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APPLICATIONS OF NANOTECHNOLOGY TO ENHANCE THE PERFORMANCE OF THE DIRECT ABSORPTION SOLAR COLLECTORS

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ABSTRACT
This research gives a comprehensive overview about the recent advances related with the application of the nanotechnology in the direct absorption solar collectors. Papers reviewed including theoretical, numerical and experimental up to date works related with the nanotechnology applications in this kind of the solar collectors. A lot of literature are reviewed and summarized carefully in a useful table (Table 1) to give a panoramic overview about the role of the nanotechnology in improving the direct absorption solar collectors. It was found that the use of the nanofluid in the direct absorption solar collectors can play a crucial role in increasing the efficiency of these devices.

1. INTRODUCTION

Solar energy is currently one of the most important sources of clean, free, inexhaustible and renewable energy with minimal environmental impact. The power from the sun intercepted by the earth is approximately 1.8×10^{11} MW [1]. About 30% of the solar power actually reaches the earth and at every 20 minutes, the sun produces enough power to supply the earth with its needs for an entire year [2]. The solar energy can be defined as the energy which comes from the sun and can be converted into electricity and heat. It has produced energy for billions of years, so the utilization of solar energy and the technologies of its materials has received much attention especially in the last ten years [3-4]. For example, some studies have indicated that about 1000 times from the global energy requirements can be achieved by using solar energy; however, only 0.02% of this energy is currently utilized [5]. The main reasons of this huge attention in the solar energy applications are due to the growing demand of energy, limited availability of fossil fuels and environmental problems associated with them such as carbon dioxide emissions. Moreover, the rapid increase in the human population can be considered as an additional serious problem, since the global population has increased by nearly 2 billion with a major contribution from developing countries [6]. Furthermore, it is proved that the consumption rate of fossil fuels by humans is much faster than they are replaced by geologic processes. In fact, the sun radiates every day, enormous amount of energy and the hourly solar flux incident on the earth's surface is greater than all of human consumption of energy in a year [7]. In spite of this huge amount of available solar energy, approximately 80% of energy used worldwide still predominantly comes from fossil fuels such as coal, petroleum and natural gas [8].

2. CONCEPT OF NANOFLUID

Nanofluid or suspensions of nanoparticles in liquids is defined as a mixture of a normal fluid such as (water, oil, ethylene glycol and molten salts) with a very small amount of solid metallic or metallic oxide nanoparticles or nanotubes which was first suggested by Choi [9] in 1995. It was considered as the new generation of advanced heat transfer fluids or a two-phase system which used for various engineering and industrial applications due to its excellent performance. Some of these applications including nuclear reactors, transportation industry, cooling of transformer oil , electrical energy, mechanical , magnetic, cooling of microchips , solar absorption and biomedical fields [10]. It is well known that metals have higher thermal conductivities than those of fluids. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil [11]. The first decade of nanofluid researches was primarily focused on measuring the thermo-physical properties of these fluids such as the thermal conductivity, density, viscosity and heat transfer coefficient [12]. Nanofluid have a good properties of radiation absorption and it has a high thermal conductivity. For example, the thermal conductivity at the room temperature of individual multi-walled carbon nanotubes (MWCNTs) were found to have values greater than 3000 W/ m.K [13]. Moreover, Assael et al. [14] indicated that about 1% volumetric fraction of MWCNT was enhanced the thermal conductivity of water by about 40%. In order to prepare nanofluids by dispersing nanoparticles in a base fluid, a proper mixing and stabilization of the particles is required. The size of nanoparticles is very small and in the range of 1–100 nm [15] which is about one-thousandth the diameter of a human hair. It is highly recommended not to add large solid particles in the base fluids (more than 100 nm) due to the following main drawbacks [7] :-

1- Mixtures become unstable and hence, sedimentation occurs.
2- Existence of large solid particles require a large pumping power and this increases the cost.
3- Large quantities of solid particles erode the channel walls and increase the pressure drop.
4- They lead to clogging of pumps and valves used in the overall system.

Therefore, nanofluid can be used efficiently to solve these drawbacks, since it has many advantages such as:-

1- It increases the effective thermal conductivity of the suspension and as a result enhances the heat transfer characteristics. Since, high thermal conductivity of nanofluids and Brownian motion of nanoparticles increase the heat transfer performances.
2- It has a very small size, so it fluidizes easily inside the base fluids and can be moves faster inside solid blocks such as the porous media.
3- It has a large surface area (more than 100 m^2/g) to volume ratio, dimension-dependent physical properties and lower kinetic energy. In fact, the large surface area increases the heat transfer rate between the base fluid and solid particles.
4-The nanofluid reduces the problem of rapid settling of micro or millimeter sized particles when they used in the conventional collectors.
5-The properties like viscosity, specific heat, thermal conductivity and density may be varied easily by changing particle concentrations to be suitable with different industrial applications [16].
6- The pumping power required for the equivalent heat transfer is less than that compared to pure liquids [17].
7- The heat transfer increases as a result of increase in the heat transfer surface area between the particles and fluids.
8- In contrast to conventional heat transfer fluids, nanofluids are not transparent to solar radiant energy; but, they absorb and scatter significantly the solar irradiance passing through them.
9-The high stability of nanofluid make them to stay in the liquid phase for months or even years and its stability can be increased by the Brownian motion.
10- Nanoparticles dispersed quickly in liquids, so it reduce the friction and wear occur in the pipelines and pumps.
11-Nanfluid has a high thermal capacity, since the small volume of nanoparticles make them easily to store a large quantity of heat. This of course will reduce the energy losses and increasing the efficiency of the system [18].
12- Nanoparticles increase significantly the mixing fluctuation and turbulence of the fluid [19].

However, the science which deals with the nanofluids is called the Nanotechnology and it provides a new area of research to deal with these new types of fluids [20]. This technology has the potential to dramatically re-define the methods used for developing lighter, stronger and high-performance structures and processes with clear and non-traditional properties. For comprehensive details about the applications and challenges of nanofluids , the reader can be go back to the review by Saidur et al. [21].

3. SOLAR COLLECTOR

The solar collector is one of the most important components of a solar energy and water heating systems which can be defined as a green heat exchanger device which converts the energy in sunlight or incident solar radiation either to the thermal energy in solar thermal applications, or to an electrical energy directly in PV (photovoltaic) applications. Therefore, the main job of the solar collector is that it collects the solar energy and transfers it to a fluid passing in contact with it. The ideal solar collector absorbs the concentrated solar radiation and converts it to a heat and then transfer this heat to the collector fluid. Therefore, higher the heat transfer to fluid, means higher outlet temperature and higher the collector efficiency in the power cycle [22]. So, the major challenge is how can we improve this device to increase its efficiency to convert the solar energy into a thermal or electrical energy. Solar collectors can be used for a variety of residential and small commercial applications such as water heating systems in homes, solar space heating, solar desalination, solar drying devices, electricity production and small solar power plants. For solar thermal applications, the solar irradiation is absorbed by a solar collector as a heat and then transferred to its working fluid (air, water or oil). The heat carried by the working fluid can be used to either provide domestic hot water/heating, or to charge a thermal energy storage tank where the heat can be used later at night or cloudy days. For photovoltaic applications, a PV module not only converts solar irradiation directly into electric energy, but it also produces plenty of waste heat, which can be recovered for thermal use by attaching PV board with recuperating tubes filled with carrier fluids [23]. The performance of the solar collector depends upon the properties of the working fluid which are used to maximize the solar energy absorption in the solar collector. Examples of solar thermal collectors are solar water heaters, solar cookers and solar ponds. Many researchers are presented a literature review papers about the solar collectors such as Kalogirou [24], Jaisankar et al. [25] and very recently by Wang et al. [26].

4. DIRECT ABSORPTION SOLAR COLLECTOR

The direct absorption solar collector (DASC) was firstly proposed in 1975 by Minardi and Chuang [27] and used to enhance the efficiency of the flat plate collector by making the fluid to directly absorb the solar radiation. It is also called as a volumetric solar collector and has the ability to offer an unlimited source of renewable energy with minimal environmental impact. This type has some advantages compared to the conventional one. Besides larger solar absorption area and actual installation surface area ratio, it is capable to avoid surface heat losses due to the excessive temperature on the surface absorption collector. But, the main disadvantage of this device is that its efficiency is limited by the absorption properties of the working fluid, which is very poor for typical fluids used in solar collectors [28]. In this configuration, the hottest part of the system is the operating fluid and this allows to have a more efficient conversion. There are many kinds of direct absorption solar collector such as volume trap solar collectors, black liquid collectors and small particle collectors.

5. APPLICATIONS OF NANOFLUID IN DIRECT ABSORPTION SOLAR COLLECTORS

Tyagi et al. [29] investigated theoretically the possibility of using water and aluminum nanofluid as an absorbing medium for a low-temperature (<100 °C) direct absorption solar collector. The results showed that the nanofluid increased the absorption of the incident radiation by more than nine times over that of the pure water. Moreover, the efficiency of the collector was found to be up to 10 % higher than that of a flat-plate collector under similar operating conditions. Otanicar et al. [30] investigated both numerically and experimentally the performance of nanofluid-based direct absorption solar collector. Three different groups of nanofluids, with water as a base fluid, were considered which graphite (30 nm diameter) are, carbon nanotube (6-20 nm diameter) and silver (20 and 40 nm diameters) .They demonstrated an efficiency improvements of up to 5 % in solar thermal collectors by utilizing nanofluids as an absorption mechanism. Taylor et al. [31] examined experimentally the effectiveness of various nanofluids in direct absorption solar collectors by testing their absorption of the solar spectrum. They observed that for materials used in their study, over 95% of incoming sunlight could be absorbed (in a nanofluid thickness ≥10 cm) with extremely low nanoparticle volume fractions less than 1×10^{-5}, or 10 parts per million. They concluded, that nanofluids could be used to absorb sunlight with a negligible amount of viscosity and/or density increase. Poinern et al. [32] investigated experimentally the photo-thermal response of nanoparticles of functionalized carbon nanospheres (CNS) for potential application in direct solar absorption collectors. The synthesized CNS were examined and characterized using field-emission scanning electron microscopy, transmission electron microscopy, X-ray diffraction spectroscopy, Raman spectroscopy, thermal gravimetric analysis and ultraviolet-visible analysis. The photo-thermal response of both nanofluids and films composed of CNS were investigated under 1000 W/m^2 solar irradiation. Saidur et al. [33] investigated theoretically the effect of aluminum - water nanofluid on the performance of the direct absorption solar collector. They concluded that the volume fraction of just 1.0 % gave a satisfactory improvement to the solar absorption and as a result the Al - water nanofluid was a good option for improving the performance of the direct absorption solar collector. Also, it was found that, the collector efficiency was increased slightly with an increase in the particle size as shown in Fig.1.

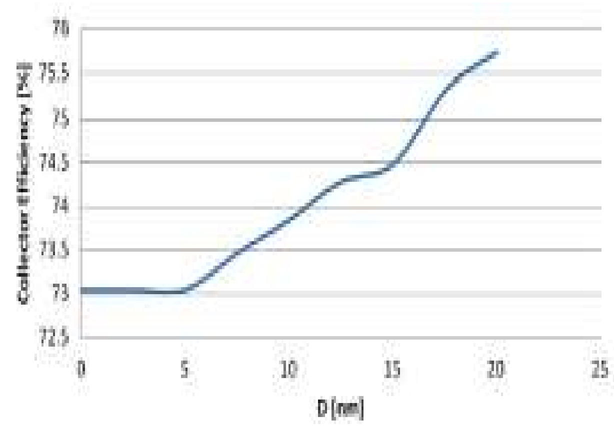

FIGURE 1 COLLECTOR EFFICIENCY AS A FUNCTION OF THE PARTICLE SIZE (D) [Saidur et al.[33]]

Moradi et al. [34] performed a CFD modeling of the direct absorption solar collector with nano-fluid used in civil applications. Recent measurements of the optical properties of nano-fluids with different concentrations were used for the radiation heat transfer and the fluid dynamic modeling. They concluded as shown in Fig.2, that the increasing concentration of nanoparticles initially increased the efficiency of the solar collector but, beyond a certain value of concentration, a further increase in the nanoparticle concentration decreased the efficiency due to the high surface temperature. Kundan and Sharma [35] performed an experimental study to improve the efficiency of the direct absorption solar collector by using a CuO-water based nanofluid in it. They concluded that the efficiency of the solar collector was increased by 4-6% compared to the conventional water-based solar collector. They mentioned that one of the main reasons of getting a high efficiency was the very small particle size, which enhanced the absorption capacity of nanofluids and improved the solar collector efficiency.

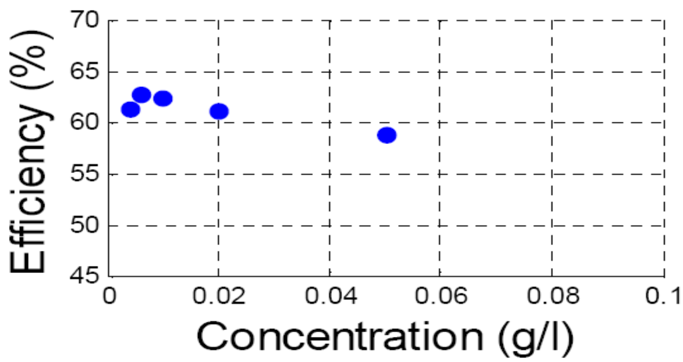

FIGURE 2 EFFECT OF NANOPARTICLE CONCENTERATION ON EFFICIENCY OF SOLAR COLLECTOR [Moradi et al.[34]] .

Verma and Kundan [36] investigated experimentally the effect of Al_2O_3-H_2O based nanofluids as an absorbing medium in a direct absorption solar collector (Fig.3). The volume fractions of Al_2O_3 nanoparticles used were 0.005% and 0.05% respectively. Efficiency of the collector was calculated for different mass flow rates (60, 80 and 100 ml/hr) of the nanofluid. It was found that, the collector efficiency was increased about 3-5% when the nanofluid was used as compared to a simple water. This behavior was illustrated in Fig.4. They concluded also that the collector efficiency depended on the size, shape and the volume fraction of nanoparticles.

FIGURE 3 DIRECT ABSORPTION SOLAR COLLECTOR [Verma and Kundan [36]]

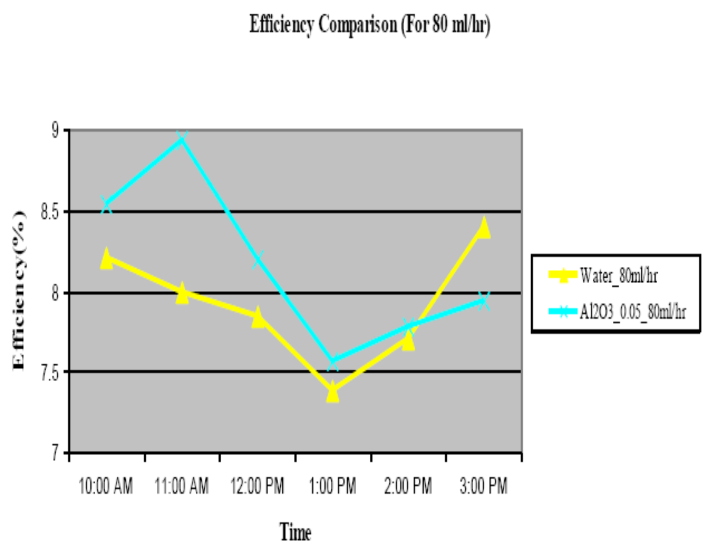

FIGURE 4 VARIATION OF EFFICIENCY OF NANOFLUID AND WATER FOR (80 ml/hr) AT DIFFERENT INSTANTS OF TIME [Verma and Kundan [36]]

Ladjevardi et al. [37] investigated numerically the effects of using graphite / water nanofluid in the improvement of solar radiation absorption efficiency in a volumetric solar collector (Fig.5) to understand the appropriate values of nanoparticles volume fractions and diameters which provided a better efficiency and lowest cost. It was found that, by using nanofluid with a volume fraction around 0.000025%, it would be possible to absorb more than 50% of the incident irradiation energy, while pure water solar collector absorbed around 27 % of the incident irradiation energy under the same conditions.

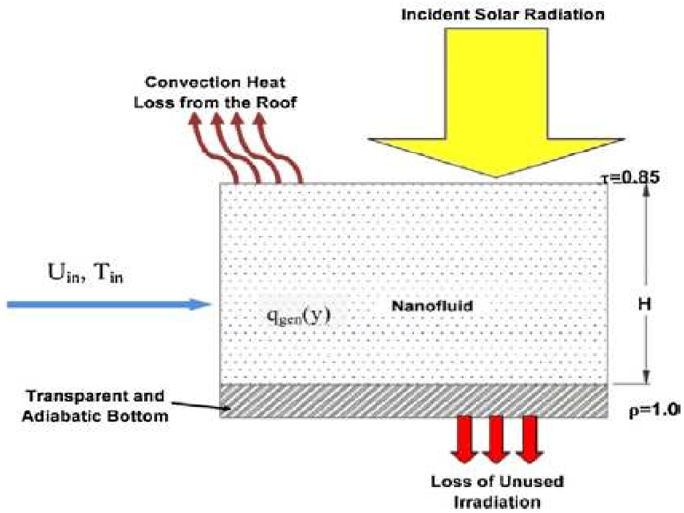

FIGURE 5 VOLUMETRIC SOLAR COLLECTOR [Ladjevardi et al. [37]]

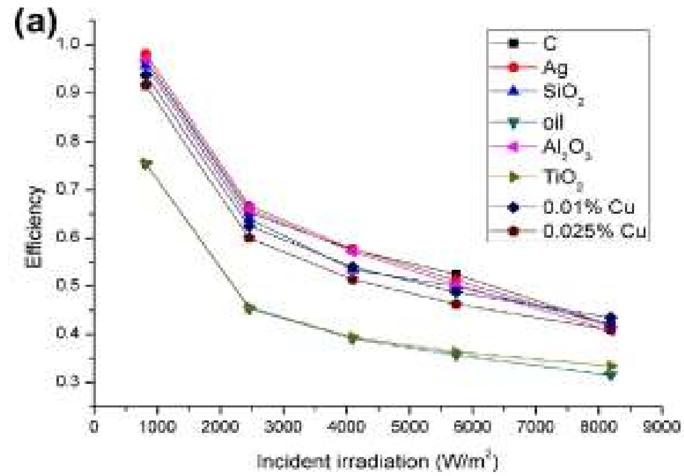

FIGURE 6 PHOTO-THERMAL EFFICIENCY AGAINST INCIDENT RADIATION INTENSITY OF THE DIRECT ABSORPTION SOLAR COLLECTOR [Luo et al. [41]]

Hector and Singh [38] investigated theoretically the development of a nano-heat transfer fluid carrying direct absorbing receiver system (DARS) for concentrating solar collectors. Graphene and aluminum nanosphere-based suspensions in Therminol VP-1 were simulated to identify the optimum thermo-geometric configuration of DARS. It was found that reducing DARS diameter was recommended to achieve higher mean nanofluid outlet temperatures. Zhidong et al. [39] investigated the thermal performance of a simulated direct absorbing solar collector with the application of magnetic nanofluid as a heat transfer media. It was found that the collector efficiency by using magnetic nanofluid was greater than that by using pure ethylene glycol. The higher efficiency could be obtained at a lower particle volume fraction. It was indicated that the use of both magnetic field and magnetic nanofluids enhanced the heat transfer efficiency of the collector. Lee et al. [40] experimentally measured, the extinction coefficient of water-based nanofluids containing multi-walled carbon nanotubes (MWNCTs). With the obtained extinction coefficient, the efficiency of a flat-plate direct-absorption solar collector (DASC) was theoretically estimated. The results showed that the DASC concept can further improved the efficiency of the conventional flat-plate type solar collectors.Luo et al.[41] studied both numerically and experimentally the performance of a nanofluid direct absorption solar collector. Nanoparticles such as TiO_2, Al_2O_3, Ag, Cu and SiO_2, as well as graphite and carbon nanotubes were added directly into Texatherm oil to prepare a stable suspension colloids. They concluded that, nanofluids improved the outlet temperature by 30-100 K and the efficiency by 2–25% than the base fluid. It was found also that nanofluids, even of low-content, had a good absorption of the solar radiation. Moreover, it was indicated that the photo-thermal efficiency was decreased with the increase of the incident radiation as shown in Fig.6.

Filho et al. [42] investigated experimentally the photo-thermal conversion characteristics of silver-de-ionized water nanofluids. The results showed that silver nanoparticles had an excellent photo-thermal conversion capability even under very low concentrations. Also, it was found that the stored thermal energy was increased by 52%, 93% and 144% for silver particle concentration of 1.62, 3.25 and 6.5 ppm respectively at the peak temperature. They characterized the photo-thermal conversion efficiency of nanoparticles by the specific absorption rate (SAR) , which described the particle's capability in the absorbing energy per unit mass and was given by :-

$$SAR = \frac{(m_w c_w + m_p c_p)\Delta T_n - m_w c_w \Delta T_w}{1000 m_p \Delta t} \quad (1)$$

Parvin et al. [43] investigated numerically the heat transfer performance and the entropy generation of forced convection through a direct absorption solar collector with Cu-water and Ag-water nanofluids (Fig.7). The effects of solid volume fraction of nanoparticles and Reynolds number on the mean Nusselt number, mean entropy generation, Bejan number and the collector efficiency were studied. The results showed that the collector efficiency enhanced about two times with increasing Reynolds number and solid volume fraction. They suggested a correlation to compute the collector efficiency which was given by:-

$$\eta = (2.488 + 0.327\phi)(\mathrm{Re})^{0.4684} \quad (2)$$

When $0\% \leq \phi \leq 3\%$ and $200 \leq \mathrm{Re} \leq 1000$

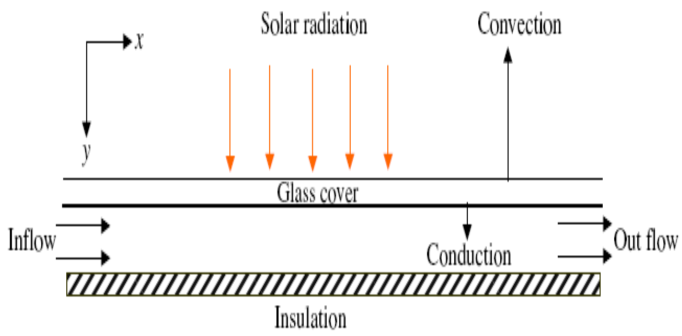

FIGURE 7 SCHEMATIC OF THE DIRECT ABSORPTION SOLAR COLLECTOR [Parvin et al. [43]]

Hordy et al. [44] quantitatively examined both the long-term and high-temperature stability of MWCNTs nanofluids for use in the direct absorption solar collector. The optical properties of four base fluids (water, ethylene glycol, propylene glycol and Therminol VP-1 [mixture of biphenyl and diphenyl oxide]) were characterized with a range of concentrations of corresponding nanofluids. Optical characterization of nanofluids demonstrated that MWCNTs were close to 100% solar energy absorption, even at low concentrations and small collection volumes which made them as an ideal candidate in the direct absorption solar collectors. Karami et al. [45] examined experimentally the dispersion stability, optical properties and the thermal conductivity of CNTs suspension in water as a nanofluid for application in low-temperature direct absorption solar collector. They demonstrated that the thermal conductivity improvements was reached to 32% by adding only 150 ppm of CNTs to water as an absorbing medium. They concluded that this kind of nanofluids was much recommended for increasing the overall efficiency of the direct absorption solar collectors. Zhang et al. [46] investigated both experimentally and theoretically the radiative properties of ionic liquid-based nanofluids for medium-to-high-temperature direct absorption solar collectors. Three different types of nanoparticles with an average sizes of 40 nm were considered (carbon-coated Ni (Ni/C), Ni and Cu). It was found that the optical absorption property of the ionic liquid was greatly enhanced by adding a low volume fraction of nanoparticles in it. They concluded that the excellent radiative properties of the ionic liquid -based nanofluids made them a good option to be used as an absorber for direct absorption solar collectors. Sadique and Verma [47] performed an experimental study on the effect of the nanofluid on the performance of a direct solar thermal collector. Three different groups of nanofluids with water were considered [Graphite sphere-based 30 nm diameter , carbon nanotube-based 6-20 nm diameter and silver sphere-based 20 and 40 nm diameters].They concluded that nanofluids could be used to absorb sunlight with a negligible amount of viscosity and/or density increase. Very recently, Moradi et al. [48] investigated numerically the utilization of carbon-nanohorn based nanofluids for a direct absorption solar collector used in the civil applications. In their work, a three-dimensional model of the absorption phenomena in nanofluids within a cylindrical tube was coupled with a CFD analysis of the flow and temperature fields. They computed also the heat losses due to the conduction, convection and radiation at the boundaries.

6. CHALLENGES AND DIFFICULTIES

The application of the nanofluid in the direct absorption solar collectors suffers from many problems which can be summarized in the following points:-

1- The nanofluid requires a long time in order to be stable with base fluids.
2- The specific heat of the nanofluid is low in comparison with the base fluid.
3- The toxicity of the nanofluid is high, so it needs to be careful during the preparation of it.
4- The preparation and testing of the nanofluid is high costly.
5- The high viscosity of the nanofluid leads to the increase of the pressure drop and the required power for pumping is increased also.
7- The presence of nanoparticles in the nanofluid may leads to a corrosion and erosion of solar collector for a long time.

7. CONCLUSIONS

The present work gives a comprehensive overview and understanding about the recent advances related with the application of the nanotechnology in the direct absorption solar collectors. The results presented in this study provide a very useful source of references for enhancing the direct absorption solar collector performance by using the nanofluid technology. Some important conclusions are summarized below:-

1-The future researches must be directed towards inventing efficient energy transport methods of nanofluid in direct absorption solar collectors such as the enhancement of the heat transfer rate by studying the effect of particle shape on the thermal conductivity of nanofluid.
2-The future researches must be directed towards inventing a non-toxic and low cost nanoparticles to reduce further the cost of nanofluid based solar collector and to meet quickly with the market needs.
3- More efforts are needed to study the reliability of using nanofluids in direct absorption solar collectors from both environmental and economical point of view.
4- Nanoparticles must be dispersed uniformly in the base fluid to enhance the solar-weighted absorption and increase the efficiency of the solar collector.
5-Volume fraction of nanoparticles must be chosen accurately to enhance the performance of nanofluid collector.

6- It is recommended to use carbon nanohorns (CNHs) as a nanoparticles to improve the optical properties of the direct absorption solar collectors. This is due to their large surface area and large number of cavities.
7-Further researches must be directed towards various significant challenges in the field of nanotechnology and its application in the solar collector such as: Brownian motion of particles, particle migration, changing thermophysical properties with temperature, tendency of nanoparticles to agglomeration, changing nanofluid properties by using additives and the stability of nanofluids.

NOMENCLATURE

c_w	Specific heat of water (kJ /kg °C)
c_p	Specific heat of nanoparticle (kJ /kg °C)
m_w	Mass flow rate of water (kg/s)
m_p	Mass flow rate of nanoparticle (kg/s)
Re	Reynolds number
SAR	Specific absorption rate (kW/ g)

Greek Symbols

ϕ	Nanoparticles volume fraction
η	Efficiency of the collector
ΔT_n	Temperature rise at the same time interval for nanofluid (°C)
ΔT_w	Temperature rise at same time interval for water (°C)
Δt	Time interval (s)

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APPENDIX 1

TABLE 1 SUMMARY OF INVESTIGATIONS OF NANOFLUID IN THE DIRECT ABSORPTION SOLAR COLLECTOR

Model	Reference	Year	Nanofluid type	Results and remarks
Theoretical	Tyagi et al. [29]	2009	Aluminum - water	Nanofluid increased the absorption of incident radiation by more than nine times over that of pure water.
Experimental and numerical	Otanicar et al. [30]	2010	Carbon nanotubes - water Graphite - water Silver - water	Efficiency improvements of up to 5% in solar thermal collectors by utilizing nanofluids as an absorption mechanism.
Experimental	Taylor et al. [31]	2011	Graphite -water Aluminum-water Sliver-water Copper-water	Nanofluids could be used to absorb sunlight with a negligible amount of viscosity and/or density increase.
Experimental	Poinern et al. [32]	2012	Carbon nanospheres (CNS)	Photo-thermal response of both nanofluids and films composed of CNS were investigated under 1000 W/m^2 solar irradiation.
Theoretical	Saidur et al.[33]	2012	Aluminum-water	Al - water nanofluid was a good option for improving the performance of the collector.
Numerical	Moradi et al.[34]	2013	Glycol-based and water-based nanofluids	When the concentration of nanoparticles increased , the efficiency of the collector increased up to a certain limit and then decreased.
Experimental	Kundan and Sharma [35]	2013	CuO-water	Efficiency of the solar collector was increased by 4 - 6% compared to conventional water-based solar collector
				Collector efficiency

Experimental	Verma and Kundan [36]	2013	Al_2O_3-water	was increased about 3-5% when nanofluid was used as compared to a simple water.
Numerical	Ladjevardi et al. [37]	2013	Graphite - water	Nanofluid capable to absorb more than 50% of incident irradiation energy.
Theoretical	Hector and Singh [38]	2013	Graphene - Therminol VP-1 Aluminum - Therminol VP-1	Reducing DARS diameter was recommended to achieve higher mean nanofluid outlet temperatures.
Experimental	Zhidong et al. [39]	2014	Magnetic nanofluids	Both magnetic field and magnetic nanofluids enhanced the heat transfer efficiency of the collector.
Experimental and Theoretical	Lee et al. [40]	2014	MWNCTs - water	DASC concept can further improved the efficiency of conventional flat-plate solar collectors
Experimental and Numerical	Luo et al.[41]	2014	TiO_2 -Texatherm oil Al_2O_3 -Texatherm oil Ag -Texatherm oil Cu -Texatherm oil SiO_2 -Texatherm oil	Nanofluids improved outlet temperature by 30-100 K and efficiency by 2–25% than the base fluid.
Experimental	Filho et al.[42]	2014	Silver- de-ionized water	Stored thermal energy increased by 52%, 93% and 144% for silver particle concentration of 1.62, 3.25 and 6.5 ppm respectively at the peak temperature.
Numerical	Parvin et al.[43]	2014	Cu-water Ag-water	Collector efficiency enhanced about two times with increasing Reynolds number and solid

				volume fraction.
Experimental	Hordy et al. [44]	2014	MWCNTs - water MWCNTs - ethylene glycol MWCNTs - propylene glycol MWCNTs - Therminol VP-1	MWCNTs were close to 100% solar energy absorption, even at low concentrations and small collection volumes.
Experimental	Karami et al. [45]	2014	CNT - water	CNT - water nanofluid was very recommended for increasing the overall efficiency of direct absorption solar collectors.
Experimental and theoretical	Zhang et al. [46]	2014	Ni/C- ionic liquid Ni -ionic liquid Cu -ionic liquid	Optical absorption property of the ionic liquid was greatly enhanced by adding a low volume fraction of nanoparticles in it.
Experimental	Sadique and Verma [47]	2014	Graphite-water Carbon nanotube-water Silver-water	Nanofluids could be used to absorb sunlight with a negligible amount of viscosity and/or density increase.
Numerical	Moradi et al. [48]	2015	Carbon-nanohorn	Heat losses due to conduction, convection and radiation at the boundaries were computed.