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Review

Stability, thermophsical properties of nanofluids, and applications in solar collectors: A review

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Abstract: Recently, renewable energies have attracted the significant attention of scientists. Nanofluids are fluids carrying nano-sized particles dispersed in base fluids. The improved heat transfer by nanofluids has been used in several heat-transfer applications. Nanofluids' stability is very essential to keep their thermophysical properties over a long period of time after their production. Therefore, a global approach including stability and thermophysical properties is necessary to achieve the synthesis of nanofluids with exceptional thermal properties. In this context, the objective of this paper is to summarize current advances in the study of nanofluids, such as manufacturing procedures, the mechanism of stability assessment, stability enhancement procedures, thermophysical properties, and characterization of nanofluids. Also, the factors influencing thermophysical properties were studied. In conclusion, we discuss the application of nanofluids in solar collectors.

Keywords: thermophysical properties; nanofluids; stabilization techniques; thermal enhancements; solar collectors

Abbreviations: PTSC: Parabolic trough solar collector; FPSC: Flat plate solar collector; DASC: Direct absorption solar collector; HTF: Transfer fluid; CNT: Carbon nanotube; MWCNT: Multi-walled carbon nanotube; CVD: Chemical vapor deposition; IEP: Isoelectric point; SDBS: Sodium Dodecyl Benzene Sulphonate; $A\lambda$: The absorbance; k: Thermal conductivity (W/m·k); Cp: Specific heat of fluid (kJ/kg·K); μ: Dynamic viscosity (Pa·s); EG: Ethylene glycol

1. Introduction

The development of solar energy production is one of the most efficient ways to provide for the world's needs.To face the recent problems associated with global warming, the depletion of fossil fuels and an increasing population. The sun is a renewable energy source and available in sufficient quantity, whose energy potential is high due to the high temperature of the sun (about 5760 K) [1,2]. Researchers from various fields have been interested in an exceptional improvement in thermal conductivity by adding solid particles to heat transfer fluids. These suspensions, known as nanofluids, are considered to have great potential in heat transfer applications for the development of heat systems [3]. To this effect, the number of research studies on nanofluids has increased significantly since their invention by Choi and colleagues in 1995 [4]. Researchers have observed a significant enhancement of thermal conductivity by introducing nanoparticles into a base fluid at very low concentrations [5,6]. Visconti et al. [7] developed a programmable electronic system to control ambient parameters. Their objective was to manage the electrical functions of a thermo-solar power plant in order to achieve a more optimized plant and maximize its efficiency. The performance of the nanofluid-based solar collector was compared to that of the traditional collector. To verify the results, experimental measurements were performed using traditional water-based and Al_2O_3-based nanofluid solar thermal collectors. The experimental results showed that the use of nanofluid as a heat transfer fluid in such a system increases the efficiency. Furthermore, nanofluids with various types of nanoparticles, such as metal oxides, have been widely studied for use in solar energy systems. As a result, nanofluid is an attractive choice for the working fluid of direct absorption solar collectors efficiently converting sunlight into heat [8,9]. It was found that nanofluids showed enhanced thermophysical properties, such as thermal conductivity, specific heat, viscosity and convective heat transfer, relative to base fluids like oil or water. The thermophysical properties of nanofluids are currently under investigation and need to be further developed. Gupta et al. [10] showed a comprehensive review of the thermophysical properties of nanofluids (thermal conductivity, viscosity, specific heat capacity, and density) and the elements that can modify these properties.They noted that the concentration, shape, size and material of the nanoparticles, as well as the base fluid and temperature, are the main factors that influence these properties.The enhanced properties of nanofluids lead to great potential applications in many fields. However, the poor stability of nanofluids can impede their performance. Particularly, particle aggregation and sedimentation can lead to increased viscosity and low thermal properties, which is detrimental to their applicability. Therefore, the stability aspect of nanofluids needs to be addressed, starting with preparation, evaluation, stabilization methods and operational aspects. Chakraborty and Panigrahi [11] showed a comprehensive review that touches on different approaches to nanofluid stability, from preparation to deployment in practical applications. The stability of nanofluids as a function of operating conditions (high temperature, pressure, isolation, composition, salinity, etc.) is of particular interest in many applications, such as heat transfer, microfluidics, lubrication, etc. The different methods of nanofluid stability as well as several types of devices for stability inspection were reviewed as it is important for the improvement of heat transfer for other possible applications [12]. Verma and Tiwari [13], Mahian et al. [14], Kasaeian et al. [15] showed a comprehensive review of nanofluids as heat transfer fluids (HTFs) in solar collectors, including recent advances and their potential use in solar thermal and photovoltaic systems. Different factors may explain the differences in the enhancement of the thermal properties of nanofluids, such as particle size and shape, pH of the suspension, temperature, stability methods applied and measurement techniques chosen. This paper will focus on methods of production and the mechanism of stability, methods to evaluate the stability of nanofluids, the effect of nanofluids on thermal efficiency, improvement of the heat transfer coefficient and pressure drop in solar collectors, as well as the heat transfer properties of nanofluids and the factors influencing their properties.

2. Categories of nanofluids

Based on the types of nanoparticles used in the manufacture of nanofluids, nanofluids can be classified into four distinct categories: (1) metallic nanofluids, (2) ceramic nanofluids, (3) carbon nanotubes nanofluids, and (4) hybrid nanofluids. The suspension of these nanoparticles in the base fluid, such as water, ethylene glycol, transformer oil, etc., was used to produce a nanofluid. Nanofluid selection for any application must take into account not only the improvement of its physical properties, but also the method of preparation and its stability. Figure 1 shows the thermal conductivity of various solids and liquids.

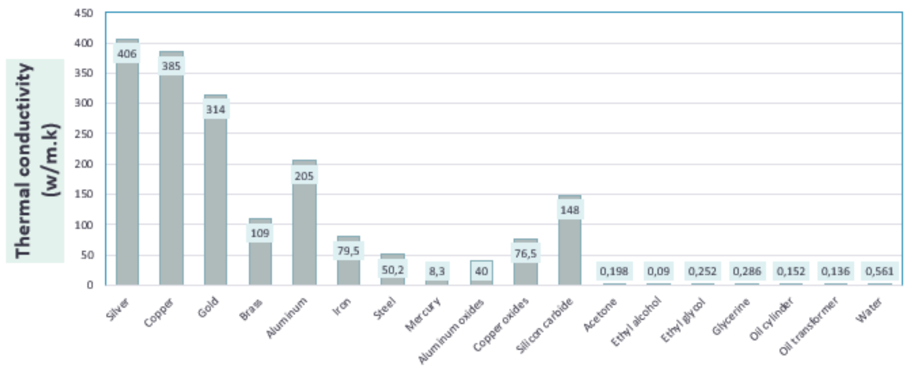

Figure 1. Various solids and liquids thermal conductivity [16,17].

2.1. Metallic nanofluids

The term "nanofluid" which refers to fluids containing particles dispersed at the nanoscale, is used to form nanoparticles of a single element (e.g., Cu, Fe, and Ag). Nikkam et al. [18] produced Cu nanofluids based on diethylene glycol using a one-step method. The mixture of diethylene glycol and Cu nanoparticles was sonicated and the suspensions proved stable for a few weeks. An increase in thermal conductivity of 3.5%, 6%, and 7.2% was achieved with particle concentrations of 0.4%, 0.8%, and 1.6% by weight at 20 °C. Torres-Mendieta et al. [19] investigated the enhancement of the thermal conductivity of Au nanofluids using thermal oil. The one-phase method was used to manufacture Au nanofluids. The results of the study resulted in a maximum improvement in thermal conductivity of only 4.06%.

2.2. Ceramic nanofluids

The cost of metallic nanoparticles is the main factor preventing their large-scale industrial application. Nanoparticles such as Al_2O_3, ZnO, CuO, and TiO_2, etc., are preferred to metallic ones to synthesize nanofluids because they are chemically more stable in solutions as they resist oxidation [20]. Nemade and Waghuley [21] evaluated the dispersion stability of CuO nanofluids in water using an ultrasonic sensor over a period of 15 to 60 min. They observed a strong relationship between stability and sonication time. The study showed that the probe's sonication was sufficient to stabilize the CuO nanofluids in an aqueous solution. Ezzat and Hasan [22] experimentally examined the improvement of nanofluids' thermal conductivity with Al_2O_3 nanoparticles of 10 nm diameter in distributed water at various volume concentrations, 0.13%, 0.24%, 1%, and 1.7%. The suspensions were treated by sonication using an ultrasonic probe and simultaneously agitated with a magnetic stirrer for up to 6 h. Thermal conductivity was improved from 0.3 to 4.5% for nanofluids with a particle concentration of 0.13 to 1.7% by volume. Leena and Srinivasan [23] manufactured TiO_2 nanofluids by the two-step method. The TiO_2 nanoparticles were distributed in distilled water at particle concentrations of 0.04–0.2% by weight, and the suspensions were treated by sonication for 3 h at room temperature. The resulting solutions remained stable for more than 4 h. The applications of ZnO nanoparticles are very diverse. They are widely applied for their catalytic, electrical, photochemical and optoelectronic characteristics [24]. The thermophysical properties of ZnO nanofluids have also been investigated.

2.3. Carbon nanotubes nanofluids

Compared to base fluids, carbon-based nanofluids have much higher thermal properties. Nevertheless, their high cost limits their large-scale commercial use. Choi et al. [25] investigated the thermal conductivity effectiveness of 1.0 vol% MWNTs dispersed in a synthetic poly(a-olefin) oil. They were the first to study CNT-based nanofluids and reported a 160% increase in thermal conductivity. Lamas et al. [26] investigated the colloidal stability of functionalized CNT-based nanofluids, and the findings indicated that the functionalization of CNTs contributes to the formation of a very stable nanofluid.

2.4. Hybrid nanofluids

Hybrid nanofluid is a new generation of nanofluid in which more than one type of nanoparticle is combined in a nanofluid, giving it thermal properties that are superior to those of nanofluids consisting of a single type of nanoparticle. Manasrah et al. [27] studied the thermal conductivity enhancement of CNT nanofluids decorated with Fe_2O_3 nanoparticles. For a 10% wt% Fe_2O_3 load on the CNT surfaces, the thermal conductivity of the nanofluids improved by 9%, 11%, and 16% at nanoparticle concentrations of 0.01, 0.05, and 0.1 wt, respectively. Nine et al. [28] manufactured the nanofluid Al_2O_3–MWCNT-Water and found an 8% improvement in thermal conductivity value compared to pure Al_2O_3 nanofluid.

3. Fabrication of nanofluids

Preparation is known to be the most important thing and the first step in the experimental study of different nanofluids, since nanofluids do not only form in a solid-liquid mixture but require special conditions to be present in the suspension, such as homogeneity, physical and chemical stability, durability, and dispersibility. The researchers employed two main techniques to make a nanofluid: the one-step method, which allows small-scale production, and the two-step process, appropriate to mass manufacturing for its reduced manufacturing cost [29]. Figure 2 shows the different physical and mechanical process of synthesis nonofluids.

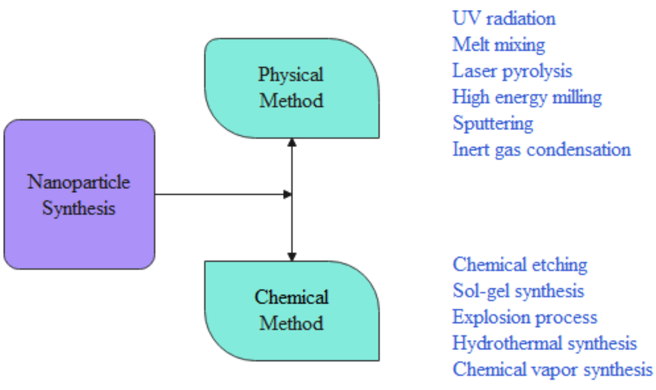

Figure 2. Physical and mechanical methods of synthesizing nanoparticles.

3.1. Single-step method

This technique involves the synthesis and dispersion of nanoparticles in a single step, as illustrated in Figure 3. This technique can only be used for certain nanofluids but avoids agglomeration and oxidation of the nanoparticles. An example of this process is the condensation of metal vapor in a nanoparticle reactor on a liquid film at low vapor pressure [30]. Akhavan et al. [31] has employed the chemical vapor deposition (CVD) process to fabricate nanofluid multi-walled carbon nanotubes (MWCNTs) with deionized water.

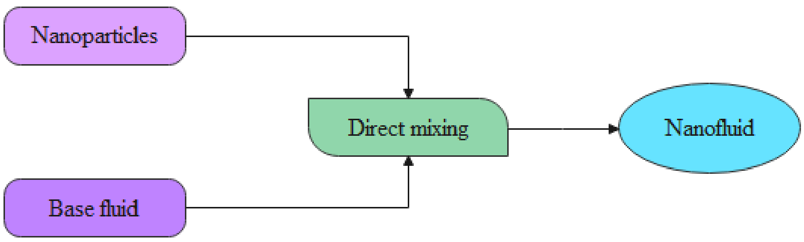

Figure 3. One-step processpresentation.

3.2. Two-step method

The two-step technique, as illustrated in Figure 4, is the one most largely used for the nanofluid preparation method. The nanoparticles, nanofibers, nanotubes, and other nanomaterials employed in the two-step method are initially manufactured as a dry powder by chemical or physical processes. Then, the nanomaterials (nanoscale powder) are then dispersed in a base fluid using ultrasonic agitation, magnetic force agitation, etc. Due to their large surface area and surface activity, nanoparticles exhibit a great degree of aggregation. The use of surfactants is an important technique to improve the stability of nanoparticles. However, their use in high temperatures is also a major concern [32]. Gupta et al. [33] prepared Al_2O_3-water by using a two-step approach.

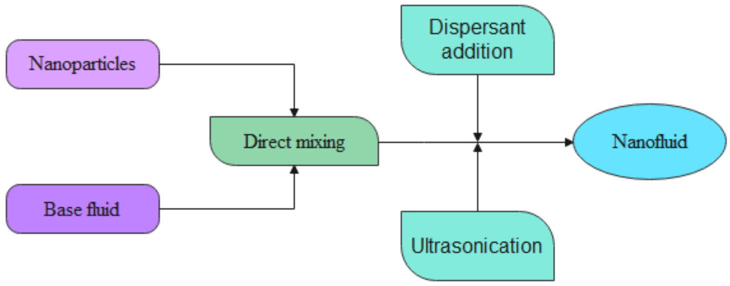

Figure 4. Two-step process presentation.

4. Improvement of nanofluid stability

Due to their ability to agglomerate, nanofluids lose their ability to transfer heat. Their stability is indeed an important element for the evaluation of nanofluids that can change their thermophysical properties for applications. Chemical (surfactant addition, surface modification, and pH adjustment) and physical (ultrasonic agitation, homogenization, and ball milling) methods were employed to improve the long-term stability and thermal properties of the nanofluids. [34]. Figure 5 shows the important elements of stability. Hwang et al. [35] used two approaches to prepare the nanofluids. They observed that the most optimal technique for breaking up agglomerated nanoparticles in the two-step method was the high-pressure homogenizer, while the magnetron sputtering system showed better stability than the high-pressure homogenizer. Sharma et al. [36] employed a two-step centrifugation and non-centrifugation method to produce long-term stable CNT/water nanofluids. However, the two-step method with centrifugation showed a stability of 15 months while the latter method only 3 weeks.

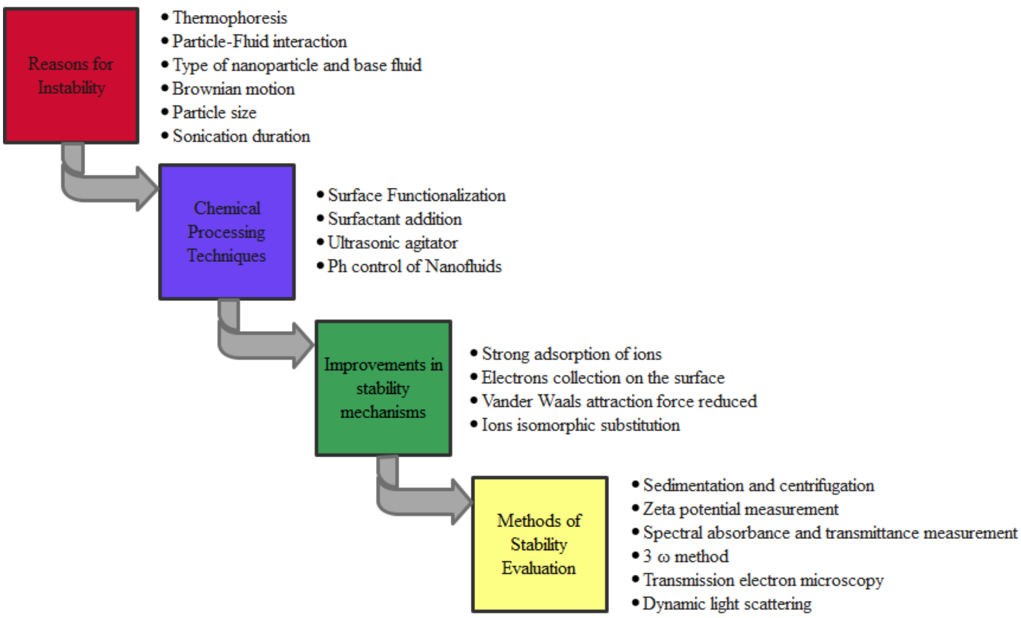

Figure 5. Essential aspects of stability.

4.1. Chemical processing techniques

The addition of surfactants or surface modification of particles enhances the dispersion of nanoparticles in base fluids, such as the dispersion of CNTs in water or oxide particles in oil. Surfactants are the active agents that act as a link between nanoparticles and base fluids to prevent particle aggregation. The surface modification applied to the nanoparticles to disperse them in the base fluid is another method of chemical stabilization. The insertion of acids or bases can keep the pH of the solution further away from its isoelectric point (IEP), which can improve the stability of the colloidal suspension.

4.1.1. Surfactants addition

Nanofluids are stabilized by adding surfactants to the base fluids to reduce their surface tension and increase particle immersion. Also, the surfactants increase the thermal resistance between the nanoparticles and the base fluids, which reduces the improvement in thermal conductivity. Surfactants are classified into two groups: oil-soluble and water-soluble. The type of surfactant can be selected according to the choice of the base fluid [37,38]. The surfactant sodium dodecyl benzene sulfate (SDBS) is the most suitable for nanofluids' long-term stability [39].

Colangelo et al. [40] carried out thermal conductivity enhancements of 3% and 4% for volume fractions of 0.7% and 1%, respectively. In addition, they show that the use of surfactants significantly improves the stability of the nanofluids.

4.1.2. Surface functionalization

The surfaces are changed by functionalization (coating of nanoparticles with a molecule), which can reduce the surface energy of the nanoparticle, leading to better dispersion in base fluids. Covalent coupling, physical adsorption, and electrostatic bonding are the three main techniques adopted for functionalization [41]. Plasma treatment can be applied to change the surface of diamond nanoparticles to enhance their dispersion properties in water [42].

4.1.3. pH control of nanofluids

The stability of nanofluids is related to their electrokinetic properties. For this reason, controlling the pH of these nanofluids can increase their stability [43]. Nanoparticles are more stable when the pH of the solution is far from the isoelectric point (IEP), in which the surface charge of the particles and the values of the zeta potential are zero [44,45]. For this purpose, the pH of the suspension must generally be maintained around the neutral point, as an alkaline or acid solution can cause corrosion of the heat transfer surfaces and dissolution of the nanoparticles [12].

4.2. Mechanical stabilization

This method consists of injecting high energy into nanofluids by ultrasound, homogenization, or bead grinding to break up the nanoparticle clusters and form a homogeneous and well-dispersed colloidal suspension. Usually, surfactants are then added to prevent re-agglomeration of the nanoparticles.

4.2.1. Ultrasonication

Ultrasonic probes are most commonly used to break up clusters of nanoparticles physically. Probe sonication is the most widely used stabilization method in physical method treatments. To disperse nanoparticles in a base fluid and to break up clusters of nanoparticles, sound energy is applied at an ultrasonic level of 20 kHz or more for a predetermined period [46]. It is generally observed that the need for a longer duration of ultrasonication of nanofluids may not be valid. Indeed, many recent experimental studies indicate that there may be an optimal duration for improved dispersion stability, which may not necessarily be the longest duration of ultrasonication tested [47]. Nemade and Waghuley [21] examined the influence of the variation of sonication time on the stability of CuO-water nanofluids. They conclude that the sonication process of the probe is sufficient to achieve stable CuO-water nanofluids.

4.2.2. Homogenization

High shear homogenizers are used to break up nanoparticle clusters in colloidal suspensions [48]. Hwang et al. [35] employed various methods such as; stirrer, ultrasonic bath, ultrasonic disruptor, and high-pressure homogenizer to stabilize nanofluid samples. They tried to measure the size of the colloids to study the agglomeration of particles in the suspensions. They indicated that the high-pressure homogenizer is a powerful device for breaking up agglomerates of nanoparticles.

4.2.3. Ball milling

Ball milling is the least studied method of improving stability; it is another technique for dispersing or dissociating nanoparticles and nanotubes in the fluid base. Many researchers have indicated that this is an effective process for obtaining well-dispersed suspensions. Farbodet et al. [49] have experimented with engine oil-based nanofluids with CuO nanoparticles. The oil, nanoparticles, and grinding balls were placed in a container and crushed for 3 h by a planetary mill on a laboratory scale. The balls, one centimeter in diameter, and the container were made of stainless steel, and the weight ratio of the balls to the nanofluid was 7:1. After crushing, the nanofluids were very stable, and no sedimentation was observed for more than 30 d. Besides, no changes were observed in the morphology of nanoparticles. Munkhbayar et al. [50] produced an aqueous MWCNT nanofluid by combining the use of a planetary ball mill and ultrasonic technology. Planetary ball milling reduces the average cluster size and increases the stability of the resulting nanofluid.

5. Stability evaluation methods for nanofluids

Several methods are used in the literature to assess the stability of nanofluids, namely sedimentation, zeta potential measurement, spectral absorbance, and transmittance measurement. These techniques are briefly described in the following section. Figure 6 shows the stability verification procedures for nanofluids

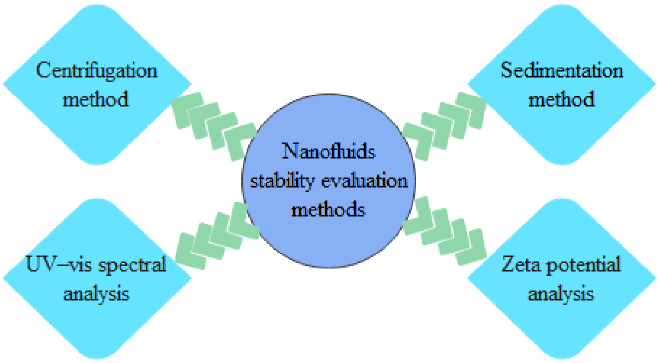

Figure 6. Nanofluids stability evaluation methods.

5.1. Sedimentation

The sedimentation process is the method most frequently used to assess stability. This technique is founded on the formation of sediment at the bottom of the liquid column under the effect of gravity. The centrifugation technique is a different sedimentation method that requires relatively less time to assess the stability of the nanofluid. Zhu et al. [51] applied the sedimentation method's principle in their experimental device to measure the stability of the graphite suspension. Li et al. [52] carried out the EG-based SiC nanofluid sedimentation experiment and observed that the nanofluids were uniform and steady within a month.

5.2. Zeta potential test

Zeta potential is considered a key indicator of colloidal dispersion stability. The zeta potential is the voltage between the surface of the nanoparticles and the stationary layer of the base fluid that is attached to the nanoparticles [48]. Several researchers have examined the zeta potential of nanofluids. Kim et al. [53] analyzed the zeta potential of Au nanofluids and discovered their stability. Khaleduzzaman et al. [54] carried out a zeta potential analysis to evaluate the stability of Al_2O_3–water nanofluids, and the zeta potential value was measured to be 53.6 mV. The nanofluids were shown to be stable for 30 d.

5.3. Spectral absorbency

Spectral analysis by UV-Vis spectrophotometer is an effective method to evaluate nanofluid stability. Shankar et al. [55] studied the stability of a silicon dioxide (SiO_2) nanofluid and a titanium dioxide (TiO_2) nanofluid by UV light absorption versus spectroscopy. They indicated that the absorbance of TiO_2-based nanofluid increased to 4.58 A_λ. At 250 nm, the absorbance of SiO_2-based nanofluids is only 2.97 A, indicating that the TiO_2-based nanofluid absorbs light due to the high concentration of nanoparticles and the absence of agglomeration, whereas the latter absorbs less light due to the lower concentration, indicating that the nanoparticles have agglomerated. Farbod et al. [56] examined the stability of carbon nanotubes (CNTs) with and without reflux by UV-vis absorption spectra, and the nanofluids were stable for 80 d.

6. Thermophysical properties of nanofluids

The thermophysical properties of solutions are profoundly modified by the addition of nanoparticles, and a large number of factors have a significant effect on this modification, including the type of material, the size and shape of the nanoparticles used as well as the volume concentration of the suspended particles and the conductivity of the base fluid [57]. These new types of fluids have been formed with different thermophysical properties such as density, heat capacity, thermal conductivity, convective heat transfer, thermal diffusivity, and viscosity [58]. Figure 7 depicts a diagram of differents thermphysicals properties of nanofluids.

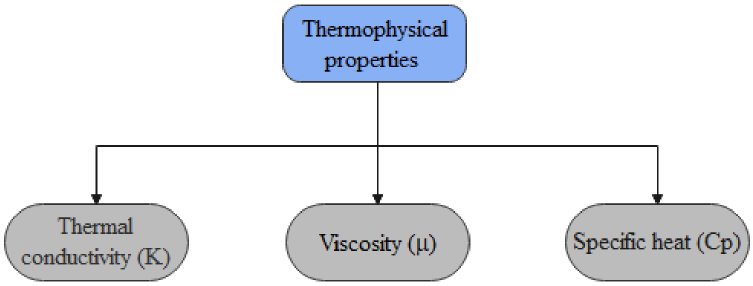

Figure 7. Nanofluids thermophysical properties.

6.1. Thermal conductivity

Thermal conductivity is the ability of a material to conduct or transmit heat. It is the most important property for improving the thermal performance of a heat transfer fluid. Several theoretical and experimental studies were performed to estimate the value of the thermal conductivity of a nanofluid. This property depends on multiple parameters such as media temperature, base fluid conductivity, the thermophysical properties of nanoparticles, the size and shape of particles, the Brownian motion, and the volume fraction of suspended particles [59]. There are different methods to measure the thermal conductivity of nanofluids, such as the transient hot-wire [60], the steady-state parallel plate [61], the cylindrical cell [62], the temperature oscillation [63], and the 3w method [64]. Esfe et al. [65] conducted a study on the thermal conductivity of Al_2O_3 nanoparticles in ethylene glycol (EG) for volume concentrations of 0.2 to 5.0%. This study showed that the effective thermal conductivity of Al_2O_3/EG nanofluids increased with increasing nanoparticle concentration and temperature. They showed a maximum improvement of up to 12.7% at concentrations above 1.0%.

In 1881, Maxwell [66] was one of the first to study analytically the heat conduction of a fluid containing spherical particles in suspension, ignoring the effects of interaction between these particles. The resulting equation is:

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f + 2(k_s - k_f)\varphi}{k_s + 2k_f - (k_s - k_f)\varphi} \quad (1)$$

where k_{nf}, k_f and k_s represent the thermal conductivities of the nanofluid, the base fluid and the nanoparticles, respectively, and φ the volume fraction of the particles.

6.2. Viscosity

Viscosity is an important factor for thermal applications involving fluids. In addition, heat transfer by convection is influenced by viscosity [67]. As a result, viscosity requires the same attention as thermal conductivity because of its very significant impact on heat transfer. The viscosity of nanofluids increases mainly by increasing the concentration of nanoparticles and decreases by raising the temperature [68]. Several viscometers with various functional bases have been employed to measure the viscosity of nanofluids, such as the capillary tube viscometer, Vibro-viscometer, rotational rheometer, drop/fall ball, piston viscometer, and cup viscometer [69]. Among others, the rotary rheometer, piston rheometer, and capillary tube viscometer are the most commonly used devices for viscosity measurements of nanofluids [70]. Moghaddam et al. [71] prepared graphene and glycerol-based nanofluids and performed experimental measurements of the rheological properties of the nanofluids. These results indicate that the viscosity of graphene-glycerol nanofluids is dependent on mass fraction and temperature. The viscosity improves with increasing mass fraction and decreases with increasing temperature. In this investigation, the 401.49% increase in viscosity of glycerol was obtained by loading 2% of graphene nanosheets at a shear rate of 6.32 s^{-1} and 20 °C.

Einstein [72] studied the dynamic viscosity of a nanofluid for a mixture consisting of dilute suspensions of fine, spherical particles. The expression that characterizes this model is the following:

$$\mu_{nf} = \mu_f(1 + 2.5\varphi) \tag{2}$$

with μ_{nf} and μ_f are respectively the dynamic viscosities of the nanofluid, the base fluid and φ the volume fraction of the nanoparticles.

6.3. Specific heat

Specific heat is one of the essential properties and has an essential role in influencing the thermal transfer rate of nanofluids. Specific heat is the quantity of heat needed to raise the temperature of one gram of nanofluid by one degree centigrade [73]. Sang and Liu [74] conducted studies with four different nanoparticles (SiO_2, CuO, TiO_2, Al_2O_3) to investigate the specific increase in heat capacity of ternary carbonate. Their experimental data asserts that the SiO_2 nanoparticle is the best particle to improve the specific heat capacity of ternary carbonate nanofluids, and they showed that the specific heat capacity of the nanofluid depends mainly on the type of nanoparticle and the nanostructure. Sardinia et al. [75] experimented with the specific thermal capacities of CuO-based oil nanofluids with particle weight fractions of 0.2–2% at different temperatures. In this experiment, the nanofluids showed a less specific heat capacity than the base fluid, and it decreased with the increasing concentration of the nanofluids. This result indicates that the specific heat of nanofluids at a fraction of 2% by weight is about 23% lower than that of the base fluid at 40 °C. The specific heat of a nanofluid is determined by two formulas. Or the first is estimated by Pak and Cho [76] as follows:

$$(C_p)_{nf} = (1 - \varphi)(C_p)_f + \varphi(C_p)_s \tag{3}$$

where $(C_p)_{nf}$,$(C_p)_f$ et $(C_p)_s$ are respectively the specific heats of the nanofluid, the base fluid and the nanoparticles.

7. Elements impacting the thermophysical properties of nanofluids

The two most important transport properties of nanofluids are viscosity and thermal conductivity [77]. Both thermal conductivity and the viscosity of nanofluids are influenced by several factors. These parameters will be discussed in this section based on observations from previous work. Figure 8 represents the main factors influencing the thermo-physical properties of nanofluids.

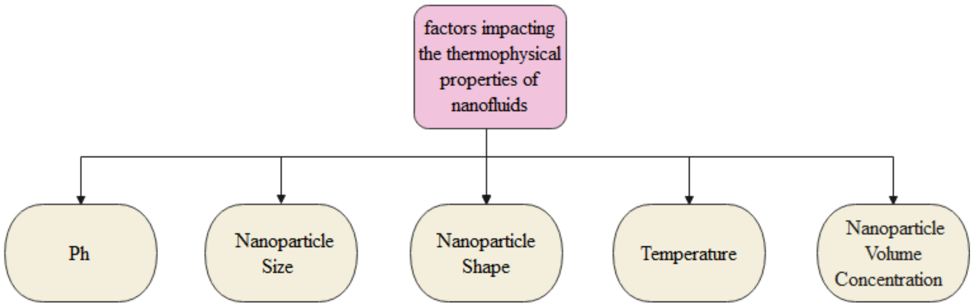

Figure 8. Important factors influencing the thermo-physical properties of nanofluids.

7.1. Nanoparticle volume concentration

Several researchers have investigated the effect of the volumetric loading of suspended nanoparticles on the improvement of thermal conductivity. Increasing the concentration of particles increases thermal conductivity but also increases viscosity. Some researchers have found this relationship to be non-linear [78]. Chandrasekhar et al. [79] examined the viscosity of Al_2O_3/H_2O nanofluids experimentally. The results showed that the viscosity of the nanofluids increases with the volume concentration of the nanoparticles. In this investigation, a 2.3 increase in viscosity was obtained compared to the base fluid at a concentration of 5% by volume. Colangelo and Milanese [80] numerically simulated the performance of alumina nanofluid in solar thermal collectors and found an increase of up to 8% in thermal efficiency for a volume fraction of 3% emerging in water.

7.2. Nanoparticle size

Particle size plays an important role in improving the thermal conductivity of nanofluids. The thermal conductivity of nanofluids improves with decreasing particle size, and the stability of the suspension deteriorates with particle size [81]. Teng et al. [82] examined the impact of particle size (charge and size), and temperature, on the thermal conductivity of alumina (Al_2O_3)/nano aqueous fluids. Their results indicate that thermal conductivity is improved with small nanoparticles, at high temperatures, and with a high weight fraction.

7.3. Nanoparticle shape

The effect of the shape of nanoparticles has been studied by Xie et al. [83]. Particles with two morphologies (spherical and cylindrical) are commonly used in nanofluid research. Those with cylindrical morphologies have a higher thermal conductivity than nanofluids with spherical particles. Kim et al. [84] studied the influence of aspect ratio on the thermal conductivity and viscosity of nanofluids with spherical alumina nanoparticles. It was observed that fibrous alumina nanofluids exhibited a greater improvement in thermal conductivity than spherical alumina nanofluids. The increase in viscosity of the fibrous alumina was also higher than that of spherical nanofluids.

7.4. Temperature

Several researchers have studied the effect of the temperature of nanofluids on improving their thermal conductivity. Toghraie et al. [85] studied the thermal conductivity of nanofluids, which increases significantly with temperature. Nasiri et al. [86] manufactured nanofluids from various types of CNTs. The thermal conductivity of all the nanofluids was improved by temperature, regardless of the synthesis methods, but the trends varied from case to case.

7.5. pH

The pH value of nanofluids is one of the key parameters affecting thermal conductivity and viscosity as well as particle clustering and stability of nanofluids [87]. Sahooli and Sabbaghi [88] examined the effect of pH on the stability of nanofluids. These results indicate that the best stability and improvement in thermal conductivity can be obtained at the optimal pH of the suspension. Zhu et al. [89] examined the effect of pH values on the thermal conductivity of nanofluids. This study allowed us to synthesize Al_2O_3-H_2O nanofluids and to study the thermal conductivity under different pH values of water.

8. Application of nanofluid on solar collectors

The solar collector is equipment that attracts solar radiation and transmits heat to the absorbing fluid, thus increasing its internal energy that can be used for domestic or industrial use. In summary, the solar collector converts energy from solar radiation to heat energy. The method of heat transfer between the sun and the absorbing fluid is essentially radiation. The absorption plate serves as a means of heat transfer and transfers the heat it has acquired to the absorbing fluid. In this section, we focus on three types of solar collectors: parabolic trough solar collector, flat plate solar collector and direct absorption solar collector.

8.1. Parabolic trough solar collector

The parabolic trough solar collector (PTSC) is a type of solar concentrator that is curved into a parabola and arranged in a straight line, and constructed with an array of mirrors to constitute a parabolic reflector and a receiver at the focal length as well as aligned by a laser beam [90]. Due to its ability to support a high-temperature load, synthetic oil is used as a heat transfer fluid, and the range is 100–500 °C (Figure 9).

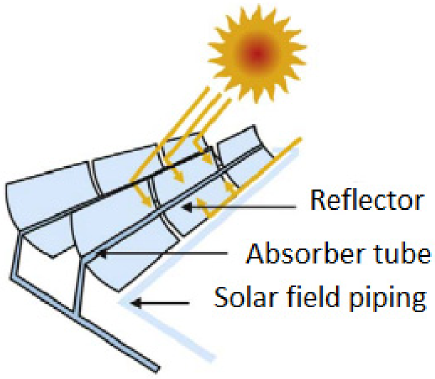

Figure 9. Parabolic trough collector schematic model.

Table 1 represents the thermal performance of nanofluids in the PTSC. Sokhansefat et al. [91] numerically studied the turbulent mixed convection heat transfer of Al_2O_3/synthetic thermal oil nanofluid in a PTC with a receiver tube. The receiver is under non-uniform heat flux. The mean heat transfer coefficient at the working temperature of 400 K increased by 8.6% with the addition of 5% by volume of Al_2O_3 nanoparticles. The Nusselt number increases with increasing Reynolds number. After 0.2% volumetric concentration of nanoparticles, the maximum performance is achieved at a volumetric fraction of 0.5% [92]. Coccia et al. [93] experimented with the use of various nanoparticles in water at different concentrations and found no specific improvement in thermal efficiency. Mwesigye et al. [94] used Cu-Therminol® VP-1 nanofluid to enhance the performance of a parabolic trough solar energy system. Thermal efficiency was increased by up to 12.5%. In addition, the use of convergent-divergent geometries within the absorber, which create passive vortices, is also a promising way to increase the thermal efficiency of PTCs [95]. Amina et al. [96] observed the thermal improvement with the addition of nanoparticles. Application of nanofluid as an internal HTF absorber with baffles improved the thermal performance. Amina et al. [97] have shown a three-dimensional numerical heat transfer study of a parabolic trough receiver with longitudinal fins and nanofluids with a volume fraction of 1%. The thermal performance was shown to increase with improved heat transfer. Ghasemi et al. [98] investigated the use of Al_2O_3 and CuO nanoparticles dispersed in water for PTCs. They showed an improvement in the heat transfer coefficient of nearly 28% for Al_2O_3 and 35% for CuO. An experimental study on a novel high temperature parabolic collector (PTC) with a transparent receiver tube was performed by Potenza et al. [99], they concluded that the average efficiency is about 65%. Ghasemi et al. [100] carried out a numerical simulation with forced convection flow of the nanofluid through a receiving tube. The addition of nanoparticles improved effective thermal conductivity and heat transfer, resulting in an increase in the average Nusselt number. Nevertheless, there was an increase in the friction factor with the addition of nanoparticles in the base fluid. Bellos et al. [101] examined the effect of using nanoparticles and internal fins on the performance of PTCs with Syltherm 800/CuO HTF. They reported that the use of nanoparticles and internal fins increased the thermal efficiency by up to 1.54%.

Table 1. Synthesis of parabolic trough solar collector performance with nanofluids.

Refs.	Type of nanofluids	Particle size (nm)	Absorber	Results
[91]	Al_2O_3/synthetic oil	10	Tube	Improvement of the heat transfer coefficient of the absorber tube and an increase in the volume fraction. The heat transfer coefficient for a given Reynolds number decreases as the absorber tube's operating temperature increases.
[92]	Al_2O_3/water	40	Tube	The use of nanofluid increased the number of Nusselt, but an asymptotic trend was observed after a volumetric concentration of 0.2% nanoparticles, with maximum yield at a volume fraction of 0.5%.
[93]	TiO_2, SiO_2, Fe_2O_3, ZnO, Al_2O_3, Au/water	N/A	Low-Enthalpy Parabolic Trough Collector	The enhanced energy efficiency of the low enthalpy parabolic trough collector compared to pure water.
[94]	Cu/therminol VP-1	N/A	Parabolically shaped mirror	Heat transfer performance is improved and increases with increasing volume concentration. Improved maximum thermal efficiency at the highest inlet temperature.
[95]	Al_2O_3/thermal oil	20	Converging-diverging absorber tube	The increased efficiency of the parabolic-cylindrical collector. Increase the average yield by 4.25%.
[96]	CNT/therminol VP-1	-	Tube	A thermal improvement was observed due to the addition of nanoparticles. Application of a nanofluid as an internal HTF absorber with baffles improved thermal performance.
[97]	Al_2O_3, Cu, SiC, C /Dowtherm A	13	Tube	In combination with the internal fin, Copper/Dowtherm A provides the greatest coefficient of convective heat transfer, secondary to Carbon/Dowtherm A, Silicon Carbide/Dowtherm A, and Aluminum/Dowtherm A.
[98]	Al_2O_3, CuO/water	30	Receiver tube	The nanofluid CuO/water performs best than Al_2O_3/water. Heat transfer coefficients were found to be improved by 28% and 35% using Al_2O_3-water and CuO-water nanofluids (ϕ = 3%), respectively.
[99]	Air disperse CuO nanopowder	7.4	Transparent quartz receiver	The average efficiency is about 65%. The temperature of 180 °C is the maximum value in the nanofluid circuit.circuit.
[100]	Al_2O_3/therminol-66	20	Receiver tube	A considerable increase in the number of Nusselt using a nanofluid, compared to the base fluid.
[101]	CuO/syltherm 800	N/A	Tube	Improved efficiency, convection heat transfer, and pressure drop.

8.2. Flat plate solar collector

The concept of the flat plate solar collector (FPSC) is relatively simple and broader in applications such as water heating, space heating, domestic, commercial, and industrial use [102]. In this sensor, no optical concentration is present, and this type of sensor is used when the required temperature is between 40 and 100 °C. The temperature increase in this type of collector is in the range of 0–50 °C. This collector division is very important because of its simple construction, no moving parts, easy maintenance, and low operating cost. Figure 10 shows a schematic of flate plate solar collector.

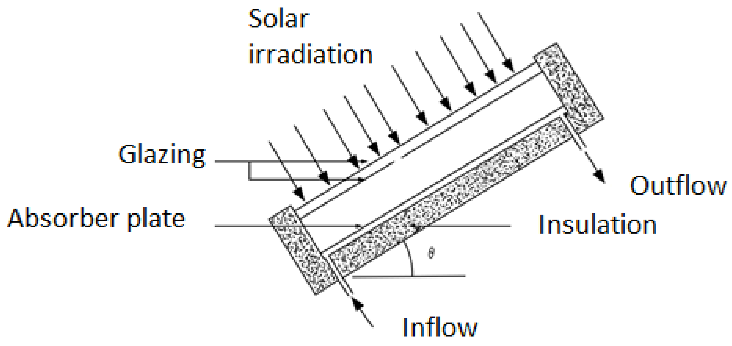

Figure 10. Schematic of flat plate solar collector.

Table 2 shows the resume of certain important prior studies based on the performance enhancement of flat plate solar collectors using nanofluids. Natarajan and Sathish [103] investigated the thermal conductivity enhancement of base fluids by employing carbon nanotubes (CNTs) and proposed that these fluids, used as a heat transport medium, increase the efficiency of conventional solar water heaters. Yousefi et al. [104] investigated an experimental study of the effects of pH variation of MWCNT-H_2O nanofluid on the efficiency of a flat plate solar collector. They employed a water-based MWCNT with 0.2% and Triton X-100 as a surfactant for nanoparticle dispersion. Alim et al. [105] studied the entropy generation generated by the flow of some nanofluids (Al_2O_3/water, CuO/water, SiO_2/water, TiO_2/water) of 4% volume fractions in a solar collector. It is found that by using CuO/water nanofluid instead of water, the heat transfer coefficient increases by 22.15% while the entropy generation is reduced by 4.34%. Jamal-Abad et al. [106] investigated the performance of a flat plate solar collector and discovered that the use of Cu/water nanofluids with a weight fraction of 0.05% improved performance;instead of pure water provides a 24% higher efficiency. The efficiency of the improved flat plate solar collector using CuO/H_2O nanofluid was 16.7% for 3 kg/min at a volume concentration of 0.4% and 40 nm particles [107]. Said et al. adopted two processes to produce a more stable TiO_2-water nanofluid [108]. In the first method, they used polyethylene glycol 400 as a dispersant. In the second method, they used a high-pressure homogenizer to disperse the nanoparticles in the base fluid. TiO_2-water nanofluids are used to make the flat plate solar collector. The energy efficiency of the flat plate solar collector using the nanofluid was higher than that of the flat plate solar collector using water. Meibodi et al. [109] investigated the thermal efficiency of a flat plate solar collector using SiO_2/EG-water nanofluid and discovered that, despite the poor thermal conductivity of SiO_2 nanoparticles, the efficiency was improved when SiO_2/EG-water nanofluid was used for the solar collector. Verma et al. [110] performed an experimental study of FPSC using MgO/water nanofluid at varying concentrations and mass flow rates. Thermal and energy efficiency improvement was observed to be the maximum, 9.34% and 32.23% for a particle volume concentration of 0.75% and a mass flow rate of 0.025 kg/s. Noghrehabadi et al. [111] investigated experimentally a square FPSC with SiO_2/water nanofluid with a 1% concentration under both laminar and turbulent flow regimes. They concluded that using a 1 wt% SiO_2/water nanofluid improved thermal efficiency by 2.5% and 1% at mass flow rates of 2.8

and 0.5 kg/min, respectively. For direct absorption solar collectors, nanofluids have a significant influence on the thermal performance of the collector.

Table 2. Synthesis of the performance of a flat-plate solar collector with nanofluids.

Refs.	Type of nanofluids	Particle size (nm)	Volume fraction (%)	Surfactant	Collector area (m^2)	Results
[103]	MWCNT/water	-	0.2–1.0	SDS	N/A	Dispersion CNTs prepared with SDS were very stable. The thermal conductivity increased by 41% to a volume fraction of 1%.
[104]	MWCNT/water	10–30	0.2 and 0.4	Triton X-100	2	Unstable nanofluid samples in the absence of a surfactant. Performance increased by 0.4% by weight. Experimental results indicate that the differences between the nanofluid's pH and the pH of the isoelectric point are greater the higher the efficiency of the collector.
[105]	TiO_2, Al_2O_3, SiO_2, CuO/water	N/A	1–4	N/A	1.5	The heat transfer characteristics have improved remarkably, and the convection heat transfer coefficient has increased. Increasing the volume concentration of nanoparticles improves the heat transfer coefficient .
[106]	Cu/water	35	0.05 and 0.1	SDS	1 × 0.67	Collector efficiency was improved from approximately 24% to 0.05% by weight. The nanofluid was found to be more effective at low average irradiance.
[107]	CuO/water	40	0.4	Without	1.5	Solar collector efficiency increased by 16.7% due to the use of CuO/water compared to water.
[108]	TiO_2/water	20 and 40	0.1 and 0.3	PEG400	1.84	Increase in thermal conductivity to 6% with a volume fraction of 0.30. The greatest energy and exergy efficiencies were 76.6% and 16.9%, respectively.
[109]	SiO_2/EG-water	~40	0.5, 0.75,1	Without	1.59	Thermal efficiency increases with an increase in volume concentration, and the result of 0.75% and 1% volume concentration is very close.
[110]	MgO/water	~40	0.25, 0.5, 0.75, 1.00, 1.25, 1.5	Cetyl Trimethyl Ammonium Bromide	0.375	Solar collector efficiency improved from 9.34% to 0.75 volume concentration and 1.5 lpm. Energy efficiency improved by 32.23% and pumping power loss by 6.84%.
[111]	SiO_2/water	~12	1	Without	1	Enhanced efficiency of a flat plate square solar collector compared to pure water and increases in volume concentration.

8.3. Direct absorption solar collector

The incident rays fall directly on the fluid and are absorbed by direct absorption solar collectors (DASC). They are characterized by direct and volumetric absorption of the rays incident on the fluid, which implies minimal convective losses and higher efficiency and offers less thermal resistance compared to the flat type solar collector. Figure 11 shows a schematic of a direct absorption solar collector. Table 3 gives an overview of the significance and improvement of the direct absorption solar collector with nanofluids.

Karami et al. [112] experimentally investigated the thermo-optical properties of low temperature direct absorption solar collectors using a mixture of distilled water and ethylene glycol. The diameter of the nanoparticles is less than 40 nm at different temperatures for different volume fractions. The results of the experimental observations showed an increase in the absorption capacity of the nanofluid at very low volume concentrations. When the concentration is 100 ppm, there is an increase in absorption of up to 4 times that of the base fluid for the same path length of 1 cm. The thermal conductivity increases from 5.6% to 13.7% for this volume concentration and temperature range. He et al. [113] experimented with the photothermal properties of copper/water nanofluids. The results showed that the temperature of copper/water nanofluids (0.1%) was increased by up to 25.3% compared to that of deionized water. Different nanoparticles, volume fractions and different types of collectors have significant impacts on the efficiency of solar energy utilization. Different materials, volume fractions and types of collectors have significant impacts on the efficiency of solar utilization. The choice of fluid is critical for improved performance in the DASC. Parvin et al. [114] performed a mathematical model and analysis of the effect of Cu and Ag nanoparticles on entropy generation and thermal efficiency. Indeed, their results reveal that Cu nanoparticles with the highest Re and φ = 3% are the most efficient fluid to improve the heat transfer rate. The collector efficiency increases by two times and more when the Reynolds number and solid volume fraction increase with Ag and Cu nanoparticles. Gupta et al. [115] experimentally examined the efficiency of a low-temperature DASC under outdoor conditions. For different volume concentrations of water-based Al_2O_3 (0.001–0.05 vol%), the improvement in efficiency of the nanofluid solar collector is compared to the use of water. Instantaneous efficiency compared to reduced temperature plots showed that increasing the nanoparticle concentration above 0.005 vol% had an inverse effect on efficiency. The maximum efficiency improvement of 39.6% was observed for the use of 0.005% vol nanofluids. Delfani et al. [116] experimentally studied the MWCNT/water-EG nanofluid in a direct absorption solar collector. These researchers studied the impact of MWCNT volume fraction and nanofluid mass flow rate on the collector efficiency. The efficiency of the collector was increased from 10% to 29% compared to using the base fluid. Furthermore, it was concluded that increasing the flow rate and volume fraction of MWCNTs had positive effects on the collector efficiency. Gorji and Ranjbar [117] experimentally investigated the impact of various nanoparticles immersed in deionized water on the thermal properties in a direct absorption solar collector. The results show that magnetite dispersions achieved the highest thermal and energy efficiencies, followed by graphite and silver nanofluids, respectively.

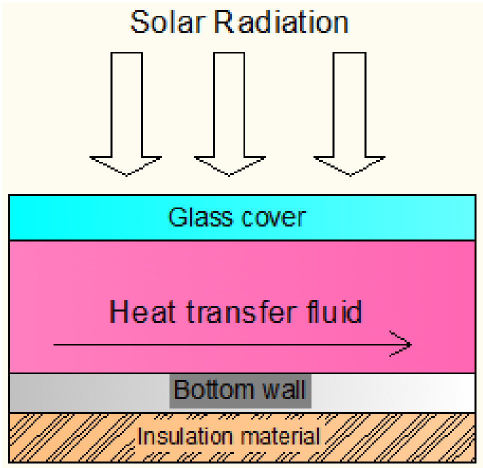

Figure 11. Schematic of direct absorption solar collector.

Table 3. Summary of nanofluid research in direct absorption solar collector.

Refs.	Type of nanofluids	Particle size (nm)	Volume fraction (%)	Surfactant	Collector area (m^2)	Results
[112]	CNT, graphite, and silver/water	(6–20), 30, 40	0–1	PVP	0.03 × 0.05	For graphite nanoparticles of 30 nm, the efficiency improvement was 3%. The maximum improvement in efficiency for 20 nm silver nanoparticles was 5%.
[113]	Cu/water	25, 50	0.02, 0.1, 0.004, 0.002, 0.001	SDBS	N/A	Cu/H_2O nanofluids show good solar energy absorption ability and can improve the efficiency of solar absorption. Cu/H_2O nanofluids have the potential to be used in direct absorption solar collectors.
[114]	Cu/water	5	0–7%	Without	0.3 × 0.3	With a higher Reynolds number, Cu nanoparticles at 3% by volume, were the most effective in increasing the heat transfer rate. The efficiency is more than twice as high with the increase in the Reynolds number
[115]	Al_2O_3/water	20–30	0.001, 0.005, 0.01, 0.05	Without	1.44	Improvements in instantaneous efficiency of 22.1%, 39.6%, 24.6%, and 18.75% were observed for a volume fraction of 0.001%, 0.005%, 0.01%, and 0.05%, respectively.

Continued on next page

Refs.	Type of nanofluids	Particle size (nm)	Volume fraction (%)	Surfactant	Collector area (m^2)	Results
[116]	MWCNT/H_2O-EG	(10–20)	0.0025, 0.0050 and 0.01	Without	0.6 × 0.6	The performance of the collector improves with the volume fraction of the nanofluid and the flow rate. The collector efficacy has improved by (10–29%) for different mass flow rates and % vol.
[117]	Graphite, Magnetite, Silver/water	40/15/20	5–40 ppm	Graphite mixture of Sulfur acid, nitric acid. Magnetite, Silver–TPABr	0.55 × 0.12	Nanofluid magnetite/water achieved the highest thermal and energy efficiency, with graphite and silver following.

9. Conclusion

In this paper, we have discussed the different types of nanofluids, all the important research that has been done on the preparation and stability of nanofluids. We learned that the two-step preparation method is recognized by most researchers as being simple and cost-effective. Also, we discovered the steps required to stabilize these fluids. Moreover, the mechanisms corresponding to the evaluation of the stability of these fluids are also discussed. The thermophysical properties of nanofluids, such as thermal conductivity, viscosity, and specific heat, and the factors determining these properties were examined. Indeed, a summary on the recent achievements of the use of nanofluids in solar collectors, namely PTSC (parabolic trough solar collector), FPSC (flat plate solar collector), direct absorption solar collector (DASC), the impact of the method of preparation of nanofluid, the type of additive chosen and other factors influenced on the performance and efficiency of solar collectors. Finally, the major difficulties are still the high production cost, the stability, the agglomeration of the particles, the pumping power and the pressure drop.

Conflict of interest

I declare that there is no conflict of interest between the authors.

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