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Enhancement the Performance of FPSC by Utilizing Hybrid Nanofluids - An Extended Review

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ABSTRACT

Common ordinary fluids including water, glycol, and oils are extensively employed in solar thermal applications. However, because of their poor thermal performance and limited thermal conductivity, these fluids limit heat transfer. Hybrid nanofluids have proven themselves as a new and highly useful alternative because of their enhanced thermophysical characteristics in solar thermal applications. Recently, the focus in studies on hybrid nanofluids have increased as a continuation of the study of mono nanofluids. An extensive analysis of hybrid nanofluids research is presented in this review. This review focuses on the methods by which hybrid nanofluids is prepared as well as techniques to improve stability. Numerous studies have examined how hybrid nanoparticles affect thermophysical characteristics as density, viscosity, specific heat, and thermal conductivity. In this review, hybrid nanofluids were investigated as operating fluid in flat plate solar collector by a thorough examination of numerous theoretical, computational, and experimental research. The main objective of HNF application is to increase thermal efficiency. Ultimately, issues and limitations were covered, and suggestions for further research were provided. The results of the studies showed that water is the most suitable base liquid for use compared to other types of base liquids. As for nanoparticles, MWCNT and h-BN when mixed with metal oxides such as TiO_2 and Al_2O_3 are the most suitable for use.

1. INTRODUCTION

With the high rate of population increase in the world and with the high demand for energy use in all areas of life. So, it became necessary to develop energy resources. The energy currently produced is (80%) of conventional fuels and this has adverse effects on the climate by increasing carbon in the atmosphere [1]. Since these sources are non-permanent and are expected to run out in the long term, it has become necessary to rely on clean energy sources and reduce the disadvantages of using fossil energy fuels [2]. To reduce the disadvantage of conventional fuels, it is advised to employ clean energy sources like solar-energy. Natural resource-based clean energy sources include solar, wind, tidal, and wave energy due to its greater availability and ease of use. Solar-energy is one of the most significant alternative energy sources. Solar-energy is currently in vogue for usage in daily life; the most popular application is for H_2O heating. However, there are numerous obstacles to solar-energy, the most significant being heat storage [3]. Solar-energy, also known as solar radiation and heat, is one of the most important sources of pure, free, limitless, clean energy available today that has no environmental impact. About 1.8×10^{11} MW of solar radiation is intercepted by the globe. There is enough energy produced by the sun every 20 minutes to sustain life on Earth, but only around 30% of that energy ever reaches the planet [4]. When it comes to both cost and environmental impact, solar thermal energy is among the best. Solar collector technology transforms thermal energy from solar radiation into thermal energy [5]. One of the most popular kinds of solar collectors is the FPSC, which gathers solar thermal energy and transforms it into operating fluid [6]. This type of solar collector distinguishes over other types is the cost of its production and its ability to collect solar radiation without the need for solar radiation tracking equipment [6]. The goal of researchers in the past years was to develop this technology by increasing its efficiency by improving the collector's performance, as well as quickening the flow of heat between operating fluids and pipelines. The collector's form, coating, absorber design, flow turbulences, porous media, and the use of nanofluids all work out efficient ways to increase the collector's performance [7].

The dispersion of nanofluids in the base liquid leads to an improvement in the thermal characteristics of the operating fluid [8]. An important thermal property that is greatly improved is the operating fluid's thermal conductivity due to many influencing factors [9]. An adverse factor in the addition of nanomaterials is increased viscosity, which requires high pumping energy as well as a reduction in the capacity to transmit heat [9]. To keep an appropriate heat transfer rate, nanofluids must be pumped slowly. Therefore, it is necessary to ascertain the optimal concentration of highly thermally conductible, low-viscosity NPs [9]. However, stability is one of the fundamental prerequisites for using nanofluids in applications of heat transfer. Since stability has a major impact on thermal conductivity, it is thought to be the most critical influencing element [10]. Agglomerations brought on by van der Waals forces are one of the elements affecting the stability of nanofluids, and as a result of these agglomerations, the thermal conductivity starts to decline. Many researchers are using nanofluids in solar collector heat transfer applications as a result of their improved thermal characteristics [9].

In this review, HNF preparation and characterization techniques were the main topics of a thorough assessment of literature pertaining to the subject. In addition to theoretical and experimental research, which was one of the primary justifications for using HNFs in FPSCs, the impact of incorporating hybrid nanomaterials on thermophysical characteristics, thermal conductivity, viscosity, specific heat, and density was examined. In the last part, challenges, conclusions and future recommendations were discussed, it is worth noting that (90%) of the articles reviewed were in the last six years.

2. HYBRID NANOFLUID

Subsequently, a new type of fluid called HNFs was introduced. HNFs are the focus of multiple recent studies as an extension of nanofluids research. HNFs are produced by distributing two or more NPs in the base liquid in a composite or mixed form the study [11]. A number of methods were suggested for the production of hybrid NPs, including in situ, thermochemical, mechanical alloying, ball milling, wet chemical, solvothermal, and chemical vapor deposition [12]. The NPs most commonly used in flat solar collectors Al_2O_3, SiO_2, CuO, TiO_2, MWCNTs, GNPs, while H_2O, EG, oil and molten salt are used as base liquids.

2.1 Hybrid nanofluid preparation

A HNF is produced when two or more different types of NPs are combined in a base liquid under the correct conditions. Figure 1 shows most of the NPs used in the preparation of a HNF. The agglomeration of NPs resulting from sinking due to gravity is a fundamental problem that may lead to a reduction in the improvement of properties as well as clogging of pipes and valves, and hence careful preparation of the nanofluid is necessary to prevent these agglomerates.

Preparation process for a HNF is usually done in one of two ways, both the 1-step and 2-step methods. In the 1-step method of producing and suspending NPs in the base fluid synchronously, this process stabilizes and inhibits the formation of oxides and assemblies more successfully [13]. The laborious procedures with this system, such as storage, drying and mixing processes are by passed. Both the 1-step and 2-step methods are shown in Figure 2. However, the most popular technique that researchers employ to prepare nanomaterials is the 2-step procedure, initially the NPs are prepared in the form of a dry powder that is done using chemical or mechanical procedures, then the dry powder is suspended using ultrasonic in either EG or H_2O, the base liquid. The 2-step process is commonly used, yet it has the drawback of causing particles to aggregate due to high Van der Waals forces before they are distributed in the base liquid. This causes particles to deposit in the liquid, which lowers heat conductivity. Many physical and chemical methods have been used to solve this problem, including ultrasound, the use of surfactants, and pH modifications [14].

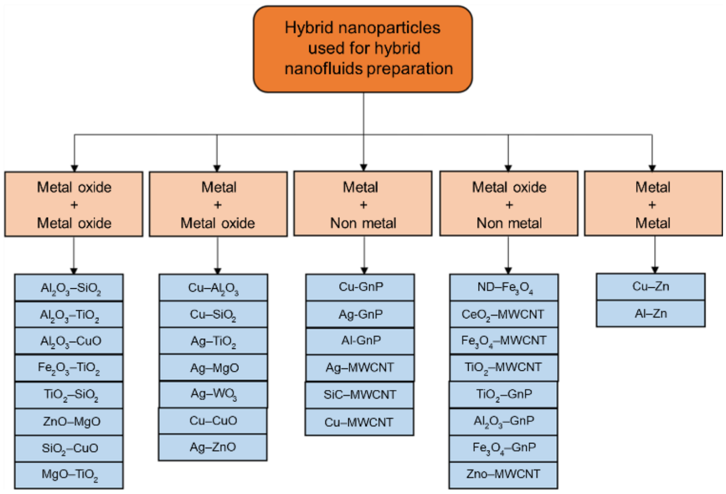

Figure 1. Categorization of NPs utilized in the production of HNFs [15]

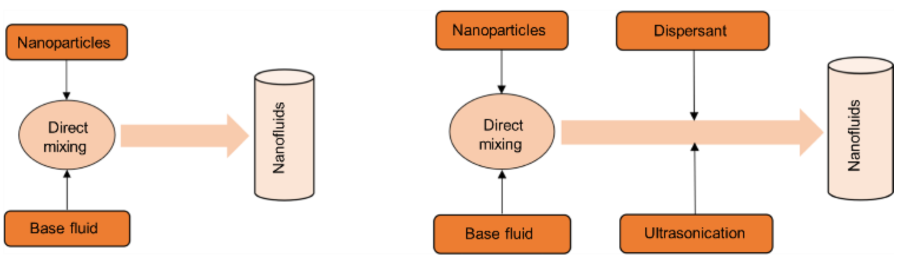

Figure 2. 1-step and 2-step preparation procedure illustration [15]

The following section presents a taxonomy of hybrid NPs used in the synthesis and processing of HNFs.

2.1.1 Metal oxide + Metal oxide

The 2-step method of assembling and preparing a hybrid Al_2O_3-SiO_2/H_2O. The Al_2O_3 and SiO_2 at (0.01%) were distributed in 1000 milliliters of H_2O only, and the mixing-ratio between the particles was (50:50). The colloidal particles are first stirred for a duration of six hours at 50°C in a magnetic stirring [16]. Then homogenization is done by a homogenizer to cause turbulence.

In a related study [17], Al_2O_3 NPs and SiO_2 are prepared independently utilizing a volumetric proportion of (0.5%) distributed in the synthesis of (60:40), H_2O/green bio-glycol as bases fluids. These processes are explored in the synthesis and preparation of Al_2O_3- SiO_2 HNFs. Because of the fact that the Al_2O_3 NPs and SiO_2 show distinctive physical phases, the method of their preparation was also distinct, three hours were spent sonicating the HNFs, which had four different mixing-ratios produced: 10:90, 30:70, 50:50, and 70:30. Preparation of HNFs of TiO_2-Al_2O_3 with the use of H_2O as the base fluid, and achieving this through a 2-step process, in this study, the different mixing ratios used for Al_2O_3 and TiO_2 were (20:80), (40:60), (50:50), (60:40) and (80:20). First, the NPs were mechanically stirred for two hours while suspended in the H_2O, after which ultrasound technology was used to maintain a volume concentration of 0.1% [18]. HNFs studied Al_2O_3-CuO, Al_2O_3-TiO_2 based on H_2O using the 2-step method [19]. The optimal ratio chosen in this study was (80:20) (Al_2O_3/TiO_2 and Al_2O_3/CuO). Another study conducted for HNFs by Zhang et al. [20] where Al_2O_3-CuO were prepared and added to distilled H_2O, and magnetic stirring was performed at 2000 rpm for one hour. The NPs were then suspended in the distilled H_2O evenly as this led to the formation of HNF with different mass concentrations. Abbas et al. [21] studied Fe_2O_3 coated TiO_2 NPs were created via hydrothermal reduction, and then HNFs were created utilizing the ultrasonic acoustic cavitation method. Synthesis and production of nanofluid from Fe_2O_3-TiO_2/H_2O. The HNF TiO_2-SiO_2/green bio-glycol was made using the 2-step process presented by Zainon and Azmi [22]. HNF was first prepared at volumetric fractions of (0.5-3%), then the NPs were mixed with a ratio of (20:80) (TiO_2/SiO_2) and then added to the green bio-glycol base liquid. Vidhya et al. [23] studied Synthesis and preparation of HNF MgO and ZnO to H_2O and EG using combined and sol–gel method. Where the ratio of mixing of NPs was equal in a mixture of H_2O and EG (60:40) to form HNF of MgO and ZnO. Akilu et al. [24] studied preparing HNF from SiO_2-CuO/C HNF in two steps, where in the beginning CuO powder to carbon was created using solvothermal methods SiO_2-CuO/C synthesis in a mixing-ratio of (80:20) (mass ratio) was investigated using the ultrasonic assisted wet mixing method, applying the methodology demonstrated in the study of Li et al. [25]. Subsequently, the NPs were suspended in EG and base glycerol at a mass ratio of 60:40 to generate HNF SiO_2-CuO oxide to carbon.

2.1.2 Metal + Metal oxide

HNF Al_2O_3-Cu was produced in 2-step and added to H_2O at varying volumetric concentrations (0.3-1.5%). Al_2O_3 NPs were used in sizes of 20, 30 and 50 nm, the mixing-ratio was (80:20) (Al_2O_3/Cu), and in the same way, the Al_2O_3-Cu HNF was prepared at a concentration of (0.1-2%) by dispersing the NPs in pure H_2O [26]. Amiri et al. [27] studied Synthesis and preparation of SiO_2-Cu in base liquids such as EG and H_2O. Using the Stöber procedure, SiO_2 particles were created by hydrolyzing and condensing tetraethyl orthosilicate (TEOS) over the course of around two hours. Additionally, stirring, filtration, ethanol washing, and drying procedures were used to the preparation reaction, which was kept at 100°C for two hours. Then the SiO_2 and Cu NPs were formed, and (25 ml) of SiO_2 NPs were added to 100 milliliters of H_2O in a stirring beaker. Next, for six hours, (11.74 milligrams) of ammonia and (11.16 milligrams) of $CuCl_2$ were added. Following the ethanol's filtration and purification, the products were left to dry at room temperature for two hours. The last stage involved dispersing the SiO_2 and Cu particles in EG and deionized H_2O, then using a magnetic stirrer to agitate for three hours to create a HNF [28]. Using the same NPs [29], the HNF was prepared using a 2-step procedure to produce a more stable result. First, the SiO_2 and Cu NPs were suspended directly in the base liquids. Next, a magnetic mixing process was carried out for one hour, followed by an ultrasonic process for two hours. This method produced a HNF that was mixed 50:50 between SiO_2 and Cu in glycerin and H_2O (30:70). Chawhan et al. [30] created Ag-doped TiO_2 hybrid NPs by utilizing ultrasonic technology, then filtering and rinsing the particles with pure H_2O and ethanol. TiO_2 and Ag-doped NPs are then suspended in H_2O to create HNFs, and they are dried at (80°C) for two hours prepared a HNF of Ag-MgO/H_2O in a 50:50 ratio suspended the mixture in H_2O to create a HNF with volumetric concentrations between (0-2%) [31]. Aberoumand and Jafarimoghaddam [32] utilized the electrical explosion of wire (EEW) method, also referred to as the 1-step method, to prepare a HNF consisting of tungsten (III) oxide (WO_3), silver, and transformer oil. The advantage of this method is that it can create NPs from any substance that can form a thin wire.

2.1.3 Metal + Non-Metal

The Cu-graphene/H_2O HNF was prepared in 2-step using GnP NPs with a diameter of less than 2 µm, Cu NPs and Cu NPs having a diameter of (30-50 nm). The mixing-ratio of the NPs was (70:30) and (30:70) Cu to graphene. H_2O was mixed with hybrid NPs to create a HNF of graphene and copper with volumetric fractions of 0.01-0.02 percent [33]. A HNF of GnP/Ag prepared with H_2O by mixing Ag and graphene in a ratio of (1:1) and three mass concentrations of (0.001, 0.002 and 0.003%) and used magnetic stirring technology to suspend the NPs evenly in the base liquid [34]. Additionally, a GnP-Ag HNF in H_2O was made using the 2-step method [35]. At the beginning of the preparation, the graphene nanoplates were functionalized because they are hydrophobic and unable to diffuse directly into the H_2O. In the next step, the Ag NPs were mixed with graphene in a ratio (1:6) with limited amounts of H_2O added to the composition to produce a HNF of different concentrations. Li et al. [36] developed HNF of SiC and MWCNTs for solar applications. The SiC and MWCNT powders were combined in the first step at a ratio of 8 to 2. Hexane was then added to the mixture and stirred for 20 minutes. The mixture was then subjected to an ultrasonic drying process, and the dry product was then dispersed in EG, which served as the base liquid for the creation of a HNF that would combine SiC and MWCNTs with glycol at different mass fractions (0.1-1%). Munkhbayar et al. [37] used the 1-step method to prepare Ag-MWCNTs HNF using the (PWE) method where the device uses four basic elements High voltage DC power supply, high voltage Gap switch, condenser bank, condensation/evaporation chamber. The 500 ml vial containing the MWCNTs nanofluid was subsequently placed into the PWE apparatus. Ag NPs were created using the PWE technique and added straight to the base liquid inside the chamber walls. In the end, a HNF comprising MWCNTs at various concentrations was produced.

2.1.4 Metal oxide + Non-Metal

Applying the in situ growth method and chemical co-precipitation, the same materials with different mixing-ratios were studied in order to build synthesized nanodiamond (ND)/Fe_3O_4 NPs with mixing-ratios (72:28) mass ratios [38], and mass ratios of (28:72) [39]. Two base liquids used to suspend composite NPs, namely H_2O and EG [40], many different ratios of (20:80, 40:60, 60:40) (mass ratios) of EG and H_2O were employed. While in the study of Sundar et al. [39], a single mixing-ratio of (40:60) was used, the mass ratio of EG/H_2O was used in both studies, different concentrations were (0.05, 0.1 and 0.2%) [39, 40]. The same investigation was carried out again from Saleh and Sundar [41] studied the preparation of HNFs consisting of nanodiamond-Fe_3O_4 with base fluids consisting of H_2O//ethylene with mixing ratio (40:60 and 60:40) (H_2O/ethylene). Tiwari et al. [42] utilized the 2-step procedure to create HNFs from MWCNT and CeO_2 and the mixing-ratio was (80:20%) (mass ratio) CeO_2/MWCNT of NPs and their dispersion in different base liquids H_2O, EG, therminol VP-I and silicon oil with different volumetric concentrations (0.25-1.5%). In many recent studies, many different NPs have been used with MWCNT to prepare HNFs. In a study conducted [43], a HNF was prepared from MWCNT and Fe_3O_4 with H_2O was used as the base liquid combining the chemical reduction approach using various volumetric concentrations (0.05, 0.1, 0.2, and 0.3%) in the situ growth method. In another study conducted [44], MWCNT NPs and Fe_3O_4 were prepared and mixed in equal proportions and then scattered in a base liquid of EG to create a HNF with varying volumetric fractions (0.1-2.3%). Alklaibi et al. [45] made a carboxyl (–COOH) connection between Fe_3O_4 and MWCNT and treated MWCNT with strong acids to form a HNF Fe_3O_4-F-MWCNT. This process involved the use of chemical reduction technology. H_2O was used as the base liquid, and the NPs were combined in quantities ranging from 0.05 to 0.3% [46]. Describes the 2-step process for creating a HNF MWCNTs-TiO_2, MWCNT prepared first, then the HNF MWCNT and TiO_2 prepared, and then the dispersion of NPs by (40:60) (MWCNT/TiO_2) in H_2O as a base liquid with mass fractions ranging from (0.025-0.1%). A similar study was conducted by Safi et al. [47] to prepare a HNF from MWCNTs-TiO_2. First, MWCNT was prepared and added TiO_2 using Solvothermal technology. Different concentrations of TiO_2 and MWCNT from (0.02-0.08%) of the mass, were used with the use of H_2O as the base liquid, then the use of MWCNT NPs with TiO_2 [48] Al_2O_3 [49] and Fe_3O_4 [50] to produce HNFs, and the 2-step method was used to prepare HNFs at concentrations from (0-1%).

2.1.5 Metal + Metal

Created and prepared a Cu–Zn HNF and using mechanical milling method to prepare Cu–Zn NPs. The mixing-ratio between the NPs was (50:50, 25:75 and 75:25), the particles were suspended in vegetable oil as a base liquid with volumetric concentrations of (0.1-0.3%) with the use of ultrasound for three hours [51]. Similar studies conducted [52, 53] in situ and the preparation of Cu–Zn NPs had an equal mixing-ratio between Cu–Zn and H_2O used it as the base liquid for the production of HNFs. Al/Zn were prepared via mechanical alloys [54] and with EG being utilized as a base liquid and the use of ultrasonic technology to produce a HNF. Table 1 shows some techniques for preparing HNF for several researchers.

Table 1. An overview of HNF production techniques for different publications

Classification	Method	Base Liquid	NPs	Ref.
Metal Oxide & Metal Oxide	2-step	H_2O, H_2O-bio-glycol	Al_2O_3-SiO_2	[16]
	2-step	H_2O	TiO_2-Al_2O_3	[18, 19]
	2-step	H_2O	Al_2O_3-CuO	[19, 20]
	2-step	H_2O	Fe_2O_3-TiO_2	[21]
	2-step	H_2O-bio-glycol	TiO_2-SiO_2	[22]
	2-step	H_2O-bio-glycol	MgO-ZnO	[23]
	2-step	Glycerol-EG	CuO/C-SiO_2	[24]
	2-step	H_2O	MgO-TiO_2	[55]
Metal & Metal Oxide	2-step	H_2O	Al_2O_3-Cu	[26, 28]
	2-step	H_2O-EG	SiO_2-Cu	[27]
	2-step	glycerin	SiO_2-Cu	[29]
	2-step	H_2O	TiO_2-Ag-doped	[30]
	2-step	H_2O	MgO-Ag	[31]
Metal & Non-Metal	1-step	Transformer oil	Ag-WO_3	[32]
	2-step	H_2O	Cu-GnP	[33]
	2-step	H_2O	Ag-GnP	[34, 35]
	2-step	EG	SiC-MWCNTs	[36]
	1-step	H_2O	Ag-MWCNTs	[37]
Metal Oxide & Non-Metal	2-step	H_2O/bio-glycol	ND-Fe_3O_4	[38, 39, 41]
	2-step	H_2O, silicon oil, EG, and Therminol VP-I	CeO_2-MWCNT	[42, 56]
	2-step	H_2O-EG	Fe_3O_4-MWCNT	[44, 45, 57]
	2-step	H_2O	TiO_2-MWCNTs	[47]
	2-step	H_2O	TiO_2-GnP	[48]
	2-step	Therminol	Al_2O_3-GnP	[49]
	2-step	Kerosene	Fe_3O_4-GnP	[50]
Metal & Metal	2-step	Vegetable Oil	Cu – Zn	[51, 52]
	2-step	H_2O	Al – Zn	[58]

The results of the preparation and preparation of HNFs showed that the 2-step method is the best way to prepare a HNF, despite its difficulty and complexity, to produce a stable HNF because the stability of HNFs is the most prominent challenge for the use of this technology, so many researchers have done different ways to improve the stability of these fluids, including adding surfactants, pH modifications and using different mixing techniques such as mechanical stirring, ultrasonic techniques, magnetic stirring method, and others. Also, the stability and efficiency of the HNFs depends on the concentration's ratios used, as each type of molecule has a mixture with another type where there is an appropriate mixing-ratio. Because increasing the concentration of hybrid NPs in the base liquid has adverse impact on their stability and on the performance of the solar collector in general.

3. THERMOPHYSICAL PROPERTIES OF HYBRID NANOFLUID

Improving the thermophysical characteristics of HNFs is one of the objectives of employing NPs. Among these properties, thermal conductivity, viscosity, density, and specific heat are the most significant. We'll talk about a number of variables that affect these characteristics, including the kind and size of the material, the form of the NPs, the temperature, and the particle size concentration.

3.1 Thermal conductivity

Achieving high thermal conductivity raises thermal efficiency and improves system performance. The kind of base liquid, the operating temperature, and the concentration of the NPs all have a significant impact on the thermal conductivity of HNFs [59]. To enhance the heat conductivity, some researchers have employed experimental data and thermal conductivity measuring tools like the KD2 Pro and thermal characteristics analyzer.

$$k_{hnf} = \frac{(k_1 + k_2) + 2k_f - 2\phi_1(k_f - k_1) - 2\phi_2(k_f - k_2)}{(k_1 + k_2) + 2k_f + \phi_1(k_f - k_1) + \phi_2(k_f - k_2)} \quad (1)$$

3.2 Viscosity

An essential component for fluid-based thermal applications is viscosity. Numerous parameters, including pressure drop, pumping energy, and the convectional heat transfer coefficient, are impacted by the liquid's viscosity [30], so this property is very influential [60]. Before taking into consideration HNFs for usage in solar thermal applications, their viscosity in comparison to base liquids needs to be carefully investigated and assessed.

$$\mu_{hnf} = \frac{\mu_f}{\left(\mu_f - \phi_{np1} - \phi_{np2}\right)^{2.5}} \quad (2)$$

3.3 Specific heat and density

One important characteristic of HNFs is specific heat; as solids usually have lower specific temperatures than liquids, adding NPs to the base liquid causes the specific heat of the HNF to fall [60]. Another crucial characteristic of HNFs is density, which rises with increasing NP concentration and falls with rising temperature. The settling of the particles in the base liquid is caused by this important factor [51].

$$\rho_{hnf} = \rho_1\phi_1 + \rho_2\phi_2 + \rho_f(1 - \phi_1 - \phi_2) \quad (3)$$

$$(C_p)_{hnf} = C_{p_1}\phi_1 + C_{p_2}\phi_2 + (C_p)_f(1 - \phi_1 - \phi_2) \quad (4)$$

4. HYBRID NANOFLUID APPLICATIONS IN FPSCS

The most popular type of solar collector for low thermal applications (temperatures below 90°C) is the FPSC due to its exceptional capacity to generate heat energy from sunlight. These applications include space heating, swimming pool heating, domestic hot H_2O production, and solar cooling systems [61, 62]. Figure 3 outlines the components of the FPSC, which are as follows:

1. One or more of sheet glass whose task is to reduce convection losses.
2. Heat transfer tubes can be enhanced using techniques to enhance heat transfer inside the tube: fins corrugation grooves [63].
3. The absorber, which is used to collect solar-energy and transport heat to the pipes and subsequently the operating fluids, has a large absorbability and low emission.
4. Heat losses from the sides and bottom of the solar collector to the environment are minimized via insulation.
5. The container, which is used to protect all parts from dust and moisture.

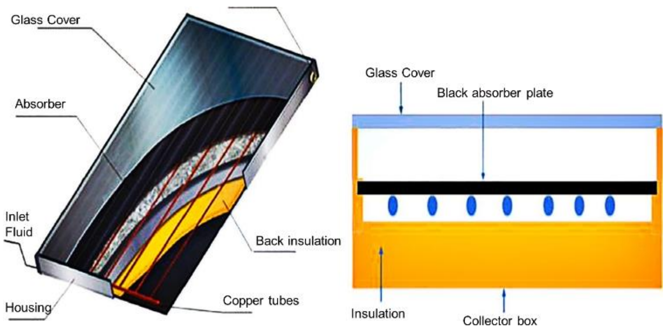

Figure 3. FPSC schematic [62, 63]

From the advantages of FPSCs is that they are inexpensive, combine both radial and diffuse radiation, be stationary, and do not need to track the sun [64]. In order to increase the efficiency of these collectors, HNFs are used. Many theoretical, computational, and experimental research have been done in an attempt to improve the thermal performance of these collectors by using HNFs.

The findings demonstrated that H_2O is the ideal base liquid for creating HNFs for a number of reasons, chief among them being that it has a higher thermal conductivity than other types, which improves the thermal performance of the solar collector; additionally, H_2O requires less pumping energy and has a less detrimental effect on the solar collector's components. Regarding the NPs, the outcomes demonstrated that combining materials like MWCNT with metal oxide enhances the solar collector's thermal efficiency. However, because of their propensity for rapid aggregation and sedimentation, these NPs have serious stability issues. Consequently, these NPs require many treatments to increase their stability, which raises the solar collector's thermal efficiency but has a detrimental effect on its performance. The extremely high cost of these NPs makes it challenging to use them in many applications, which is another drawback. When combined with MWCNT, other NPs, such as h-BN, demonstrated excellent efficiency. Table 2 shows several numerical, theoretical and experimental studies of the use of HNF in FPSC.

Table 2. An overview of analyzed some theoretical, numerical, and experimental papers of using HNFs in FPSCs

Inves.	(Base Liquids) & NPs	Result	Ref.
Theor.	(H_2O) Cu CuO Cu/CuO	The findings showed that for HNF, the FPSC's thermal efficiency was 71.8%.	[65]
Theor.	(H_2O/EG) CuO Fe_3O_4 MWCNTs CuO/MWCNTs Fe_3O_4/MWCNTs	The MWCNT-CuO HNF performed better in three solar collectors than the MWCNT-Fe_3O_4 HNF, with a 71% thermal efficiency.	[66]
Theor.	(H_2O) Fe_2O_4 Zn-Fe_2O_4	In comparison to single nanofluids and H_2O, the HNFs' thermal efficiency was superior. 80.1% was the maximum efficiency.	[67]
Num.	(H_2O) TiO_2-Ag	A collector's maximum energy efficiency is roughly 71.92%.	[7]
Num.	(H_2O) Fly Ash-Cu	Enhances the FPSC's thermal performance by 73%.	[2]
Num.	(Therminol VP-1) MgO-MWCNT	The findings showed that FPSC has a 55% thermal efficiency.	[68]
Exp.	(H_2O) CuO/MWCNTs MgO/MWCNTs	For MgO and CuO, the energy efficiency of the HNF collector is 70.55% and 69.11%, respectively.	[57]
Exp.	(H_2O) MWCNT Al_2O_3 MWCNT/Al_2O_3	According to the findings, utilizing hybrid MWCNT-Al_2O_3 can boost efficiency to 74%.	[69]
Exp.	(H_2O) CF-GNPs/CF MWCNTs/h-BN	The solar collector's thermal efficiency rose to 85% when HNF was used.	[70]

5. LIMITATIONS AND CHALLENGES

HNFs offer numerous advantages in terms of enhancing the thermal performance of solar collectors; nevertheless, in order to achieve the necessary efficiency, certain issues and constraints need to be resolved, as seen in Figure 4.

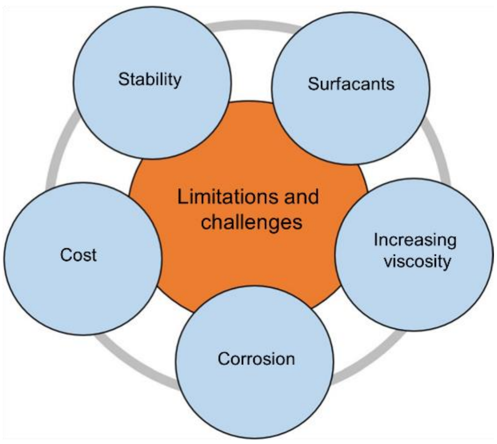

Figure 4. Limitations and challenges of HNFs [15]

HNFs enhance the efficiency of solar collectors' heat but face several challenges that need to be addressed for optimal efficiency. Key issues include achieving good dispersion and long-term stability, as NPs tend to agglomerate due to Van der Waals forces. While surfactants can improve particle dispersion, they may reduce thermal conductivity over time. Additionally, HNFs have higher viscosity than base liquids, which can increase pumping energy requirements and clogging in tubes, which lead to reduce system performance. Another issue is surface corrosion when exposed to HNFs. Additionally, HNFs are more expensive than base liquids; additionally, although increasing the concentration of NPs can improve heat conductivity, doing so comes with a price increase.

6. CONCLUSIONS

The review examines the preparation and characterization of hybrid nanomaterials for use in FPSCs. Key findings include:

1. The 2-step method is preferred over the simpler 1-step technique for producing HNFs due to better control over fluid concentration.
2. Stability is crucial, especially at high NP concentrations, as gravity can cause clumping, adversely impacting thermophysical properties.
3. Techniques such as adding surfactants, adjusting pH, and using ultrasonic or magnetic agitation are necessary to enhance stability.
4. Increased hybrid NP concentration improves thermal conductivity but also raises viscosity.
5. Graphene NPs (GNP) and multiwalled carbon nanotubes (MWCNT) both show significant gains in heat conductivity.

6. Higher viscosity can lead to pipe blockages and increased pumping energy requirements.

7. As an alternative to theoretical models, artificial neural networks can accurately predict the thermophysical features of HNFs.

8. Research has demonstrated that the efficiency of solar collectors' heat can be improved by HNFs when compared to base liquids and single nanofluids.

9. Techniques like disturbances in porous media can further enhance heat transmission by using HNFs.

The recommendations for improving HNFs in FPSCs include:

1. Investigating how various elements affect the stability of HNFs, as stability is crucial for their application.

2. Conducting studies to optimize NP mixing-ratios to achieve high thermal conductivity with lower viscosity.

3. Researching thermal conductivity behavior at high temperatures, relevant for solar collector operation.

4. Addressing corrosion issues in tubes caused by hybrid NPs in future studies.

5. Exploring new types of hybrids nanofluids to improve the solar collectors' thermal performance.

6. Considering the economic implications of using HNFs in solar thermal technologies due to their high costs.

7. Enhancing techniques like turbulator and porous media to further improve thermal performance.

8. Implementing hybrid secondary fluids in real-world systems on a large scale to monitor efficiency improvements.

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NOMENCLATURE

FPSC	FPSC
Al_2O_3	Alumina
SiO_2	Silicon dioxide
CuO	Copper oxide
TiO_2	Titanium dioxide
MWCNTs	Multi-Walled Carbon Nanotube
GNPs	Global Natural Products Social
Fe_2O_3	Iron Π trioxide
EG	EG
CNT	Carbon Nanotube
Ag	Silver
ZnO	Zinc oxide
MgO	Magnesium oxide
C	Carbon
Fe_2O_4	Iron Π oxide
TEOS	Tetraethyl Orthosilicate
Cu	Copper
CNC	crystal nano-cellulose
EEW	electrical explosion of wire
WO_3	Tungsten trioxide
SiC	Silicon carbide
PWE	pulsed wire evaporation
ND	Nanodiamond
Fe_3O_4	Iron III oxide
CeO_2	Cerium oxide
Zn	Zinc
Al	Aluminum
GO	Gadolinium
h-BN	hexagonal boron nitride
C_P	specific heat, J. kg^{-1}. K^{-1}
k	thermal conductivity, W.m^{-1}. K^{-1}
NP	Nanoparticles
NF	Nanofluids
HNFs	Hybrid Nanofluids

Greek symbols

ρ	dynsity, kg. m^{-3}
ϕ	solid volume fraction
μ	dynamic viscosity, kg. m^{-1}.s^{-1}

Subscripts

np	Nanoparticles
f	fluid
nf	nanofluid
hnf	Hybrid Nanofluid