

Single and Hybrid Nanofluids to Enhance Performance of Flat Plate Solar Collectors: Application and Obstacles

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Abstract

Solar energy represents the best alternative for traditional energy sources used in many thermal energy systems. Among solar thermal systems, Flat Plate Solar Collectors (FPSCs) are the most utilized type implemented in low and medium-level thermal domestic applications. Recently, the usage of nanofluids (NFs) to enhance FPSCs is one of the newest technologies that has drawn the attention of researchers to improve the overall thermal efficiency of solar systems. This paper briefly reviews the recent studies carried on thermal performance enhancement of FPSCs by implementing NFs (single and hybrid NFs) considering the main influential parameters such as particle concentration, particle size, and collector area. Finally, the main obstacles reported by the researchers such as the instability, viscosity, concentration limit, corrosion effect and others are identified, which is believed to be useful for interested newcomers in this research area. Based on the studies investigated in this paper, NFs, even under low concentrations, can remarkably improve the energetic and exergetic efficiency of FPSCs.

Keywords

nanofluid, hybrid nanofluid, Flat Plate Solar Collector (FPSC), thermal efficiency, solar energy

1 Introduction

Flat Plate Solar Collector (FPSC) is a popular type of solar collectors used in solar thermal applications. It is widely used in solar heating, cooling and domestic hot water applications [1–3]. Despite the simple-construction and low initial cost compared with other types, FPSC practically has low thermal efficiency and outlet temperature since the first development by Hottel and Whillier in the 1950s [4]. The water or air is usually employed as a heat transfer working fluid in FPSCs. The water-based collector has higher energetic and exergetic thermal performance compared with air-based collectors. Therefore, they are used in many applications. The typical FPSC comprises from glass cover, absorbing layer, fluid heat exchanger tubes, insulation layer and a frame, as shown in Fig. 1. The beam solar radiation passes through the glass layer and is accumulated in the form of heat inside the collector. The dark absorbing layer traps the heat and minimizes the reflected radiation. The heat then is transported to the

water through heat exchanger pipes which are in contact with the absorbing layer. The frame supports the layers and protects them from weather conditions.

Many improvements have been made to increase the thermal performance of FPSC by dealing with the material of collector layers, collector configuration, heat exchanger

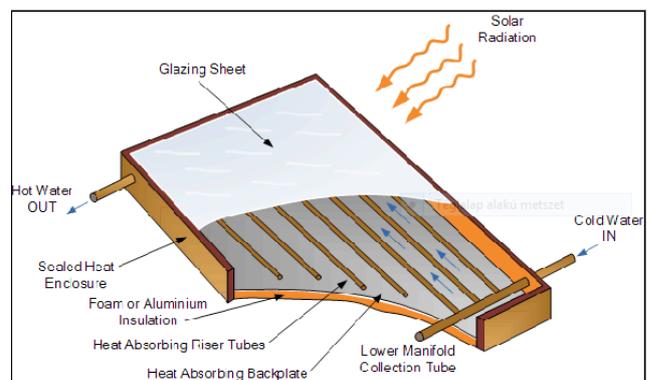


Fig. 1 Schematic of a typical FPSC.

or the working fluid. Vetrivel and Mathiazhagan [5] replaced the single top glass layer of FPSC by double glass layers in order to reduce the heat transfer from the collector through the glass layer. The results revealed that the collector efficiency and outlet water temperature increased by 43 % and 10–15 °C, respectively compared with the single glass collector. Bhowmik and Amin [6] used reflectors to concentrate the direct and diffuse solar radiation towards FPSC. The reflectors were rotated in different angles to reflect as much as possible of sunlight. This technique improved the efficiency of FPSC by up to 10 %. Sakhaei and Valipour [7] coated the absorbing layer of three FPSCs by black paint, black chrome-coating, and carbon-coating to investigate the absorptivity of each collector. The results showed that the carbon-coating has the highest absorption rate because of the trapped sunlight and minimized reflection where the thermal efficiency increased by up to 69.4 %. Moreover, compared with the black-painted collector, the efficiency was increased by 13 % and 11.3 % using carbon-coating and black chrome-coating, respectively. Kim et al. [8] used coloured fluids to increase the absorptivity of the absorbing layer of FPSCs. They installed transparent tubes on the absorption layer of a traditional FPSC. Four coloured fluids (pure water, red, violet, and black) were flowed inside the transparent tube to investigate their absorptivity, which enhances the capability of absorbing layer. The study reported that the black fluid showed the best thermal performance, and up to 5 % collector efficiency improvement was obtained. Fan et al. [9] introduced a new V-corrugated aluminum absorbing layer made with multi triangular channels to increase the optical and thermal performance of a conventional FPSC. The results showed that the optical and thermal efficiency of the new collector was improved by 15.8 % and 10.8 %, respectively, over the traditional one. Further, the pumping power required to circulate the fluid of the new collector was reduced by about 4.1 times compared with that required for the traditional one. Various techniques have been proposed by researchers to improve the thermal performance of FPSC such as the arrangement of fluid heat exchanger pipes in a zig-zag manner [10], insertion of porous metal foam blocks [11], utilization of wire-coils and twisted-tapes [12], and recently, usage of nanofluids for overall heat transfer enhancement.

In the literature, there are thousands of published items each year dealing with the applications of NFs in different fields of heat transfer. Fig. 2 [13] shows the number of published items from the year 2015 to 2020 considering

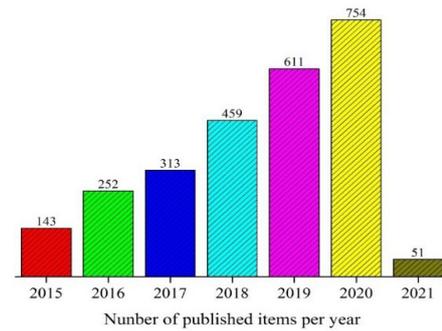


Fig. 2 Statistics of published items in Scopus database considering the keywords "nanofluids in flat plate solar collectors" [13].

the enhancement of FPSCs efficiency against the number of reviewed items in the current work.

In this paper, a review on the use of single and hybrid NFs in FPSCs in the recent research work has been presented and discussed. Different types of NF used in FPSCs were detailed, focusing on the thermal efficiency enhancement and considering the main affecting parameters such as particle size, particle concentration, and collector area. Moreover, a brief discussion on the main obstacles restricting the applicability of NFs based FPSC is also mentioned to highlight the necessary research works needed in future studies.

2 Nanofluids

2.1 Overview of nanofluids

The term nanofluid (NF) refers to the suspension of nanoparticles (NPs) with a size less than 100 nm into a base (host) fluid. This technology was presented for the first time by Maxwell [14]. NFs have proved an essential enhancement in the heat transfer of many thermal applications and showed excellent results in solar collector applications [15–17]. The most commonly used conventional fluids as a base fluid in NFs are dispersed water, ethylene glycol, a mixture of water and ethylene glycol and, engine oil and paraffin [18–21]. The types of NPs used to prepare NFs can be made from different materials, as listed in Table 1 [22]. These suspended NPs showed essential enhancement in the thermo-physical properties of the base fluid such as thermal conductivity, convective heat transfer coefficient, specific heat, and thermal diffusivity compared with the base fluid alone. Fig. 3 [23] shows the thermal conductivity range of different NPs and base fluids.

Different NP types are intensively studied by the researchers during the last years with much focus on the oxide ceramics in general, as shown in Fig. 4, Al₂O₃, for an instant, got the most attention among other NPs due

Table 1 Type of materials used to synthesize NPs [22].

Material category	Examples
Metals	Cu, Ag, Au, Fe, Al
Oxide ceramics	Al ₂ O ₃ , CuO
Nitride ceramics	AlN, SiN
Carbide ceramics	SiC, TiC
Semiconductors	TiO ₂ , SiC
Carbon nanotubes and composite materials	Alloyed NPs such as Al ₇₀ Cu ₃₀ and NP core-polymer shell composites

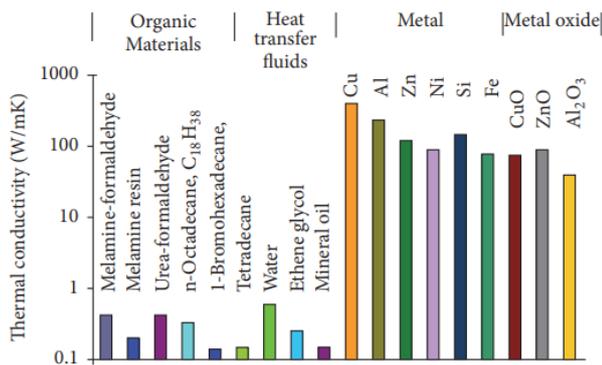


Fig. 3 Thermal conductivity of different NPs and base fluids [23].

% of Researchers used specified nanoparticles

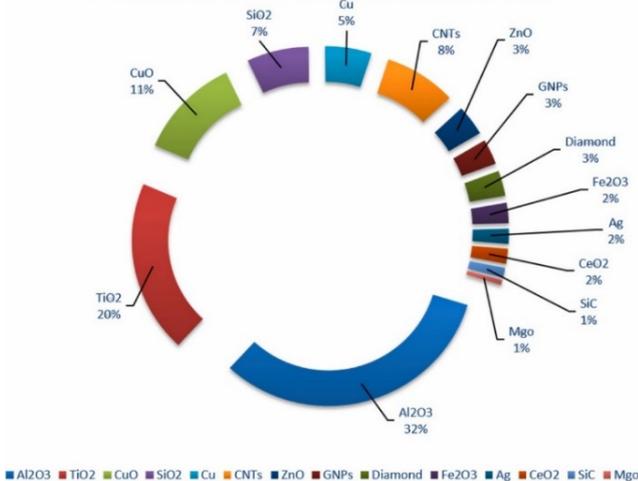


Fig. 4 Percentage of NP materials used in the literature studies [18].

to its wide availability, low cost, good stability with base fluids, high thermal conductivity, and other physical properties [24]. Further, many other materials are still not highlighted, mainly due to their high cost, which makes this area under research.

2.2 Classification and preparation of NFs

NFs are classified into two main categories: single material NF where a single kind of NP material is immersed into the base fluid, and the hybrid NF where more than one type of NPs are used to prepare the NF. The latter represented

an advanced category and was introduced for the first time by Jana et al. [25] which showed better thermo-physical properties than the liquids with single NPs.

Preparation of NFs represents the first foot-step in the way of NF application. It can be done in single or two-steps method to get a homogenous fluid with neglected agglomeration for long-term operation and stable thermo-physical properties. In the single-step method, NPs can easily be prepared via physical vapour deposition technique or liquid chemical method. Therefore, the drying/storage/dispersion/ transportation processes are averted [26], which minimize the agglomeration. The main disadvantage of this method is that residues of reactants are left in the NF due to incomplete reaction or lack of stability which affects the purity of NF. Furthermore, only low-vapour pressure base fluids can be used in this method, which limits its application [26]. In the two-step method, NPs are produced by a chemical vapour deposition technique, inert gas condensation technique, etc. to produce powder NPs [27]. Then, the powder is mixed with the base fluid with the help of induction of intense magnetic force agitation, ultrasonic excitation, high shear mixing, ball milling and homogenization. The major disadvantage of this method is that due to the high surface area and surface gravity, NPs tend to agglomerate, which reduces the thermal conductivity of NF and affects its stability. In general, the single-step method is appropriate for small production, and the two-step method is cost-effective for mass production [28]. Moreover, the two-step method is optimal for tri-hybrid NFs (when three different NPs concentrations are mixed) to obtain a long time stable suspension [29].

More details on this subject can be found in [30–32]. Many researchers highly recommend the two-steps method as it showed better characteristics of the prepared NFs as well as its economic advantage. Hybrid NFs possess a big challenge in preparation studies due to the use of more than one type of NPs (Fig. 5 [33]). Babar and Ali [22] discuss more detailed information about this aspect.

2.3 Applications of NFs in solar systems

Broadly, NFs have been showing essential enhancement in the overall thermal performance of many engineering systems. Focusing on solar applications, NFs positively improved the heat transfer of numerous systems other than FPSCs such as: Solar desalination systems [34], photovoltaic/thermal systems [35], solar heat exchangers [36], parabolic trough solar collectors [37], evacuated tube solar collectors [38], heat pipe in solar collectors [39], solar thermal energy storage systems [40], etc.

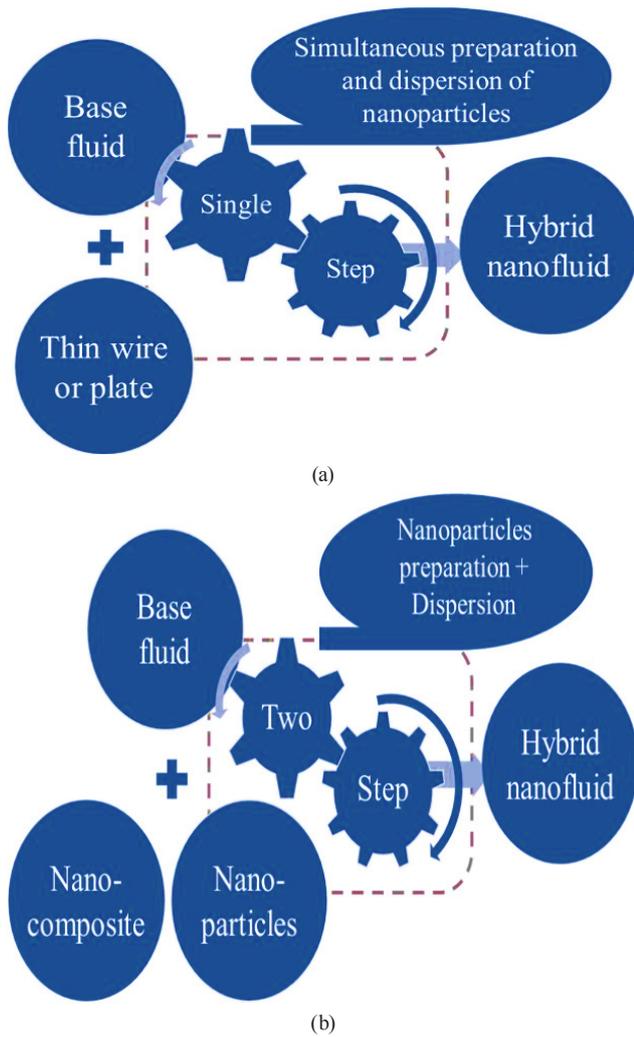


Fig. 5 Illustration of (a) single and (b) two-step methods [33].

The use of NFs in solar thermal systems results in many advantages, which can be summarized as follows:

- Technical considerations: NFs enhance fluid properties such as thermal conductivity, convective heat transfer coefficient and thermal diffusivity, which increases the heat transfer rate of the system thanks to the Brownian motion [41]. In FPSCs, the optical absorption of the fluid increases [42], the convective and radiative heat transfer losses will decrease as the heat transfer between the absorbing layer and heat exchanger increases. All in all, the overall thermal efficiency of the system improves remarkably.
- Economic considerations: Despite the initial and operational cost, with the use of NFs the area of the solar collector reduces, leading to a reduction in the collector cost. The size of FPSC can be reduced in different percentages depending on the type of NPs, as shown in Fig. 6 [43]. Furthermore, it has

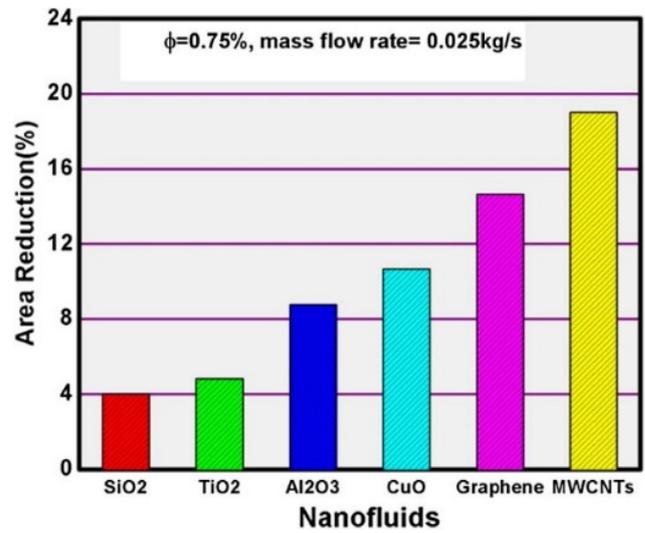


Fig. 6 Size reduction of FPSC using various NF types [43].

been reported that the use of hybrid NFs is cost-effective rather than single NFs thanks to their high potential of Thermal Conductivity Elevation (TCE) as illustrated in Fig. 7 [44].

- Environmental consideration: The increased efficiency of solar collector thanks to NFs cuts the CO₂ emissions and decreases the reliance on traditional energy sources.

3 Application of NFs to enhance performance of FPSCs

Many numerical and experimental studies discussed the potential of NFs to improve the efficiency/thermal performance of FPSCs. These studies reported the correlation of thermo-physical characteristics of the prepared NFs with the type of NPs and their concentration where most findings showed enhancement in the heat transfer

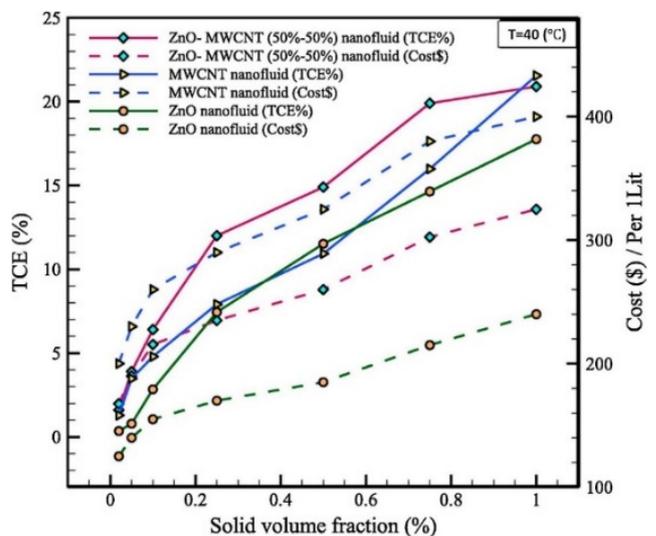


Fig. 7 Cost-effectiveness of hybrid NFs compared with single NFs [44].

coefficient, thermal conductivity, and optical absorptivity [45, 46]. Furthermore, the efficiency of FPSC and thermophysical properties of new fluid will be changed remarkably depending mainly on the type of NPs dispersed and its concentration [47, 48]. For instance, Fig. 8 and Fig. 9 [49] show the improvements in fluid properties when single and hybrid NPs are used.

The experimental studies of NFs in FPSCs show a more realistic behaviour of NFs rather than numerical studies which the latter relies on engineering approximations. Verma et al. [50] illustrated the experimental methodology analysis that should be followed to study the optimal exploitation of NF for solar collectors, as shown in Fig. 10. All aspects of prepared NF (thermal conductivity, density, and viscosity) must be investigated in conjunction with the technical parameters of the solar collector (inlet and outlet temperature, collector inclination, ambient temperature) to study the optimal utilization of NF and its impact on the performance of solar collector.

Improvement of FPSC using NFs has been studied using various types of NPs with different concentrations. Hawwash et al. [51] numerically and experimentally investigated the enhancement of FPSC using Double Distilled Water (DDW) and alumina NF at six different concentrations ranging between 0.1–3 %. They conducted the study according to ASHRAE standard 86–93 under Egyptian climate conditions. The results showed that alumina NF could improve the collector thermal efficiency over the DDW by about 18 % with a high-temperature difference. Furthermore, the numerical results obtained using ANSYS Fluent 17 software indicated that the increase of volume fraction of alumina NF until 0.5 % increased the thermal efficiency of FPSC. However, a further increase in concentration inversely impacted the thermal performance

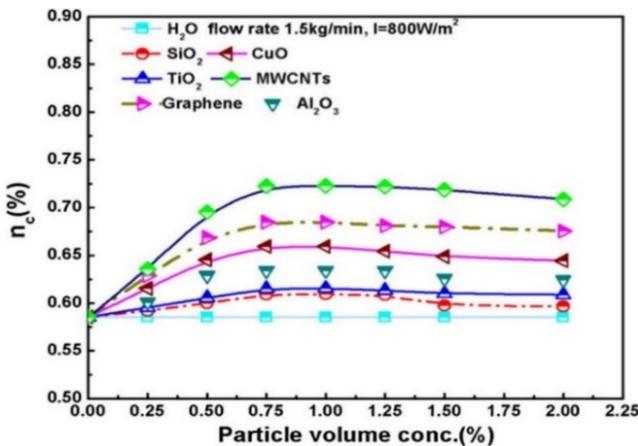


Fig. 8 FPSC efficiency (n_c) versus concentration for different NPs [43].

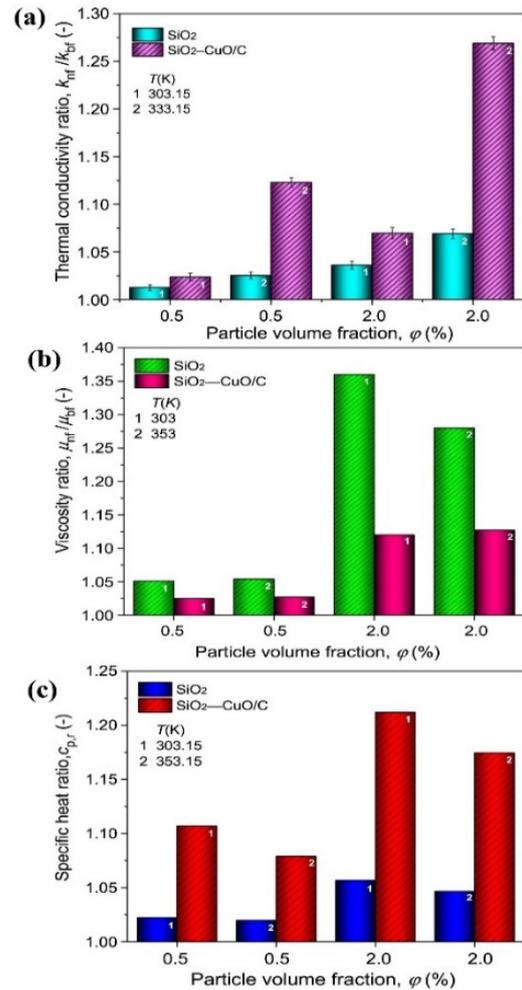


Fig. 9 Enhancements in thermophysical characteristics of single and hybrid NPs: (a) thermal conductivity, (b) viscosity, (c) specific heat [49].

due to increasing pressure drop. The effect of using CeO₂ (25 nm)-water as a NF to enhance the efficiency of FPSC was experimentally studied by Sharafeldin and Gróf [52] under Hungarian climate conditions. The volume fractions of NPs used in the experiment were 0.0167, 0.0333 and 0.0666 % prepared with the sonication method and the NF studied with a pumping rate of 0.015, 0.018 and 0.019 kg/s m². The results revealed that the maximum collector efficiency achieved was 10.74 % at 0.666 % volume fraction and 0.019 kg/s m² mass flux rate which proved that the collector efficiency was directly proportional to the volume fraction and mass flux rate. Genc et al. [53] studied the enhancement of FPSC based Al₂O₃-water NF compared with the water as a working fluid. The heat transfer of NF was analyzed at 1, 2 and 3 % volume fraction and mass flow rate ranged between 0.004 and 0.06 kg/s to investigate the thermo-physical properties under different Reynolds numbers. The results indicated that the highest collector thermal efficiency obtained

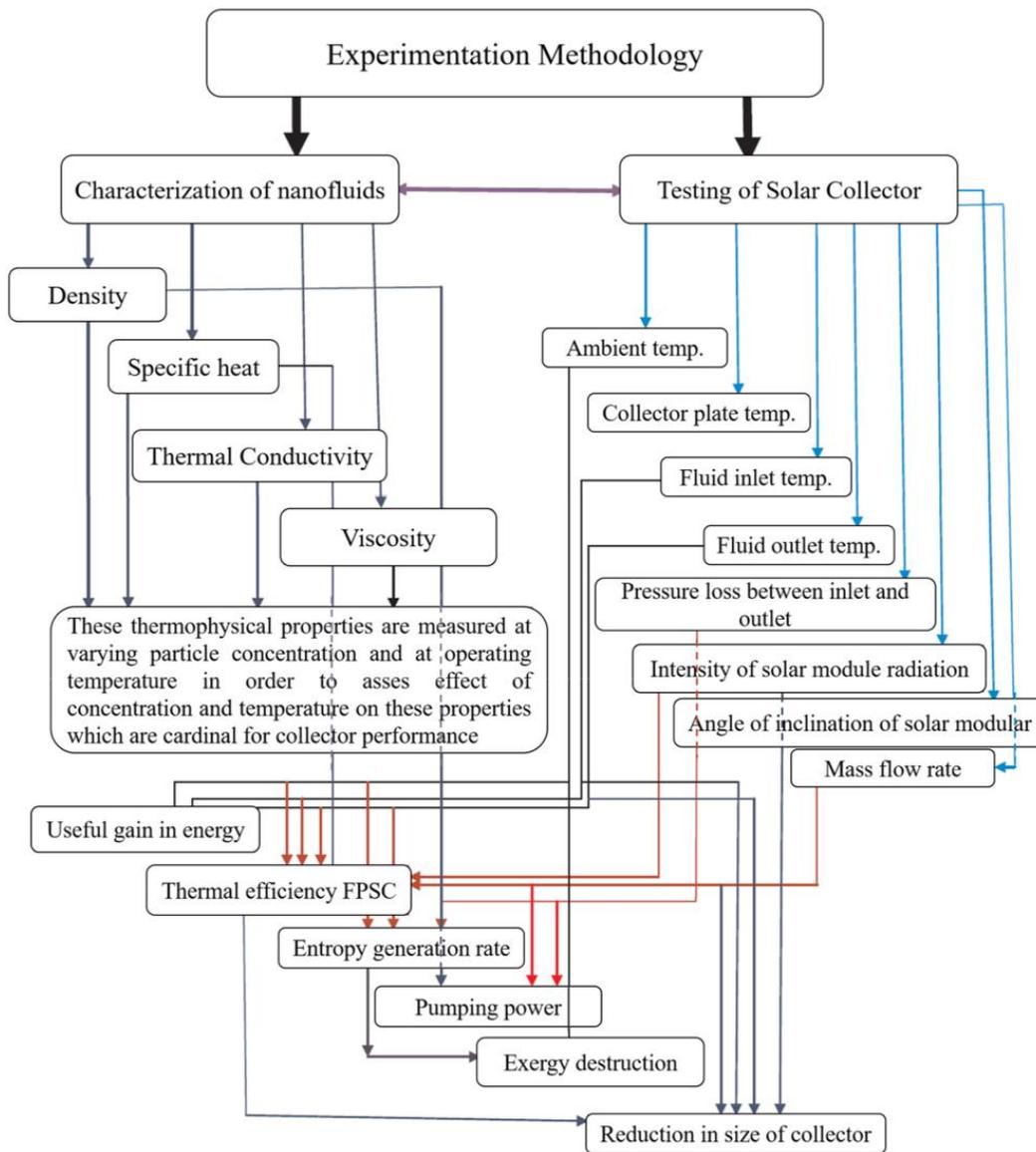


Fig. 10 Flowchart of investigating NFs in FPSC [50].

was 83.90 % at 1 % volume fraction and 0.06 kg/s mass flow rate. Furthermore, an increment of collector outlet temperature by 7.20 % achieved at 3 % volume fraction and 0.004 kg/s mass flow rate. The results also revealed that the efficiency of FPSC could increase using NF at a low flow rate and the base fluid can be an effective working fluid beyond the critical flow rate which was 0.016 kg/s in their study. Performance improvement of FPSC using TiO_2 -water NF was experimentally investigated by Kiliç et al. [54]. They mixed 2 % concentration of TiO_2 NPs with 0.2 % of Triton X-100 surfactant using the ultrasonic bath for 8 h to get stable NF and prevent the agglomeration during working time. The improvement of collector efficiency was estimated based on ISO 9806:2017 standard [55], where the highest instantaneous efficiency obtained was 48.67 %

and 36.20 % for the NF and pure water fluid, respectively. Alawi et al. [56] experimentally investigated the thermal performance of FPSC using Pentaethylene Glycol treated Graphene nanoplatelets (GNPs)/water as a working fluid at 0.025, 0.05, 0.075, and 0.1 % concentrations. The experiment set with 303, 313, and 323 K collector inlet temperatures and 0.00833, 0.01667, and 0.025 kg/s mass flow rates was exposed to 500, 750, and 1000 W/m^2 heat flux intensities. The results revealed that the thermal conductivity, viscosity and density were augmented as the concentration of NPs increases and the efficiency of FPSC was directly proportional to the flow rate and heat flux. Moreover, the efficiency of FPSC increased using NFs by 10.7 %, 11.1 %, and 13.3 % with the mentioned mass flow rates compared to the case where water was used as the working fluid.

Hybrid NFs are the newest generation and advanced working fluids [57], which showed good improvements on the thermo-physical properties of different solar thermal applications over the single NFs [58]. The literature has limited studies regarding the use of hybrid NFs for FPSC as this trend is still under research. Babu et al. [59] analytically investigated the enhancement of FPSC using Cu-CuO/H₂O hybrid NF and compared with Cu/H₂O and CuO/H₂O NFs in terms of energetic and exergetic performance of the collector. The hybrid NF showed higher thermo-physical properties over the single NFs under different flow rates and concentrations. Findings showed the enhancement in the thermal conductivity of Cu-CuO/H₂O hybrid NF by 17.52 % whereas it was enhanced by 15.72 % and 15.35 % with Cu/H₂O and CuO/H₂O NFs, respectively. Moreover, the enhancement in collector thermal efficiency was 2.175 %, 1.05 %, and 0.93 %, the improvement in the collector exergy efficiency was 2.59 %, 2.32 % and 2.18 %. In contrast, the increase in the pressure drop was 2.918 %, 3.09 %, and 2.74 %, respectively for Cu-CuO/H₂O, Cu/H₂O and CuO/H₂O NFs. Tahat and Benim [60] experimentally studied the thermo-physical properties of hybrid NF contains Al₂O₃-CuO immersed in ethylene glycol and water mixture with a ratio of 25:75 (by weight) and examined its effect on the efficiency enhancement of FPSC at different concentrations (0.5 %, 1 %, 1.5 % and 2 %). Outcomes of their study showed that viscosity and density increased as the concentration increases, and the thermal efficiency was improved by up to 95 % compared with the water as a base fluid. Furthermore, the thermal efficiency was increased by 42 %, 45 %, 48 %, and 52 % at concentration of 0.5 %, 1 %, 1.5 % and 2 %, respectively. Verma et al. [50] experimentally investigated the effect of hybrid NFs combinations of CuO and MgO with Multi-Walled Carbon Nanotubes (MWCNTs) mixed with water base fluid. The combinations were tested for 0.25, 0.5, 0.75, 1, 1.25, 1.5 and 2 % concentrations with fluid flow rate varied between 0.5 and 2 lpm to observe the energetic and exergetic performance of FPSC. The results indicated that higher thermal performance of the collector was achieved under MgO-MWCNTs NF, where the energetic and exergetic efficiencies were 71.54 % and 70.55 % compared to 70.63 and 69.11 % for CuO-MWCNTs NF. The enhancement of total collector efficiency gained from MgO-MWCNTs hybrid NF was higher by 25.1 % and 16.28 % when compared with the case of water and MgO/water NF, respectively. More investigations on the thermal performance of NFs employed for FPSCs are summarized in Table 2 [61–77].

It is worth mentioning that there are several studies reporting improvements in solar systems driven by FPSCs based NFs solar systems such as solar stills, solar heating and refrigeration, solar domestic hot water, and power generation. In this regard, Table 3 [78–85] summarizes several systems and improvements.

4 Obstacles of NFs in FPSCs

In the studies conducted in the last few years, NFs have been proved to be an excellent potential technique for increasing the heat transfer of different applications of solar collectors [86, 87]. Due to its low thermal efficiency and suitability for a wide range of hot-water applications, FPSC has received remarkable attention from researchers who attempted to improve its performance by NFs. Although significant improvement of the efficiency using various types of NFs has been reported, the research in this area is still ongoing day by day to optimize the heat transfer rate and reduce the limitations and obstacles for better adaptability with the lowest cost toward its commercialization. The main obstacles in applying NFs in FPSCs are addressed below.

4.1 Instability

Instability of NF means that NPs could not suspend in the base fluid over the service period [24]. Instability decreases the ability of fluid to transfer heat and lower its efficiency, and thus, it may eliminate the purpose of using NPs. The main reason for NF instability is the interaction between the NPs and the base fluid, or between the particles themselves [88]. NF instability caused due to two opposite forces; the well-known Van der Waals force and double-layer repulsive force. Van der Waals force attracts NPs surfaces into each other and forms the so-called cluster/ agglomerations which then separate from the base fluid and sediment due to gravitation. The other opposite force is the double layer repulsive force among NPs due to steric and electrostatic repulsion [89]. Based on those statements, the stability of NF is established when the effect of Van der Waals force is lesser than the repulsive force over the lifetime of NF operation.

Several methods are applied to make the NF stable, such as sonication, magnetic stirrer and adding of surfactants (Fig. 11), which is the most recommended method in this regard [90]. Sonication is a method that utilizes the sound energy to shake particles or intermittent fibers in a liquid. As frequency larger than > 20 kHz is used in this method, it is also known as ultrasonication method. Sonication usually conducted by either an ultrasonic bath

Table 2 Detailed summary of NFs enhanced FPSCs.

NPs Type	Base fluid	Particle size (nm)	Concentration (wt%) (%) (vol%)	Flow rate	Study type	Collector area (m ²)	Main findings and remark	Ref.
Al ₂ O ₃ CuO	Water	20	0.5, 1.0, and 1.5 were used for Al ₂ O ₃ nanofluid, and 0.1, 0.3, 0.5, 0.7 for CuO nanofluid.	0.047 kg/s	E	2.03/1.912/1.877	- The highest efficiency obtained was 77.5 % and 73.9 % at 0.01 wt% for Al ₂ O ₃ and CuO nanofluids, respectively.	[61]
		40					- The exergy efficiency of FPSC at 1.0 wt% Al ₂ O ₃ and 0.5 wt% CuO nanofluids improved by 59.6 % and 49.6 %, respectively.	
Cu	Water	25 and 50	0.01, 0.02, 0.04, 0.1 and 0.2	140 L/h	E	2	- The efficiency of FPSC enhanced by 23.83 % using Cu/H ₂ O nanofluid at 0.1 wt%, - The water temperature and heat gain of FPSC increased by up to 12.24 % and 24.52 % at 0.1 wt%.	[62]
MgO	Water	40	25, 0.5, 0.75, 1.0, 1.25 and 1.5	Up to 5 l/min	E	0.375	- Enhancement of thermal and exergetic efficiencies was respectively 9.34 % and 32.23 % at 0.75 % and flow rate of 1.5 lpm. - Reduction of collector area by 12.5 % was obtained.	[63]
SiO ₂	Ethylene glycol/ Water (50:50 vol.%)	40	0.5, 0.75, and 1	0.018, 0.032, and 0.045 kg/s	E	1.59	- FPSC efficiency enhanced by 4–8 % - The efficiency of FPSC based nanofluids at 0.75 wt% and 1 wt% was very close to each other.	[64]
MWCNTs	Distilled water	20 μm length and 10–40 nm diameter	0.01, 0.05 and 0.1	0.375529, 0.5042 0.46835 and 0.41823 l/min	E	2	- FPSC efficiency increased by 16 %, 21 %, 34.13 % at 0.01 wt%, 0.05 wt% and 0.1 wt%, respectively compared with that based distilled water. - Reduction of collector size obtained by 34 %.	[65]
TiO ₂	Water	21	0.1 and 0.3	0.5 to 1.5 kg/min	E	1.84	- Increment of energy efficiency by 76.6 % and exergy efficiency by 16.9 % at 0.1 wt% and 0.5 kg/min flow rate.	[66]
SWCNTs*	Water	1–3 μm length and 1–2 nm diameter	0.1 and 0.3	0.5, 1.0 and 1.5 kg/min	E	1.84	- Enhancement of energy and exergy efficiency of 95.12 % and 26.25 %, respectively, was achieved.	[67]
Al ₂ O ₃ TiO ₂ Al ₂ O ₃ /TiO ₂	Water	20	0.1	1.5, 2.0 and 2.5 l/min	E+N	1.85	- FPSC thermal efficiency enhanced by 19 %, 21 %, 26 % using Al ₂ O ₃ , TiO ₂ and their mixture, respectively.	[68]
		15 (20/15)					- Increase the concentration of hybrid nanofluid from 0.1 wt% to 0.2 wt% improved the thermal efficiency of FPSC by 5 %.	
CF-MWCNTs CF-GNPs/ h-BN	Distilled water	CF-MWCNTs (5 μm length and 15 nm diameter. CF-GNPs (Max. 2 μm)	(20/20/60)	2, 3 and 4 l/min	E	1.89	- Highest thermal efficiency of FPSC by up to 85 % was obtained.	[69]
CuO	Water	75	0.05	0.01 and 0.1 kg/s	E	2.184	- Thermal performance of the solar system improved by 6.3 %.	[70]
Al ₂ O ₃	Water	20	1	1, 2 and 4 l/min	E	1.51	- FPSC efficiency increased by 23.6 %.	[71]
WO ₃	Water	90	0.0167, 0.0333 and 0.0666	0.0156, 0.0183, and 0.0195 kg/s m ²	E	1.78	- Max. FPSC efficiency enhanced by 71.87 % at 0.0066 vol%, - The absorbed energy parameter enhanced by 13.48 %.	[72]

NPs Type	Base fluid	Particle size (nm)	Concentration (wt%)(%) (vol%)	Flow rate	Study type	Collector area (m ²)	Main findings and remark	Ref.
SiO ₂	Water	12	1	0.35–2.8 l/min	E	1	- Up to 59 % thermal efficiency reached.	[73]
Al ₂ O ₃	Water	20, 50 and 100	0.5, 1.0 and 1.5	0.047 kg/s	E	2	- FPSC maximum efficiency of 74.9 % obtained at 20 nm and 1.0 vol% which is 14.8 % higher than water.	[74]
GNNPs	Water	2 nm lateral size, 2 nm thickness	0.025, 0.075 and 0.1	0.0133, 0.0200 and 0.0260 kg/s m ²	E	0.4645	- Highest thermal performance of FPSC of 78 % obtained at 0.1 wt%, which is 18.2 % higher than water as a working fluid.	[75]
ND-Co ₃ O ₄	Water	N/A	0.05, 0.1 and 0.15	0.56–1.35 L/min	E	3	- Thermal conductivity and viscosity of base fluid enhanced by up to 15.71 % and 45.83 %, respectively at 0.15 % concentration. - The thermal efficiency of FPSC improved by 59 % for at 0.15 % concentration against that of water which was 48 %.	[76]
Al ₂ O ₃ Fe Al ₂ O ₃ /Fe	Water	29 46 84 (1:1)	0.05, 0.1, and 0.2	0.00–0.07 kg/s	E+N	1.51	- Al ₂ O ₃ -water at 0.1 % concentration enhanced FPSC thermal efficiency by 2.16 %, while it has been reduced by 1.79 % for Al ₂ O ₃ /Fe compared to the water alone. - Al ₂ O ₃ /Fe provides 56 % and 72 % heat transfer coefficient compared with the water base fluid. - The hybrid nanofluid provided an exergetic efficiency enhancement of 6.9 % against 5.7 % for Al ₂ O ₃ -water nanofluid.	[77]

Notes:- E: Experimental; N: Numerical; SWCNTs: Single Wall Carbon Nanotubes; CF-MWCNTs: Covalent Functionalized-Multi Wall Carbon Nanotubes, CF-GNNPs: Covalent Functionalized-Graphene Nanoplatelets, h-BN: hexagonal Boron Nitride, ND-Co₃O₄: Nanodiamond-cobalt oxide.

Table 3 Improvements of systems driven by FPSCs based NFs.

Application	FPSC(s) Area (m ²)	NF characteristics (water is the base fluid in all cases)			Flow rate	Main findings and remark	Ref.
		Type	Particle size (nm)	Concentration			
Solar domestic hot water	1.2	GNPs	2 μm diameter, and 2 nm thickness	0.0005 %, 0.001 % and 0.005 %	0.0075, 0.015 and 0.225 kg/s	- FPSC efficiency improved by 83.54 %, 89.71 % and 93.24 % at 0.0005 %, 0.001 % and 0.005 % concentration, respectively which is suitable for domestic hot water applications. - SiO ₂ /water enhanced the evaporation rate of solar still at high temperatures, whereas, Cu/water performed better at low temperatures compared with pure water-based FPSC.	[78]
Solar distillation	4.6	SiO ₂ Cu	7 40	0 %, 0.5 %, 1 % and 2 %	5 × 10 ⁻⁵ , 6.67 × 10 ⁻⁵ , and 8.33 × 10 ⁻⁵ m ³ /s	- The best performance of FPSC based Cu/water at 4 % concentration where the yield, thermal efficiency, and exergy efficiency of the solar still were enhanced by 9.86 %, 9.91 %, and 11.8 %, respectively. - On a daily basis, the use of Cu/water at 2 % concentration enhanced the performance of FPSC. It improved the parameters of the chiller as follows: collector exergetic efficiency (2.25 %), chiller exergy efficiency (0.62 %), system exergy efficiency (3.99 %), collector thermal efficiency (1.02 %), system coefficient of performance (COP) and daily cooling production (0.84 %).	[79]
Absorption chiller	100	Cu	100	0 %–2 %	2 m ³ /s	- The highest increase in the system efficiency was achieved by CuO/water, whereas the lowest was obtained by TiO ₂ /water. - At 0.2 % particle concentration, the maximum efficiency obtained was 71 %, 87.8 %, and 52.5 % for Al ₂ O ₃ /water, CuO/water and TiO ₂ , respectively.	[80]
Hot water solar energy system	2	Al ₂ O ₃ CuO TiO ₂	< 50 < 50 < 25	0.2 %, 0.4 % and 0.8 %	250 l/h	- The maximum daily thermal efficiency of CCHP system improved by 38.61 % and exergy efficiency improved by 17.03 %, compared with the water as a working fluid.	[81]
Combined Cooling, Heating and Power (CCHP) system	395	CuO	N/A	0.00 %–0.02 %	N/A	- The increase of NF concentration up to 2 % increased the efficiency of the solar collector by 5 % compared to the collector based water. Therefore, the efficiency of solar heating systems was improved using NFs.	[82]
Solar heating system	2	CuO	25	0.1 %, 0.5 %, 1 %, 1.5 %, 2 %, 2.5 %, 3 % and 3.5 %	0–0.02 kg/m ²	- The COP of solar cycle was increased by 17.98 % and 14.51 % using CuO and Al ₂ O ₃ respectively, at 5 % concentration.	[83]
Solar absorption refrigeration cycle	325	CuO Al ₂ O ₃	N/A	0 %–5 %	N/A	- The total product cost rate decreased by 10.4 % and 5.35 % using CuO and Al ₂ O ₃ nanofluids with 5 % concentration. - CuO nanofluid was more preferred in terms of decreasing the exergy-based cost of cooling.	[84]
Solar desalination	N/A	CuO	N/A	0.05 %	N/A	- The maximum mass of steam produced from the solar distiller was 71.72 kg. - CuO/Water increased the volumetric efficiency by 66.23 % against 58.36 % for the system without NF.	[85]

or probe (Fig. 11). This method is often used for dispersing NPs into base fluids, de-agglomeration of NPs, reducing the particle size, synthesis of particles and precipitation [91]. The main limitation of the sonication method is that optimal sonication time is not determined [92]. Furthermore,

the stability of NF influences when the sonication time exceed the optimal sonication time [93]. A magnetic stirrer is another effective method for stable nanofluid preparation by increasing its homogeneity and decrease the sedimentation. As shown in Fig. 11, there are two knobs

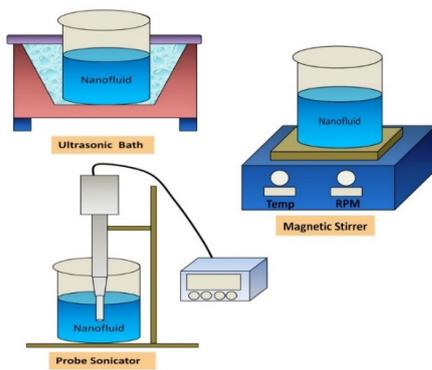


Fig. 11 Sonication and magnetic stirring methods [95].

in the magnetic stirrer; one for stirring speed rate and the other for heating. The magnetic stirring speed has to be optimized to avoid the formation of bubble throughout the preparation of NF [94]. Nevertheless, this method cannot keep NF stable for a long time and not effective at high concentrations of NPs [95]. Therefore, sonication is often used after magnetic stirring [96]. Surfactants are a simple method, and effective chemical method applies to reduce the surface tension of the base fluid and improve the immersion of NPs for long term stability [97]. Surfactants are generally divided into four categories based on head composition; namely ionic (long-chain fatty acids, alkyl sulphates, sulfosuccinates, phosphates, and sulfonates), nonionic (polyethylene oxide, alcohols), cationic (long-chain quaternary ammonium compounds and long-chain amines), and amphoteric surfactants [98]. The quantity of surfactant added should be appropriately studied because the thermal conductivity of NF will decrease when the proper surfactant amount is exceeded [92].

Most of the researchers indicated that instability increased as the concentration of NPs in the base fluid increased; hence the search for NFs of high thermal performance with lowest concentrations is required [99]. To evaluate the instability of NF, several methods can be applied, as shown in Fig. 12.

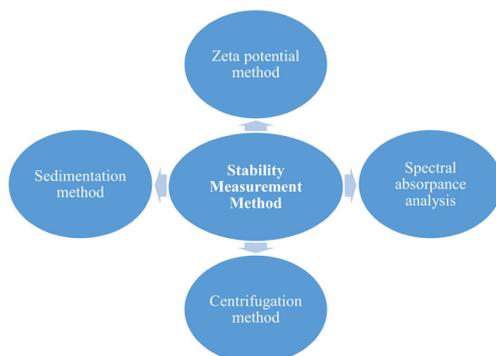


Fig. 12 Stability evaluation methods [33].

4.2 Viscosity increment

Fluid viscosity is the other issue facing the applicability of NFs in FPSC applications. Addition of NPs to the base fluid increases the viscosity of NF compared with the base fluid, which causes a higher pressure drop in pumping power. Therefore, the efficiency of the solar collector will be minimized eventually. Although most of the research work dealt with the effect of NPs concentration on fluid viscosity, there is lack of investigations in the other related effect factors such as the type of base fluid, application temperature limit, the size and shape of NPs [100]. Practically, in better use of NFs in thermal applications, there is a trade-off between the augmentation in thermal conductivity and increase in viscosity, taking into account the type of NPs, concentration/volume fraction, fluid temperature, shape, and size of NPs [101].

4.3 Concentration limit

Numerous literature studies revealed that the higher concentration of NPs the more enhancement of FPSC thermal efficiency. However, some studies reported that this enhancement has a limit. Yousefi et al. [102] found that the efficiency of FPSC at 0.2 % concentration of carbon nanotube-water NF is lower than the efficiency of the case where water was used alone as the base fluid. They also stated that the FPSC efficiency was significantly increased back at 0.4 % concentration. He et al. [62] reported that the efficiency of FPSC based Cu-H₂O nanofluids of 25 nm particle size at 0.2 wt% was lower than that of Cu-H₂O nanofluids at 0.1 wt% under the same particle size. Okonkwo et al. [77] indicated that the Al₂O₃-Fe/water hybrid NF decreased the thermal performance of FPSC by 1.79 % compared to the case of the water-based fluid. These inconsistent results call the attention of researchers to conduct more investigation in this field and imply that an optimal limit of concentration exists for each NF type.

4.4 Corrosion effect

Few authors investigated the effect of NPs corrosion on the surfaces where the NFs flow. Study of this feature is necessary as it could limit the applicability of NFs instead of traditional ones. Fotowat et al. [103] studied the effect of three NPs (aluminum, copper, and stainless steel) mixed with water base fluid on the metallic surfaces. They concluded that the copper particles possessed the highest corrosion rate; whereas stainless steel particles showed the lowest. Prajitno and Syarif [104] investigated the corrosion effect of ZrO₃ based NF on carbon steel under various temperatures ranged from 25 to 55 °C. The study concluded

that the corrosion rate gets faster as the temperature of NF increased. Several researchers such as [105] and [106] proposed successful additives and techniques that should adopt NFs in specific material surfaces. However, more research on the effect of corrosion of NPs in FPSCs applications is still in need.

4.5 Others

Several researchers reported other obstacles in the way of NFs practical adoption. The design of collector of heat exchanger pipes can affect the performance of NF by influencing fluid flow velocity as well as its thermal behaviour [107]. Colangelo et al. [108] revealed that flow velocity is the main factor affecting the sedimentation of NPs due to the poor design of standard FPSC heat exchanger. They fabricated a new collector prototype considering the change in the cross-section of the lower and top header in a way to keep the fluid axial velocity constant. This technique guaranteed no sedimentation of the tested NF (i.e. Al_2O_3 -water) over working time. It is also worth mentioning that the NPs are usually expensive either due to material itself (Ag for example), or the complicated manufacturing procedure. Therefore, it can be accounted for as another important obstacle for different solar thermal applications especially for those requiring large amount of working fluid [109, 110].

5 Conclusions and future recommendations

Applications of nanofluids in FPSCs to enhance the overall thermal performance are reviewed in this paper. A general overview of nanofluids, classification and preparation methods are briefly presented, and their thermal performance on FPSCs are discussed and analyzed. Further, the main obstacles to their applicability and commercialization are highlighted. Based on the reviewed experimental studies, several conclusions and recommendations for future work can be made as follows:

- Most of the studies reported that the efficiency of FPSC incorporating NFs improved significantly over those utilizing the traditional working fluids. The improvement mainly was associated with NPs concentration, where the higher concentration resulted in higher thermal performance. However, such benefit increases the operational cost and fluid instability as well. Seeking for new types of NFs that offer an acceptable improvement in solar collector performance at lower cost and concentration is recommended.
- Hybrid NPs showed higher enhancement in the thermal efficiency than single NPs in most cases. Unfortunately, limited studies have been conducted to investigate the potential of hybrid NFs for enhancing FPSC thermal performance, and most of them were at the laboratory level. Although most of the reviewed studies were experimental, more practical studies dealing with new mixture types at different concentrations and base fluids are needed to determine the feasibility of this technology [110].
- Generally, Al_2O_3 nanoparticles are the most widespread NP type among the performed experimental studies, and the water is extensively used as a base fluid with different NP types. More research is needed to investigate the behaviour of new nanoparticles and base fluids.
- All in all, NF instability still represents a significant challenge as most of the stability enhancement studies reported the instability during their experiments [111]. Therefore, more extended stability studies are still in need for technology commercialization.
- The economic and environmental influences of using such fluids in FPSCs are still out of view [112]; therefore, more study considering techno-economic and environmental analysis is necessary to assess their viability in such applications.

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