2[\emptyset\beta^2(k_{lr} - k_{fb}) + k_{fb}]}{\beta 1^2(k_p + 2k_{lr}) - (k_p - k_{lr})\emptyset(\beta 1^2 + \beta^2 - 1)}$

3.4 Heat Transfer by Convection of Nanofluids

In the last decade, several researchers have carried out numerous experiments with the purpose of explaining the phenomena of heat transfer in systems containing nanofluids. Currently, many publications that deal with forced convection heat transfer in tubes are available, the most important of which are described below.

In 2003, [41] studied the heat transfer for Cu/water mixtures subjected to turbulent and laminar flow in circular tubes with 10 mm diameter. The results showed that, compared with base fluid, the suspension of nanoparticles notably increases the heat transfer coefficient by convection. [42] experimentally observed the transfer of heat in the nanofluids of Al_2O_3/water. A sharp increase was observed in convective heat transfer coefficient for concerted higher nanoparticles and high Reynolds numbers. The heat transfer was also observed to be improved in the tube entrance area, decreasing with increasing axial distance. Particle migration was considered the cause of the increased convective heat transfer, which has the possibility of causing the uneven distribution of viscosity and thermal conductivity, and ultimately causing the decrease in the thickness of the thermal boundary layer. Considering the relationship between thermal conductivity and the increase of the coefficient of heat transfer, [43] conducted an investigation on the heat transfer in the nanofluids of Al_2O_3/water, subject to laminar flow, inside a circular tube with constant wall temperature. The results of their study found that other factors besides the increase in thermal conductivity, such as the Brownian motion, particle migration and chaotic movement of nanoparticles, may be linked to the rise of convective heat transfer in nanofluids. [44] produced nanofluids with titanate nanotubes (TNT) dispersed in water to investigate the heat transfer coefficient and thermal conductivity. The rise in convection heat transfer coefficient, which is greater for high Reynolds numbers and decreases at the time of the axial position, was observed. Another conclusion from the tests carried out was that nanofluids with TNT had higher values of convective heat transfer coefficient compared with nanofluids containing spherical titanium nanoparticles, demonstrating that the geometry of the nanoparticle affects the transfer coefficient of heat by convection.

To investigate the effect of mean nanoparticle size on nanofluids, [45] performed tests on Al_2O_3/water nanofluids in the developing region under a constant heat flux. They used nanoparticles with two different sizes (45 and 150 nm), observing that the nanofluid having the smaller nanoparticles had a higher coefficient of heat transfer. They concluded that the increase in heat coefficient depends on the nanoparticle size and that this increase is not just due to the rise in thermal conductivity but also to other reasons, such as particle migration and thermal dispersion. Other authors, such as [27], assessed Al_2O_3/water nanofluids in terms of their convective heat transfer coefficient and found that they flowed in a completely formed laminar flow and uniformly heated circular tube. They found that a greater increase in the convection heat transfer coefficient compared with thermal conductivity was observed. This higher increase in the convective heat transfer coefficient is possibly attributed to the flattened velocity profile, which is caused by the migration of nanoparticles triggered by the Sort effect and Brownian motion.

The effect of concentration and temperature on the convective heat transfer coefficient in water-based nanofluids and MWCNT for a laminar flow was studied by [46]. Experimental results observed for the carbon nanotube with various concentrations (0.1%, 0.12%, 0.2% and 0.25%) in nanofluids show that the presence of nanoparticles and the increase in the concentration of MWCNTs increases the coefficient of heat transfer. This effect does not occur with temperature rise when the coefficient of heat transfer is reduced in relation to the base fluid. This finding is due to the greater agglomeration of the nanoparticles at high temperatures.[47] assessed the way heat transfer coefficient is affected by the nanoparticle concentration variation. They verified that the heat transfer coefficient increases relative to the nanoparticle concentration, obtaining higher values of Reynolds numbers.[48] experimentally studied the heat transfer of Al_2O_3/water nanofluids by convection flowing pass a circular tube under constant temperature flow. The heat transfer coefficient of the nanofluid was found to increase with increasing Reynolds number and nanoparticle concentration. Following the studies performed, [49] studied the convective heat transfer of Al_2O_3 /water nanofluid in a laminar flow through a circular tube subjected to a linear heat flux. The rate of transfer is highest at the entrance of the test section or at lower axial distances (x/D). Thus, to benefit from the migration effects of nanoparticles, nanofluid should be used in developing flows. The convective heat transfer rate decreases as the Reynolds number increases with x/D.

The ability of convective heat transfer in the nanofluids of MWCNTs and water was studied by [50]. They concluded that for a nanofluid of 0.5% vol concentration of MWCNTs, moving through a cylindrical tube subjected to linear heat flux with different flow rates causes a rise of 47% in the heat transfer coefficient with respect to the fluid base (7%), but also to other factors, such as the interaction between particles and the formation of a percolation network. Table 3 presents some characteristics and the results obtained by different research groups for convective heat transfer in nanofluids.

Table 3:. Summary of some empirical results of the heat transfer coefficient by convection of nanofluids.

Ref No	Type of nanofluid/base fluid	Concentration%	Increase in heat transfer %	Type of flow
[51]	Cu/water	2	60	Laminar
[41]	Cu/water	2	60	Turbulent
[42]	Al_2O_3 / water	1.6	41	Laminar
[52]	Grafite/water	2	22	Laminar
[44]	TNT/water	2.5	13.5	Laminar
[53]	ZrO_2/water	1.32	3	Laminar
[53]	Al_2O_3 / water	6	27	Laminar
[27]	Al_2O_3 / water	0.30	8	Laminar
[54]	CuO/EG-water	6	35	Turbulent
[46]	MWCNT/water	0.12	25	Laminar
[55]	TiO_2/water	2	26	Turbulent
[55]	TiO_2/water	1	14	Turbulent
[56]	Al_2O_3-Cu / water	0.10	13.56	Laminar
[13]	MWCNT/water	0.45	159.3	Turbulent
[50]	MWCNT/water	0.50	47	Turbulent

The experimental results in Table 3 shows that heat transfer coefficient by convection is influenced by nanoparticle concentration, Reynolds number and type of nanofluid produced, with a higher increase for turbulent regimes and for nanofluids with higher nanoparticle concentration.

4. Nanofluid Applications in Solar Energy Systems

With their outstanding thermal and physical properties shown previously and in Table 4. [57], nanofluids have been theoretically and experimentally studied to improve solar energy systems, specifically solar collectors and PV/T systems. Many studies have reviewednanofluids applied in solar energy systems [58] , [59]. However, solar collector is the major part of PV/T system. Thus, the use of nanofluids in solar collector systems is discussed first in the next section as a key to study the PV/T system with nanofluids.

Table 4. Thermophysical characteristics of different types of nanofluids and water at different temperatures [57].

Thermophysical	Temperature		Base fluid		
Property	ċ	SiO_2	ZnO	CuO	Water
Thermal conductivity W/m.K	25	0.628	0.618	0.612	0.600
	35	0.655	0.648	0.641	0.637
	45	0.708	0.689	0.675	0.655
Density g/mL	25	1.051	1.025	1.012	0.998
	35	1.042	1.019	1.008	0.992
	45	1.033	1.015	1.002	0.986
Viscosity mpa/s	25	1.243	1.150	1.098	1.010
	35	0.982	0.957	0.921	0.781
	45	0.813	0.758	0.702	0.648

4.1 Nanofluids in Solar Collectors

The conversion of solar radiation into thermal energy is the purpose of flat plate solar collectors. This energy conversion provides the working fluid (water or air) with thermal heating. Efforts have been made to enhance the thermal performance of conventional solar collectors. A review of the recent developments on solar collector was conducted by [60],[61]. The developments involved the design of absorber, manufacturing material of the structure, working fluid and nanomaterial. Recently, researchers have investigated the possibility of powering solar collectors by using nanofluid as the working fluid because its superior thermal properties.[62] studied the applicability of nanofluids in the absorption of direct solar energy. The study showed that with nanofluids, the absorption of incident irradiation increases significantly. To improve the solar absorption in the solar collectors using nanofluids, [63] carried out a theoretical study on the effect of nanofluids in high flux solar collector. The findings revealed that the efficiency improved in the range of 5%–10% with nanofluids in the solar collector. Similarly, [64] found an efficiency increase of 10% with direct absorption collector compared with flat plate collector. They studied the influence of various factors on the theoretical efficiency of the direct-absorption solar collector, which contains low-temperature Al_2O_3/water nanofluid. The findings illustrate that adding nanoparticles with a volume fraction of 0.1%–5% significantly enhanced the fluid performance, which resulted in the enhanced thermal performance of the solar collector. They used Al_2O_3/water nanofluid for the study. Given the low cost and easy maintenance of flat plate collector, numerous experiments were conducted on flat plate collectors with nanofluids to improve its thermal performance. Similarly, [65] assessed the performance of direct absorption collector containing different types of nanoparticles, such as carbon tubes, silver and graphite. They noted an increase in the collector efficiency with the addition of small quantities of nanoparticles with 0.5% volume fraction, which remained constant and decreased with further increase in volume fraction. For the same type of solar collector (direct solar collector), [66] determined the influence of nanofluid as working fluid. Comparison between nanofluids and pure water showed that light transmissivity was enhanced at 1% volume fraction; the nanofluid appeared as opaque light wave. These results indicate the suitability of nanofluids (aluminium) in direct solar collectors. They found that, under constant collector height, nanoparticle volume fraction and collector length, the collector efficiency slightly increased with increasing nanoparticle size as shown in Fig. 1.

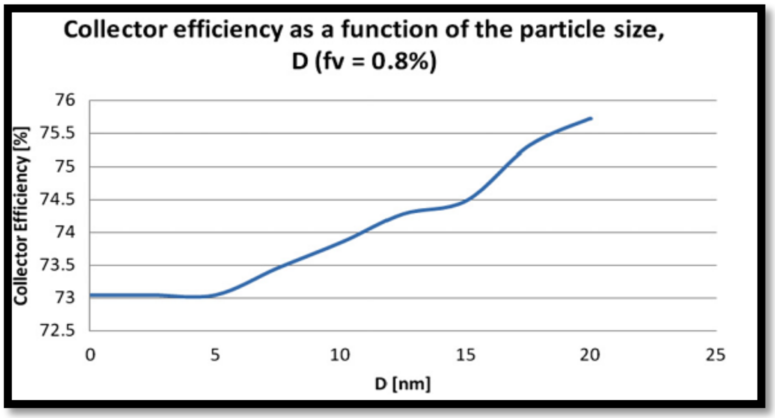

Fig 1:. The Collector efficiency with respect to particle size, volume fraction = 0.08% [66] .

[67] studied the influence of nanofluid (Al$_2$O$_3$/water) towards the efficiency of flat plate solar collectors experimentally as shown in Fig 2. The effects of nanofluids with various weight fractions (0.2% and 0.4%) and particle diameter of 15 nm were determined. The solar collector efficiency at 0.2% weight fraction nanofluid increased by 28.3%. In the same field, with different types of nanofluids, they established an experimental setup to analyse the effect of water MWCNTs toward the thermal efficiency of flat plate solar collector [68]. The efficiency of the collector containing nanofluid MWCNT–water without the surfactant was increased when 0.4 wt% nanofluid was used but decreased with 0.2 wt.% nanofluid compared with that of the collector that uses water as working fluid.

Fig 2:. Experimental work of solar collector using nanofluids [67] .

Experimental studies on different nanofluids and different types of solar collector are continuously being conducted. [69] performed an experiment with Cu/water nanofluid, and results revealed that the efficiency increased by approximately 24% for that with 0.05 wt% of nanofluid. Various surfactants with a degree of sonication was used in these studies to stabilise the nanofluids. By using the same type of nanofluid and with different types of solar collector, [70] studied the thermal performance of thermosyphone in an evacuated tubular solar collector at high temperatures. The working fluid of the collector was CuO/water nanofluid and fluid or water. The thermal efficiency of the evaporator in the solar collector with the nanofluid significantly increased by 30% compared with that containing base water. CuO nanoparticles significantly affect heat transfer in thermosyphone; the preferred 1.2% concentration is related to the effect of improved optimal heat transfer. [71] studied the effect of volume concentration on the values of thermal efficiency in order to understand the effect of CuO nanofluid on the efficiency of the direct-absorption solar collector. The findings revealed that with a 0.006% increase in the volume concentration of CuO nanofluid, a 18%–52% increase in the thermal efficiency of the solar collector was observed.

[72] developed a model of solar parabolic trough collector with width and height of 0.7 and 2 m, respectively, Fig. 3presents the schematic of the experimental setup . A steel mirror of 0.3% and 0.2% CNT/oil nanofluid was used for the reflector. The study presented a comparison between four types of absorbers. The findings revealed that compared with the bare tube, the efficiency of

the vacuum tube increased by 11%. Another comparative study on the thermal efficiencies of two types of solar collectors, flat plate and U-tube with Al_2O_3 nanofluid as a working fluid, was conducted by [73]. The results were compared against the thermal efficiency of conventional solar collector operating solely with water. The findings revealed that increasing the concentration of the nanofluid enhanced the thermal efficiency of the solar collectors. The improvement range in the thermal efficiency of the two solar collectors using nanofluid was found to be 10.7%, which is 14.8% more than that achieved by the solar collector using water.

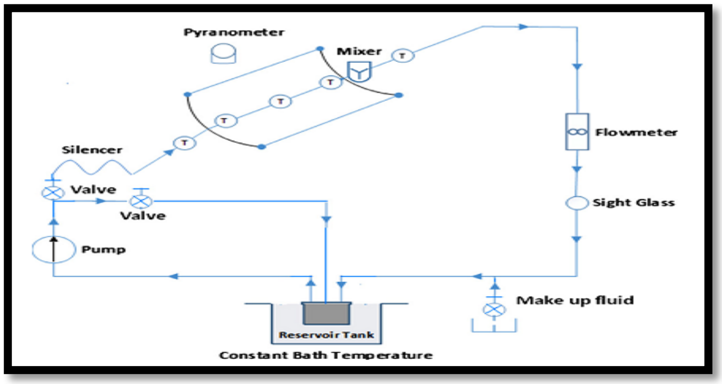

Fig 3:. The experimental schematic set up [72].

An experimental study was conducted to estimate the effect of various versions of nanofluids on the performance of direct-absorption solar collectors [74]. Different types of nanoparticles were dispersed in de-ionized water. The results demonstrated that magnetite dispersions exhibited the optimum thermal and energy efficiency, followed by silver and graphite nanofluids. [75] conducted a review on the improvement of the thermal performance of solar collectors with nanofluids. This study showed that more experimental studies on the improvement of the performance of flat plate solar collector using nanofluids were conducted compared with the numerical studies on flat plate collector with nanofluids.

Nasrin et al. conducted several numerical studies to predict the performance of solar collector with nanofluids [76], [77], [78]. The way the free convection in a solar collector was influenced by the Prandtl number was studied using Al_2O_3/water nanofluid in [76]. [77] performed a numerical study using finite element method and reported the influence of physical parameters, number of waves and wave amplitude in the natural convection flow boundary layer in a solar collector with sinusoidal absorption glass cover. Nanofluid (Al_2O_3/water) with 5% volume fraction of nanoparticle was used as working base fluid in the collector. The heat transfer rate of the Al_2O_3/water nanofluid increased by increasing the number of waves and wave amplitude, resulting in improved heat performance. Al_2O_3/water can be used to efficiently determine the level of heat transfer increase at a defined operating range. Similarly, by using the same method (finite element), they presented a simulation of forced convection in a flat plate collector based on using nanofluid with two nanoparticles [78]. The results show that utilisation of double nanoparticles (copper and alumina) resulted in better performance compared with that using only single nanoparticle (alumina). Another numerical method (finite volume technique) was used to determine the way the 3D fluid flow and natural convection heat transfer were affected by Cu/water nanofluid in a single-ended tube with non-uniform lateral heat input and adiabatic wall end [79]. This model is a simplified version of an evacuated tube solar single-ended water heater with water in a glass. The use of the nanofluid led to high heat input rate. The Nusselt number at 5% solid concentration exhibited 62% improvement of heat flux within 100 W/m^2 versus 100% in 700 W/m^2 for base fluid. [80] numerically simulated the thermal performance of the flat plate collector with Al_2O_3/water nanofluid. The results revealed good agreement with the experimental measurements.

4.2 Nanofluids in PV/T Systems

Enhancement of PV efficiency is the main goal in combining PV/T into a single system. Hybrid PV/T systems have been widely studied in the literature either theoretically or experimentally using water or air as coolant [81],[82].A growing interest has been given in developing novel methods to enhance the systems' efficiency. Several studies were presented to achieve this purpose using distinct types of PV panel [83],[84], solar collector design [85], [86] and distinct working fluids, such as nanofluids [87],[88],[89]. The effect of developing collector design on the PV/T system efficiency is limited. For example, the results show that compared with other forms of collectors, the thermal efficiency of the conventional flat plate collector is only 2% lower [90]. Recently, some works have focused on the use of nanofluid as a working fluid in PV/T hybrid system [91]. Fig 4. shows the diagram of a PV/T hybrid system using nanofluid as the cooling media [92]. The overall system efficiency may be improved with minimal changes to the design of the structure by using a working fluid with improved heat transfer properties, such as nanofluids, as exemplified in [87]. In order to make calculations of the efficiencies of a PV/T co-generation system, 2D model coupling thermal analysis and CFD simulations were conducted. Both system heating and cooling were done using nanofluids, besides the introduction of a novel thermal conductivity model. The effects of different parameters on the efficiency were numerically studied and reached as high as 70% for the nanofluid-based systems. The transient mechanism of a PV/T system equipped with a sheet-and-tube water based collector was studied by [93] with simulations and experiments using a 1D mathematical model. Likewise, an experimental and theoretical study of a PV/T system in a heating and thermo-electric cooling unit was presented by [94]. High values of 23.5% and 16.7% for the thermal and electrical efficiencies of the PV/T, respectively, were reported. An increase from 200 W/m^2 to 700W/m^2 in solar irradiation was observed in their study.

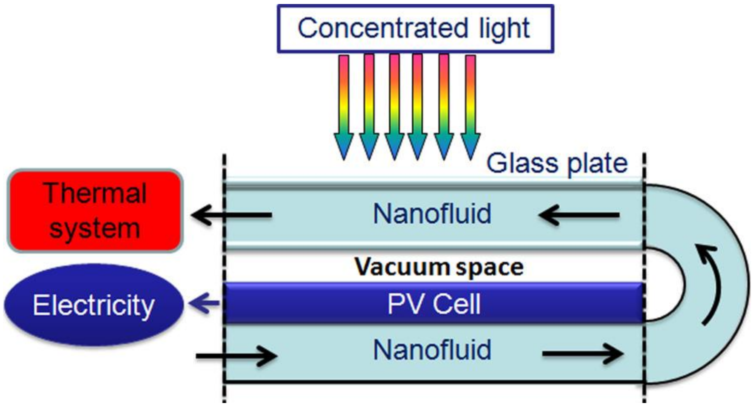

Fig 4:. Schematic diagram of PV/T system with nanofluids,[92]

[89] used nanoparticles with sizes in the range of 11–14 nm in a photovoltaic thermal flat plate system. The findings indicate that, at 3 and 1 wt%, the total energy efficiency increased at 3.6%, while the thermal efficiency rose at 12.8% and 7.6%, respectively. In addition, the solar energy in the collector area decreased by 21.6% in the system with SiO_2 as nanofluid (i.e., 220 MJ energy, which is equivalent to a 170 kg decrease in CO_2 for 1000 solar collectors per year). Another experimental study was performed to predict the effect of using nanofluids in a PV/T system [95]. The investigation was conducted to study the use of SiC nanofluid to function as a base-fluid for a PV/T system. A 24.1% increase in electrical efficiency was reported with the addition of 3% SiC nanofluid by weight as compared with the PV system alone. Conversely, a theoretical study was conducted [96] to assess the design of nanofluid-based filters for use in hybrid solar PV/T system. The nanofluid filters were explored and placed in positive comparison with traditional optical filters for five PV cell alternatives. Following that, [97],[98] studied this approach experimentally and theoretically.

Experiments for PV/T system have been made with Al_2O_3 nanofluid [99][100]. [99] studied the way in which the overall performance of the system was affected by distinct concentrations of nanoparticles (1, 1.5, and 2 wt%) by using Al_2O_3 as a working fluid in the PV/T system. With different filling ratios, they found that the optimum values were 50% (filling ratio) and 1.5 wt% nanoparticle concentration. The findings indicated that thermal and electrical efficiencies with the optimum values mention above increased by 27.3% and 1.1%, respectively, compared with the conventional PV/T systems. [100] studied the influence of using Al_2O_3 nanofluid on the performance of PV/T with different optimum conditions (mass flow rate of 40 L/H) and 1.2 wt% nanoparticle concentration. The findings revealed that with 2 wt% nanoparticle concentration, the overall, thermal and electrical efficiencies improved by 58%, 45% and 13%, respectively, compared with the PV/T system that used water as a working fluid.

Many studies used other types of nanofluids (Zn and ZnO) experimentally as a working fluid in the PV/T system to improve the system's performance [101],[102],[103]. With different nanoparticle concentrations of Zn/water (0.1%, 0.2%, 0.3%, 0.4% and 0.5%), [101] studied the effect of using nanofluids towards the performance of PV/T. They found that, with the optimum concentration value of 0.3% and mass flowrate of 2 L/min, the electrical efficiency improved by 7.8%. [102] studied the impact of using ZnO nanofluid as a working fluid in PV/T system. In addition to the effect of nanoparticle concentration, other aspects, including ambient temperature, solar radiation and mass flow rate, were studied to investigate the performance of PV/T unit. Fig 5. illustrates the study's experimental rig and the details of the PV/T system. A slight enhancement in the electrical and thermal efficiencies by 16.21% was revealed. Similarly, [103] presented an experimental study on PV/T performance with ZnO nanofluids and phase change material. The findings showed that the thermal and electrical outputs increased by 5% and 13%, respectively, compared with the performance of water-based PV/T. Later, they presented another experimental study to predict the PV/T performance with ZnO nanofluid and two other types of nanofluids (Al_2O_3 and TiO_2) [104],[105]. The parameter conditions of the study in [104] include 0.2 wt% nanoparticle concentration for different nanofluids and 30 kg/h mass flow rate. The highest performance (energy and energy efficiencies) for the PV/T system was achieved with ZnO and TiO_2 nanofluids as compared with other nanofluids, and water-based PV/T performance was shown as per the results. The findings revealed that the improvement in the overall energy efficiencies with the PV/T Al_2O_3, PV/T TiO_2, PV/T ZnO and PVT/water were 18.27%, 15.93%, 15.45% and 12.34%, respectively, compared with PV panel performance with no coolant medium (solar collector). Moreover, in [105], with same types of nanofluids, proved that with ZnO nanofluid, the PV/T achieved higher thermal efficiency compared with the other types of nanofluids and water, while, the highest electrical efficiency was achieved with PV/T TiO_2 and PV/T ZnO nanofluids compared with the other types of nanofluid and water-based technology.

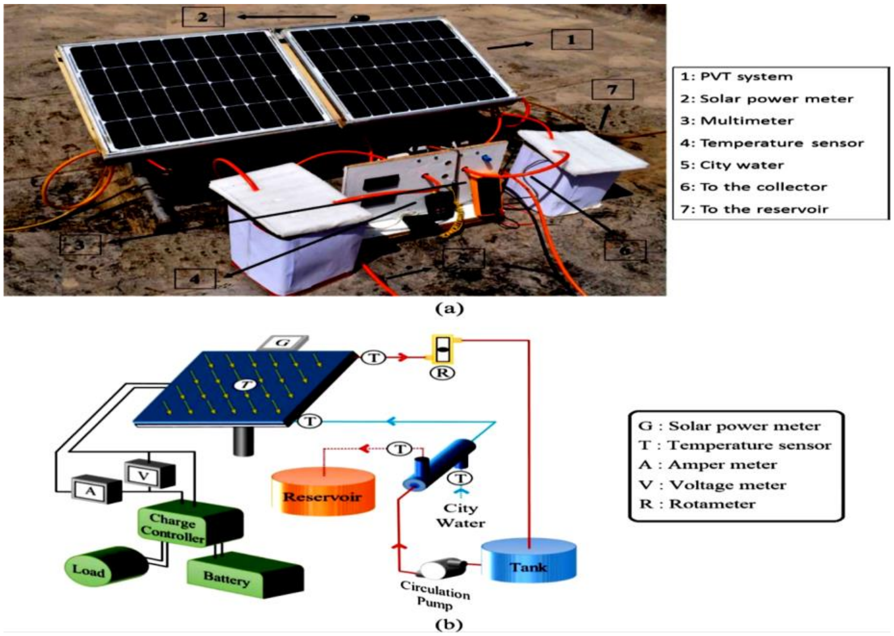

Fig 5:. A) Experimental set up photo of PV/T system with nanofluids. B) Schematic diagram of the experimental rig [102].

In many researches, Al-shamani et al. tried to study the influence of nanofluids towards the performance of PV/T [106],[107],[57]. under Malaysian climatic conditions with parameter conditions (solar radiation value 1000 W/m^2, mass flowrate 0.170 kg/s) and with different nanofluid types, PV/T performance has been investigated experimentally [106]. Findings revealed that the highest values of thermal and electrical efficiencies achieved with SiC nanofluids were 13.52% and 81.73%, respectively, followed by PV/T with TiO_2, PV/T SiO_2 nanofluids and PV/T water based. Then, they used Sic nanofluids to function as a working fluid in PV/T unit in order to study the improvement on the PV array efficiency [107]. Moreover, [57] investigated the PV/T performance with different types of nanofluid difference from the types that have been utilised in previous study [106]. Results showed that PV/T–SiO_2 achieved better improvement in the electrical and thermal and efficiencies compared with other types of nanofluids and water. They found that with SiO_2 nanofluids, the thermal and electrical efficiencies improved by 5.76% and 12.70%, respectively.To provide a clear idea on the use of nanofluids to function as working fluid in PV/T system, experimental researches are continuously being conducted on the different types of nanofluids [108],[109] ,[110]. These studies compared the effect of different types of nanofluids on the PV/T performance. [108] used different base fluids (ethylene glycol and water) with two types of nanofluids (Cu and Al_2O_3) in an experimental study. The findings revealed that the highest PV/T performance has been achieved with Cu-water compared with the other types of nanofluids and base fluids that used in the study. Other types of nanofluids (SiO_2, SiC and TiO_2) were used as working fluids in water-based PV/T system [109]. The results showed that PV/T performance with SiC nanofluid-based water achieved better values. Under the following conditions: mass flowrates 0.167 kg/s, solar radiation 1000 W/m^2 and 30 °C ambient temperature, the electrical and thermal efficiencies were 97.75%, 85.00% and 12.75%, respectively. Moreover, [110] experimentally investigated the effect of (Al_2O_3 and ZnO) with 0.05% wt% nanoparticle concentration for both types of nanofluids towards performance of the PV/T unit. The increase in the overall efficiency was found to be 4.1%.

From the literature, researchers have found that using nanofluids in the PV/T system can enhance the performance of the system. Thus, other researchers were encouraged to use different types of nanofluids, such as, MgO [111], CuO [112], Fe3O4 [113], SiC [114] and Ag nanofluids [115], to investigate their effects on the performance of the PV/T.

4.3 Cost and Performance

Performance and cost are two significant aspects that define the acceptability of using nanofluids in PV/T systems. A comparative study on the thermal and photovoltaic solar system water-based collector was performed [116]. The study the cost payback period of the PV/T system was greater compared with conventional solar thermal collector and lower compared with that of the PV module. Similarly, [117] compared the environmental and economic properties of nanofluid-based solar collectors with those of conventional types. Life cycle was the basis of the investigation because it is a capable methodology in the evaluation of the environmental and economic effects of products. The cost of maintenance and capital were \$20 and \$120 higher for nanofluid-based collectors, respectively, in a year. The payback period was considered lower in the conventional collectors. However, with the assumption of a 25-year life time based on the superior performance of nanofluid-based collectors, the life cycle savings would be roughly similar. Conversely, [118] found that an energy-saving and smaller-size system with lesser CO_2 emission is possible when nanofluids are used for solar collectors. Experimental investigations on the economic aspects of using nanofluids in the PV/T systems are uncommon, and the cost varies with the local cost of energy and the price of nanofluids (Table 5) [119]. From the cost perspective, system size reduction analysis may be a helpful approach.

Table 5.: Comparison of solar thermal nanofluid (water= 0.5 $/L)[119].

Type	Particle Vol%	Commercially available	Surfactant Vol%	Cost ($/L)
Copper	0.004	Yes	0.25	1.85
Graphite	0.0004	Yes	0.5	0.52
Gold	0.004	Yes	0.25	233
Al	0.001	Yes	0.25	0.64
Silver	0.004	Yes	0.25	3.65

From the literature, based on the improvement in the performance of PV/T system by using nanofluids as a working fluid, performance analyses were conducted for the different types of nanofluids. Fig 6. shows the effects of different types of nanofluids studied in the previous section of this work that discussed the comparison between the electrical and thermal efficiencies of the PV/T unit and water-based PV/T.

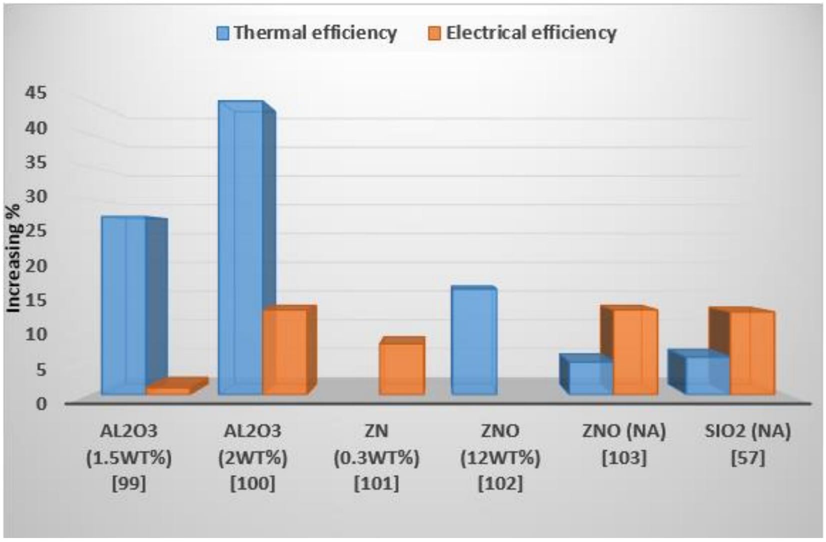

Fig 6:. Improvement of thermal and electrical efficiencies of PV/T system with different nanofluids.

5. Conclusion

The thermophysical properties of nanofluids have been widely studied using theoretical and experimental techniques. Experimental evidence indicates that nanofluids that possess few nanoparticles exhibit greater heat transfer coefficient and thermal conductivity than base fluids. A high volume fraction of solids does not usually enhance the efficiency (e.g., solar radiation absorbed in small region and the energy lost to the environment). In the case of small volume fraction, there will be a partial absorption of the incoming solar radiation. However, selecting the nanofluid at the optimal particle size and metal type is necessary to achieve the maximum heat transfer possible. Thermal conductivity and heat transfer should be optimized by choosing the appropriate nanoparticle type, shape and size to obtain the desired optical property. Improving the thermal characteristics of conventional fluids through addition of nanoparticles provides a range of possible heat transfer applications and solar systems. Heat transfer is improved by using nanofluids as a working fluid in solar energy systems. Conversely, the thermal conductivity of nanofluids plays the most significant role in determining the efficiency enhancement in solar energy systems. The most important application in solar energy systems is in a PV/T system because it generates thermal and electrical energies. Given the outstanding thermophysical properties, the researchers proved that use of nanofluids as a working fluid in the PV/T system can present the following advantages:

1) Achieved high temperature in the thermal part of the system.
2) Improved the performance of the system (electrical and thermal efficiencies).
3) Reduced the required PV/T system area due to high production system per unit area.

Different types of nanofluids exhibit different levels of improvement in the PV/T performance. However, the use of nanofluids within solar energy systems present some limitations, such as the difficulty of preparation, instability of the nanofluid, cost of solid nanoparticles, high safety requirements and increased pumping power. Future research should develop novel low-cost nanomaterials for increasing heat absorption to increase the electrical and thermal efficiencies of PV/T solar system. Lastly, in terms of the limited experimental studies on PV/T system, conducting more studies is necessary to investigate the performance of this system with nanofluids.

6. Nomenclature

$\emptyset$	Fraction	MWCNT	Carbon nanotubes with multiple walls
ρ	Density	CNT	Carbon Nanotubes
Nu	Nusselt number	EG	Ethylene/glycol
k	Thermal conductivity	fb	Base fluid

Cp	Specific heat	nf	Nanofluid
p	Particle		

Acknowledgements

The author would like to thank the Faculty of Mechanical engineering of the Universiti Teknikal Malaysia Melaka, Centre for Advanced Research on Energy in Universiti Teknikal Malaysia Melaka and Ministry of Electricity in Iraq for supporting this work.

References

[1] M. Corcione, “Heat transfer features of buoyancy-driven nano fl uids inside rectangular enclosures differentially heated at the sidewalls,” Int. J. Therm. Sci., vol. 49, no. 9, pp. 1536–1546, 2010.
[2] W. Yu and H. Xie, “A Review on Nanofluids: Preparation, StabilityMechanisms, and Applications,” J. Nanomater., vol. Volume 201.
[3] A. Makki, S. Omer, and H. Sabir, “Advancements in hybrid photovoltaic systems for enhanced solar cells performance,” Renew. Sustain. Energy Rev., vol. 41, pp. 658–684, 2015.
[4] V. V Tyagi, S. C. Kaushik, and S. K. Tyagi, “Advancement in solar photovoltaic / thermal (PV / T) hybrid collector technology,” Renew. Sustain. Energy Rev., vol. 16, no. 3, pp. 1383–1398, 2012.
[5] M. Gupta, N. Arora, R. Kumar, S. Kumar, and N. Dilbaghi, “A comprehensive review of experimental investigations of forced convective heat transfer characteristics for various nanofluids,” pp. 1–21, 2014.
[6] W. Duangthongsuk and S. Wongwises, “Effect of thermophysical properties models on the predicting of the convective heat transfer coefficient for low concentration nanofluid,” Int. Commun. Heat Mass Transf., vol. 35, no. 10, pp. 1320–1326, 2008.
[7] H. Akoh, Y. Tsukasaki, S. Yatsuya, and A. Tasaki, “Magnetic properties of ferromagnetic ultrafine particles prepared by vacuum evaporation on running oil substrate,” J. Cryst. Growth, vol. 45, no. C, pp. 495–500, 1978.
[8] M. Wagener, B. S. Murty, and B. Gunther, “Magnetro Rotating Drum,” vol. 457, pp. 149–154, 1997.
[9] C.-H. LO, T.-T. TSUNG, and L.-C. CHEN, “Ni Nano-Magnetic Fluid Prepared by Submerged Arc Nano Synthesis System (SANSS),” JSME Int. J. Ser. B, vol. 48, no. 4, pp. 750–755, 2005.
[10] S. M. S. Murshed and C. A. Nieto De Castro, “Superior thermal features of carbon nanotubes-based nanofluids - A review,” Renew. Sustain. Energy Rev., vol. 37, pp. 155–167, 2014.
[11] Y. Li, J. Zhou, S. Tung, E. Schneider, and S. Xi, “A review on development of nanofluid preparation and characterization,” Powder Technol., vol. 196, no. 2, pp. 89–101, 2009.
[12] J.-H. Lee, S.-H. Lee, C. J. Choi, S. P. Jang, and S. U. S. Choi, “A Review of Thermal Conductivity Data, Mechanisms and Models for Nanofluids,” Int. J. Micro-Nano Scale Transp., vol. 1, no. 4, pp. 269–322, 2011.
[13] V. Kumaresan and R. Velraj, “Experimental investigation of the thermo-physical properties of water-ethylene glycol mixture based CNT nanofluids,” Thermochim. Acta, vol. 545, pp. 180–186, 2012.
[14] B. C. Pak and Y. I. Cho, “Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles,” Exp. Heat Transf., vol. 11, no. 2, pp. 151–170, 1998.
[15] R. S. Vajjha, D. K. Das, and B. M. Mahagaonkar, “Density measurement of different nanofluids and their comparison with theory,” Pet. Sci. Technol., vol. 27, no. 6, pp. 612–624, 2009.
[16] L. S. Sundar, S. Ramanathan, K. V. Sharma, and P. S. Babu., “Temperature dependent flow characteristics of Al2O3 nanofluid,” Int. J. Nanotechnol. Appl., vol. 2, no. 1, pp. 35–44, 2007.
[17] Harkirat and D. Gangacharyulu, “Preparationg and characterization of nanofluids and some investigation in biological applications,” Mech. Eng. Carbondale South. Illinois Univ., no. June, 2010.
[18] Y. Xuan and W. Roetzel, “Conceptions for heat transfer correlation of nanofluids,” Int. J. Heat Mass Transf., vol. 43, no. 19, pp. 3701–3707, 2000.
[19] I. C. Nelson, D. Banerjee, and R. Ponnappan, “Flow Loop Experiments Using Polyalphaolefin Nanofluids,” J. Thermophys. Heat Transf., vol. 23, no. 4, pp. 752–761, 2009.
[20] B. X. Wang, L. P. Zhou, X. F. Peng, X. Z. Du, and Y. P. Yang, “On the specific heat capacity of CuO nanofluid,” Adv. Mech. Eng., vol. 2010, 2010.
[21] R. S. Vajjha and D. K. Das, “Experimental determination of thermal conductivity of three nanofluids and development of new correlations,” Int. J. Heat Mass Transf., vol. 52, no. 21–22, pp. 4675–4682, 2009.
[22] G. Ramesh and N. K. Prabhu, “Review of thermo-physical properties, wetting and heat transfer characteristics of nanofluids and their applicability in industrial quench heat treatment,” Nanoscale Res. Lett., vol. 6, no. 1, p. 334, 2011.
[23] M. Jahanshahi, S. F. Hosseinizadeh, M. Alipanah, A. Dehghani, and G. R. Vakilinejad, “Numerical simulation of free convection based on experimental measured conductivity in a square cavity using Water/SiO2nanofluid,” Int. Commun. Heat Mass Transf., vol. 37, no. 6, pp. 687–694, 2010.
[24] G. Paul, T. Pal, and I. Manna, “Thermo-physical property measurement of nano-gold dispersed water based nanofluids prepared by chemical precipitation technique,” J. Colloid Interface Sci., vol. 349, no. 1, pp. 434–437, 2010.
[25] W. Yu, H. Xie, L. Chen, and Y. Li, “Investigation on the thermal transport properties of ethylene glycol-based nanofluids containing copper nanoparticles,” Powder Technol., vol. 197, no. 3, pp. 218–221, 2010.
[26] S. Habibzadeh, A. Kazemi-Beydokhti, A. A. Khodadadi, Y. Mortazavi, S. Omanovic, and M. Shariat-Niassar, “Stability and thermal conductivity of nanofluids of tin dioxide synthesized via microwave-induced combustion route,” Chem. Eng. J., vol. 156, no. 2, pp. 471–478, 2010.
[27] K. S. Hwang, S. P. Jang, and S. U. S. Choi, “Flow and convective heat transfer characteristics of water-based Al2O3nanofluids in fully developed laminar flow regime,” Int. J. Heat Mass Transf., vol. 52, no. 1–2, pp. 193–199, 2009.
[28] B. C. Lamas et al., “EG/CNTs Nanofluids Engineering and Thermo-Rheological Characterization,” J. Nano Res., vol. 13, pp. 69–74, 2011.
[29] M. Chopkar, P. K. Das, and I. Manna, “Synthesis and characterization of nanofluid for advanced heat transfer applications,” Scr. Mater., vol. 55, no. 6, pp. 549–552, 2006.
[30] W. Yu, H. Xie, L. Chen, and Y. Li, “Enhancement of thermal conductivity of kerosene-based Fe3O4nanofluids prepared via phase-transfer method,” Colloids Surfaces A Physicochem. Eng. Asp., vol. 355, no. 1–3, pp. 109–113, 2010.
[31] T. X. Phuoc, M. Massoudi, and R. H. Chen, “Viscosity and thermal conductivity of nanofluids containing multi-walled carbon nanotubes stabilized by chitosan,” Int. J. Therm. Sci., vol. 50, no. 1, pp. 12–18, 2011.
[32] J. C. Maxwell, A Treatise on Electricity and Magnetism, Vol.II, vol. I. 1881.
[33] R. L. Hamilton, “Thermal conductivity of heterogeneous two-component systems,” Ind. Eng. Chem. Fundam., vol. 1, no. 3, pp. 187–191, 1962.
[34] S. Kakaç and A. Pramuanjaroenkij, “Review of convective heat transfer enhancement with nanofluids,” Int. J. Heat Mass Transf., vol. 52, no. 13–14, pp. 3187–3196, 2009.
[35] W. Yu and S. U. S. Choi, “The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Maxwell model,” J. Nanoparticle Res., vol. 5, no. 1–2, pp. 167–171, 2003.
[36] P. Bhattacharya, S. K. Saha, A. Yadav, P. E. Phelan, and R. S. Prasher, “Brownian dynamics simulation to determine the effective thermal conductivity of nanofluids,” J. Appl. Phys., vol. 95, no. 11 I, pp. 6492–6494, 2004.
[37] Q. Z. Xue, “Model for thermal conductivity of carbon nanotube-based composites,” Phys. B Condens. Matter, vol. 368, no. 1–4, pp. 302–307, 2005.
[38] K. C. Leong, C. Yang, and S. M. S. Murshed, “A model for the thermal conductivity of nanofluids – the effect of interfacial layer,” J. Nanoparticle Res., vol. 8, no. 2, pp. 245–254, 2006.
[39] S. M. S. Murshed, K. C. Leong, and C. Yang, “Investigations of thermal conductivity and viscosity of nanofluids,” Int. J. Therm. Sci., vol. 47, no. 5, pp. 560–568, 2008.
[40] L. M. Schwartz, E. J. Garboczi, and D. P. Bentz, “Interfacial transport in porous media: Application to dc electrical conductivity of mortars,” J. Appl. Phys., vol. 78, no. 10, pp. 5898–5908, 1995.

[41] Y. Xuan and Q. Li, “Investigation on Convective Heat Transfer and Flow Features of Nanofluids,” J. Heat Transfer, vol. 125, no. 1, p. 151, 2003.

[42] D. Wen and Y. Ding, “Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions,” Int. J. Heat Mass Transf., vol. 47, no. 24, pp. 5181–5188, 2004.

[43] Y. He, Y. Jin, H. Chen, Y. Ding, D. Cang, and H. Lu, “Heat transfer and flow behaviour of aqueous suspensions of TiO2nanoparticles (nanofluids) flowing upward through a vertical pipe,” Int. J. Heat Mass Transf., vol. 50, no. 11–12, pp. 2272–2281, 2007.

[44] H. Chen et al., “Heat transfer and flow behaviour of aqueous suspensions of titanate nanotubes (nanofluids),” Powder Technol., vol. 183, no. 1, pp. 63–72, 2008.

[45] K. B. Anoop, S. Kabelac, T. Sundararajan, and S. K. Das, “Rheological and flow characteristics of nanofluids: Influence of electroviscous effects and particle agglomeration,” J. Appl. Phys., vol. 106, no. 3, 2009.

[46] A. Amrollahi, A. M. Rashidi, and M. E. Meibodi, “Convection heat transfer of functionalized MWNT in aqueous fluids in laminar and turbulent flow at the entrance region,” Proc. - 2010 8th Int. Vac. Electron Sources Conf. Nanocarbon, IVESC 2010 NANOcarbon 2010, vol. 37, pp. 439–440, 2010.

[47] M. K. Moraveji, M. Darabi, S. M. H. Haddad, and R. Davarnejad, “Modeling of convective heat transfer of a nanofluid in the developing region of tube flow with computational fluid dynamics,” Int. Commun. Heat Mass Transf., vol. 38, no. 9, pp. 1291–1295, 2011.

[48] M. M. Heyhat, F. Kowsary, A. M. Rashidi, M. H. Momenpour, and A. Amrollahi, “Experimental investigation of laminar convective heat transfer and pressure drop of water-based Al2O3nanofluids in fully developed flow regime,” Exp. Therm. Fluid Sci., vol. 44, pp. 483–489, 2013.

[49] E. Esmaeilzadeh, H. Almohammadi, S. Nasiri Vatan, and A. N. Omrani, “Experimental investigation of hydrodynamics and heat transfer characteristics of γ-Al2O3/water under laminar flow inside a horizontal tube,” Int. J. Therm. Sci., vol. 63, pp. 31–37, 2013.

[50] B. Abreu, B. Lamas, A. Fonseca, N. Martins, and M. S. A. Oliveira, “Experimental characterization of convective heat transfer with MWCNT based nanofluids under laminar flow conditions,” Heat Mass Transf. und Stoffuebertragung, vol. 50, no. 1, pp. 65–74, 2013.

[51] L. I. Qiang and X. Yimin, “Convective heat transfer and flow characteristics of Cu-water nanofluid,” Science (80-.)., vol. 45, no. 4, p. 2002, 2002.

[52] Y. Yang, Z. G. Zhang, E. A. Grulke, W. B. Anderson, and G. Wu, “Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow,” Int. J. Heat Mass Transf., vol. 48, no. 6, pp. 1107–1116, 2005.

[53] U. Rea, T. McKrell, L. wen Hu, and J. Buongiorno, “Laminar convective heat transfer and viscous pressure loss of alumina-water and zirconia-water nanofluids,” Int. J. Heat Mass Transf., vol. 52, no. 7–8, pp. 2042–2048, 2009.

[54] P. K. Namburu, D. K. Das, K. M. Tanguturi, and R. S. Vajjha, “Numerical study of turbulent flow and heat transfer characteristics of nanofluids considering variable properties,” Int. J. Therm. Sci., vol. 48, no. 2, pp. 290–302, 2009.

[55] W. Duangthongsuk and S. Wongwises, “An experimental study on the heat transfer performance and pressure drop of TiO2-water nanofluids flowing under a turbulent flow regime,” Int. J. Heat Mass Transf., vol. 53, no. 1–3, pp. 334–344, 2010.

[56] S. Suresh, K. P. Venkitaraj, P. Selvakumar, and M. Chandrasekar, “Effect of Al2O3-Cu/water hybrid nanofluid in heat transfer,” Exp. Therm. Fluid Sci., vol. 38, pp. 54–60, 2012.

[57] A. N. Al-Shamani, M. A. Alghoul, A. M. Elbreki, A. A. Ammar, A. M. Abed, and K. Sopian, “Mathematical and experimental evaluation of thermal and electrical efficiency of PV/T collector using different water based nano-fluids,” Energy, vol. 145, pp. 770–792, 2018.

[58] A. Kasaeian, A. T. Eshghi, and M. Sameti, “A review on the applications of nanofluids in solar energy systems,” Renew. Sustain. Energy Rev., vol. 43, pp. 584–598, 2015.

[59] K. Khanafer and K. Vafai, “A review on the applications of nanofluids in solar energy field,” Renew. Energy, 2018.

[60] A. Mathur, G. D. Agrawal, and M. Chandel, “RECENT DEVELOPMENTS IN THE FIELD OF SOLAR WATER HEATER USING FLAT PLATE COLLECTOR- A REVIEW Address for Correspondence,” Int. J. Adv. Eng. Technol., pp. 12–14, 2012.

[61] M.A.M. Rosli, S. Mat, M. K. Anuar, K. Sopian, M. Y. Sulaiman, and S. Ellias, “Progress on Flat-Plate Water Based of Photovoltaic Thermal (PV/T) System: A Review,” Iran. J. Energy Environ. 5 407-418, 2014.

[62] S. M. Ladjevardi, A. Asnaghi, P. S. Izadkhast, and A. H. Kashani, “Applicability of graphite nanofluids in direct solar energy absorption,” Sol. Energy, vol. 94, pp. 327–334, 2013.

[63] R. A. Taylor et al., “Applicability of nanofluids in high flux solar collectors,” J. Renew. Sustain. Energy, vol. 3, no. 2, 2011.

[64] H. Tyagi, P. Phelan, and R. Prasher, “Predicted Efficiency of a Low-Temperature Nanofluid- Based Direct Absorption Solar Collector,” J. Sol. Energy Eng., vol. 131, no. November 2009, pp. 1–7.

[65] T. Otanicar and R. S. Prasher, “Nanofluid-Based Direct Absorption Solar Collector,” J. Renew. Sustain. ENERGY, vol. 2, no. 3, 2010.

[66] R. Saidur, T. C. Meng, Z. Said, M. Hasanuzzaman, and A. Kamyar, “Evaluation of the effect of nanofluid-based absorbers on direct solar collector,” Int. J. Heat Mass Transf., vol. 55, no. 21–22, pp. 5899–5907, 2012.

[67] T. Yousefi, F. Veysi, E. Shojaeizadeh, and S. Zinadini, “An experimental investigation on the effect of Al2O3-H2O nanofluid on the efficiency of flat-plate solar collectors,” vol. 39, pp. 293–298, 2012.

[68] T. Yousefi, F. Veisy, E. Shojaeizadeh, and S. Zinadini, “An experimental investigation on the effect of MWCNT-H2O nanofluid on the efficiency of flat-plate solar collectors,” Exp. Therm. Fluid Sci., vol. 39, pp. 207–212, 2012.

[69] M. T. Jamal-Abad, A. Zamzamian, E. Imani, and M. Mansouri, “Experimental Study of the Performance of a Flat-Plate Collector Using Cu–Water Nanofluid,” J. Thermophys. Heat Transf., vol. 27, no. 4, pp. 756–760, 2013.

[70] L. Lu, Z. Liu, and H. Xiao, “Thermal performance of an open thermosyphon using nanofluids for high-temperature evacuated tubular solar collectors Part 1 : Indoor experiment,” Sol. Energy, vol. 85, no. 2, pp. 379–387, 2011.

[71] A. Menbari, A. A. Alemrajabi, and A. Rezaei, “Heat transfer analysis and the effect of CuO/Water nanofluid on direct absorption concentrating solar collector,” Appl. Therm. Eng., vol. 104, pp. 176–183, 2016.

[72] A. Kasaeian, S. Daviran, R. Danesh, and A. Rashidi, “Performance evaluation and nanofluid using capability study of a solar parabolic trough collector,” Energy Convers. Manag., vol. 89, pp. 368–375, 2015.

[73] W. Kang, Y. Shin, and H. Cho, “Economic Analysis of Flat-Plate and U-Tube Solar Collectors Using an Al2O3 Nanofluid,” Energies, vol. 10, no. 12, p. 1911, 2017.

[74] T. B. Gorji and A. A. Ranjbar, “Thermal and exergy optimization of a nanofluid-based direct absorption solar collector,” Renew. Energy, vol. 106, pp. 274–287, 2017.

[75] W. S. Sarsam, S. N. Kazi, and A. Badarudin, “A review of studies on using nanofluids in flat-plate solar collectors,” Sol. Energy, vol. 122, pp. 1245–1265, 2015.

[76] R. Nasrin, S. Parvin, and M. A. Alim, “Effect of Prandtl number on free convection in a solar collector filled with nanofluid,” Procedia Eng., vol. 56, pp. 54–62, 2013.

[77] R. Nasrin, M. A. Alim, and A. J. Chamkha, “Effects of Physical Parameters on Natural Convection in a Solar Collector Filled with Nanofluid,” Heat Transf. Res., vol. 42, no. 1, pp. 73–88, 2013.

[78] R. Nasrin and M. A. Alim, “Finite Element Simulation of Forced Convection in a Flat Plate Solar Collector: Influence of Nanofluid with Double Nanoparticles,” J. Appl. Fluid Mech., vol. 7, no. 3, pp. 543–556, 2014.

[79] M. Shahi, A. Houshang, and F. Talebi, “Numerical simulation of steady natural convection heat transfer in a 3-dimensional single-ended tube subjected to a nano fluid,” Int. Commun. Heat Mass Transf., vol. 37, no. 10, pp. 1535–1545, 2010.

[80] [80] E. A. Tora and T. Moustafa, “Numerical Simulation of an Al 2 O 3 -H 2 O Nanofluid as a Heat Transfer Agent for a Flat-Plate Solar Collector,” Int. J. Sci. Eng. Res., vol. 4, no. 5, pp. 762–773, 2013.

[81] S. Abdul Hamid, M. Yusof Othman, K. Sopian, and S. H. Zaidi, “An overview of photovoltaic thermal combination (PV/T combi) technology,” Renew. Sustain. Energy Rev., vol. 38, pp. 212–222, 2014.

[82] A. H. Besheer, M. Smyth, A. Zacharopoulos, J. Mondol, and A. Pugsley, “Review on recent approaches for hybrid PV / T solar technology,” Int. J. ENERGY Res., 2016.

[83] R. Zakharchenko et al., “Photovoltaic solar panel for a hybrid PV/thermal system,” Sol. Energy Mater. Sol. Cells, vol. 82, no. 1–2, pp. 253–261, 2004.

[84] R. Daghigh, A. Ibrahim, G. L. Jin, M. H. Ruslan, and K. Sopian, “Predicting the performance of amorphous and crystalline silicon based photovoltaic solar thermal collectors,” Energy Convers. Manag., vol. 52, no. 3, pp. 1741–1747, 2011.

[85] A. Ibrahim et al., “Performance of Photovoltaic Thermal Collector (PVT) With Different Absorbers Design,” WSEAS Trans. Environ. Dev., vol. 5, no. 3, pp. 321–330, 2009.

[86] K. Touafek, A. Khelifa, M. Adouane, E. H. Khettaf, and A. Embarek, “Experimental Study on a New Conception of Hybrid PV / T Collector,” in 14th international conference on Sciences and Techniques of Automatic control & computer engineering - STA’2013, Sousse, Tunisia, December 20-22, 2013 STA’2013-PID3271-REC Experimenta, 2013, pp. 140–145.

[87] Z. Xu and C. Kleinstreuer, “Concentration photovoltaic-thermal energy co-generation system using nanofluids for cooling and heating,” Energy Convers. Manag., vol. 87, pp. 504–512, 2014.

[88] M. N. Abu Bakar, M. Othman, M. Hj Din, N. A. Manaf, and H. Jarimi, “Design concept and mathematical model of a bi-fluid photovoltaic/thermal (PV/T) solar collector,” Renew. Energy, vol. 67, pp. 153–164, 2014.

[89] M. Sardarabadi, M. Passandideh-fard, and S. Zeinali, “Experimental investigation of the effects of silica / water nano fluid on PV / T (photovoltaic thermal units),” Energy, vol. 66, pp. 264–272, 2014.

[90] A. Ibrahim, M. Y. Othman, M. H. Ruslan, S. Mat, and K. Sopian, “Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors,” Renew. Sustain. Energy Rev., vol. 15, no. 1, pp. 352–365, 2011.

[91] M. Elmir, R. Mehdaoui, and A. Mojtabi, “Numerical Simulation of Cooling a Solar Cell by Forced Convection in the Presence of a Nanofluid,” Energy Procedia, vol. 18, pp. 594–603, 2012.

[92] D. Jing, Y. Hu, M. Liu, J. Wei, and L. Guo, “Preparation of highly dispersed nanofluid and CFD study of its utilization in a concentrating PV /T system,” Sol. ENERGY, vol. 112, pp. 30–40, 2015.

[93] S. Bhattarai, J. H. Oh, S. H. Euh, G. Krishna Kafle, and 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, vol. 103, pp. 184–193, 2012.

[94] W. He, J. Zhou, C. Chen, and J. Ji, “Experimental study and performance analysis of a thermoelectric cooling and heating system driven by a photovoltaic/thermal system in summer and winter operation modes,” Energy Convers. Manag., vol. 84, pp. 41–49, 2014.

[95] A. H. A. Al-Waeli, K. Sopian, M. T. Chaichan, H. A. Kazem, H. A. Hasan, and A. N. Al-Shamani, “An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system,” Energy Convers. Manag., vol. 142, pp. 547–558, 2017.

[96] R. A. Taylor, T. Otanicar, and G. Rosengarten, “Nanofluid-based optical filter optimization for PV/T systems,” Light Sci. Appl., vol. 1, no. OCTOBER, pp. 1–7, 2012.

[97] S. Hassani, R. A. Taylor, S. Mekhilef, and R. Saidur, “A cascade nanofluid-based PV/T system with optimized optical and thermal properties,” Energy, vol. 112, pp. 963–975, 2016.

[98] F. Crisostomo, J. Becker, S. Mesgari, N. Hjerrild, and R. A. Taylor, “Desing and on-sun testing of a hybrid PVT prototype using a nanofluid-based selective absorption filter,” Int. Conf. Eur. Energy Mark. EEM, vol. 2015–Augus, pp. 2–6, 2015.

[99] M. Moradgholi, S. Mostafa Nowee, and A. Farzaneh, “Experimental study of using Al2O3/methanol nanofluid in a two phase closed thermosyphon (TPCT) array as a novel photovoltaic/thermal system,” Sol. Energy, vol. 164, no. March, pp. 243–250, 2018.

[100] R. Gangadevi, B. K. Vinayagam, and S. Senthilraja, “Experimental investigations of hybrid PV/Spiral flow thermal collector system performance using Al 2 O 3 /water nanofluid,” IOP Conf. Ser. Mater. Sci. Eng., vol. 197, p. 12041, 2017.

[101] H. A. Hussein, A. H. Numan, and R. A. Abdulrahman, “Improving the Hybrid Photovoltaic / Thermal System Performance Using Water-Cooling Technique and Zn-H2O Nanofluid,” vol. 2017, no. 3, 2017.

[102] M. Hosseinzadeh, A. Salari, M. Sardarabadi, and M. Passandideh-Fard, “Optimization and parametric analysis of a nanofluid based photovoltaic thermal system: 3D numerical model with experimental validation,” Energy Convers. Manag., vol. 160, no. October 2017, pp. 93–108, 2018.

[103] M. Sardarabadi, M. Passandideh-fard, M. Maghrebi, and M. Ghazikhani, “Experimental study of using both ZnO/ water nanofluid and phase change material (PCM) in photovoltaic thermal systems,” Sol. Energy Mater. Sol. Cells, vol. 161, no. November 2016, pp. 62–69, 2017.

[104] M. Sardarabadi, M. Hosseinzadeh, A. Kazemian, and M. Passandideh-Fard, “Experimental investigation of the effects of using metal-oxides/water nanofluids on a photovoltaic thermal system (PVT) from energy and exergy viewpoints,” Energy, vol. 138, pp. 682–695, 2017.

[105] M. Sardarabadi and M. Passandideh-Fard, “Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT),” Sol. Energy Mater. Sol. Cells, vol. 157, pp. 533–542, 2016.

[106] A. N. Al-Shamani, K. Sopian, S. Mat, H. A. Hasan, A. M. Abed, and M. H. Ruslan, “Experimental studies of rectangular tube absorber photovoltaic thermal collector with various types of nanofluids under the tropical climate conditions,” Energy Convers. Manag., vol. 124, pp. 528–542, 2016.

[107] A. N. Al-Shamani, K. Sopian, S. Mat, and A. M. Abed, “Performance enhancement of photovoltaic grid-connected system using PVT panels with nanofluid,” Sol. Energy, vol. 150, pp. 38–48, 2017.

[108] O. Rejeb, M. Sardarabadi, C. Ménézo, M. Passandideh-Fard, M. H. Dhaou, and A. Jemni, “Numerical and model validation of uncovered nanofluid sheet and tube type photovoltaic thermal solar system,” Energy Convers. Manag., vol. 110, pp. 367–377, 2016.

[109] H. A. Hasan, K. Sopian, A. H. Jaaz, and A. N. Al-Shamani, “Experimental investigation of jet array nanofluids impingement in photovoltaic/thermal collector,” Sol. Energy, vol. 144, pp. 321–334, 2017.

[110] A. Younis, M. Onsa, Y. Alhorr, and E. Elsarrag, “The Influence of Al 2 O 3 - ZnO-H 2 O Nanofluid on the Thermodynamic Performance of Photovoltaic- Thermal Hybrid Solar Collector System,” Innivative Energy Res., vol. 7, no. 1, pp. 1–8, 2018.

[111] Y. Cui and Q. Zhu, “Study of photovoltaic/thermal systems with MgO-water nanofluids flowing over silicon solar cells,” Asia-Pacific Power Energy Eng. Conf. APPEEC, pp. 0–3, 2012.

[112] J. J. Michael and S. Iniyan, “Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide - water nanofluid,” Sol. Energy, vol. 119, pp. 439–451, 2015.

[113] M. Ghadiri, M. Sardarabadi, M. Pasandideh-Fard, and A. J. Moghadam, “Experimental investigation of a PVT system performance using nano ferrofluids,” Energy Convers. Manag., vol. 103, pp. 468–476, 2015.

[114] A. H. A. Al-Waeli et al., “Evaluation of the nanofluid and nano-PCM based photovoltaic thermal (PVT) system: An experimental study,” Energy Convers. Manag., vol. 151, no. September, pp. 693–708, 2017.

[115] S. Aberoumand, S. Ghamari, and B. Shabani, “Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study,” Sol. Energy, vol. 165, no. January, pp. 167–177, 2018.

[116] S. Bhattarai, G. K. Kafle, S. H. Euh, J. H. Oh, and D. H. Kim, “Comparative study of photovoltaic and thermal solar systems with different storage capacities: Performance evaluation and economic analysis,” Energy, vol. 61, pp. 272–282, 2013.

[117] T. P. Otanicar and J. S. Golden, “Comparative environmental and economic analysis of conventional and nanofluid solar hot water technologies,” Environ. Sci. Technol., vol. 43, no. 15, pp. 6082–6087, 2009.

[118] M. Faizal, R. Saidur, S. Mekhilef, and M. A. Alim, “Energy, economic and environmental analysis of metal oxides nanofluid for flat-plate solar collector,” Energy Convers. Manag., vol. 76, pp. 162–168, 2013.

[119] R. A. Taylor, P. E. Phelan, T. P. Otanicar, R. Adrian, and R. Prasher, “Nanofluid optical property characterization: towards efficient direct absorption solar collectors,” Nanoscale Res. Lett., vol. 6, no. 1, p. 225, 2011.