

Article

Synthesis and Application of Ternary Nanofluid for Photovoltaic-Thermal System: Comparative Analysis of Energy and Exergy Performance with Single and Hybrid Nanofluids

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Abstract: The amelioration of photovoltaic (PV) and photovoltaic/thermal (PV/T) systems have garnered increased research interest lately, more so due to the discovery of the thermal property augmentation of nanofluids. The overarching goal of this study is to conduct a comparative analysis of mono, hybrid, and ternary hybrid nanofluids utilized as fluids for heat transfer applications and particularly as cooling mediums in PV/T applications. Al_2O_3 , ZnO , $\text{Al}_2\text{O}_3\text{-ZnO}$, and $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ nanofluids are synthesized at 1% volume concentration using the two-step method. The zeta potential tests carried out showed that the fluids have high stability. The numerical model developed in this study was validated using real data culled from Cyprus International University. The findings in this study showed that the $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ ternary hybrid nanofluid and ZnO mono nanofluid were more efficient heat transfer fluids for the PV/T system. The optimum relative electrical PV/T efficiency against that of the PV is 8.13% while the electrical and thermal enhancement recorded in this study was 1.79% and 19.06%, respectively, measured for the ternary hybrid nanofluid based PV/T system. This present study shows that despite the limitation of pumping power and pressure drop associated with nanofluid in thermal systems, the close performance evaluation criterion values as compared with water is positive for practical utilization of nanofluid in PV/T systems.

Keywords: photovoltaic/thermal system; electrical efficiency; thermal efficiency; ternary nanofluid; pressure drop; pump work

1. Introduction

There has been an increasing consensus globally in the drive to reduce the effect of greenhouse gas (GHG) emissions. There have also been international agreements that have made notable investments towards renewable energy projects in countries that lack electricity and experience high GHG emissions. The production of renewable energy gives an efficient alternative to meeting growing global energy demands [1]. Solar energy is one of the renewable energy sources that can be utilized, for which photovoltaic (PV) systems have been known to grow in maturity and economic competitiveness over the years. There has been an approximately 50% increase in PV installations globally between the year 2010 and 2017 [2]. Some experimental studies have reported that the efficiency of PV ranges between 10–30%. The recorded inefficiency of PV systems is attributed to the conversion of

the sun radiation to heat, rather than electricity. According to the first pioneers [3,4] who investigated the relationship between the efficiency of PV and the operating temperature, it was stated that PV efficiency drops linearly with a rise in temperature beyond a threshold level.

By designing an effective cooling system, which is hybridized with the PV system, the temperature of the PV system can be maintained at a low level. The heat absorbed could also be used for other applications. This will increase the overall efficiency of the system. This hybrid system of PV and heat recovery is called a photovoltaic/thermal system (PV/T) [5]. Of note is that the type of fluids used in the heat recovery system is an important research interest in the continuing goal of increasing the performance of PV and PV/T systems (especially when the structure of the system is unchanged). The application of air [6,7] and water [8,9] as a heat transfer fluid has been experimentally investigated in numerous studies, alongside their overall efficiencies.

In recent times, the enhancement of thermal conductivity of base fluids with the dispersion of nanoparticles in them has been elaborated in several studies. A conventional nanofluid is a fluid that contains a single type of nanoparticle of scale 1–100 nm dispersed in a base fluid [10]. As compared to conventional base fluids, like water, coolant air, and ethylene glycol, nanofluids are excellent heat transfer fluids, and their applications span the medical field, thermal processes, electronics, and solar energy technology systems [11–13]. The utilization of nanofluids as heat transfer fluids (HTFs) for cooling purposes has also gained widespread attention [14]. The superior thermophysical and rheological properties of nanofluids have caused an increase in their utilization in solar technology applications [15]. The enhanced thermophysical properties of nanofluids are attributed to several factors: temporary local heat transfer effects [16], Brownian movement of nanoparticles [17], the charge on the surface of the particles [18], and higher conductive heat transfer coefficient of nanoparticles [19]. Several studies [20–25] have experimentally observed the enhanced thermophysical properties of nanofluids [26]. Several experimental studies have analyzed the enhancement of PV/T systems with nanofluids as heat transfer fluids. A study by Al-Waeli et al. [27] experimentally explored the use of nanofluid and nano-PCM in controlling the heat capacitance of a PV/T system to increase its electrical efficiency and overall efficiency. The experimental design, which was done in Selangor, Malaysia, recorded an increase in electrical efficiency from 7.1% to 13.7% and an optimum thermal efficiency of 72%. A comparable experimental study was undertaken by Mohammad et al. [28], which utilized both ZnO/water and a phase change substance in cooling a PV/T collector. It was observed in their study that there was a 5% improvement in the thermal output when nanofluid is used and a 9% improvement when PCM was used, in comparison with water. The study also recorded a 23% increment in exergy efficiency in the nanofluid/PCM based PV/T collector as against the conventional PV module. A study by Sadegh et al. [29] used Ag/water as the heat transfer fluid for cooling a PV/T system. The study, which investigated the effects of laminar and turbulent flow on the performance of the PV/T system, observed that the exergy efficiency of the nanofluid based PV/T was 30% higher than when water was used as the HTF. Additionally, their study showed that an increase in the volume concentration of nanofluids further improves the power output of the system. A study by Lari et al. [30] investigated the impact of nanofluids on PV/T performance, as it relates to meeting the electrical demands of residents in Dhahran, Saudi Arabia. Their outcome showed that the electrical output was improved by 8.5% when nanofluid was used as HTF as against a PV/T system with water as a cooling fluid. Additionally, their study showed an increase of 13% in thermal output with the nanofluid based PV/T as compared with PV/T system with water as a cooling fluid. A study by Mohammad et al. [31] analyzed the energy and exergy efficiencies of a nanofluid based PV/T collector. The study synthesized 0.2% volume concentration Al_2O_3 , TiO_2 , and ZnO nanofluids and used them for the experimental setup. In their study, which experimented with a steady mass flow rate of 39 kg/h, an optimum exergy efficiency of 18.27% was recorded for the PV/T system with an Al_2O_3 nanofluid. Their study also recorded an exergy efficiency

enhancement of 3.59% and 3.11% for the PVT/TiO₂ and PVT/ZnO systems, respectively, as against a PVT/water system. A study by Al-Waeli et al. [32] synthesized SiC nanofluid for cooling purposes in a PV/T collector. The recorded maximum was 8.1% electrical efficiency of the PV system. It was observed in their study that there was a 24.1% increase in the PV/T's electrical efficiency by utilizing 3wt% of SiC nanofluid as against a PV system alone. Their study also observed an 88.9% overall efficiency for the PV/T system.

The reviewed researches show that varying degree of improvement in the experimental PV/T system is observed based on varying factors investigated. However, a limitation of nanofluids in PV/T systems is the complexity involved in ensuring the stability of nanofluids, coupled with the high cost of synthesis and application to real PV/T systems. This limitation has been buffered by performing numerical simulations that streamline the magnitude of pilot experimental setups. Several studies have been conducted on numerical simulations of nanofluids on PV/T systems. A study by Ali et al. [33] examined the performance of the PV/T system based on the heat transfer effects of SiC, CuO, and Al₂O₃ nanofluids. The results of these studies showed that the nano-SiC nanofluid had the optimum heat transfer property. A study by Sarafraz et al. [34] utilized a water based multi-walled carbon nanotube as HTF for cooling a PV system. Their study also did a comparison with multi-walled carbon nanotube–paraffin phase change material (PCM) and the cooling pipes were passed through the PCM. Their result showed that the optimum thermal and electrical efficiency was measured at 0.2wt%. Their study also concluded that the pumping power was augmented at a higher mass concentration of nanofluid. A study by Abbood et al. [35] conducted a mathematical analysis of the performance of PV/T collectors using a SiO₂/water nanofluid and PCM materials. Their study analyzed the thermal and electrical efficiency of the system and observed that there was an enhancement of 8% and 25% in the electrical and thermal efficiency, respectively. Their study also observed that the thermal efficiency enhancement of the 3wt% SiO₂/water nanofluid was 10.41% as compared to 3.51% recorded for 1% mass fraction. A study by Yuting et al. [36] explored, using mathematical models, the comparative performance of an Al₂O₃ and TiO₂ based nanofluid and water-cooled PV/T system. Their study also investigated the mass flow in the range of 0.0005 kg/s and 0.03 kg/s. Their study observed that the optimum thermal power of 12.11% was recorded for the Al₂O₃ nanofluid with a flow rate of 0.03 kg/s. In addition, the study demonstrated an increment in thermal power when the channel height was decreased. A study by Ali et al. [37] probed, by numerical methods, the utilization of nano-magnesium oxide, nano-multiwall carbon nanotube (MWCNT), and the hybrid nanofluids in a 3D PV/T system. The parametric analysis was carried out in different flow regimes. Their results indicated that at an increase in mass fraction of the MWCNT from 3% to 6%, there was a drop in the cell temperature by 0.3 °C. Their results showed the optimum overall exergy efficiency as 61.07% for the MWCNT nanofluid.

There has also been growing interest in the synthesis and behavior of hybrid nanofluids. Hybrid nanofluids are a synthesis of more than one nanoparticle dispersed in a base fluid [38]. Their improved thermophysical properties are due to the synergistic effect of the nanoparticles used [39]. The interest in hybrid nanofluids is also due to their better heat transfer properties compared with mono-nanofluids of the same volume concentration [40]. A study by Marjan et al. [41] synthesized a ZnO-MWCNT hybrid nanofluid at a volume concentration range between 0.05% and 0.8% and a temperature range of 5–55 °C. Their study showed that the viscosity of nanofluid increases with the volume fraction of nanoparticles and decreases with increasing temperature. A study by Yeping et al. [42] synthesized an Al₂O₃-Cu hybrid nanofluid at volume concentrations of 0.125 to 2.0, and between a temperature range of 25–50 °C. Their study, which used the two-step method, retrieved the thermal conductivity behavior of the hybrid nanofluid, which was used in developing correlation equations for estimation. Recently, the enhanced thermophysical properties of hybrid nanofluids are considered to be important in the study of cooling of PV/T systems. The application of hybrid nanofluids on PV/T collectors has been studied. A study by Natasha et al. [43] numerically studied the utilization of Ag-SiO₂ in PV/T systems for

cooling purposes. Their study observed a 30% increase in the overall efficiency of the PV/T system by using 0.026wt% Ag-SiO₂ nanofluid compared to when using water alone. A study by Wole-Osho et al. [44] investigated the efficiency of a PV/T collector based on the effect of the mixture ratio of Al₂O₃-ZnO nanofluids. From the result, it was seen that at a mixture ratio of 0.47, an optimum thermal and electrical efficiency of 55.9% and 13.8%, respectively, were obtained. Their study also showed that at a mass flow rate of 0.01 kg/s, the cell temperature dropped by 21%. Some studies [45–50] have also synthesized three (3) particle nanofluids and analyzed their thermophysical properties. However, the literature for ternary nanofluid is limited.

Furthermore, the specific heat capacity (SHC) of nanofluids (which determines the heat storage capacity of fluids) is an ongoing study concerning the heat storage capacity of hybrid nanofluids. A study by Neeshoun et al. [51], which investigated the performance of a hybrid Al₂O₃-CuO on a compact heat exchanger, reported that the hybrid nanofluid showed a lower SHC as compared to the mono nanofluids (Al₂O₃, and CuO), except at higher volume concentrations of 0.06%. Their study conclusively stated that upon the result of the SHC, hybrid nanofluids would gain and lose heat more rapidly, and therefore would be a better choice for heat transfer purposes. In a similar study by Nizar et al. [52], Al₂O₃-Graphene hybrid nanofluids were prepared and used for a mini channel heat exchanger. The comparison of the hybrid's SHC with the alumina and graphene conventional nanofluids showed that the hybrid nanofluid had a lower SHC as compared to the alumina nanofluid, but its SHC was higher than graphene. Upon these behaviors of SHC of hybrid nanofluids, it creates a gap to further investigate their applications on heat transfer systems, and make comparisons with conventional nanofluids, across different working conditions. This would give future researchers a more defined and clear understanding of the applications of nanofluids when choosing between conventional and hybrid nanofluids.

As can be seen in the literature, the study of hybrid nanofluids as HTF in PV/T collectors have shown improvement in the collector system. The results also give an impetus for continual research in synthesizing nanofluids with better heat transfer properties, as better efficiencies of the systems are desired. The creation of three-particle hybrid nanofluids (also known as ternary hybrid nanofluids) has recently piqued researchers' curiosity. Similarly to how two-particle hybrid nanofluids are thought to have improved thermophysical properties due to synergistic effects, ternary nanofluids are better heat transfer fluids in experimental studies. Amin et al. [53] synthesized a Cu-SiO₂-MWCNT ternary hybrid nanofluid in water with a volume concentration range of 1% to 3% and a temperature range of 15 °C to 65 °C. Their findings revealed that the ternary nanofluid (TNF) had higher thermal conductivity and dynamic viscosity than mono and hybrid nanofluids. The improved thermophysical properties of ternary hybrid nanofluid can be attributed to the contributory effect of the unique properties of the individual nanoparticles in the ternary mixture [54].

To the extent of the authors' knowledge, despite the few studies that have shown excellent thermophysical properties of ternary hybrid nanofluids, however, no study has investigated the utilization of ternary nanofluids in PV/T systems. Therefore, this study adds to the novelty of investigating the synergistic effect of ternary hybrid nanofluids on solar energy technologies. In this study, a ternary hybrid nanofluid (Al₂O₃-ZnO-Fe₂O₃/water), hybrid nanofluid (Al₂O₃-ZnO/water), and mono nanofluids (ZnO/water and Al₂O₃/water) are synthesized at 1% volume concentration using the two-step method, and stability was tested using the zeta potential analysis. The effects of mass flow rate, mixture ratio, and solar irradiance on the performance of the PV/T collector is examined. This study uses the meteorological data retrieved from the Cyprus international university solar farm for validation of the numerical model developed. When choosing these particles, a variety of criteria were considered: ZnO was chosen for its better stability features, Al₂O₃ was chosen for its availability and chemical inertness, and Fe₃O₄ was chosen for its conductivity.

This study is important to the continuing research towards improvement of the electrical, and total equivalent electrical efficiency of photovoltaic systems. Additionally, considering that the choice of heat transfer fluids for optimum performance of PV/T systems is crucial, this study provides a comparative analysis of different ‘nanofluid types’.

2. Nanofluid Study

The utilization of nanofluid in heat transfer applications have gained increasing research interest due to their better heat transfer characteristics as compared to conventional fluids. The parameters that are influential to the enhancement of heat transfer properties of nanofluids are the base fluid, stability of nanofluids, purity of nanofluids, size of nanoparticles, the temperature of fluids, viscosity, and dispersion of nanoparticles [55].

2.1. Synthesis and Characterization

2.1.1. Preparation, Characterization of Al_2O_3 and ZnO, and Fe_3O_4 Nanoparticles

In a solution of 140 mL de-ionized water and 10 mL liquid ammonia, 0.1 M aluminum (III) chloride was dissolved. After mixing well for 2 h with a magnetic stirrer, the resultant solution was aged for 4 h, resulting in the development of white colored precipitates. The mixed solution was then centrifuged for 15 min at 12,000 rpm, and the precipitate was washed three times with ethanol to eliminate the organic contaminants. Finally, aluminum oxide nanoparticles were obtained by calcination of the product at 800 °C for 1 h in a furnace. Al_2O_3 with an average particle size of 29 nm was synthesized using this method.

The ZnO nanoparticles were synthesized via a direct precipitation process, with Zinc nitrate tetrahydrate ($\text{Zn} \cdot (\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$) as a precursor material and sodium hydroxide as a precipitating agent (NaOH). A 250 mL Erlenmeyer flask was filled with 150 mL of 0.2 molar $\text{Zn} \cdot (\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ and thoroughly agitated at 70 °C on a magnetic stirrer. At a temperature of 80 °C, 0.4 molar NaOH was added in drops. As a result of the mixing, a white hazy precipitate appears. After two hours of continuous mixing, the mixture was allowed to settle and the precipitate was rinsed with de-ionized water. It was then calcinated for three (3) hours at 500 °C. The calcinated particles were then crushed into a fine powder.

The farm at Cyprus International University was the source of the *Olea europaea* leaves used for the preparation of the Fe_3O_4 nanoparticle. The leaves were cut into pieces after being washed with distilled water (to rid them of dirt). Drying of the leaves followed to get rid of the water content in the leaves; the drying of the cut leaves was done with the use of the oven at 40 °C and it spanned a full day. The cut and dried *Olea europaea* leaves were then crushed by an electric blender. Following that, the preparation of the olive leaves extract (OLE) as a portion (10 g) of the crushed leaves was submerged in 100 mL of ethanol. Extraction was then done with a rotary evaporator, filtration and drying of the resultant (cool temperature) was then conducted before further characterization and synthesis of nanoparticles. The reducing agent of 10 mL of FeCl_3 was put into 20 mL of OLE to synthesize Fe_3O_4 nanoparticles. The resulting mixture was then homogenized for a period of up to 2 h with consideration of room temperature in producing the nanoparticles, which was then centrifuged at 600 rpm for 30 min. After centrifuging, the residue was then collected, washed, and immersed in ethanol. Heating the resulting solution at 80 °C until it was dry resulted in powdered Fe_3O_4 nanoparticles.

The average size of ZnO NP was 70 nm based on particle XRD measurement. As shown in Figure 1a–c the reflections in the XRD pattern corresponded to the structural characteristics of dry ZnO and Al_2O_3 and hybrid nanoparticles, respectively are shown. The pattern obtained for the ZnO nanoparticles is shown by the red line in the XRD image. Cu K radiation (1.5406 Angstrom) was used to record the diffraction, and the XRD pattern was captured at 2 θ for values ranging from 20° to 80°. The XRD pattern for Al_2O_3 nanoparticles (green line) seemed to peak at 32°, 39°, 48°, 57°, 62°, and 68°, all of which correlate with the distinctive reflections of (220), (222), (400), (422), (511), and (440) and are well-coordinated with JCPDS card no. 02-1420.

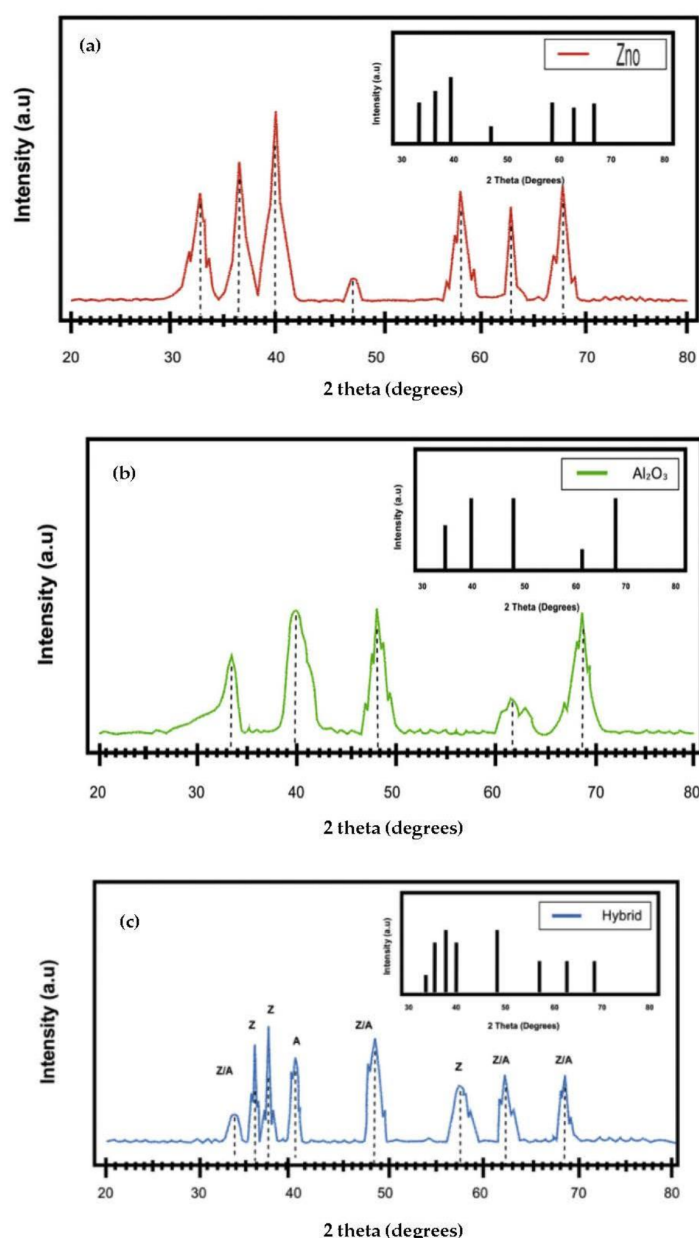


Figure 1. XRD characterization for ZnO, Al₂O₃, and Al₂O₃-ZnO water nanofluids.

2.1.2. Preparation and Characterization of Al₂O₃-ZnO Hybrid Nanofluid

The hybrid nanofluids were prepared using a two-step procedure. The nanoparticles are dispersed in distilled water, which was utilized as the base fluid, in the first step of the process. The Al₂O₃ and ZnO utilized had average diameters of 29 nm and 70 nm, respectively. An ultrasonic vibrator (400 W, 24 kHz) was employed to mix the nanofluid for 3 h without dispersant to ensure appropriate dispersion of nanoparticles in water. PH modulation was also used to establish the hybrid nanofluids' optimal stability. The experiment was carried out with a 1:1 nanoparticle mixing ratio and a 1% volume concentration. The volumetric concentration of hybrid nanofluids was obtained using Equations (1) and (3). The XRD pattern for the Al₂O₃-ZnO hybrid is shown in Figure 1c. The peaks indicate the nanoparticles' excellent purity. The blue line indicates a mixture of both nanoparticles, and the corresponding peaks show the presence of ZnO and Al₂O₃.

2.1.3. Preparation and Characterization of Al₂O₃-ZnO-Fe₃O₄ Ternary Hybrid Nanofluid

The magnetic stirrer was employed in a beaker containing up to 100 mL of water, to get aluminum oxide (Al₂O₃), zinc oxide (ZnO), and iron (III) oxide (Fe₃O₄) combined. Additionally, the nanoparticles were spread all over in an equal manner and consideration of varying volumes was done to obtain them. For the preparation of the nanofluid, which is Al₂O₃-ZnO-Fe₃O₄ ternary hybrid nanofluid, the two-step method was used. The volumetric concentration of the ternary hybrid nanofluids was obtained using Equations (2) and (4). It was discovered that agglomeration of nanoparticles normally occurs and to avoid this while preparing these nanofluids, the processor, which is ultrasonic, was employed to disperse the nanoparticles uniformly. The ternary nanofluid that had been prepared revealed that agglomeration of the nanoparticles had been completely avoided. Morphological investigation of the nano-composites was carried out using SEM images, as shown in Figure 2.

$$\varphi = \frac{\left[\frac{w_{\text{Al}_2\text{O}_3+\text{ZnO}}}{\rho_{\text{Al}_2\text{O}_3+\text{ZnO}}} \right]}{\left[\frac{w_{\text{Al}_2\text{O}_3+\text{ZnO}}}{\rho_{\text{Al}_2\text{O}_3+\text{ZnO}}} \right] + \left[\frac{w_{\text{water}}}{\rho_{\text{water}}} \right]} \times 100 \quad (1)$$

$$\varphi = \frac{\left[\frac{w_{\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3+\text{ZnO}}}{\rho_{\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3+\text{ZnO}}} \right]}{\left[\frac{w_{\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3+\text{ZnO}}}{\rho_{\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3+\text{ZnO}}} \right] + \left[\frac{w_{\text{water}}}{\rho_{\text{water}}} \right]} \times 100 \quad (2)$$

$$\rho_{\text{Al}_2\text{O}_3+\text{ZnO}} = \frac{(\rho_{\text{Al}_2\text{O}_3} \times w_{\text{Al}_2\text{O}_3}) + (\rho_{\text{ZnO}} \times w_{\text{ZnO}})}{w_{\text{Al}_2\text{O}_3} + w_{\text{ZnO}}} \quad (3)$$

$$\rho_{\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3+\text{ZnO}} = \frac{(\rho_{\text{Al}_2\text{O}_3} \times w_{\text{Al}_2\text{O}_3}) + (\rho_{\text{Fe}_2\text{O}_3} \times w_{\text{Fe}_2\text{O}_3}) + (\rho_{\text{ZnO}} \times w_{\text{ZnO}})}{w_{\text{Al}_2\text{O}_3} + w_{\text{Fe}_2\text{O}_3} + w_{\text{ZnO}}} \quad (4)$$

where the density is denoted as ρ , w represents the mass of the nanocomposite, and φ is the volume concentration of the ternary nanofluid.

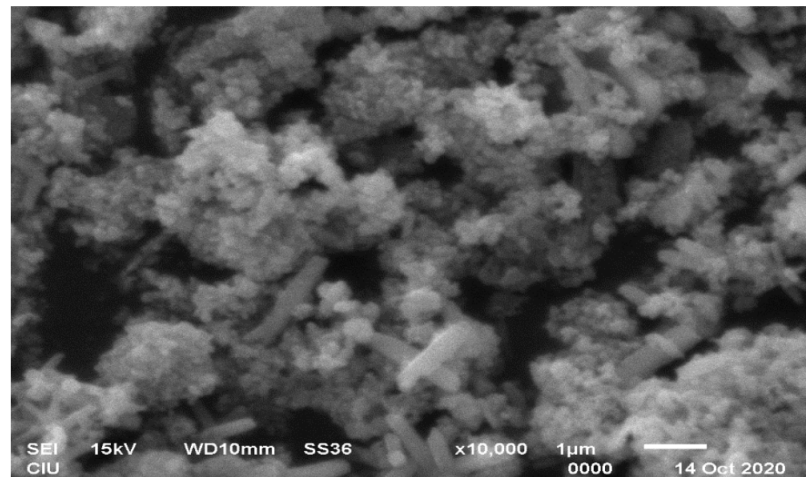


Figure 2. SEM image of Al₂O₃-ZnO-Fe₃O₄ nanocomposite.

The particle size distribution is important in the characterization of nanoparticles. Figures 3 and 4 show the particle size of the Al₂O₃-ZnO-Fe₃O₄, and Al₂O₃-ZnO hybrid and nanocomposites, respectively. The results, as shown in Figures 3 and 4, give the average size of 90 nm for the Al₂O₃-ZnO-Fe₃O₄ nanocomposite and 78 nm for the Al₂O₃-ZnO nanocomposite. As regards measurement repeatability in estimating the particle size, measurement was collected at least three times for all measured quantities. Furthermore, no dispersants were used in the synthesis of the nanofluids. The thermophysical properties of the nanoparticles are shown in Table 1.

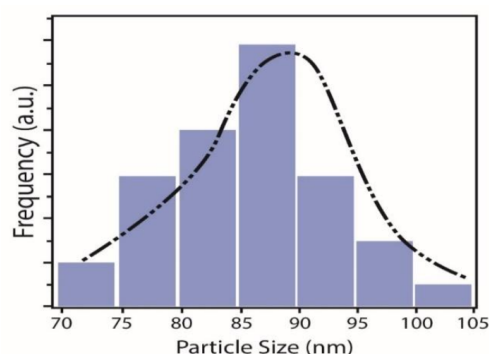


Figure 3. Particle size distribution of Al_2O_3 -ZnO- Fe_3O_4 ternary nanocomposite.

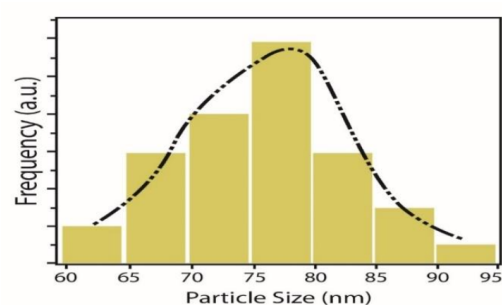


Figure 4. Particle size distribution of Al_2O_3 -ZnO hybrid nanocomposite.

Table 1. Thermo-physical properties of synthesized nanoparticles.

Parameters	Nanoparticles		
	Fe_3O_4	Al_2O_3	ZnO
Specific heat capacity (J/KgK)	4182	773	514
Thermal conductivity (W/mK)	0.6024	40	23.4
Average size (nm)	20–30	29	70
Purity	>98%	>98.5%	>87%
Nanoparticle shape	Spherical	Spherical	Spherical

The stability of nanofluids is an important factor to be considered especially for practical applications. In this study, the stability of the prepared ternary nanofluids was determined using the zeta potential method. The zeta potential was determined using a Malvern zeta sizer nanozs90 model. The stability tests were done on days 7 and 12. The results proved that the nanofluids were more stable on day 12 than on day 7. The prepared nanofluids were desirably stable. The prepared ternary nanofluid was observed after 1 week and no agglomeration of nanoparticles was visible.

2.2. Measurement of Thermophysical Properties

2.2.1. Viscosity Measurement

A Brookfield DV-I PRIME digital viscometer was used to measure the viscosity of the nanofluids in this study. The Viscometer was equipped with a temperature bath to keep the samples at a consistent temperature during viscosity measurements. Temperatures of 25, 35, 45, 55, and 65 °C were used in the experiments. The device's accuracy is 2%, while its repeatability is 5%. The accuracy of the experiments was ensured by measuring the viscosity of the base fluid (Water) at different temperatures before evaluating the viscosity of nanofluid samples.

2.2.2. Thermal Conductivity Measurement

The Thermal Properties Analyzer KD2 Pro was used to measure the thermal conductivity of the nanofluids (Decagon Devices Incorporation: Pullman, WA, USA). The transient hot-wire approach is used in the KD2, which has a single probe with a length of 6 cm and a diameter of 1.3 cm. Before testing, the KD2 analyzer was calibrated with deionized water and glycerin.

2.2.3. Specific Heat Capacity Measurement

Differential scanning calorimetry, (DSC) 823 model, was used to determine the specific heat capacity of the nanofluids (Mettler Toledo: Schwerzenbach, Switzerland). The heat flux in an empty pan (Aluminum pan in DSC823 Mettler Toledo), a reference (in this case a sapphire disc), and a pan containing the nanofluids sample are compared. To begin, measurements with two empty samples were performed to establish a baseline. After obtaining the reference curve using a pan holding a sapphire standard disc and an empty pan, the measurement was performed using a pan containing the sample and an empty pan. The heating was done at a temperature of 25 °C to 65 °C at a rate of 20 °C/min.

2.3. Stability Tests

The Brownian mobility of nanoparticles causes them to collide with one another. When particles collide, the Van der Waals force of attraction causes them to aggregate, which increases particle size and density. The sedimentation method or the zeta potential test can be used to determine the stability of nanofluids. The zeta potential test was performed to determine the stability of nanofluids in this investigation. PH and zeta potential were measured using a pH meter and a Malvern zeta sizer nano zs90 model, respectively. The zeta potential tests were carried out after 7 and 14 days of preparation. A zeta potential value of −30 mV and 28 mV is recorded after 7 and 14 days, respectively, for the Al_2O_3 : ZnO: Fe_3O_4 ternary nanofluid with 1% volume concentration. At a pH value of 12, the zeta potential result for the Al_2O_3 , ZnO, and Al_2O_3 -ZnO nanoparticles was −39 mV, −25 mV, and −39 mV, respectively.

2.4. Uncertainty Analysis

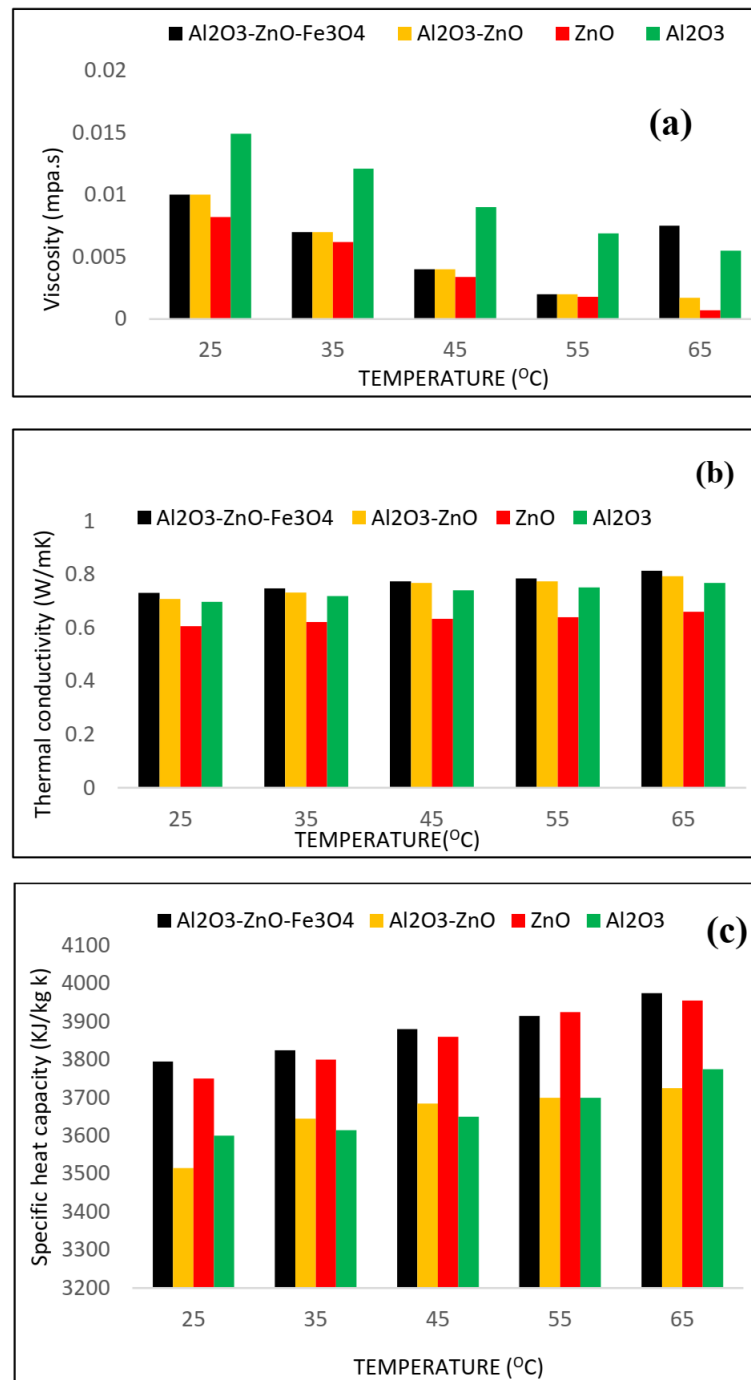
It is a well-known fact that throughout any experimental investigation, both systematic and random errors are likely to occur. As a result, all measured quantities in this investigation were subjected to an acceptable level of uncertainty. The Shaw measurement uncertainty approach [56] was used to examine this uncertainty. The volume, temperature, weight, specific heat capacity, and viscosity deviations were all measured. The estimated uncertainties related to viscosity and specific heat capacity were four per cent and five per cent, respectively, in the measurement parameters.

2.5. Correlation Model of Thermophysical Properties

In this study, correlation models were developed for estimating the thermophysical properties of the nanofluids, due to the limitations of existing determination methods. Equations (3)–(16) give the correlation of thermal conductivity (k), viscosity (μ), and specific heat capacities (C_p) of the nanofluids considered in this study. To verify the accuracy of the correlation models, the correlation coefficient (R^2) and root mean square (RMSE) values were used, as shown in Table 2. Figure 5 is a graphical representation of the experimental values of the thermophysical properties of the nanofluids synthesized. The result presented in Figure 5a shows that the Al_2O_3 nanofluid gave the highest viscosity value, while the lowest viscosity was recorded for ZnO nanofluid. It is also seen that the viscosity of the nanofluids decreases with increasing temperature. This result agrees with similar reported results in the literature [39,57–59]. The thermal conductivity result shows that Al_2O_3 -ZnO- Fe_3O_4 and Al_2O_3 -ZnO have the highest values between the temperatures of 25 °C and 65 °C. The optimum thermal conductivity values for the Al_2O_3 -ZnO- Fe_3O_4 and Al_2O_3 -ZnO are 0.814 W/mK and 0.794 W/mK, respectively, as shown in Figure 5b.

Table 2. Correlation coefficients and RMSE.

Nanofluid	μ		k		C_p	
	$R^2(\%)$	RMSE	$R^2(\%)$	RMSE	$R^2(\%)$	RMSE
Al ₂ O ₃	99.77	0.00016527	99.58	0.0016000	99.97	1.0690
ZnO	99.29	0.00023373	97.58	0.0028041	99.24	6.6332
Al ₂ O ₃ -ZnO	99.42	0.00024095	98.01	0.0043831	96.32	14.233
Al ₂ O ₃ -ZnO-Fe ₃ O ₄	84.55	0.0011006	98.45	0.0036000	99.43	4.8107

**Figure 5.** Properties of Al₂O₃-ZnO-Fe₃O₄, Al₂O₃-ZnO, ZnO, Al₂O₃ Nanofluids (a) Viscosity (b) Thermal conductivity (c) Specific heat capacity.

The optimum specific heat capacity was measured for the $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ nanofluid, having a value of 3975 KJ/Kg K as seen in Figure 5c. The ZnO nanofluid has a better specific heat capacity value than the $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ at a temperature of 55 °C. The correlation equations for estimating the thermophysical parameters are given below.

Al_2O_3 nanofluid

$$\mu = 2.54335714\text{E} - 02 + (-4.84285714\text{E} - 04 * T) + (2.71428571\text{E} - 06 * T^2) \quad (5)$$

$$k = 6.30375000\text{E} - 01 + (3.08000000\text{E} - 03 * T) + (-1.50000000\text{E} - 05 * T^2) \quad (6)$$

$$C_p = 3.64823214\text{E} + 03 + (-4.32857143 * T) + (9.64285714\text{E} - 02 * T^2) \quad (7)$$

ZnO nanofluid

$$\mu = 0.0167007143 + (-0.000386857143 * T) + (0.00000214285714 * T^2) \quad (8)$$

$$k = 0.578307143 + (0.00113142857 * T) + (0.00000142857143 * T^2) \quad (9)$$

$$C_p = 3571.62500\text{E} + (7.6 * T) + (-0.0250000000 * T^2) \quad (10)$$

$\text{Al}_2\text{O}_3\text{-ZnO}$ nanofluid

$$\mu = 0.0230028571 + (-0.000627428571 * T) + (0.00000457142857 * T^2) \quad (11)$$

$$k = 0.607810714 + (0.00465714286 * T) + (-0.0000278571429 * T^2) \quad (12)$$

$$C_p = 3133.91071 + (19.8571429 * T) + (-0.167857143 * T^2) \quad (13)$$

$\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ nanofluid

$$\mu = 0.0340642857\text{E} + (-0.00125714286 * T) + (0.0000128571429 * T^2) \quad (14)$$

$$k = 0.688375000 + (0.00158000000 * T) + (0.000005 * T^2) \quad (15)$$

$$C_p = 3727.64286 + (1.92857143 * T) + (0.0285714286 * T^2) \quad (16)$$

The density for the ternary nanofluid was computed using Equation (17) and the density of the mixture of nanoparticles is calculated using Equation (18). The choice of the classical model is due to its proven accuracy being within 1% of the experimental data. This high accuracy can be attributed to the fact that density is purely a physical quantity.

$$\rho_{nf} = \rho_{bf}(1 - \varphi_t) + \rho_{hnp}\varphi_t \quad (17)$$

$$\rho_{hnp} = \frac{\sum_{i=1}^{nnp} \varphi_i \rho_i}{\sum_{i=1}^{nnp} \varphi_i} \quad (18)$$

3. Analysis of PV/T Collector

The integration of the thermal collectors with solar PV systems has improved the overall energetic performance, however, there is a need to develop more efficient heat transfer systems to further increase the performance of PV/T collectors. In this study, the integration of mono, hybrid, and ternary nanofluids with PV/T collectors is analyzed. In this section, the equations used for the mathematical modelling and the calculation of the energetic/exergetic performances of the systems are presented. The PV/T design parameters are shown in Table 3.

Table 3. PV/T design parameters.

PV/T	Value	Symbol
Collector width	0.505 m	W_c
Collector Perimeter	3.3 m	P_c
Collector Area	1.6665	A_c
Collector width	0.505 m	W_c
Slope	14	β
absorber plate's thermal conductivity	51 W/mK	k_{abs}
Material of Absorber plate	Copper	
Back Insulation thermal conductivity	0.045 W/mK	k_b
Back insulation thickness	0.05 m	L_b
Edge insulation thickness	0.025 m	L_e
thickness of absorber	0.002 m	δ
distance between tubes	0.0151	W_{tubes}
Outer diameter of tubes	0.0252 m	D_{tubes}
Number of tubes	13	N_{tubes}
thickness of collector	0.03752 m	L_c
length of collector	1.6971 m	L
Number of glass covers	1	N
Emittance of glass	0.88	ε_g
Emittance of plate	0.82	ε_p
Mass flow rate of fluid	0.008 kg·s ^{−1}	m_{fluid}
Transmittance	0.88	t
absorptance	0.75	α
Temperature factor of PV efficiency	0.0045	β_{ref}
Electrical efficiency for the reference temperature	0.14	η_{ref}

3.1. Numerical Model

The PV/T system was studied for the city of Lefkosa, Turkish Republic of North Cyprus (35.1856° N, 33.3823° E). The numerical simulation in this study was made with consideration of the assumptions listed below.

- The study neglected the ohmic losses of the PV cells
- The sky is a black body with a temperature of T_{sky}
- There is uniformity of fluid flow in the tubes
- Radiation heat loss in the collector is neglected due to low temperatures

3.2. Thermal Model for PV/T Collector

The parameters used in the estimation of the thermal performance of the PV/T collector are discussed in this section. In determining the useful thermal energy, Equation (17) is used following the Hottel–Whillier equation [30], where the temperature of the fluid leaving the collector is T_o :

$$Q_u = F_R A_c [(\tau\alpha)_p (S - I_T \eta_{mp}) - U_L (T_i - T_a)] \quad (19)$$

The transmittance-absorption product of the PV plate is denoted with the $(\tau\alpha)_p$. The heat removal factor of the collector is shown as F_R , the inlet fluid temperature is represented as T_i , and T_a is the ambient temperature. A_c represents the collector area, S is the absorbed radiation, I_T is the incident solar radiation and η_{mp} is the conversion efficiency of the collector. U_L represents the overall heat loss coefficient, which is an addition of the loss coefficients from the top, bottom, and edges of the collector. The thermal efficiency η_{th} is calculated using Equation (20):

$$\eta_{th} = \frac{Q_u}{I_T A_c} \quad (20)$$

$$T_o = T_i + \frac{Q_u}{C_{p,fluid} \dot{m}_{fluid}} \quad (21)$$

where the outlet temperature is shown as T_o , the mass flow rate is denoted as $\dot{m}_{fluid}$, and the $C_{p,fluid}$ is the specific heat capacity of the fluid in the collector. The electrical efficiency and equivalent efficiency of the PV/T system is estimated using Equations (22) and (23), where the cell temperature is denoted by T_c . [60,61].

$$\eta_{el,PVT} = \eta_{Tref} \left[1 - \beta_{ref} (T_c - T_{ref}) \right] \quad (22)$$

$$\eta_{equivalent,PVT} = \eta_{el,PVT} + \left(c_f \cdot \eta_{th,PVT} \right) \quad (23)$$

where $c_f = 0.38$ is the conversion factor to convert the thermal output of the system to an equivalent electrical output [28,62].

The relative electrical efficiency of the PV/T system is calculated using Equation (24).

$$\eta_{el,relative} = \frac{|\eta_{el,PVT} - \eta_{el,PV}|}{\eta_{el,PV}} \quad (24)$$

The total exergy efficiency of the system can be found using Equations (25) and (26).

$$\varepsilon_{PVT} = \frac{\int_{t_1}^{t_2} (A_c \dot{E}x_t + A_{pv} \dot{E}x_{pv}) dt}{A_c \int_{t_1}^{t_2} \dot{E}x_{sun} dt} \varepsilon_{PV} + \zeta \varepsilon_t \quad (25)$$

$$\varepsilon_{PVT} = \varepsilon_{PV} + \varepsilon_t = \eta_{PV} + \left(1 - \frac{T_a}{T_{fm}} \right) \eta_t \quad (26)$$

where the exergetic efficiency of the PV cells is denoted by ε_{PV} , the exergetic efficiency of the thermal collector is denoted by ε_t , the ambient temperature is T_a , and the final temperature of the fluid medium is T_{fm} . While ε_{PV} is equivalent to η_{PV} , ε_t is related to η_t by the Carnot efficiency. In a study by Hisashi et al. [63], a similar definition of the ε_{PVT} , is also utilized, where a comparison of brine cooled PV/T collector with a PV panel, and solar collector is investigated. Additionally, a study by Chow et al. [64], used a similar definition in an exergy analysis of a PV/T parallel-plate air collector. It is of note that the simplification in the computation of Equation (25) has also been made in a study by Fujisawa and Tani [65], as the packing factor, ζ , is ignored. This is because it is challenging to paste solar cell encapsulation on the whole surface of a PV/T collector plate during the fabrication process (i.e., $0 < \zeta < 1.0$), and selection of the ζ value will be dependent on the exact amounts of electricity and heat demanded. Therefore, Equation (26) is only applicable when the ζ equals 1.0. Furthermore, the exergy of solar radiation was not calculated; instead, the energy of radiation was taken as the exergy of radiation. The simplification of this computation was also done in the works of Anand and Arvind [66]:

$$\dot{E}x_{pv} = \dot{E}x_{pv} \quad (27)$$

$$\dot{E}x_t = \left(1 - \frac{T_a}{T_{fm}} \right) \quad (28)$$

$$\dot{E}x_{sun} = \left[1 - \frac{4}{3} \left(\frac{T_a}{T_{sun}} \right) + \frac{1}{3} \left(\frac{T_a}{T_{sun}} \right)^4 \right] \quad (29)$$

where the $\dot{E}x_{pv}$ is the photovoltaic exergy output per unit PV cell area, $\dot{E}x_t$ is the thermal exergy output per unit collector area, $\dot{E}x_{sun}$ is the exergy input of solar radiation T_{fm} is the

mean temperature of the fluid as it flows through the collector and T_{sun} is the temperature of the sun.

3.3. Heat Transfer Characteristic Formation

In describing the heat transfer characteristics of flow systems, the dimensionless Reynolds number, Nusselt number, and Prandtl number are utilized. The accurate prediction of flow patterns in a flow field is made using the Reynolds number. This is an important characteristic because it helps to characterize the heat transfer behavior of the thermal system. The Prandtl number shows the relative contribution of momentum diffusion over thermal diffusion in heat transfer. The Nusselt number is the ratio of convective to conductive heat transfer between a fluid and solid body [67].

$$Re = \frac{4 \times \dot{m}_{tubes}}{\pi \times D_{tubes} \times \mu_{nf}} \quad (30)$$

where $\dot{m}_{tubes}$ is fluid mass flow rate. The diameter of each of the tubes under the PV/T collector is represented by D_{tubes} .

$$Nu = 0.021 \times Re^{0.8} \times Pr^{0.5} \quad (31)$$

Equations (31) and (32) are valid for:

$$10^4 < Re < 10^5, 6.54 < Pr < 12.33, 0 < \varphi < 2.0\%, Pr = \frac{\mu_{nf} \times C_{p,nf}}{k_{nf}} \quad (32)$$

In estimating the heat transfer between the fluid and the wall of the tube, Equation (33) is used [68].

$$h = \frac{Nu \times k_{nf}}{D_{tubes}} \quad (33)$$

This is an important variable in the flow model analysis of PV/T collectors [69]

3.4. Pressure Drop, Pumping Power, and Performance Evaluation Criterion

In moving the fluid through the system, it is required to determine the size of the pump and the necessary power. To calculate these parameters, the pressure drop of the fluid should be determined. Equation (34) is used in computing the pressure drop [70]. The friction factor is computed using Equations (35) and (36).

$$\Delta P = \frac{f \rho L}{2 D_{tubes}} \left(\frac{4 \dot{m}_{tubes}}{\rho \pi D_{tubes}^2} \right)^2 \quad (34)$$

$$f = \frac{64}{Re} \quad Re < 2300 \quad (35)$$

$$f = 0.3164 Re^{-0.25} \quad Re > 2300 \quad (36)$$

where ρ is the density of the fluid, L represents the length of the collector, and n_{tubes} is the number of tubes under the PV/T collector.

The Nusselt number and friction factor estimations of the heat transfer explain their effect on the performance of the PV/T collector. However, the overall efficacy of nanofluids is more difficult to estimate. The performance evaluation criterion (PEC) is an accurate way of estimating this performance. The PEC is the ratio of useful thermal power to the required pumping power and is determined by using Equation (37) [71]:

$$PEC = \frac{Q_u}{\dot{V} \Delta P} \quad (37)$$

$$\dot{V} = \frac{\dot{m}_{fluid}}{\rho} \quad (38)$$

4. Model Validation

An examination of the developed model is first checked against the retrieved real-site data from the Cyprus international university. The electrical efficiency retrieved is compared with the estimations calculated by the numerical model. The numerical calculation is made using the parameters of solar radiation, wind speed, and ambient temperature. The accuracy of the model is related to the degree of deviation of the numerical results from the measured on-site data. The deviation is calculated as the percentage difference between the electrical efficiency derived using the model described in the present study and the experimental results from the previous study used for validation. The efficiency results are compared for selected dates in a year at the same location. The maximum deviation of 2.05% (Figure 6) of numerically estimated values from the measured data is considered the proof of the accuracy of the model, and is therefore used in evaluating the performance of the nanofluid based PV/T system in this study.

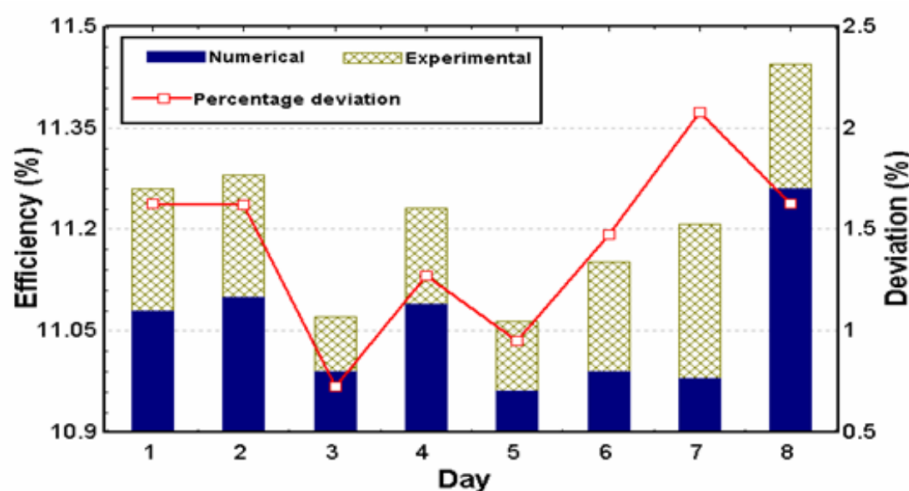


Figure 6. Model validation analysis.

5. Results and Discussion

This section gives detailed results and discussions of the performance of the PV/T collector with and without nanofluids. As explained in previous sections, the utilization of nanofluids as a heat transfer fluid in PV/T collectors has shown impressive enhancement of PV/T total equivalent electrical efficiency. This study will numerically show the extent of performance that can be measured when different ‘types’ of nanofluids are used. The nanofluids synthesized and utilized are a one particle nanofluid (Al_2O_3 , ZnO), a two-particle nanofluids (Al_2O_3 - ZnO), and a three-particle nanofluid (Al_2O_3 - ZnO - Fe_3O_4). The nanofluids were synthesized at a 1% volume concentration. This is important because it offers a suitable basis for the comparison of the performances of these different nanofluids. In investigating the PV/T system, measured solar-related data are used to model the solar system. Figure 7 shows the measured incident solar radiation and ambient temperature data for a typical summer period. Researchers have shown that the performance of PV systems is dependent on atmospheric conditions. A study by Sanusi et al. [72] explained the effect of ambient temperature on PV performance and prediction. Figure 7 shows that the maximum solar radiation and ambient temperature culled from the solar farm as used in this study is 928 W/m^2 and 32.9°C , respectively. The time frame considered was between 8 AM and 6 PM, as the performance of the system is to be analyzed across different periods of sun availability. A study by Al-Waeli et al. [73] concerning the analysis of PV/T systems considered the time frame of analysis from 8:25 AM to 5:41 PM.

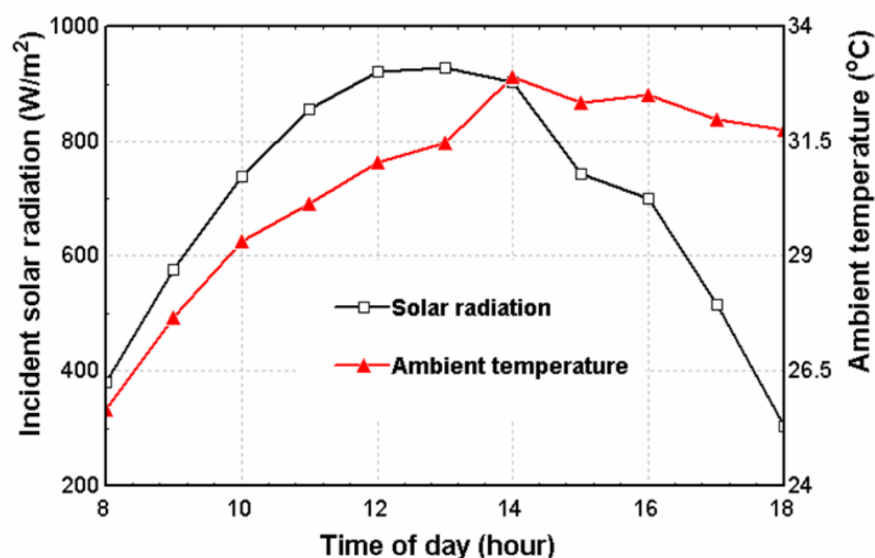


Figure 7. Meteorological data of solar farm used in this study.

The argument for cooling of PV systems is graphically represented in Figure 8. The optimum PV electrical efficiency of 13.11% was measured in the early hours of the morning. It is seen that the efficiency of the PV system drops from the early hours of the morning and gets to the lowest efficiency of 11.91% at 2 PM. It is noteworthy that at 2 PM the solar radiation peaks at 928 W/m². This trend is attributed to by the fact that above a threshold solar radiation hitting the solar cells, the part of solar energy not converted to electrical energy is then converted to heat [74,75], resulting in increased cell temperatures. This result is corroborated by an experimental study done by Moharram et al. [76], which showed that increasing cell temperatures beyond a certain range reduces the efficiency of the PV system.

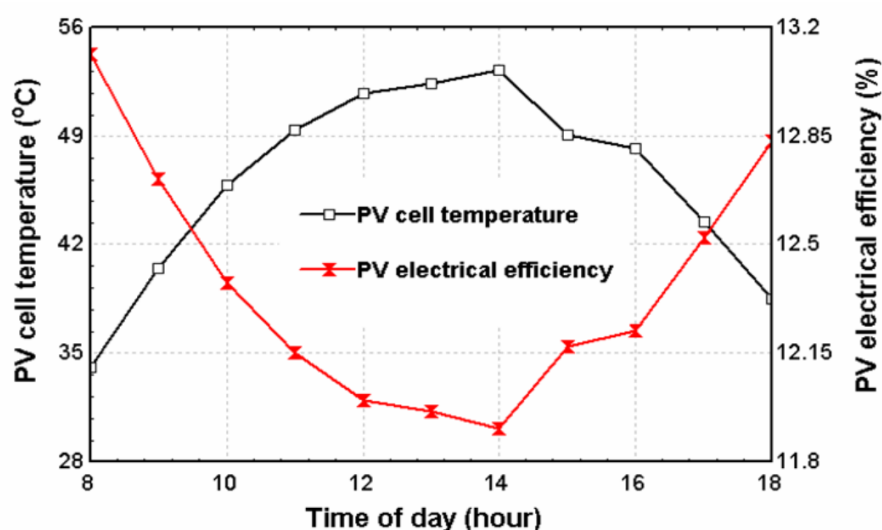


Figure 8. Numerical result of PV efficiency.

This result in Figure 8 necessitates the utilization of fluids for cooling PV systems, especially during high radiation periods of the day. Figures 9–18 will graphically show the effect of different factors involved in utilizing nanofluids to improve the efficiency of the system.

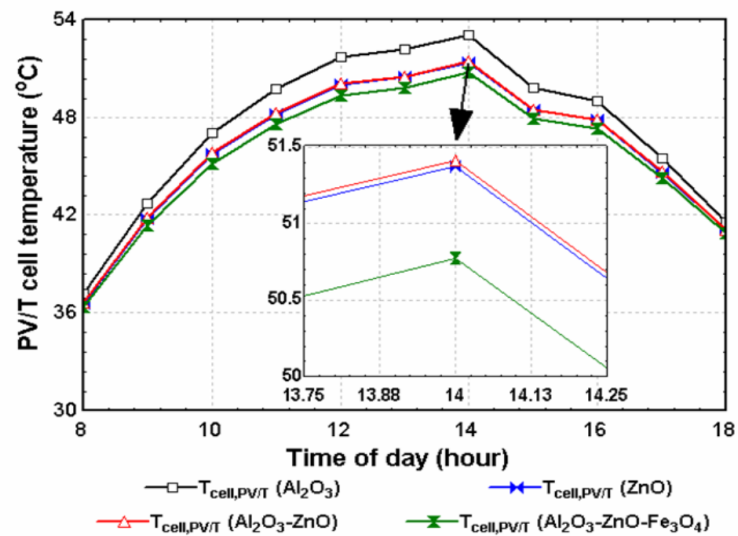


Figure 9. Numerical result of PV/T cell temperature.

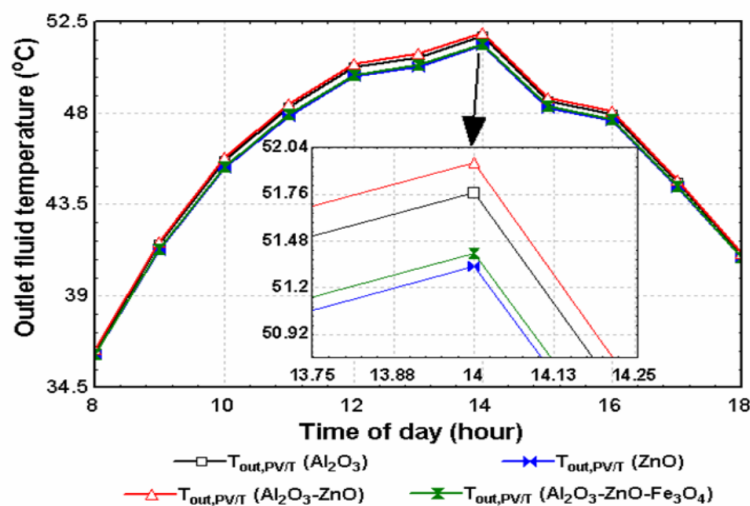


Figure 10. Numerical result of PV/T outlet temperature.

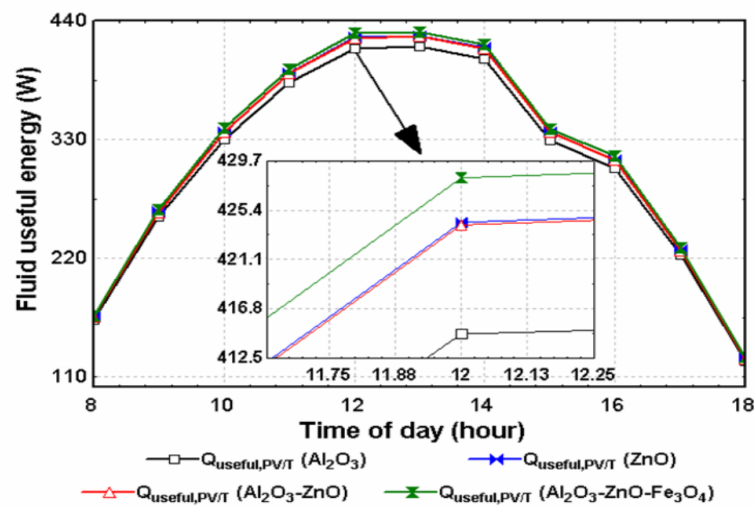


Figure 11. Numerical result of fluid useful energy of PV/T.

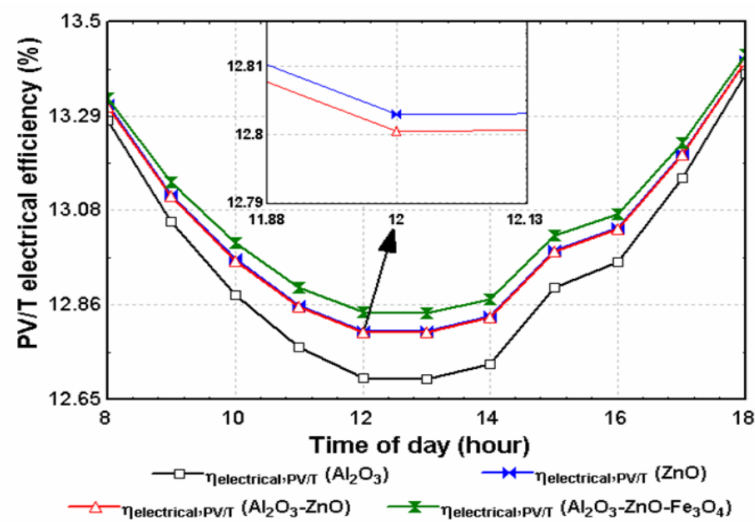


Figure 12. Electrical efficiency of PV/T system.

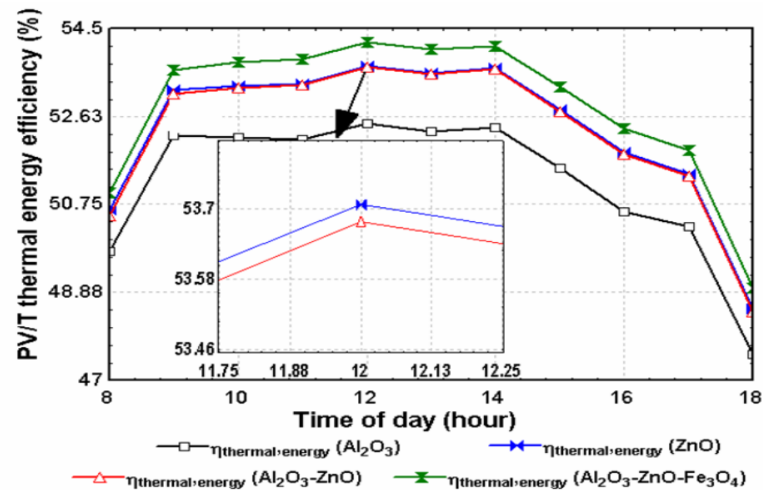


Figure 13. PV/T performance in thermal analysis.

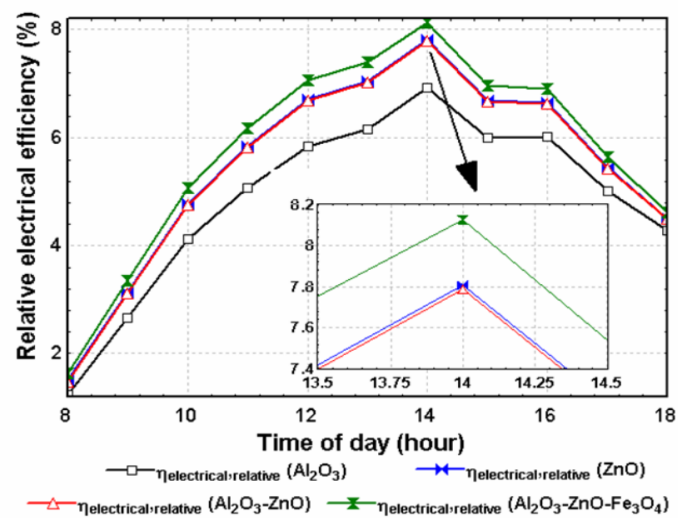


Figure 14. Relative electrical efficiency of PV/T system.

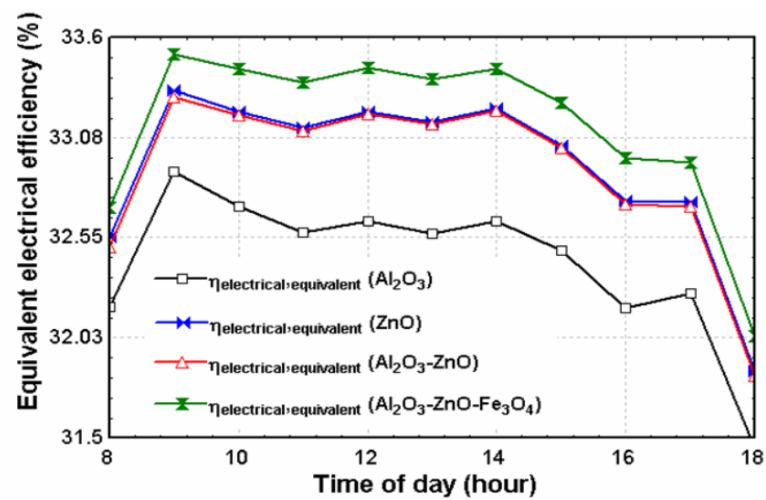


Figure 15. Equivalent electrical efficiency of PV/T system.

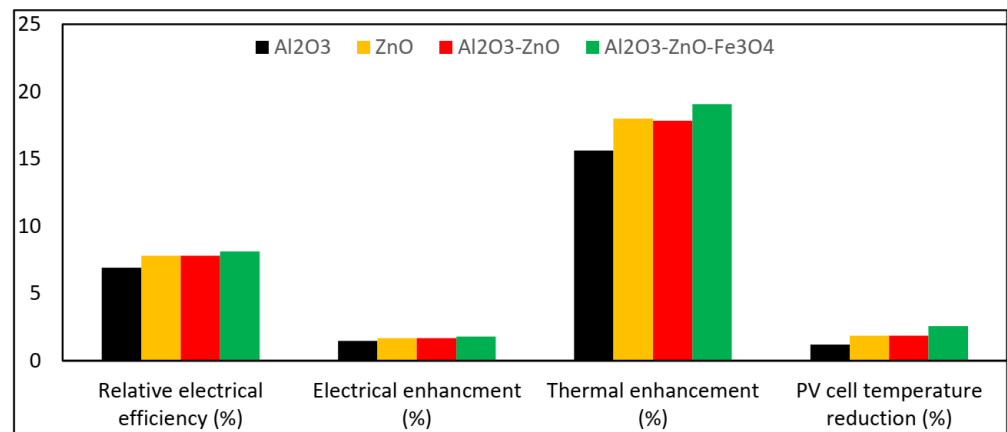


Figure 16. Comparative enhancement of different nanofluids considered.

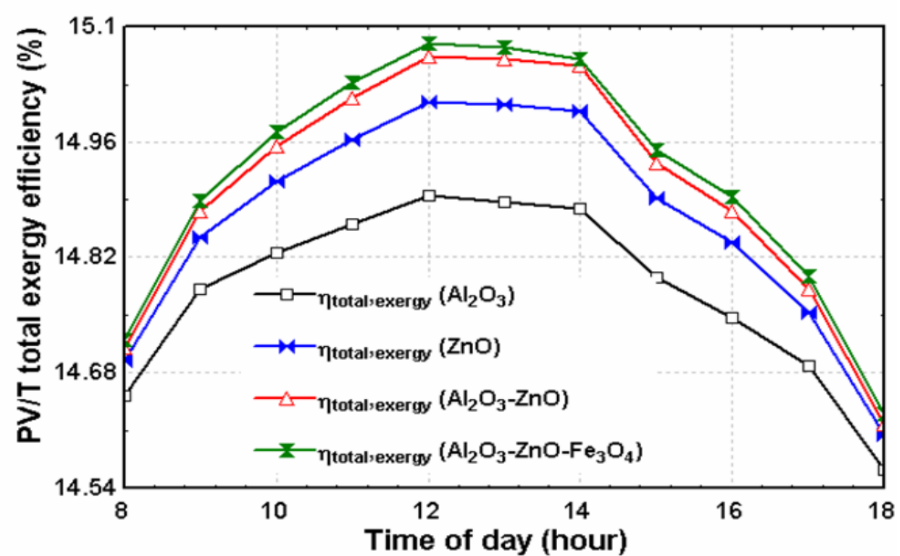


Figure 17. PV/T total exergy efficiency.

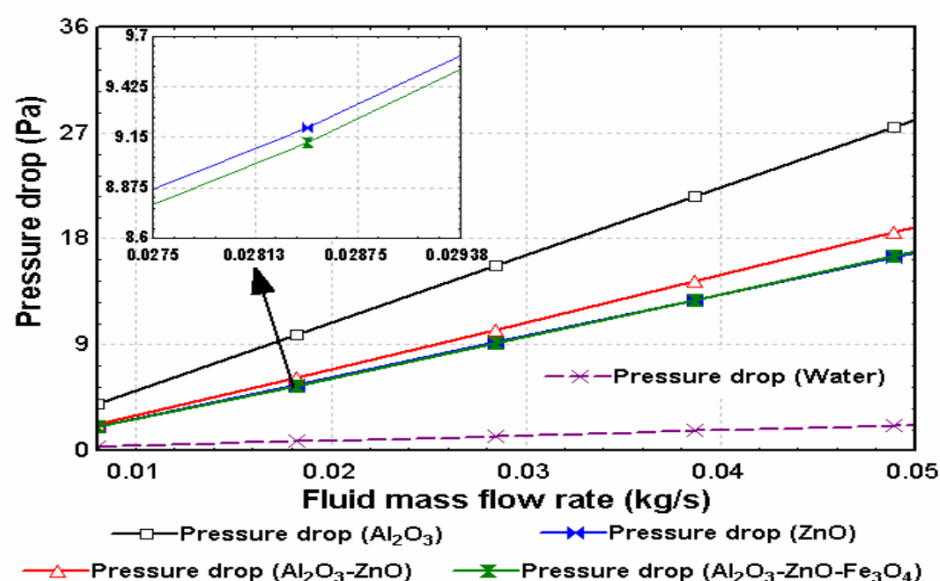


Figure 18. Pressure drop of heat transfer fluids.

The heat transfer fluids passed through the pipe for cooling of the PV systems absorb the excess heat and cool the PV system and this cooling ensures better efficiencies. Figure 9 shows that the PV cell temperature is consistent with the trend of the solar radiation across the day as shown in Figure 7. However, in comparison with the normal PV cell temperature without cooling, a reduction in PV cell temperature is noticed. The optimum PV cell reduction is recorded for the Al_2O_3 -ZnO- Fe_3O_4 ternary hybrid nanofluid. The PV cell temperature was reduced from 52.35°C to 49.79°C at 1 PM, which represents a 4.89% cell temperature reduction. The ZnO nanofluid is seen to perform better than the Al_2O_3 -ZnO hybrid nanofluid in reducing the cell temperature. This can be attributed to a better heat transfer property at the 1% volume concentration. The excellent performance of the ZnO nanofluid as a heat transfer fluid was shown in a study done by Mohammad et al. [26]. Their study, which investigated the utilization of metal oxides in nanofluids as HTF, showed that ZnO nanofluids outperformed the other fluids. Figure 10 presents the outlet fluid temperature of the nanofluids. The outlet fluid temperature is affected by the specific heat capacity of the HTF used. The result shows that at the volume fraction considered, the Al_2O_3 -ZnO nanofluids extracted more heat from the PV cells.

To be able to retrieve as much useful energy from solar radiation when using PV systems, thermal collectors are important [77]. Figure 11 shows that the highest useful thermal energy removal from the PV/T system was 429.8 W. This result is obtained when Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid was used as the HTF.

A major criterion to analyze how effective a PV or PV/T system operates is electrical efficiency. Figure 12 shows that an optimum PV/T electrical efficiency of 13.43% was retrieved using the Al_2O_3 -ZnO- Fe_3O_4 heat transfer fluid. This is a 4.68% enhancement as compared with the efficiency of the conventional PV system. The high performance of the ternary nanofluid is attributed to the hybridization effect of the fluid. At the same concentration, the synergistic effect of the nanoparticles gives better heat transfer properties. This explanation is corroborated by a study by Bellos and Christos [78] which investigated both mono and hybrid nanofluids for solar collector systems. Their study further explained that the better performance of the hybrid nanofluid is attributed to the higher Nusselt number compared to that for the mono nanofluid.

The thermal efficiency of the PV/T enhances the overall efficiency of the system. This is important because the heat absorbed by the heat transfer fluid can be used, for example as domestic hot water. Figure 13 shows the comparative result of the thermal energy efficiency of the PV/T using the different nanofluids considered. It is seen that an optimum thermal efficiency of 54.11% is retrieved when the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid is

used. The ZnO nanofluid records a thermal efficiency of 53.66%. This result is attributed to the better thermal conductivity of the ternary nanofluid. This is corroborated by a study done by Wole-Osho et al. [79]. The relative electrical efficiency, which is a metric of assessing the efficiency of the PV system as a function of the thermal system, is computed using Equation (22). The result shows an optimum relative electrical efficiency of 8.13% measured using the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid as HTF (Figure 14). Figure 15 shows the equivalent electrical efficiency of the PV/T system. The lowest efficiency was recorded using the Al_2O_3 nanofluid, while the optimum value of 33.44% was recorded using the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid. The ternary nanofluid outperformed the Al_2O_3 nanofluid by 2.48%. As explained earlier, the superior performance in the equivalent electrical efficiency of the PV/T system is due to the higher extraction of the residual heat in the PV panels by the ternary nanofluid, which also results in the higher thermal performance of the system.

Figure 16 shows the enhancements of the PV/T systems using the nanofluids. It is seen that the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid resulted in an enhancement of 1.79% and 19.06% in the electrical and thermal efficiencies, respectively.

To investigate the quality of the output energy of the system, the total exergy efficiency is usually analyzed [28] using Equation (24). Figure 17 shows that the optimum exergy efficiency of 15.08% was retrieved using Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid as HTF. The Al_2O_3 -ZnO hybrid nanofluid is relatively close in performance in comparison with the TNF, as its optimum total exergy efficiency recorded is 15.06%. Figure 17 explains the excellent heat transfer properties of hybrid nanofluids, which can be utilized in practical experimental works in cooling PV systems.

The hybridization effect of ternary hybrid nanofluid [80] is a novel method of generating a single fluid with good thermal and physical properties for convective heat transfer. The higher thermal conductivity of ternary hybrid nanofluid can be attributed to the presence of increased Brownian motion in the base fluid due to the presence of more varied nanoparticles. Furthermore, studies have shown that the arrangement of particles in the base fluids influences the thermophysical behavior of nanofluids [81]. The presence of different unique nanoparticles in the base fluid creates varied possibilities of effective nanoparticle arrangement for local heat transfer in the fluid. This reason is corroborated by a study done by Cakmak et al. [46], which synthesized a $\text{rgO-Fe}_3\text{O}_4\text{-TiO}_2$ ternary hybrid nanofluid. Their study showed that the thermal conductivity of the $\text{rgO-Fe}_3\text{O}_4\text{-TiO}_2$ ternary hybrid was higher than mono Fe_3O_4 , TiO_2 , and their corresponding hybrid nanofluids.

However, despite the impressive performance of nanofluids as HTFs, an important consideration needed to be made is the pressure drop and pump work associated with their usage. Pressure drop is a limitation of using nanofluids in practical applications [82]. Studies [83–85] have shown that the pressure drop increases with increasing viscosity of nanofluids, therefore, careful consideration of the volume fraction of nanoparticles in base fluids should be made. The pump work is affected by the pressure drop of fluids in the pipes [86].

Figure 18 shows that the pressure drop of Al_2O_3 -ZnO- Fe_3O_4 is the closest to the base fluid, with a value of 2.026 Pa at a mass flow rate of 0.008 kg/s. The greatest pressure drop is recorded for Al_2O_3 and Al_2O_3 -ZnO hybrid nanofluid. The pump work of the ZnO and Al_2O_3 -ZnO- Fe_3O_4 HTFs are relatively close. It is also shown (Figure 19) that the pressure drops and pump work increases as expected with increasing mass flow rate. The increase of pressure with a volumetric flow rate is corroborated by a study done by Eric et al. [87].

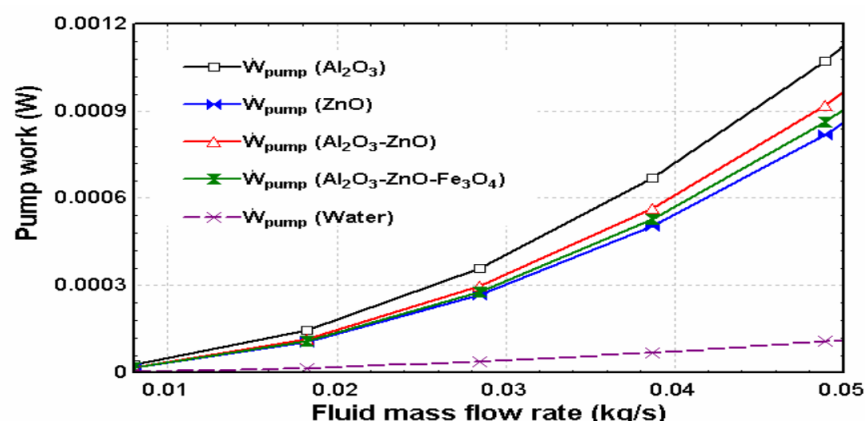


Figure 19. Pump work of heat transfer fluids.

For the economic viability of using nanofluids as heat transfer fluids, the useful heat transfer (heat rate removed from the cell) must be higher than the pumping power. The performance evaluation criterion (PEC) is a dimensionless number used to represent the heat transfer and hydraulic performance of thermal applications [88]. The PEC is computed using Equation (34). Figure 20 shows that the PEC decreases with an increased mass flow rate, which is attributed to the increasing Reynold number. The PEC for $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ decreased from 4.36×10^6 at 0.02 kg/s to 5.65×10^5 at 0.05 kg/s. It is also seen that as the mass flow rate increases, the difference between the PEC of water and the nanofluids decreased. There was an 86.7% reduction in PEC between water and the $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ at 0.02 kg/s and 0.05 kg/s. This result is corroborated by a study done by Parag et al. [89]. It is shown that the PEC value for ZnO and $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ nanofluids is closer to the PEC for water.

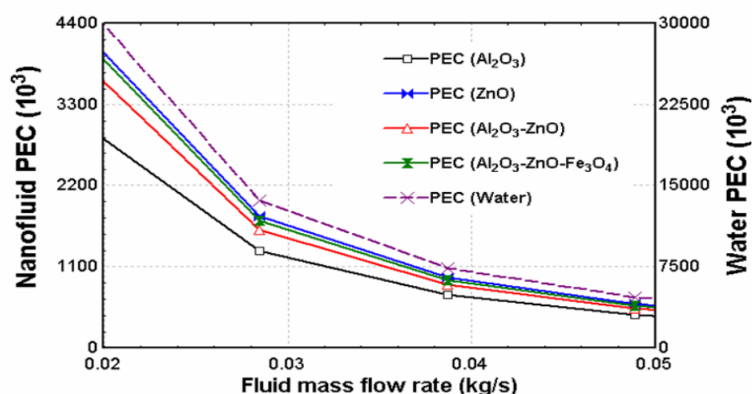


Figure 20. PEC of heat transfer fluids.

6. Conclusions

This paper gives a detailed energy and exergy analysis of the PV/T system utilizing mono, hybrid, and ternary nanofluids. In this study, the Al_2O_3 , ZnO, $\text{Al}_2\text{O}_3\text{-ZnO}$, and $\text{Al}_2\text{O}_3\text{-ZnO-Fe}_3\text{O}_4$ were synthesized at 1% volume concentration using the two-step method. Characterization and stability tests were carried out in the laboratory. The numerical model for estimating the PV/T performance was validated using meteorological data culled from the solar farm installed at Cyprus International University, Cyprus. Furthermore, the study comparatively analyzed the pressure drop, pump work, and performance evaluation criterion of the different nanofluids studied. The main findings of this study are:

- There is a performance enhancement of PV and PV/T systems when utilizing nanofluids as against conventional PV and water-based PV/T systems. This better perfor-

mance is tied to the excellent heat transfer coefficient of nanoparticles dispersed in base fluids.

- The Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid performed better than the other nanofluids. This is attributed to the hybridization effect of three particle nanofluids at the same volume concentration as other nanofluids.
- An optimum thermal efficiency of 54.11% is retrieved for the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid.
- The PEC for Al_2O_3 -ZnO- Fe_3O_4 decreased from 4.36×10^6 at 0.02 kg/s to 5.65×10^5 at 0.05 kg/s.
- There was an 86.7% reduction in PEC between water and the Al_2O_3 -ZnO- Fe_3O_4 at 0.02 kg/s and 0.05 kg/s.
- The optimum electrical and thermal enhancement recorded in this study was 1.79% and 19.06%.
- The least equivalent electrical efficiency was recorded using the Al_2O_3 nanofluid, while the optimum value of 33.44% was recorded using the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid.
- Optimum electrical, thermal, and exergy efficiencies of 13.43%, 54.11%, and 15.06%, respectively, were measured with the Al_2O_3 -ZnO- Fe_3O_4 ternary nanofluid based PV/T system.
- The study showed that despite the limitation of pressure drop and pumping power associated with nanofluid in thermal systems, the close PEC values as compared with water is a positive for practical utilization of nanofluid in PV/T systems.

The authors recommend that the economic effects of the nanoparticle and nanofluid synthesis as related to costs should be given more research interest. This would assist in the decision making and practical utilization of different nanofluids as cooling fluids in PV/T systems.

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