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Applications of Graphene Nanoplatelets as Working Fluids in Photovoltaic Thermal Systems: A Review

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ABSTRACT

The application of nanofluids, specifically graphene nanoplatelets, as a working fluid in photovoltaic thermal (PV/T) has attracted much attention due to the enhanced thermophysical properties of nanofluids compared to those of conventional working fluids. In comparison to traditional fluids, nanofluid is a potential heat transfer fluid that can significantly improve system efficiency. The nanoparticle's large surface area and small size result in an increased rate of heat transmission. This review addressed the use of graphene nanoplatelets (GNP) as a working fluid in PV/T systems. Incorporating GNP into PV/T systems can attain many advantages, including enhanced thermal conductivity and increased energy conversion efficiency. The review goes through the difficulties in synthesizing and characterizing GNP and the thermophysical properties of GNP. In addition, the review highlights the experimentation on the performance of PV/T systems in terms of thermal properties that use GNP as their working fluid. The integration of graphene nanoplatelets (GNP) as a working fluid in photovoltaic thermal (PV/T) systems holds immense promise for enhancing system efficiency and energy conversion rates. The demonstrated benefits of GNP, including its superior thermal conductivity and increased heat transmission efficiency, underscore its potential as a key component in advancing PV/T technology. The reviews concluded that the composition of 0.5 wt.% with a ratio of 1:1 to the surfactant shows the best formulation and can achieve good dispersion of the nanofluid.

Keywords: *Graphene, Nanofluid, Photovoltaic thermal, Surfactant*

1. INTRODUCTION

With the increasing demand for renewable energy and dependency on electrical power, solar energy is considered a top renewable energy source due to its simplicity, accessibility, and low cost [1]. The use of photovoltaic (PV) panels is one of the most prevalent methods for transforming solar energy into electricity [2]. A form of solar energy technology known as photovoltaic thermal (PV/T) systems combines photovoltaic (PV) and thermal energy conversion into a single system. By utilizing the heat produced by the PV cells in addition to turning sunlight into electricity, these systems can significantly increase the energy efficiency of solar power production. The PV/T efficiencies can be achieved in a range of 50 – 70% [3].

Recently, nanofluids have received much attention as the working fluid in PV/T systems due to their superior thermophysical properties compared to more traditional working fluids like water, oil, and air [4]. A study by Al-Shamani *et al.* [5] shows that the usage of several types of nanofluids leads to a higher efficiency of the PV compared to water. Although interest in using nanofluids as working fluids to enhance the performance of PV/T systems has grown over the past few years, more research is still needed in this field. There is a need to further optimize the properties of nanofluids for PV/T applications. This includes tailoring nanofluid compositions, nanoparticle sizes, concentrations, and surface modifications to achieve the most favorable thermal conductivity, stability, and compatibility with PV/T systems. Several studies have investigated the use of nanofluids in PV/T systems and have shown promising results. Madas et al. [6] and Murtadha [7] both found that using nanofluids as coolants in PV/T systems led to increased electrical efficiency and power output. Ensuring the long-term stability and reliability of nanofluids is crucial for practical applications. Research is required to assess the durability and performance of nanofluids over extended periods, accounting for factors such as nanoparticle agglomeration, sedimentation, and potential degradation under varying operational conditions [8], [9]. While nanofluids show promise in enhancing heat transfer and energy conversion efficiency in PV/T systems, there is a need for comprehensive studies that quantify and validate these enhancements under diverse operating conditions.

Understanding the mechanisms behind the improved performance will further guide optimization efforts. One recent study area that has generated interest is using graphene nanoplatelets as the working fluid in PV/T systems. Graphene nanoplatelets (GNP) are stacks of graphene sheets, which are two-dimensional materials made of carbon atoms organized in a hexagonal lattice [10].

GNP has potential advantages in PV/T systems, including improved thermal conductivity and energy transfer efficiency. GNP's superior thermal conductivity produces lower operating temperatures and higher electrical efficiency, allowing for more exceptional heat transfer between the solar cells and working fluid. According to Seki *et al.* [11], the system's thermal performance can be improved even further by using GNP, which can also thin the thermal boundary layer and lower the barrier to heat transmission.

Numerous studies have been conducted on the efficiency of PV/T systems using GNP as the working fluid, and the results are encouraging. More research is still needed to better understand the resilience and long-term performance of PV/T systems and enhance the synthesis and integration of GNP in these systems.

1.1. Overview of Nanofluids

The formation of nanofluids represents a relatively recent development in fluid science. In general, nanofluids are created by dispersing nanoparticles in a base fluid. Nanoparticles give these fluids unique characteristics like excellent thermal conductivity, better heat transfer coefficients, and improved stability [12]. Because of this, they have recently become a prominent research subject, and many studies have been carried out to comprehend their characteristics and possible uses.

To formulate a nanofluid, there are several methods that can be used, like the one-step and two-step methods. The synthesis or production of nanoparticles and their dispersion or addition into a base fluid are done simultaneously in a one-step method to formulate nanofluids [13]. These approaches aim to simplify the process by integrating nanoparticle manufacturing and dispersion into the fluid in a single step. Most researchers used the two-step method in formulating a nanofluid. One primary reason why the one-step method is less widely used compared to the two-step method is the control over the size, shape, and dispersion of nanoparticles. It is a challenge to achieve stability in colloidal suspensions [14]. Nanofluids are made of a base fluid and nanoparticles, and the stability of the nanofluid is crucial for its performance [15]. Different techniques, such as surfactant addition or surface modification, are suggested for enhancing the stability of nanofluids. However, the one-step method may not provide sufficient stability for the nanofluids, leading to agglomeration and sedimentation of the nanoparticles [16] which can limit the viability of the nanofluid for desired applications. Additionally, Younes *et al*. [17] stated that one-step methods might lead to variations in particle characteristics and distribution, impacting the overall performance of nanofluids. Therefore, a two-step method is often preferred for preparing nanofluids with improved stability. The two-step method often allows for more precise control and optimization of these factors, ensuring consistent stability and desired properties that can result in more stable nanofluids [18]. The complexity of the synthesis process and the need for reproducibility in many applications often favor the two-step method. In the two-step method, the nanoparticles are produced separately and suspended in a base fluid [18]. Figure 1 shows an overview of the two-step method for formulating a nanofluid.

Nanofluids have been extensively studied for their ability to improve heat transfer and thermal efficiency in various thermal systems. Nanofluids have the potential to revolutionize several fields, including cooling systems, refrigeration, and electronics. To fully achieve their potential, addressing the difficulties with their synthesis, stability, and cost is necessary. The synthesis and characteristics of nanofluids need to be optimized, and there is still work to be done to create efficient production techniques. Research has shown that adding nanoparticles to the working fluid can improve the thermophysical properties of nanofluids, leading to better heat transfer rates. A study by Aswad *et al.* [20] shows that the use of nanofluids can improve the heat transfer and thermal efficiency of PV/T by about 12%. Other than that, studies by Ray *et al.* [21] have demonstrated that nanofluids can significantly increase the heat transfer rate compared to traditional heat transfer fluids, even without considering the Reynolds number effect. It has also been discovered that adding nanofluids to heat exchangers enhances their functionality, making them more compact and effective for a variety of industrial uses [22]. Studies into the thermal enhancement of nanofluids in channel flows by Jbeili *et al.* [23] have shown that nanoparticles close to the wall raise the local heat flux and lower the local wall temperature, which raises the heat transfer coefficient. Experimental studies by Barai *et al.* [24] have also shown that nanofluids can improve the efficiency of heat pipes, with increased heat transfer coefficients and reduced thermal resistance. Overall, the use of nanofluids has shown enormous potential for enhancing heat transfer and thermal efficiency in various systems.

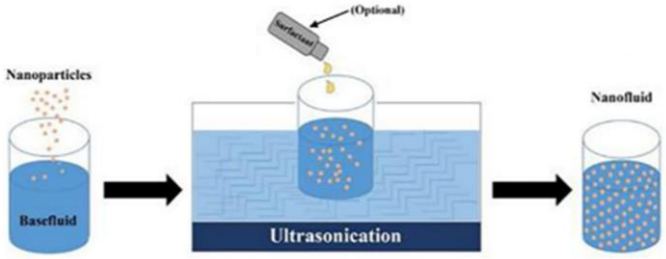

Figure 1. Overview of the two-step method [19]

1.2. Photovoltaic Thermal System (PV/T)

A photovoltaic thermal system is the combination of the technology of a photovoltaic system and a solar thermal system. In simple terms, the two separate systems' overall performance is improved by this hybrid technology [25]. According to Rosli *et al*. [26], the PV acts as a typical flat plate solar collector, absorbing sunlight and generating energy from the irradiance. The temperature increase of the PV cells is regrettably the biggest cause for concern because it can have a bad impact on electrical performance. Thus, lowering the temperature of the PV cells by removing extra heat via heat transfer fluids can increase electrical efficiency [27], [28].

In comparison to traditional fluids, nanofluid is a potential heat transfer fluid that can significantly improve system efficiency. The nanoparticle's large surface area and small size result in an increased rate of heat transmission. Due to this, it has lately acquired a new aspect for investigations to improve its thermal behavior for applications in the engineering field. Figure 2 shows the setup of the PV/T system studied by Rejeb *et al.* [29], where they discuss the numerical and experimental validation of a photovoltaic thermal (PV/T) nanofluid-based collector that also covers the electrical and thermal performances of the PV/T system using different types of nanofluid. Their studies compared the performance of PV/T using Al_2O_3 and Cu nanoparticles with different base fluids, which are pure water and ethylene glycol. The main findings of this study found that the use of pure water as a base fluid in PV/T collectors gives better performance compared to ethylene glycol. On top of that, the results of their studies show that the combination of Cu/water shows the best thermal and electrical efficiency compared to other combinations.

According to Said *et al.* [30], the top nanofluid-based optical filter can transmit 82% of the PV cells' intended spectrum. In terms of electrical efficiency, the separate channel system outperformed the double-pass design in concentrated systems by 8.6%. In the economics area, the study also demonstrates that nanotechnology lowers production costs as a result of adopting a low-temperature technique.

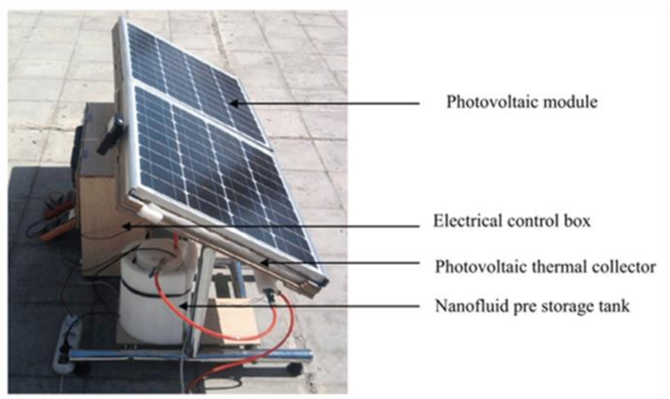

Figure 2. Experimental setup of the PV/T system [29]

Another factor that can influence the performance of the PV/T is the design of the collector tube. A study by *Rosli et al.* [31] stated that the heat transfer between the PV and serpentine collection absorber can be improved by using numerous tubes. The use of the F-Chart method can also be useful in aiding in the selection of the size and type of solar collector [32].

2. GRAPHENE AS NANOFLUIDS

Graphene nanoplatelets (GNP), as shown in Figure 3, are a type of graphene that is made of thin, platelet-shaped particles with a large surface area [33]. These materials are advantageous in a range of applications, including photovoltaic thermal (PV/T) systems, because of their distinctive thermal and electrical properties. The use of GNP as a working fluid in PV/T systems has attracted increasing attention in recent years, and several studies have explored their possible advantages.

It has been demonstrated that GNP are consequently better at transferring heat, allowing PV/T systems to operate at higher temperatures and achieve higher thermal efficiencies [34], [35]. The addition of GNP to the transfer fluid in PV/T collectors has been found to significantly increase the overall energy efficiency of the system [36]. In one study by Venkatesh *et al.* [37], the use of water-based graphene nanofluids improved the energy efficiency of PV/T systems by 13%. In addition to its thermal properties, GNP has good electrical conductivity; one study by Borode *et al.* [38] proved that the use of GNP/Fe_2O_3 hybrid nanofluids exhibited better electrical conductivity than water. In PV/T systems that integrate solar cells, the GNP can aid in releasing extra heat and reduce the risk of hotspots or thermal damage to the solar cells, which can be beneficial [39]. Additionally, the use of GNP in PV/T systems has been shown to reduce the temperature of the solar panel, further improving the system's efficiency [40].

Figure 3. Graphene nanoplatelets powder

With encouraging outcomes, several researchers have investigated the use of GNP as a working fluid in PV/T systems. For instance, a study by Alous *et al.* [41] examined how well a PV/T system performed when GNP was used as the working fluid. Compared to a traditional water-based system, the study discovered that the GNP increased the system's thermal efficiency by 22.1%. In a different study [36], the GNP's application in a PV/T system was examined, and the study discovered that, compared to a system that only used distilled water, the GNP increased the system's overall efficiency by 56.1%.

Besides the potential of using GNP as a working fluid in PV/T systems, several issues still must be resolved. One concern is the cost of generating GNP, which could reduce its commercial viability. Furthermore, there are still some concerns about the long-term stability and endurance of the GNP in PV/T systems.

2.1. Features and Qualities of GNP

Graphene nanoplatelets (GNP) have been extensively studied and found to be useful in a wide range of applications in the energy field. GNP can be used in a broad scale of applications, including energy storage, electronics, composites, coatings, and many more. They have been shown to enhance the efficiency of various energy storage and harvesting technologies, including supercapacitors, batteries, solar cells, and triboelectric nanogenerators [42] [43], [44], [45]. They can be used to increase the energy storage capacity of supercapacitors, enhance the power density of batteries, and improve the efficiency of solar cells. GNP's layered structure gives them a huge surface area, allowing for more outstanding performance and increased reactivity in various applications [46]. The high thermal and electrical conductivity, mechanical strength, and large surface area of the GNP make them ideal for improving the performance and stability of these energy-related applications. With a tensile strength that is more than 200 times stronger than steel, GNP is also incredibly strong and rigid [47]. Moreover, GNP is remarkably lightweight, making it perfect for lightweight composites [48]. GNP is very conductive, making it ideal for electronic and energy storage technology applications. Because it is highly thermally conductive, GNP is suitable for thermal management applications.

3. METHODOLOGY

3.1. Preparation of Graphene Nanoplatelets

The nanofluid preparation can be extremely important because it significantly affects the stability and qualities of the nanofluids, and as a result, extreme vigilance must be exercised. There are numerous methods that can be used to prepare GNP nanofluids, like the one-step and two-step methods. All the studies reviewed utilized the two-step method to formulate the nanofluids. The use of surfactant in formulating nanofluid is optional. Figure 4 shows an overview of the two-step method and procedure used to formulate the nanofluids. Basically, the mass/volume fraction or concentrations are calculated using the equation as stated in Eq. (1) [49].

$$\varphi = \left[\frac{\frac{w}{\rho_p}}{\frac{w}{\rho_p} + \frac{w_{bf}}{\rho_{bf}}} \right] \times 100 \quad (1)$$

In this equation, 'φ' is the concentration, 'w' is the weight of nanoparticles, 'ρ_p' is the density of nanoparticles, and 'w_{bf}' and 'ρ_{bf}' are the weight and density of the base fluid, respectively.

Generally, the two-step method is the most extensively utilized method in producing nanofluids [37], [50], [51], [52], [53]. The dry powder nanoparticles employed in this technology are made via chemical or physical procedures. The nano powder will then be homogenized and ultrasonically agitated before being dissolved in a fluid. This two-step method is the most cost-effective method to generate nanofluids on a large scale because techniques for the synthesis of nano powder have already been scaled up to levels of production that are commercially viable [54]. Given that high-surface-area nanoparticles tend to aggregate and agglomerate, the use of surfactants is being explored to increase the nanofluids' stability. It is important to formulate the nanofluid properly and carefully, as it will affect the thermophysical properties and later affect the PV/T's performance.

3.2. Characterization Analysis

To understand the characteristics, behavior, and possible uses of nanoparticles, it requires characterization studies. The characterization of nanoparticles is a critical step in formulating a nanofluid to improve the efficiency of the results needed. By giving thorough details about the nanoparticles' size, shape, composition, surface attributes, and behavior, characterization analysis enables researchers to comprehend and alter these characteristics. The thermophysical properties of a nanofluid are highly influenced by its morphology. As such, Ali [55] stated in his study that X-ray diffraction (XRD) helps to examine the crystallinity of the GNP and confirm the purity of the nanoparticles. It is due to the fact that materials such as metals, metal oxides, polymers, and semiconductors can all be found in nanoparticles. As shown in Figure 5, the XRD pattern of the highest peak (002) has shown that the pattern corresponds to graphene and supports the manufacturer's claim.

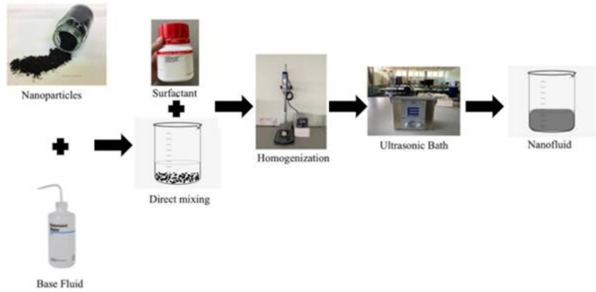

Figure 4. Two-step method procedure

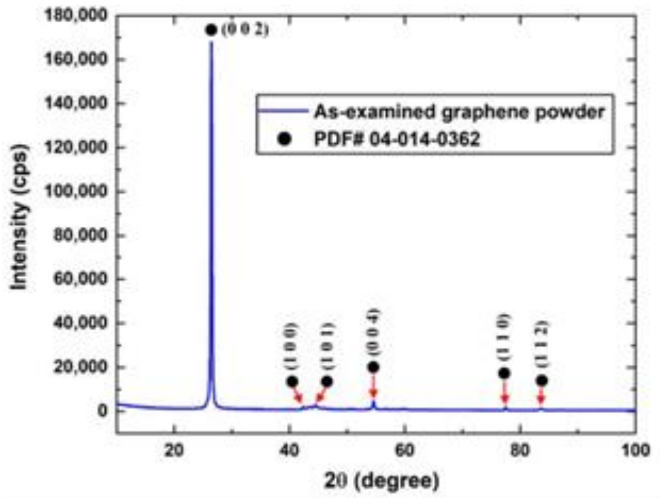

Figure 5. XRD analysis of the supplied graphene nanoplatelets [55]

While for Field Emission Scanning Electron Microscopy (FESEM), it is to show that the nanomaterial used has platelets with a morphological shape [56]. The surface of whole or fractioned objects can be visualized using a FESEM to show extremely tiny topographic characteristics. As shown in Figure 6, Ahmadi *et al.* [57] found that the morphology and form of nanoparticles are visible in the FESEM images of GNP.

FESEM can demonstrate whether the particles have a certain shape, such as a sphere, a rod, a plate, or another shape. Nanoparticle shape is significant because it influences both their physical and chemical characteristics. For instance, compared to spherical nanoparticles, elongated nanoparticles may display distinct optical or electrical behaviors [58].

By using characterization approaches, it enables researchers to customize nanoparticles' characteristics, improve their functionality, and guarantee their safety in a variety of disciplines by giving them extensive information on their size, shape, composition, surface qualities, and stability.

3.3. Stability of Graphene Nanoplatelets

One major issue that is always related to nanofluid is the high potential of the nanoparticles to agglomerate and sediment. It is due to the nature of the nanoparticles that the concentration of the nanoparticles in the base fluid is highly affecting the stability of the nanofluid. The stability of the nanofluid can be achieved by different methods.

In this section, the stability of GNP is reviewed. The key issues in formulating graphene nanofluid are the nanomaterial's stability and successful dispersion in the base fluid. Due to the fact that graphene is hydrophobic, stability becomes a significant issue. To achieve thermal conductivity in the nanomaterial, the size and quantity of layers are crucial. The nanofluids always tend to aggregate and agglomerate because of the large surface area of the

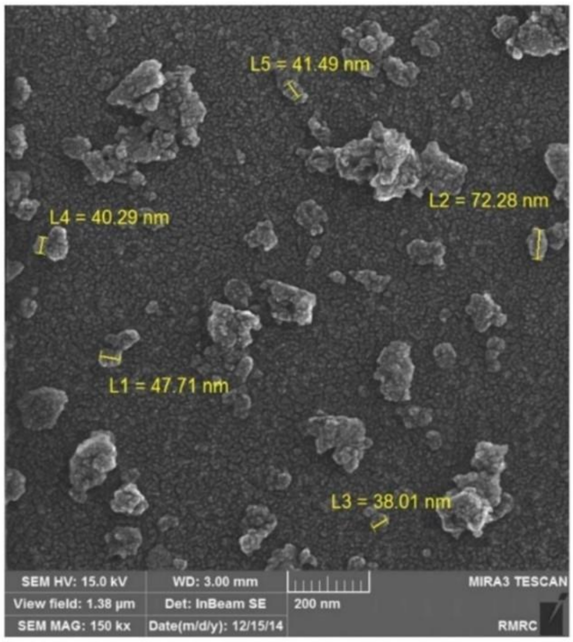

Figure 6. FESEM image of graphene nanoplatelets. [57]

nanoparticles [59]. The addition of surfactants can improve the stability of nanofluids and prevent nanoparticle agglomeration [60]. Surfactants play a critical role in increasing nanofluid dispersion by reducing surface tension and preventing agglomeration [61]. The choice of surfactant depends on the specific properties of the nanoparticles and the liquid medium. The surfactant should be compatible with the nanoparticles and the liquid, as well as be able to form a stable adsorption layer on the particle surface.

Besides maintaining stability, surfactants can aid in enhancing the dispersion and homogeneity of nanoparticles in the fluid, which can enhance performance in various applications, particularly PV/T systems. The summary of surfactants used in previous studies is shown in Table 1. In the context of graphene nanoplatelets, the surfactant can aid in maintaining stability by adsorbing onto the GNP surface, forming a stabilizing layer that hinders particle attraction and allows for improved dispersion in the formulation [62]. Depending on the surfactant mechanism, different surfactant types can affect GNP dispersion in different ways. Surfactants have hydrophilic and hydrophobic regions that enable them to adsorb onto GNP surfaces [63]. Besides, according to a study by Abedi *et al.* [64], surfactants can also influence the electronic, thermal, and mechanical properties of GNP. Some surfactants may also alter the electronic structure of GNP, impacting its conductivity.

4. RESULTS AND DISCUSSION

4.1. Thermophysical Properties of GNP

The addition of nanoparticles to the base fluid will alter the thermophysical properties of the nanofluids, making them superior. As discussed in the previous section, it is

Table 1. Surfactants used in previous studies

Surfactant	Duration of Observation	Stability test method	References
SDS	45 days	UV-Vis	[55]
SDS	72 hours	Sedimentation analysis	[65]
SDC	Not stated	Zeta Potential Distribution	[37]
SDBS	Not stated	Sedimentation method	[66]
SDBS SDS CTAB GA	60 days	UV-Vis Zeta potential TEM	[67]
SDC	30 days	Not stated	[68]
WRA	1 month	Sedimentation	[69]
SDC	15 days	Zeta potential analysis	[70]

extremely important to carefully formulate the nanofluid, as it will affect the thermophysical properties and later impact the performance of the PV/T. The most important thermophysical properties that have always been discussed in other studies are thermal conductivity, viscosity, density, and specific heat capacity. Table 2 summarizes the thermophysical properties of GNP from past research.

In general, a higher thermal conductivity provides a better thermal effect. A material with a higher thermal conductivity will transmit heat more effectively. This practically translates to the material's ability to absorb and transfer heat quickly, improving thermal effects [71]. This efficiency is crucial, as materials with higher thermal conductivity can transfer heat more rapidly [37]. This is critical in situations where efficient heat dissipation is required, such as in thermal management systems. Other than that, higher thermal conductivity helps achieve more uniform temperatures across a material [72]. Moreover, it also leads to improved energy efficiency, where efficient heat transfer reduces the need for excessive heating or cooling [73], [74]. It also contributes to better cooling performance, as the use of nanofluids in PV/T systems is intended to aid in better cooling techniques. Ahmadi *et al.* [57] found that increasing the GNP mass fraction by up to 0.2 wt% could increase thermal conductivity by 38.63%. In two studies, GNP's thermal conductivity showed the same result, where it achieved up to 5000 W/mK [41], [75]. While a study by Alshikhi *et al*. [36] shows a result of 1.1755 W/mK for thermal conductivity.

The viscosity of a nanofluid is a measurement of the suspension's tendency to resist flow, which influences the convective heat transfer coefficient [76]. Viscosity plays a major part in determining the heat transfer properties of the fluid [77]. As a result, the addition of 0.1 wt.% GNP produces an excellent result, with a 44% increase in viscosity compared to the base fluid. There is also an increment of 15.65% when the volume is 0.01% at room temperature. While in another study [57], the viscosity of the GNP increased by 7.52%.

4.2. Experimentation on the Thermal Performance of PV/T Systems Utilizing GNP

Experimental studies have been conducted to investigate the thermal performance of the PV/T systems utilizing the GNPs and are reviewed in this section. Mahamude *et al.* [75] stated that the thermal conductivity of the GNP increases by 17%, and the viscosity is also enhanced by about 50%. The heat transmission capability of the graphene nanofluids is enhanced by their greater surface area and volume production. Table 3 summarizes previous research on the thermal performance of PV/T systems using GNP as a working fluid.

4.3. Applications of GNP in PV/T

Numerous studies have been done on the performance of photovoltaic thermal (PV/T) systems that use GNP as the working fluid. In one study, Taheri *et al.* [80] compared the performance of PV/T using nanofluids with and without a transparent glass cover. According to the research, using GNP as the working fluid in a PV/T system led to a 22.65% boost in overall efficiency when compared to a system that used only deionized water. GNP's enhanced thermal conductivity enabled the working fluid to transfer heat from the solar cells more effectively, lowering running temperatures and raising electrical efficiency. Another study done by Huq *et al.* [81] showed that the thermal performance of a PV/T system was enhanced by using GNP as the working fluid by lowering thermal resistance at the working fluid-solar cell interface. As a result, the heat removal rate went up, increasing the system's thermal efficiency. Alshikhi *et al.* [36] also proved that GNP's results are better than those of hybrid nanofluid and distilled water because it has better thermal and overall efficiency, which increased by about 7.3% and 7.7%, respectively.

A study by Ali [55] focuses on the thermophysical properties and dispersion stability of graphene-based nanofluids, focusing on the influence of nanomaterial concentrations and surfactant ratios. The study shows that using a low concentration of surfactant demonstrated

Table 2. Summary of thermophysical properties of GNP

Base Fluid	Surfactant	Thermal Conductivity (W/mK)	Viscosity (mPa.s)	Density, (kg/m³)	Specific Heat Capacity (kJ/kg.K)	References
Water	-	1.1755	-	1259.5	2803	[36]
Deionized water	SDS	2.2	1.03	995	3400	[55]
Ethylene glycol	SDC	0.313	-	-	-	[70]
Water	SDC	0.716	-	-	-	[70]
Deionized water	-	0.69	-	-	-	[78]

Table 3. Summary of PV/T thermal performance utilizing GNP as nanofluid

Base Fluid	Concentration	Surfactant	Findings	References
Distilled water	0.5 wt.%	No surfactant	GNP shows superior thermal efficiency with overall efficiency of 56.1% compared to distilled water and hybrid nanofluid	[36]
Water	0.01 wt.% 0.02 wt.%	No surfactant	Thermal efficiency of PV/T increase up to 18.87%	[57]
Water	0.1 vol% 0.2 vol% 0.3 vol%	SDC	The efficiency of PV/T improved significantly which is 85% for 0.085 kg/s at 0.3 vol%	[37]
DI/EG	0.05 wt.%	No surfactant	Thermal conductivity of GNP increases by 17% and leads to improved heat transfer capacity due to higher surface area	[75]
DI Water	0.005 – 0.5 vol%	No surfactant	The maximum efficiency achieved by using GNP is 93.24% at mass flow rate of 0.015 kg/s	[79]
Water	0.025 wt.% 0.5 wt.% 0.075 wt.% 0.1 wt.%	No surfactant	The maximum efficiency achieved by the collector is 90.7% at 1.5 L/min with 0.1 wt.% of GNP	[50]

short-term stabilization capability, while a 1:1 weight ratio of graphene to surfactant and higher caused the dispersion to be physically stable for 45 consecutive days.

Moreover, researchers have demonstrated that using GNP in PV/T systems can enhance the mechanical properties of the working fluid, such as viscosity and shear strength [57], [75], [82]. Based on the studies, this can reduce the pumping power required to circulate the fluid, resulting in improved flow stability and reduced energy consumption.

In general, using GNP as a working fluid in PV/T systems has shown encouraging results in terms of enhancing system performance and reducing system size and weight. However, more investigation is required to improve the synthesis and incorporation of GNP in PV/T systems and to comprehend the durability and long-term performance of these systems.

4.4. Discussion

Despite the potential applications of nanofluids, particularly for GNP, their use is still limited due to several challenges. The main challenge of using graphene as a nanofluid is the sonication of graphene. It is also quite a challenge to maintain the ideal thermophysical properties to achieve the needed heat transfer rate to increase thermal efficiency. Suitable surfactants must be chosen to create effective nanofluids [75].

Due to various circumstances, the synthesis and characterization of GNP can be challenging. Primarily, the need for exact control of the reaction parameters, such as temperature, pressure, and precursor materials, makes it challenging to synthesize high-quality GNP. The final nanofluid's quality can also be influenced by the quality of the starting materials, the reaction duration, and the kind of surfactant employed.

Furthermore, advanced methods like high-resolution transmission electron microscopy (HRTEM), Raman spectroscopy, Fourier transform infrared (FTIR), and atomic force microscopy (AFM) are needed for characterizing GNP. On the other side, particle size analysis is also important to be done, as it can confirm the particle size of the nanoparticles before formulating them into nanofluids. There are not many results on particle size analysis, as it is rarely done by researchers.

Additionally, GNP can simply aggregate and agglomerate due to its large surface area and strong van der Waals forces within the layers [83]. As a result, it may be difficult to characterize them and determine how this affects their characteristics.

GNP can also be contaminated during the synthesis process, which can affect their properties and make characterization challenging. It can be challenging to remove impurities and control the composition of the final product. The properties of GNP can vary depending on their size, shape, number of layers, and quality. This variability can make it difficult to achieve consistent results, especially in large-scale production.

Overall, the synthesis and characterization of GNP can present some challenges, but with proper techniques and equipment, these difficulties can be overcome. Advances in synthesis and characterization techniques can lead to improved quality, consistency, and control of GNP for a range of applications.

5. CONCLUSION

This paper presents an overview of the utilization of GNP in PV/T systems and the recent works carried out on solar energy systems. The use of GNP as the working fluid in PV/T systems is by far showing a good result. The literature shows that most of the research is focusing on thermal aspects, specifically thermal conductivity, and heat transfer enhancements. There are several conclusions that can be drawn from this review:

- The characterization of GNP, such as XRD, SEM, FESEM, and particle size analysis, are crucial to be examined as they influence the results of the formulated nanofluid and later will affect the efficiency of the PV/T.
- The best solution for nanofluid is 0.5 wt% GNP-DI water.
- The use of deionized water as a base fluid results in better nanofluid mixing and stability.
- The best mixing method for nanofluids has proven to be the two-step method.
- The use of SDS as a surfactant in a ratio of 1:1 with graphene can achieve a good dispersion of nanofluid.
- The stability of the nanofluids played a significant role in the nanofluid formulation to ensure a good mixing of nanofluids.
- The thermophysical properties of the nanofluids are highly influenced by their particle morphology.
- The use of GNP in PV/T has been proven to enhance the efficiency and performance of PV/T up to 22.65%.

In general, intensive research and development is being done to improve the use of GNP as a working fluid in PV/T systems, and the results thus far are encouraging. More research will be required to fully comprehend the possible advantages and restrictions of this strategy, as well as some of the necessary technological and financial obstacles.

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