Enhancing the thermal performance of solar collectors using nanofluids

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Abstract
Solar energy remains the most ubiquitous and inexhaustible source of energy. This energy can be utilized by several approaches including the use of solar collectors. Several studies have illustrated that the efficiency of solar collectors can be significantly improved by the introduction of nanofluids which have shown improved thermal conductivity up to 160% with a subsequent reduction in greenhouse gases such as CO2. To produce nanofluids, nanoparticles such as Al2O3, hybrid ZnO + Al2O3, and metals (Al, Cu) particles are dispersed into the based fluids such as water, glycerol, and bio-fluids. The added nanoparticles enhance the viscosity, absorption rate, convective heat transfer coefficient and heat losses of the fluid. The performance of details the applications and effectiveness of different nanofluids in four types of solar collectors - parabolic trough, flat plate, direct absorption, and evacuated tube. In addition, the work sheds light on the future trend and challenges of nanofluids (including toxicity) in solar collectors. Regardless of its toxicity, researchers have shown more interest in nanofluids use in solar collectors because of its strong sustainability to a safe environment and the exploration of hybrid nanofluids to better enhance solar collectors. Solar collectors can also be modulated by using different nanofluids at varying concentrations.

Keywords: Nanofluids, Solar collectors, Parabolic trough solar collector, Flat plate solar collector (FPSC), Direct absorption solar Collector (DASC), Evacuated tube solar collector (ETSC), Thermal Efficiency
1. Introduction

Energy researchers and policy makers are shifting focus from non-renewable energy, such as oil and coal, to renewable sources such as solar, wind and geothermal. This is strongly connected to the fact that the combustion of oil/coal produces environmental pollutants or greenhouse gasses and subsequent leads to depletion of the ozone layer. Various solutions have been proposed to ease the transition between these energy sources with solar energy utilization occupying the forefront [1]. Although solar energy has been utilized from the time immemorial, achieving maximum energy conversion with minimum waste remains a challenge [2-3]. Different solar technologies have been developed to convert sun radiation into thermal energy (e.g. thermal collectors) or electrical energy (e.g. solar panels). However, the cost of development and operation coupled with low conversion efficiency remains a huge challenge [4-7]. Solar collectors, which convert solar irradiance into thermal via heat exchanging fluid, have low efficiency with relatively high initial cost. To enhance the collectors’ efficiency, studies have shown that the addition of nanoparticles such as ceramics oxide (Al₂O₃, CuO), non-metals (Graphite and Carbon nanotubes), metals (Ag, Fe) with associated high thermal conductivity can significantly increase thermal conversion efficiency [8-9]. This review examines the progress made thus far with the application of nanofluids in various solar collectors.

1.1 Solar Collectors

A solar collector is a device that actively gathers solar radiation, convert it to heat and transform such heat to a receiving medium such as air, water or solar fluid which is then used for domestic purposes. Solar collectors are divided into two main categories. The concentrating solar collectors are designed to track the sunlight to fully absorb radiation from the sun. This collector can be one axis such as parabolic trough, cylindrical trough and linear Fresnel collector, etc or two axes sun tracking collector such as parabolic tower, parabolic dish, circular Fresnel solar collector etc. The non-concentrating solar collectors use liquid or air as the absorbing medium. Flat-plate solar, vacuum tube, compound parabolic, and bowl collectors make use of heated liquids while ventilated cartridge and uncoated transparent solar collectors utilize heated air.
1.1.1 Parabolic Trough Solar Collector

Parabolic Trough Solar Collector (PTSC) is desirable for Medium-Temperature applications usually in the range of 100 °C to 400 °C [10]. Of the available concentrating solar power technologies, parabolic trough collectors are favored to be the most commercially proven technology owing to its numerous advantages such as high storage capacity, hybrid concept, modular system, low operating cost, and land use factor [11]. PTSCs are “U” shaped concentrators constructed as a linear parabolic mirror to concentrate sunlight on to the absorber tube that is situated along its focal line (Figure 1). The heat transfer fluid absorbs solar radiation energy and recirculates it through the pipe located along with the focal point. The receiver surface is usually covered with a selective coating that has low irradiance and high solar radiation absorption for thermal radiation. To reduce the convective heat loss in the vacuum region between the absorber and the glass cover, the absorber tube is wrapped with a transparent material [12]. By employing a tracking mechanism, the movement of the sun from east to west is successfully tracked as PTSC is aligned to the north-south axis. The tracking mechanism employed in parabolic trough could either be single-axis or dual-axis.

Parabolic Trough Solar Collect has a concentration ratio of 30-100 and receiver temperature of about 400 °C. It allows for efficient solar power generation and is currently used in many solar thermal generation plants. PTSC accounts for about 90% of the total available energy from the concentrator solar panel system [13]. Hence, the desire to improve its performance by enhancing the functionality of the components such as reflector, receiver tube, support structure, and tracking system.

The critical section of a parabolic trough solar collector is the heat transfer fluid flowing within the tube, which is typically a mixture of water or hot oil and other additives such as nanoparticles that increase the heat transfer rate. The temperature at which the fluid is injected through the tube and absorbs heat from the sun exceeds 200 °C. The heat exchanger is then used to transfer the heated fluid for domestic use. Compared to the traditional parabolic trough concentrators, nanofluidic concentrated parabolic solar collectors (NCPSC) have better energy absorption and conduction heat transfer performance [14]. The application of nanofluids as working fluids in parabolic trough solar collectors (PTSC) is receiving increasing attention.
Figure 1. Diagrammatic representation of a Parabolic Trough Solar Collector [15]

1.1.2 Flat Plate Solar Collector
Flat plate solar collector was developed in the 1950s, and several techniques and methods have been deployed to enhance its thermal performance and efficiency [16]. A flat plate solar collector consists of various components such as aluminium rails, insulation, absorber, glass, back sheet, riser and header pipes. The surface is covered with glass for optimal heat transmission to the absorber. For high efficiency, absorbers are made from aluminium coated with a high absorbing material [17-18].

Figure 2. Typical representation of a flat plate solar collector

1.1.3 Direct Absorption Solar Collector
Direct Absorbed Solar Collector is a simplified approach to solar energy collection. This technique was originally proposed in the 1970s as a way of absorbing solar energy directly within the fluid media. Recently, direct absorption solar collectors (DASC) based on nanofluids have been proposed [19-29] and it is considered as the newer class of collectors with enhanced energy utilization capability [30]. DASC has shown potentials for efficient solar-to-thermal energy conversion with excellent stability and high solar energy absorption capabilities [31]. DASC uses nanofluid for both
solar absorption medium and heat-transfer fluid [32] and has no absorber plate [33]. Unlike solid absorber, this technique eliminates intermediate heat transfer medium [31] and can utilize parabolic trough and dish, linear Fresnel collector and heliostat field collector (solar tower) among others [34].

1.1.4 Evacuated tube solar collector
This solar collector is made up of evacuated glass pipes with outer and inner tubes. The transparent form of the outer tube allows light rays to penetrate reaching the inner tube where it is absorbed. For maximal absorption, a copper pipe is welded and coated to an absorber plate before being inserted (Figure 3). Due to the minimal reflection of both tubes, sun rays penetrate through the outer tube while the heat is reserved inside the inner tube. Solar radiation trapped between two tubes by creating a vacuum that is then fused on top of each other with no trapped air. The radiated heat from the sun stays inside the inner tube where it is effectively utilized. Therefore, ETSC is considered as a great device for an efficient collection of solar energy [35].

Figure 3. Schematic representation of direct absorption solar collector

Figure 4. Evacuated tube Collector with the Inner and Outer tube [35]
2. Nanofluids
Nanofluids (NFs) are fluids containing nanoparticles (particles of size less 100 nm). They are produced by suspending nanoparticles in a base fluid usually water. Its use has been found to produce desired heat transfer when compared with conventional base fluid [36]. Most nanoparticles used in producing NFs are metals, non-metals, carbon nanotubes among others. Nanofluids are very useful in heat transfer and have found applications in fuel cells, boiler flue gas temperature, heat exchanger reduction, and vehicle thermal management. NFs have shown good thermophysical properties like viscosity, optical absorption, thermal diffusivity which has helped to improve the performance of solar collectors.

2.1 Nanofluids preparation
2.1.1 One step method
Generally, the preparation of nanofluids requires a setup comprising a cylindrical drum with an upper section, a lower section, and an inner surface. The base liquid is poured into the lower section forming the base liquid pool. A material that is capable of evaporating is then provided to serve as the nanoparticle. A stirrer is then used to create a speed equal to or exceeding the speed required to drag part of the liquid in the liquid pool creating a rotating liquid film along the inner surface of the drum. The evaporating material is positioned in proximity to the rotating liquid film with heating that is sufficient to evaporate the evaporant to form nanoparticles, the formation of the nanoparticles inside the rotating liquid film forms the nanofluid (Figure 5). A one-step method is simply the process by which particles in nanocrystalline forms are produced by deposition onto a low vapor-liquid. Nanoparticles produced via a one-step method avoids at a lot of processes such as dispersing, drying storage which is viewed with massive potential but its shortcoming is that nanoparticles less than 10 nm cannot be processed to form nanofluid.

Figure 5. Schematic representation of the one-step method for the production of nanofluid
2.1.2 Two-step method

This is the widely accepted method used in the production of nanofluids. The steps involve the production of nanoparticles, either metallic oxides or from pure metals which are then dispersed into the base fluids with some degree of agitation (Figure 6). The problem associated with this method is the continuous agglomeration of the nanoparticles after mixing. The clustering can be minimized by adding surfactant as seen from various studies. However, surfactants can break down at very high temperatures. A combination of two-step and one-step method has been reported to form stable nanofluids.

![Figure 6. Schematic representation of the two-step method for the production of nanofluids](33)

2.2 Properties of Nanofluids

The addition of nanoparticles enhances convective heat transfer coefficient about tenfold especially when they are properly dispersed. Furthermore, nanofluids with great volume fraction have a high thermal conductivity which increases with temperature. Also, both optical and absorption rate can be improved by using nanofluids. This is in addition to higher thermal diffusivity and viscosity.

3. Nanofluid based parabolic trough solar collector

Bellos et al. [37] classify nanoparticles being used in solar collectors into metallic nanoparticles such as Fe, Cu, Zn, Al, Au, and non-metallic nanoparticles such as Al₂O₃, Fe₂O₃, SiO₂, TiO₂, ZnO, single-walled carbon nanotubes (SWCNT), and multi-walled carbon nanotubes (MWCNT). Nanofluids thermal conductivity is majorly influenced by the diameter and dispersion of constituent nanoparticles. About 41% of nanofluids based research utilized Al₂O₃, which is followed by CuO and then TiO₂. About 30% of the published works on nanofluid based solar collectors are experimental. In these studies, the impact of different nanofluids and the percentage of nanoparticles have been the major focus. For instance, Sharma et al. [38] compared the influence of Al₂O₃/water and CuO/water at 0.01 and 0.05
vol. % on the thermal performance of PTSC. The results show that 0.05 vol.% CuO has the maximum overall thermal efficiency of 15.25% compared to 12.39% and 10.58% for Al₂O₃/water and water, respectively. This translates to a 44% increase in efficiency when 0.05 vol.% CuO/water nanofluid is used compared to water as the base fluid.

Compared to Sharma et al. [38], moderate increase in concentration of Al₂O₃ to 0.06 vol.% improved thermal efficiency by 28.95% [40]. Similarly, the heat transfer coefficient, thermal efficiency and Nusselt number were enhanced by 32%, 7%, and 32%, respectively for 1 vol% Al₂O₃ [42]. In addition, Subramani et al. [45] reported an 8.54% increase in the thermal behaviour of the PTSC at 0.5 vol % of Al₂O₃. Kandwal et al. [41] studied two nanofluids, CuO/water, and CuO/ethylene glycol at different concentrations (0.01, 0.05, and 0.1 vol. %) and flow rates. The results show that the highest thermal efficiencies of 11.01%, 8.03%, 7.46%, and 6.04% were obtained for CuO/water, CuO/ ethylene glycol, water, and ethylene glycol, respectively at 160 L/h. This implies 82% increased thermal efficiency for CuO/water nanofluid in comparison with ethylene glycol. Menbari et al. [44] conducted both experiment and numerical research to study the effect of CuO/water nanofluid on thermal efficiency and temperature distribution in a direct absorption parabolic trough collector for a different range of volume fraction. The results show that thermal efficiency improves by 18-52% for 0.002–0.008 vol.% CuO nanoparticles.

Coccia et al. [43] reported no significant change in thermal properties when Fe₂O₃, SiO₂, TiO₂ and ZnO nanoparticles were used. However, 0.01 vol.% Au/water nanofluids raised convection heat transfer by approximately 50%. Another experimental study carried out on the effect of MWCNT/mineral oil (with 0.2 and 0.3 wt %) on the performance of PTSC indicates a 5-7% increase in thermal efficiency [39]. In another study, however, 0.3 vol.% MWCNT/ethylene glycol improved thermal efficiency by 30.4% compared to 14% for 0.3 vol.% SiO₂/EG [46]. The summary of previous works is shown in Table 1.
Table 1. Summary of experimental works conducted on the nanofluid usage in PTSC.

| Study            | Nanofluid  | Nanoparticle | Max. Increase% | Finding(s)                                      |
|------------------|------------|--------------|----------------|------------------------------------------------|
|                  | Type       | φmax         | Size (nm) | θth | h | ΔP |                      |
| Sharma et al. [38]| Water      | Al₂O₃, CuO   | 0.05 vol. % | 20–40 | 44 | - | CuO had the highest thermal efficiency. |
| Kasaeian et al. [39]| Mineral oil| MWCNT        | 0.3 wt % | 10  | 7 | - | The first study uses carbon nanotube as nanoparticle in PTSC. |
| Siva Reddy et al. [40]| Water     | Al₂O₃        | 0.06 vol. % | <50 | 28.98 | - | Minimization of losses and prevention of nanoparticles settlement can augment the thermal efficiency of PTSC. |
| Kandwal et al. [41]| EG, Water  | CuO          | 0.1 vol. % | 25–55 | 82 | - | CuO/water nanofluid had better thermal efficiency in comparison with CuO/EG nanofluid. |
| Chaudhari et al. [42]| Water     | Al₂O₃        | 0.1 vol. % | 40 | 7 | 32 | Nusselt number increases by application of nanofluid. Although, an asymptotic trend was observed after nanoparticle volumetric concentration of 0.2%, the maximum efficiency achieved at 0.5% volume fraction. |
| Subramani et al. [45]| Water     | Al₂O₃        | 0.5 vol. % | 40–50 | 8.54 | - | The optimal nanoparticle concentration was proposed to be 0.2% by parametric study (Semi) empirical equations were obtained for Nusselt number, friction factor and collector efficiency using experimental data. |
| Kasaeian et al. [46]| EG        | MWCNT, SiO₂  | 0.3 vol. % | 4,6 | 30.4 | - | MWCNT/EG was more efficient nanofluid in term of higher thermal efficiency than SiO₂/EG. |
| Sekhar et al. [47]| Water     | CeO₂, Al₂O₃, TiO₂ | 3 vol. % | - | 27 | - | (CeO₂)/water nanofluid had the highest thermal efficiency enhancement followed by alumina and titania nanofluids. |
| Coccia et al. [43]| Water     | Fe₂O₃        | 20 wt % | - | ~0 | ~50 | Application of nanofluid didn’t cause thermal... |
| Study                                | Nanofluid Composition   | Volume Fraction | Thermal Efficiency Increase | Collector Efficiency Enhancement |
|--------------------------------------|-------------------------|-----------------|-----------------------------|----------------------------------|
| Rehan et al. [48]                    | Water, Al₂O₃, Fe₂O₃     | 0.30 wt %       | 20-40                       | Al₂O₃/water had a higher thermal efficiency enhancement compared to Fe₂O₃/water nanofluid. |
| Subramani et al. [49]                | Water, TiO₂             | 0.5 vol. %      | 20                          | Nanofluid has higher absorbed energy factor compared with the base fluid. |
| Marefati et al. [50]                 | Water, Al₂O₃, CuO, SiC  | 5 vol. %        | -                           | CuO/water nanofluid is the best option for thermal efficiency enhancement followed by alumina and SiC nanofluid. |
| Okonkwo et al. [51]                  | Therminol VP-1, Al₂O₃, CuO, Fe₃O₄ | 3 vol. %       | 0.22                        | Al₂O₃/Therminol VP-1 nanofluid is the best practical fluid to achieve the highest efficiency followed by CuO/Therminol VP-1, and Fe₃O₄/Therminol. |
| Alsaady et al. [52]                  | Magnetic nanofluids     | 0.05 vol. %     | 25                          | The application of ferrofluid in PTSC seems to be a promising field of study. |
| De Los Rios et al. [53]              | Water, Al₂O₃            | 3 vol. %        | 10                          | An experimental study was conducted on the thermal efficiency of parabolic trough linear concentrator collector. |
| Okonkwo et al. [54]                  | Pressurized water, OLE-TiO₂, BH-SiO₂ | Up to 0.05 vol.% | 70, 100, 0.08, 138, 14.25 | The incident angle of the collector had an important role in enhancing the thermal efficiency of the collector (a small increase in incident angle can cause thermalefficiency enhancement) |
| Menbari et al. [44]                  | Water, CuO              | Up to 0.008 vol. % <100 nm | 52% | A general trend of increasing thermal efficiency (ranging from 18–52%) having nanoparticle volume fraction increase (from 0.002% to 0.008%) when water/CuO nanofluid was used in direct absorption parabolic trough collector by comparison with the base fluid. |
Another approach being employed to study the influence of nanofluids on the thermal performance of solar collectors is numerical analysis. Numerical studies account for about 60-70% of published articles in this area and is largely a cost saving approach. Numerical analysis is mostly done using commercial software such as ANSYS Fluent, COMSOL, SolTrace and EES among others. The first numerical study, conducted by Kasaeian and Sokhansefat [55], utilized CFD to study the role of Al$_2$O$_3$/synthetic oil nanofluid in PTSC at 1-5 vol. % of Al$_2$O$_3$. It was found that 5 vol.% Al$_2$O$_3$ enhanced the heat transfer coefficient by ~14% at 300K. At 500K however, nanoparticles effect was insignificant. Similarly, Sokhansefat et al. [56] studied the effect of Al$_2$O$_3$/synthetic oil by simulating flow through an absorber tube at 1–5 vol.%. At 5 vol.% the convection heat transfer in PTSC was increased by 14–15%. The influence of higher temperature is similar to that reported elsewhere [55]. As an improvement over the previous studies, Zadeh et al. [57] investigated the effect of using Al$_2$O$_3$/synthetic oil (with 0-6.5 vol. %) using a hybrid optimized model coupled with CFD analysis. The proposed model improved the maximum convection heat transfer coefficient by 36% at 300K. In another study [36], 4 vol.%, 6 vol.% and 8 vol.% Al$_2$O$_3$/synthetic oil nanofluids enhanced convective heat transfer coefficient by 35, 54 and 76%, respectively. About 40% increase in pressure drop at 4 vol.% was also reported implying more pumping power.

For 6 vol.% CuO/syltherm 800 nanofluid, the maximum increase in the heat transfer coefficient and thermal efficiency are 38 and 15%, respectively [58]. Pressure drop was also reported by Bellos and Tzivanidis [37], where they simulated Al$_2$O$_3$/water nanofluid by minimizing entropy generation and maximizing different volume fractions of Reynolds number for Al$_2$O$_3$ located at different sections of a circular tube. The results show that for a given Reynolds number, the heat transfer performance (Nusselt number) and the value for friction factor are almost the same regardless of the volume fraction. Also, it was verified that there is an optimum cross-section of the tube that causes a minimum generation of entropy. An 18% increase in convective heat transfer was reported by Basbous et al. [61] in their numerical investigation of Al$_2$O$_3$/syltherm 800 nanofluid in the range of 1-5%. For the same system, Bellos et al. [62] reported a 4.25% increase at 2 vol.% Al$_2$O$_3$. They also reported a 6.34% increase in thermal efficiency when pressurized water was used as a working fluid. However, the application of pressurized water requires more effort which makes its utilization less acceptable.

The effects of different volume fractions (0.5-5%) of Al$_2$O$_3$/hot oil nanofluid on the performance of PTSC were studied by CFD simulations [63]. It was reported the efficiency
enhancement around 1.2% in their model (at 5% volume fraction). They also found that increasing the nanofluid volume fraction can lead to a slight decrease in the longitudinal displacement of the absorber. Similarly, the horizontal displacement of the absorber was reported to slightly decrease by volume fraction increase.

Kaloudis et al. [64] conducted a CFD simulation to investigate the effect of different volume fractions (0.5-4%) of Al₂O₃ in Al₂O₃/syltherm 800 nanofluid on PTSC performance. They used two different modelings for nanofluid: two-phase simulation and one phase simulation. They concluded that utilizing two-phase modeling of nanofluid had more accuracy in the results. More specifically, the numerical results suggested a maximum of 10% thermal efficiency enhancement at a maximum Al₂O₃ volume fraction of 4%.

Benabderrahmane et al. [65] numerically modelled the effect of utilizing nanofluid as well as internal fins in the receiver of PTSC using CFD. In a report [66], conclusions were made that combining both internal fins and nanofluid applications can enhance the heat transfer behaviour of the PTSC greatly. To be specific, the authors utilized four different nanofluids (Al₂O₃/Dowtherm A, Cu/Dowtherm A, SiC/Dowtherm A, C/Dowtherm A) at different volumetric concentration of 1% and found that the metallic nanofluids (Cu/Dowtherm) had better thermal enhancement performance comparing with non-metallic ones (SiC/Dowtherm A, C/Dowtherm A, Al₂O₃/Dowtherm A). Also, the friction factor reported being higher when nanofluid is applied. A 68% increase in convection heat transfer coefficient was reported [67].

Ghasemi et al. [68] performed numerical simulations of Al₂O₃/water and CuO/water as working fluids at different volume fractions, 0.5-3%, in PTC were investigated. They realized that the application of 3% CuO/water nanofluid could lead to a higher convection heat transfer coefficient compared with Al₂O₃/ water and water itself. Although CuO/water nanofluid caused a 7% more increase in heat transfer coefficient compared with Al₂O₃/water nanofluid (35% compared with 28% enhancement), the friction factor caused by the application of Al₂O₃ was lower than the one caused by CuO.

Mwesigye et al. [69] conducted another CFD simulation on Cu/Therminol VP-1 nanofluid and the effects of nanofluids with different volume fractions (1-6%) on the thermal and thermodynamic properties of PTSC were studied. At a maximum, 6% volumetric concentration of Cu, convective heat transfer coefficient and thermal efficiency increased to 32% and 12.5%, respectively. Furthermore, the pressure drops via the receiver at 400 K and Reynolds number of approximately 650,000 increases roughly by more than 100% (from nearly 3000 to 7734 Pa/m). Finally, the minimum entropy generation rate at a certain Reynolds number was obtained by their model. This point is crucial as it shows the Reynolds
number in which we have the maximum heat transfer irreversibility and minimum friction irreversibility. Specifically, there is a maximum 30% decrease in the entropy generation rate at 6% volume fraction comparing to the base fluid. Basbous et al. [70] numerically modeled the thermal performance of PTSC utilizing different metallic nanofluids. Syltherm 800 as base fluid and Cu, CuO, and Al₂O₃, and Ag with 5% volumetric concentrations were considered as studied nanofluids. The results suggested that silver is the best nanoparticle to be used to induce the best thermal enhancement followed by copper, cupric oxide and aluminum oxide with convection heat transfer enhancement of 36, 33, 27, and 18%, respectively. They also concluded that as the density of the nanoparticle increases, the thermal performance enhances better. Finally, a 21% decrease in heat loss was observed.

Toghyani et al. [71] conducted numerical modeling and optimization of the effect of different nanoparticles on the performance of the PTC used in a Rankin cycle. CuO, SiO₂, TiO₂, and Al₂O₃ were dispersed in Therminol-55 at 2–5.5 vol. %. The results show that the use of nanofluids in solutions can slightly improve thermal efficiency. Finally, the optimization results revealed that using Al₂O₃/Therminol-55, caused the maximum enhancement in the overall exergy efficiency of the system by 11%. Nayak et al. [72] modeled Al₂O₃/Synthetic oil nanofluid up to 5% volumetric concentration to investigate and optimize the thermal behavior of the PTSC. They reported an approximately 7% enhancement in heat transfer coefficient when 5% volumetric concentration of Al₂O₃ was used comparing with Synthetic oil only. Ferraro et al. [73] used Al₂O₃/Synthetic oil nanofluid to analyse the nanofluid effect on PTSC performance numerically. Their results showed that thermal efficacy and pressure drop almost stays the same. However, the maximum increase of approximately 60% was observed at a 5% volumetric concentration of Al₂O₃ for the convection heat transfer coefficient. Kharkah et al. [74] conducted a CFD simulation on the receiver system of PTSC using Al₂O₃/Synthetic oil nanofluid as a working fluid at 5% volumetric concentration. The enhancement of 14.3% was reported in the system thermal efficiency. Table 2 summarizes the details and important notes about numerical studies.

4. Flat plate solar collectors review using nanofluids

Researchers have studied the efficiency and thermal performance of flat-plate solar collectors, and the effects of nanofluids and nanoparticles on them. Extensive investigations on the use of flat plate solar collectors were carried out [85-87]. Yousefi et al. [86] experimentally studied the effects of multi-walled carbon nanotubes/water nanofluids as heat transfer fluids
on the efficiency of FPSC. The results show that the efficiency of MWCNT nanofluid is lower than when the working fluid is water. To improve the diffusion and reduce the assemblage of nanoparticles in the nanofluid, most researchers add Triton X-100 as a surfactant to the nanofluids [88-90]. Yousefi et al. [85] discovered that the addition of Triton X-100 as a surfactant to the Al₂O₃ nanofluid increases the solar collector efficiency.

The efficiency of square FPSC using SiO₂/water nanofluid was experimentally investigated by Noghrehabadi et al. [91]. It was found out that the SiO₂/water nanofluid increased the temperature performance and thermal efficiency of the solar collector when compared with water nanofluid. The efficiency of the nanofluid also increased with an increase in the flow rate. In another study Chaji et al. [92], two different surfactants (Cetyl trimethylammonium bromide and Triton X-100) were used to enhance the efficiency of the TiO₂/water nanofluid. However, the surfactants produced foam, reducing the efficiency of the collector. In addition, the flow rate of nanofluids also varies and it was discovered that the highest flow rate produced the least efficiency. Meibodi et al. [93] studied the thermal efficiency and performance characteristics of SiO₂/ethylene glycol (EG)-water nanofluids with a collector plate surface area of 1.59 m². The volume concentrations considered in the experiment were 0.5, 0.75, and 1%, respectively, and the mass flow rates were 0.018, 0.032, and 0.045 kg/s, respectively. When the thermal efficiency increases from 4% to 8% and the concentration increase from 0.5 to 1%, the heat loss parameter is limited to zero.

Alim et al. [94] used different types of nanofluids (CuO, Al₂O₃, SiO₂, TiO₂ dispersed in water) to analyze the pressure drops and entropy production in FPSC having an absorption area of 1.51 m². The analysis was performed for different volume fractions (1-4%) and volumetric flows (1-4 L/s). Zamzamian et al. [95] investigated the effect of synthetic copper nanoparticles/ethylene glycol nanofluids on the efficiency of FPSC. The mean diameter of the nanoparticles was considered in the experiment was 10 nm. Nanofluids with mass fractions of 0.2% and 0.3% were prepared and nanofluids were prepared in a one-step process. The volumetric flow varies from 0.5 to 1.5 L/s and the efficiency of the solar collector is calculated using the ASHRAE standard. Polvongsri and Kiatsiriroat [96] used silver nanofluids as the working fluids to study the performance of flat solar collectors. Three identical closed-loop flat solar collectors were installed having an area of 0.15 m × 1.0 m. The various achievement that has been recorded by researchers using nanofluids is summarized in Table 3.
5. Evacuated tube solar collector review using nanofluids (Figure 7)

Ghaderin and Sidik [104] used Al₂O₃/distilled water nanofluid as working fluid, and the thermal efficiency of the spherical coil all-glass passive circulating evacuated collector in the horizontal storage tank was studied experimentally. The volume fraction of the nanoparticles was 0.03% and 0.06%, respectively, and the particle size was 40 nm. In this experiment, Triton x-100 was used as a surfactant, and the performance of Al₂O₃ nanofluid and water was compared with the flow in a coil with a flow range of 20-60 l/h. They observed that when the nanofluid volume fraction is 0.06 and the mass flow rate is 60 l/h, the maximum efficiency is 57.63%. With the increase of volume fraction and flow rate of Al₂O₃ nanoparticles, the collector efficiency has been greatly improved. Research results show that alumina nanofluid can be used as the working fluid of ETSC, effectively absorbing solar rays and converting it into thermal energy. Again, Ghaderian et al. [105] observed a similar trend studying the effects of the CuO-distilled water nanofluidic ETSC water heater with a built-in coiled thermosiphon system. A volumetric fraction of 0.03-0.06% of nanoparticles with mass flow rates ranging from 20 to 60 l/h was used. When the volume fraction of CuO nanofluids is 0.03%, the efficiency of ESTC is increased to 14% compared to water.

Iranmanesh et al. [106] investigated experimentally the thermal performance of evacuated tube solar collectors (ETSC) using graphene nanoplatelets (GNP)/distilled water nanofluid. Various properties of GNP were studied at four different mass percentage and three volumetric flow rates. From their results, increment in the mass percentage with the use of graphene nanosheets leads to more gain in thermal energy as the higher fluid outlet temperature is reached. Using nanofluid with a mass concentration of 0.01%, the thermal efficiency in the ESTC reached 90.7% and volume flow rate of 1.5 l/min, while ESTC using pure water at the same flow rate attained 35.8%.
| Study                  | Method | Nanofluid  | Nanoparticle Type | Nanoparticle Size (nm) | Max Increase % | Finding(s)                                                                                                                                                                                                 |
|-----------------------|--------|------------|-------------------|------------------------|----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mwesigye et al. [75]  | CFD    | Therminol-1 | Cu, Ag, Al₂O₃     | 6 vol. %               | <1             | Dispersion of Ag had the highest thermal efficiency enhancement followed by Cu and Al₂O₃. Maximum entropy generation rate decrease of 24% at lower Reynolds number was observed when Al₂O₃/Therminol VP-1 nanofluid is used. |
| Ghasemi et al. [68]   | CFD    | Therminol-66| Al₂O₃             | 4 vol. %               | 20             | Nusselt number increases considerably by using nanofluid, compared to the base fluid. They found that CuO/syltherm 800 has the maximum thermal efficiency followed by Al₂O₃/Therminol VP-1.                                      |
| Bellos et al. [76]    | Model  | Syltherm 800| Al₂O₃, CuO        | 4 vol. %               | 1.26           | After optimization, the use of CuO nanofluid with 4.35% volumetric concentration of CuO in the solar loop along with Toluene in the organic Rankin cycle was the optimum choice.                                    |
| Bellos et al. [75]    | Model  | Syltherm 800| Al₂O₃, CuO        | 6 vol. %               | 1.91           | CuO/syltherm 800 had better thermal efficiency than CuO/molten salt nanofluid. Combination of both nanofluids and fins can lead to higher efficiency enhancement, convection heat transfer, and pressure drop.               |
| Bellos et al. [77]    | CFD    | Syltherm 800| CuO               | 6 vol. %               | 0.76           | Combination of both nanofluids and fins can lead to higher efficiency enhancement, convection heat transfer, and pressure drop.                                                                          |
| Bellos et al. [67]    | CFD    | Syltherm 800| CuO               | 6 vol. %               | 1.54           | Combination of both nanofluids and fins can lead to higher efficiency enhancement, convection heat transfer, and pressure drop.                                                                          |
| Mwesigye et al. [78]  | CFD    | Therminol-1 | SWCNT             | 2.5 vol. %             | 10             | Higher thermal conductivity doesn’t necessarily lead to higher thermal efficiency since the effect of specific heat capacity also should be considered.                                                    |
| Allouhi et al. [79]   | Model  | Therminol-1 | TiO₂, Al₂O₃       | 5 vol. %               | -              | Cu and Al₂O₃ showed the best exergy and energy performance followed by TiO₂ and Al₂O₃.                                                                                                                    |
| Bellos et al. [80]    | Model  | Syltherm 800| TiO₂, Al₂O₃, and TiO₂/Al₂O₃ | 3 vol. %               | 0.74           | TiO₂/Al₂O₃ based nanofluid had highest performance, followed by TiO₂ and Al₂O₃.                                                                                                                        |
| Bellos et al. [80]    | Model  | Syltherm 800| Cu, CuO, SiO₂, Al₂O₃, Fe₂O₃, TiO₂ | 6 vol. %               | 2.2            | Cu had the highest efficiency increase of 2.2% followed by CuO, Fe₂O₃, TiO₂, Al₂O₃, and SiO₂.                                                                                                          |
| Kasaian et al. [81]   | Model  | Thermal oil | MWCNT             | 6 vol. %               | -              | Convection heat loss increased by 220% in
| Authors          | Model | Base Fluid | Nanoparticles | Nanoparticle Volume % | Reynolds Number | Heat Transfer Coefficient % Increase |
|------------------|-------|------------|---------------|-----------------------|-----------------|--------------------------------------|
| Bilal et al. [82]| Model | Water      | Fe₃O₄         | 0.6 vol. %            | -               | 1.6                                  |
| Khular et al. [10]| Model | Therminol VP-1 | Al₂O₃ | 0.05 vol. % | 5        | 5-10                                |
| Hatami et al. [83]| CFD   | Water      | Cu, Fe₃O₄, Al₂O₃, TiO₂ | 8 vol. % | -        | -                                   |
| Minea et al. [84]| CFD   | Water, Water/EG (40%:60%) | Ag/MgO, Al₂O₃/Cu, GO/Co₃O₄ | 2 vol. % | -5-6    | 115-125                             |

When the temperature increased from 30 to 100, 56% enhancement was observed for Nusselt number at 0.6 vol. % of nanoparticles and highest Reynolds number. A combination of the fin and nanofluid applications can result in a maximum 87% increase in the heat transfer coefficient. To obtain favorable thermal efficiency and maximum outlet temperature, there should be optimizations on various variables such as nanoparticle shape, size, and material. Cu nanoparticles show the best thermal enhancement comparing with Fe₃O₄, Al₂O₃, TiO₂. Although hybrid nanofluid with hybrid base fluid (water and EG) had better thermal enhancement, it introduces higher pressure drop increase to the system, comparing with hybrid nanofluid with water as the base fluid. The application of hybrid water base nanofluid with acceptable heat transfer enhancement and lower pressure drop would be a better choice over hybrid nanofluid with hybrid base fluid (Water/EG). Convective heat transfer coefficient increase between 115–125% using 0.15% GO/Co₃O₄/W-EG (40%:60%).
### Table 3. Achievements recorded by researchers using various nanofluids

| Particle type | Base fluid | Researcher | Particle size (nm) | Findings and remark |
|---------------|------------|------------|-------------------|---------------------|
| TiO$_2$       | Water      | Kilic *et al* [97] | 30 – 60           | The FPSC thermal performance showed an enhancement of 34.43%. The absence of surfactant showed that water is more efficient than MWNCT nanofluids but improved drastically after Triton X-100 was added. |
| MWCNT         |            | Rastogi *et al* [98] | 10 – 30           |                      |
| Al$_2$O$_3$, ZnO, and Fe$_2$O$_3$ | Water | Colangelo *et al* [99] | 45, 60 and 30 respectively | The combination of Al$_2$O$_3$/water nanofluid was more stable compared to that of ZnO and Fe$_2$O$_3$. Carbon nanostructure-based particles have greater thermal conductivity than Al$_2$O$_3$. |
| Ag            | Water      | Polvongsri and Kiatsiriroat [100] | 20            | The thermal performance increased when using MWCNT and no surfactant was used. |
| Cu            | Water      | Jamal-Abad *et al* [101] | 35            | With little increase in concentration, the efficiency increased to 24%. Surfactant was used but the temperature was high, and the effect on the surfactant was not considered. |
| SiO$_2$       | Water      | Mahian *et al.* [102] | 12 and 16         | The observed fluid flow was turbulent. Solar collector with nanofluid has more efficiency than with water when the viscosity was considered. |
| Cu            | Water      | He *et al.* [103] | 25            | As the particle size increases, the FPSC efficiency decreases. In addition, it has been found that the use of Cu-water nanofluids can improve the efficiency of the collector. |
In the experiment reported in Ozsoy and Corumlu [107], thermosyphon heat pipe (THP) incorporated into the evacuated tube solar collector and its thermal efficiency were investigated using silver-water nanofluid. Two methods approach was considered by first synthesizing the silver-water nanofluid and also using a cylindrical copper THPs with nanofluid and water both tested. The results show that compared with pure water, THPs mixed with nanofluid improves the efficiency of solar collectors within the range of 20.7% and 40%, respectively.

Another approach using thermosyphon was studied by Liu et al. [108] considering the thermal performance with nanofluids in an evacuated tube type high-temperature air solar collector. A two-step process was used in the preparation of CuO-water nanofluid having a mean particle size of 50 nm. The results show that the system efficiency and outlet air temperature of the nanofluids are significantly greater than those of the pure water system. In winter, when the volume flow rate is 7.6 m$^3$/h, the outlet temperature of the nanofluidic system exceeds 170 °C. Mahendran et al. [109] conducted thermal performance experiments on ETSC using aqueous titanium oxide nanofluids. The nanofluids were prepared using titanium oxide nanopowders with an average particle size of 30 to 50 nm. A TiO$_2$-water nanofluid of 0.3% volume was prepared by diluting titanium dioxide nanopowder. The inlet and outlet temperature differences of ETSC using titanium dioxide nanofluids are greater than that of ETSC using water. The results show that the highest outlet temperature of titanium dioxide nanofluidic ETSC is 19% greater than that of water treated ETSC, and the efficiency of titanium dioxide nanofluidic ETSC is 8% higher than that of water treated ETSC.
Sharafeldin and Grof [110] studied the thermal performance of evacuated tube solar collectors with WO$_3$/Water Nanofluid. With a diameter of 90 nm, WO$_3$ nanoparticles are spherical. The volume fractions of three different WO$_3$ nanoparticles were determined to be 0.014%, 0.028%, and 0.042%, respectively, at different mass flow rates of 0.013 kg/s, 0.015 kg/s, and 0.017 kg/s. The results show that after adding WO$_3$ nanoparticles, the temperature difference of the liquid can reach 21%. When WO$_3$ nanoparticles were used, the maximum heat gain at 900 W/m$^2$ solar irradiance was increased to 23%. At the same mass flow rate, the growth ratio of the heat-removable factor of the nanofluid to water is between 1.05 and 1.16. The results show that with the addition of nanoparticles, the efficiency of evacuated tube solar collectors is improved with its efficiency reaching 72.8%.

Saad *et al.* [111] conducted a comprehensive work on the performance of nanofluids with metal oxide as absorbers for vacuum tube solar collectors. In Baghdad, the parameters measured from April 2011 to March 2012 were Al$_2$O$_3$/water nanofluid concentrations and tube inclination. They recorded in the research conducted that the optimum tilt angle of the vacuum tube is 41° per year. When 1%, 0.6%, and 0.3% Al$_2$O$_3$/water nanofluids and volume fraction of 28.4, 6.8, and 0.6%, were used, the efficiency of the collector was also improved.

Hussain *et al.* [112] further studied the evacuated tube solar collector by comparing the thermal efficiencies of metal oxide nanofluids (ZrO$_2$/water) and metal nanofluids (Ag/water). They noticed when the inlet temperature is high using nanofluids of metal nanoparticles and oxide metals as working fluids can improve the collector thermal performance. Due to the high thermal conductivity of Ag, the efficiency of a 30 nm-sized Ag trap is greater than a 50 nm-sized ZrO$_2$. Sabiha *et al.* [113] proposed an evacuated tube solar collector using water-based single-walled carbon nanotube nanofluids as an absorption channel to improve energy efficiency. The effects of volume fractions in the range of 0.05-0.2 v% and mass flow rates of 0.008, 0.017 and 0.025 kg/s on energy efficiency were investigated. Due to the high thermal performance of SWCNT nanofluids, the capture efficiency of SWCNT nanofluids with a volume ratio of 0.2% is 93.43% higher than water and 71.84% higher than water. At this concentration, it is better to use a nanofluid collector on a cloudy day than to use water on a sunny day.

Tong and his colleagues [114] may be the first to use nanofluids made of multi-walled carbon nanotubes (MWCNT) as working fluids to enhance the thermal performance of closed evacuated u-shape solar collectors. Their calculations show that when using 50 solar collectors of this type, the annual emissions of carbon dioxide and sulfur dioxide can be reduced by 1600 kg and 5.3 kg, respectively.
Hayek et al. [115] conducted two types of performance tests on glass tubes and thermal design tubes for evacuated collectors. The experiment time was 2 months and various parameters and procedures were considered. For both collectors, at high emissivity, all tilts result in almost the same overall performance. The authors also concluded that the total efficiency of the heat pipe collector is about 15-20% higher than that of the glass water collector. In summary, the heat pipe collector is more efficient than the glass water collector.

Daghigh and Zandi [116] tested and evaluate CuO, TiO$_2$ and MWCNT nanofluids on an evacuated tube heat pipe solar collector (ETHPSC) and compared its performance with water. Due to the high thermophysical properties of the nanofluids, better performance was observed when used on the collector. In August, the efficiency of collectors increased significantly, reaching 25, 12 and 5% and better results in October with 25, 15, and 7% respectively.

Using another perspective, Kaya and Arslan [117] designed and simulated an evacuated U-tube solar collector using Ag, ZnO, and MgO nanoparticles, ethylene glycol-pure water (EG-PW) and different conditions in analyzing its performance. The highest solar collector efficiency was observed with Ag/EG-PW nanofluid at 68.7% and EG-PW at 26.7%. A more innovative experiment was carried out by Al-Mashat and Hasan [118], studied the efficiency of ESTC using 16 vacuum tubes containing Al$_2$O$_3$/water nanofluids as working fluid. The results show that after adding 1% Al$_2$O$_3$ and 0.6% Al2O3, efficiency is increased by 28.4 and 6.8%, respectively.

Mahendran and Sharma [119] conducted experiments with ETSC using titanium dioxide nanofluids and reported an increase in efficiency of 42.5% compared to 2.0 vol. % of titanium dioxide nanofluidic water. When the volume flow rate of the nanofluid is small, the collector efficiency is greatly improved compared to when base fluid is water. Lu et al. [120] used deionized water and water-based CuO nanofluids for evacuated tube solar collectors. The evaporation heat transfer coefficient of nano-copper oxide can be increased by about 30%. With the use of CuO nanofluids, the wall temperature of the open thermosiphon is reduced. Using MWCNT, Al$_2$O$_3$, TiO$_2$, SiO$_2$, CuO nanoparticles, Kim et al. [121] worked on the performance of a U-tube solar collector. The nanoparticles were suspended in a propylene glycol-water base solution at a concentration of 20%. MWCNT nanoparticles achieved the highest thermal performance reaching 62.85% at a volume concentration of 0.2%. Different approaches to enhancing ESTC using nanofluids are highlighted in Table 4.

Cho et al. [122] theoretically research on double-layer glass evaporated solar collectors for heat pipes and u-tubes under different working conditions. 0.24% volume of nanofluid made
from multi-walled carbon nanotubes is used as a working fluid for the u-tube solar collector. The heat transfer coefficient of nanofluids is about 8% larger than that of water-based fluid.

6. Direct absorption solar collector review using nanofluids

The design of DASC (Figure 8) has been likened to that of a flat plate solar collector and the major difference in the design was identified to be the absence of an absorber tube in the DASC setup [131]. Different types of DASC have been elaborated which has seen different researchers adopting various setup propositions as described in Figures 3 and 4 [31]. Radzi and his group [34] reviewed and reported techniques for DASC including black liquid collectors [132], volume trap collectors [133] as well as small particle collectors [134]. Also, it was previously reported [31, 135, 136] that a distinct concept can convert carbon dioxide (CO₂) into hydrocarbons (methane) and other byproducts. The detailed dimensions of components used in the experimental setup with a view to investigating the nanofluid flow and heat transfer efficiency of nanofluid in DASC using Al₂O₃-H₂O as the base fluid [137].

Figure 8. Experimental setup of a DASC [19,131].

Al₂O₃ and TiO₂ were used as base particles dispersed in water and thermal conductivity was noted to rise up to 32% and 11% respectively [138]. A concise summary of studies with various nanofluids used in DASC is available [33], while in earlier report [34] a compilation on both experimental and patented setups of DASC in various studies also exists as shown in Table 5.
### Table 4. Different approaches to ESTC enhancement using nanofluids

| Researchers/Authors | Approach     | Nanofluid Used                           | Volume Concentration (%) | Mass Flow Rate (L/h) | Inclination angle (°) | Results                                                                                     |
|---------------------|--------------|------------------------------------------|--------------------------|----------------------|-----------------------|--------------------------------------------------------------------------------------------|
| Chougule et al. [123] | Experimental | CNT (Carbon Nanotubes)                   | 0.15                     | N/A                  | 31.5°, 50°            | At 31.5°, an efficiency of 45% was recorded at 50°, 69% efficiency was achieved           |
| Iranmenesh et al. [106] | Experimental | GNP (Graphene Nanoplatelets)              | 0.025, 0.05, 0.075, 0.1 | 0.5, 0.1, and 1.5    | N/A                   | At higher concentration, maximum efficiency was obtained.                                   |
| Kim et al. [121]    | Theoretical  | MWCNT (Multi-walled carbon nanotubes)     | 0.2                      | N/A                  | 35, 126               | The highest efficiency was gotten using 0.2% vol. of MWCNT reaching 62.8%.                |
| Shahi et al. [124]  | Numerical    | Copper oxide                             | N/A                      | N/A                  | 15, 33, 55, 75        | Mass flow rate increases by approximately 40% with enhancement ratio at 5%              |
| He et al. [125]     | Experimental | Tin Oxide CNT                            | 0.5                      | N/A                  | 45-60                 | At 0.5% concentration, CNT performed more better than TiO₂                                 |
| Eidan et al. [126]  | Experimental | Al₂O₃ & CuO/acetone                      | 0.25 and 0.5             | N/A                  | 30, 45, 60            | Optimal performance was observed at 45° angle and 70% filling ratio.                      |
| Mahbubul et al. [127] | Experimental | Single Wall Carbon nanotube              | 0.2                      | N/A                  | N/A                   | 0.2% vol of nanofluids resulted in an efficiency of 56.7% and 66%                      |
| Study          | Methodology | Material                  | Volume Concentration | Mass Flow Rate | Location | Results                                                                 |
|---------------|-------------|---------------------------|----------------------|----------------|----------|-------------------------------------------------------------------------|
| Kaya et al. [128] | Experimental | ZnO/Ethylene Glycol-Pure Water (ZnO/EG-PW) | 1.0, 2.0, 3.0, 4.0 | 0.02, 0.045 |          | There is an enhanced efficiency with an increased volume concentration of 62.87% respectively. |
| Natividade et al. [129] | Experimental | Multilayer graphene | 0.000045, 0.000068 | 6, 24, 42, N/A | 60       | Thermal efficiency was upgraded up to 31% and 76% for other concentrations. |
| Gan et al. [130] | Experimental | Titanium dioxide (TiO₂) | 0.5 | 0.033 | 3.1180°N, 101.6552°E | The performance of the ETSC increases with mass flow rate and the thermal efficiency reaches up to 16.5%. |
Table 5. Some selected papers and patented DASC at a glance

| Study authors                          | Research outcomes | Developed technique                                                                 |
|----------------------------------------|-------------------|-------------------------------------------------------------------------------------|
| Kraus and Kraus [139]                  | Patented          | Worked on systems involving particle-fluid absorber                                 |
| Hunt [140]                             | Journal paper     | A receiver with particle-gas absorber was used in the experiment conducted.          |
| Abdelrahman et al. [141]               | Journal paper     | To achieve ideal absorption, a particle-gas suspensions technique was used.          |
| Bohn [142]                             | Journal paper     | An absorber with pure flowing molten salt was experimented upon.                    |
| Parker and Langhoff [143]              | Patented          | Secondary direct absorber for large magnitude of temperature                         |
| Yogev [144]                            | Patented          | The working fluid used was organic with photon concentrated on it.                  |
| Hirsch and Steinfeld [145]             | Journal paper     | A high-temperature reactor with carbon particle having thermochemical properties was studied. |
| Schunk et al. [146]                    | Journal paper     | Researched into the abilities to rotate zinc oxide (ZnO) particle receiver            |
| Tyagi et al. [24]                      | Journal paper     | Focused on flat plate solar thermal collector based on nanofluids                   |
| Goldman et al. [147]                   | Patented          | A novel receiver with semitransparent/translucent tubes                              |
| Otanicar et al. [19]                   | Journal paper     | Tested nanofluid-based flat plate collector prototype                                |
| Sani et al. [148]                      | Journal paper     | Researched into the possibilities of using carbon nanohorns as solar collectors      |
| Taylor et al. [30]                     | Journal paper     | A prediction mechanism for the effects of nanofluids on CSP systems was reported    |
| Lu et al. [149]                        | Journal paper     | Copper oxide (CuO) thermosyphon solar collector was used in the prototype.           |
| Lenert and Wang [150]                  | Journal paper     | In other studies, closely related to this research, molten salt has been used. In this case, however, prototype nanofluid receiver was observed and tested for optimum capacities using carbon-coated particles administered in Therminol VP-1. |
The adoption of DASC in nanofluids has established a channel to estimate the collector efficiency [19,24, 151, 152,153]. A theoretical numerical study on 2-D models of DASC carried out by Tyagi et al. [24] using finite difference method in a bid to solve both radiative transport (i) and energy equations (ii): taking $k_{\text{eff, nanofluid}}$ as the spectral extinction coefficient of nanofluids, heat conductivity $k$, temperature $T$, Density $\rho$, specific heat capacity $c_p$, radiation intensity $I$, radiative heat flux $q_r$. In other to prove the solutions, Otanicar et al. [19] used varieties of nanofluids in the investigation. Numerical methods that have been applied in by various researchers include finite volume methods (FVM), finite element (FEM), and finite difference method (FDM) [153]. The study also detailed the various numerical studies conducted by researchers to solve equations (i), (ii)

$$\frac{\partial l}{\partial y} = -k_{\text{eff, nanofluid}} l$$  \hspace{1cm} (i)

$$k \frac{\partial^2 t}{\partial y^2} - \frac{\partial q_r}{\partial y} = \rho c_p U \frac{\partial t}{\partial x}$$  \hspace{1cm} (ii)

Till recent times, researchers have majorly directed their focus on the optical characteristics of water or ethylene glycol suspensions added with varieties of nanoparticles, as well as effective abilities in low-temperature solar collectors in nanofluid-based DASC [25, 32, 154, 155]. It has also been proposed for applications in water heating and purification. The efficiency of DASC has been identified to rely solely on the working fluid. A two-dimensional CFD model for direct absorption of high-temperature molten salt nanofluid concentrating solar receivers to investigate the effects of design and operational variables on receiver performance [156]. The study was able to establish that Carnot efficiency is directly proportional to increasing receiver length, solar concentration, increasing height and decreasing inlet velocity.

Balakin et al. [157] also studied a multiphase (Eulerian-Eulerian) CFD model of DASC, validating it with respect to a two (2) independent experimental data. The model is able to reproduce motion and thermal transfer in each phase. As part of the work, they altered the concentration and the nanoparticle sizes as well as the geometry and inclination of the collector. This has resulted in approximately 10% improvement in efficiency while the use of thermomagnetic convection in the collector requiring the use of magnetic nanofluid resulted in a 30% improvement in the efficiency of DASC. Won and Lee [158] investigated the light scattering defect on the thermal performance of DASC using plasmonic nanofluids. The study has shown a link between the type of material the suspended nanoparticles are made of and the absorption cross-section and the reliance on the particle sizes. Conclusions were
drawn that when light scattering due to nanoparticle suspension can increase the mean optical path length of light packets inside the collector channel, thus enhancing the solar-weighted absorption coefficient.

7. Difficulties and Challenges involved using nanofluids
The new approach of using nanofluids in solar collectors has also come with a lot of setbacks which still needs to be solved;

1) The preparation of the nanofluid is expensive and time-consuming.
2) Due to the toxicity of nanofluids, proper treatment is required.
3) The tendency to form agglomerates after homogenizing and its long requirement for stability is still of great concern.
4) The increase in the fluid circulation rate lead to erosion on the heat transfer walls thus sedimentation reduces.
5) The addition of surfactants at high temperatures can be detrimental.
6) The operating cost of solar collectors coupled with nanofluids is high.

8. Conclusion
This review paper was able to itemize the recent achievement in the use of nanofluids in solar collectors namely PTSC (Parabolic trough solar collector), FPSC (Flat plate solar collector), ETSC (Evacuated tube solar collector) and DASC (Direct absorption solar collector). Nanofluids usage in solar collectors has shown promising efficiencies but the major challenges still lie in the high cost of production, stability, particle agglomeration, pumping power and pressure drop.
The unique rise of thermal conductivity in nanofluids is not yet fully elucidated. However, the long-term stability of nanofluids is still of the paramount need to further achieve better efficiency in solar collectors. The following conclusions can be deduced from this paper;

1) To achieve better efficiency of solar collectors, it is necessary to make sure proper dispersion occurs while mixing the nanoparticle and stability in the long run.
2) Carbon nanotubes both single and multi-walled has shown optimal efficiency when used in solar collectors.
3) Surfactants addition to nanoparticle has helped in achieving stability, but at a higher temperature, it causes corrosion on the wall of solar collectors leading to detrimental
effects in the overall efficiency. Though it contributed to the overall efficiency of solar collectors.

4) Viscosity rise when nanofluids are added to base fluids which also increases the pressure drop therefore a very high pumping power is required.

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