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Applications of nanotechnology to improve the performance of solar collectors – Recent advances and overview

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ABSTRACT

This paper gives a comprehensive overview about the recent advances related with the application of the nanotechnology in various kinds of the solar collectors. Papers reviewed including theoretical, numerical and experimental up to date works related with the nanotechnology applications in the flat plate, direct absorption, parabolic trough, wavy, heat pipe and another kinds of the solar collectors. A lot of literature are reviewed and summarized carefully in a useful tables (Tables 1–7) to give a panoramic overview about the role of the nanotechnology in improving the various types of the solar collectors. It was found that the use of the nanofluid in the solar collector field can play a crucial role in increasing the efficiency of these devises. We think that this paper can be considered as an important link between the nanotechnology and all available kinds of the solar collectors. From the other side, further researches are required to study the effect of nanotechnology to enhance the solar collector industry over the next several coming years.

Contents

1. Introduction

Solar energy (or radiant light and heat from the sun) 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 min, 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

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Nomenclature

Symbol description unit

A	surface area of solar collector [Eq. (2)], [Eq. (5)] and [Eq. (10)] (m^2)
A_c	reduction in the size of collector's area [Eq. (1)] (m^2)
C_p	specific heat of the working fluid [Eq. (1)] (kJ/kg °C)
C_{pro}	water production cost [Eq. (4)]
c_w	specific heat of water [Eq. (7)] (kJ/kg °C)
c_p	specific heat of nanoparticle [Eq. (7)] (kJ/kg °C)
F_R	collector heat removal factor [Eq. (2)] and [Eq. (6)]
f	plant availability [Eq. (4)]
G_t	solar radiation on solar collector [Eq. (5)] (W/m^2)
h	local heat transfer coefficient [Eq. (2)] (W/m^2 K)
I_b	global solar radiation [Eq. (10)] (W/m^2)
I_T	incident radiation or total radiation [Eq. (1)] and [Eq. (6)] (W/m^2)
I	intensity of solar radiation [Eq. (2)] (W/m^2)
$m\cdot$	mass flow rate of the working fluid [Eq. (1)] (L/s)
m_w	mass flow rate of water [Eq. (7)] (kg/s)
m_p	mass flow rate of nanoparticle [Eq. (7)] (kg/s)
Nu_{av}	average Nusselt number [Eq. (3)]
n	number of the panels in the collecting system [Eq. (9)]
Pr	Prandtl number [Eq. (3)]
P_{net}	system collecting power [Eq. (9)] (W)
Q_{usfl}	actual useful energy gain [Eq. (2)] (W)
Q_u	rate of useful energy gained [Eq. (5)] and [Eq. (10)] (W)
Q_{cpc}	solar energy radiating on one CPC plate [Eq. (9)] (W)
Re	Reynolds number [Eq. (3)] and [Eq. (8)]
SAR	specific absorption rate [Eq. (7)] (kW/g)
TCO	total cost of ownership [Eq. (4)]
T_{fi}	fluid inlet temperature [Eq. (6)] (°C)
T_{in}	fluid inlet temperature [Eq. (1)] (°C)
T_{out}	fluid outlet temperature [Eq. (1)] (°C)
T_a	ambient temperature [Eq. (2)] and [Eq. (6)] (°C)
T_m	fluid mean temperatures [Eq. (2)] (°C)
U_L	overall loss coefficient of solar collector [Eq. (6)] (W/m^2 K)

Greek symbols

α	absorptivity [Eq. (6)]
κ	absorption rate of the absorber [Eq. (2)]
τ	transmissivity [Eq. (6)]
φ	nanoparticles volume fraction [Eq. (8)]
η	efficiency of the collector [Eq. (1)] and [Eq. (8)]
η_i	efficiency of the collector [Eq. (6)] and [Eq. (10)]
η_{net}	system collecting efficiency [Eq. (9)]
λ	rate of transmission of the solar collector cover [Eq. (2)]
ΔT_n	temperature rise at the same time interval for nanofluid [Eq. (7)] (°C)
ΔT_w	temperature rise at the same time interval for water [Eq. (7)] (°C)
Δt	time interval [Eq. (7)] (s)

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 the 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]. The present work gives a comprehensive overview about the recent advances related with the application of the nanotechnology in different types of the solar collectors. Papers reviewed including theoretical, numerical and experimental up to date works related with the nanofluid applications in the flat plate, direct absorption, parabolic trough, wavy, heat pipe and another kinds of the solar collectors. A lot of literature are reviewed and summarized carefully in a useful tables (Tables 1–7) to give the reader a panoramic review about the role of the nanofluid in improving the various types of the solar collectors.

1.1. *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

Table 1
Summary of investigations of nanofluid in a flat plate solar collector.

Model	Reference	Year	Nanofluid type	Results and remarks
Experimental	Otanicar and Golden [53]	2009	General	The nanofluid based solar collector had a lower embodied energy (about 9%) and approximately (3%) higher levels of pollution offsets than a conventional collector
Experimental	Natarajan and Sathish [54]	2009	MWCNT–water	Nanofluids were more effective than the conventional fluids and if were used as a heat transport medium, it increased the efficiency of the traditional solar water heater
Experimental	Polvongsri and Kiatsiriroat [55]	2011	Silver–water	Nanofluid improved the thermal performance of the collector especially at high inlet temperature
Experimental	Yousefi et al. [56]	2012	Al_2O_3–water	Using 0.2 wt% of nanofluid increased the efficiency of the collector in comparison with water by about 28.3%
Experimental	Yousefi et al. [57]	2012	MWCNT–water	Using 0.2 wt% of MWCNT nanofluid without surfactant decreased the collector efficiency, while with surfactant increased it
Experimental	Yousefi et al. [58]	2012	MWCNT–H_2O	When pH of nanofluid was varied, a clear effect on the efficiency of the solar collector was observed
Numerical	Tora and Moustafa [59]	2013	Al_2O_3–water	Thermal conductively of the nanofluid and the collector efficiency had better values with higher particle sizes
Experimental	Jamal-Abad et al. [60]	2013	Cu–water	Efficiency of the collector at 0.05 wt% was approximately 24% more than that of the pure base fluids
Experimental	Faizal et al. [61]	2013	MWCNT	Collector's size can be reduced up to 37% of its original size when applying MWCNT nanofluid
Experimental	Gangadevi et al. [62]	2013	Al_2O_3–water	Efficiency of the collector was increased about 30% by using Al_2O_3–water nanofluid
Experimental	Chaji et al. [63]	2013	TiO_2–water	Collector efficiency was improved between 2.6 and 7% by using nanofluid
Theoretical	Tiwari et al. [64]	2013	Al_2O_3–water	Nanofluid increased the thermal efficiency in comparison with water by about 31.64%
Numerical	Faizal et al. [65]	2013	CuO–water SiO_2–water TiO_2–water Al_2O_3–water	25.6%, 21.6%, 22.1% and 21.5% solar collector area reduction were achieved for using CuO, SiO_2, TiO_2 and Al_2O_3 nanofluids
Experimental	Said et al. [66]	2013	AL_2O_3–water AL_2O_3–ethylene glycol/water mixture	Pressure drop and pumping power of the nanofluid flows were very close to that of the base liquid for low volume concentration
Theoretical	Alim et al. [67]	2013	Al_2O_3–water CuO–water SiO_2–water TiO_2–water	CuO/water nanofluid was reduced the entropy generation by 4.34% and enhanced the heat transfer coefficient by 22.15%
Experimental	Colangelo et al. [68]	2013	Al_2O_3–water	Convective heat transfer coefficient was increased up to 25% at a concentration of 3% volume
Numerical	Shankar and Manivannan [69]	2013	CuO–water	About (10.88%) of an improved efficiency was observed at (0.025%) volume fractions
Numerical	Nasrin and Alim [70]	2014	Ag–water Cu–water CuO–water Al_2O_3–water	Cu–water nanofluid was more effective in order to promote heat loss system through the riser pipe of a flat plate solar collector
Experimental	Polvongsri and Kiatsiriroat [71]	2014	Silver–water	The overall heat loss coefficient of the solar collector with nanofluid was reduced and more solar heat gain was obtained
Numerical	Ekramian et al. [72]	2014	MWCNT–water CuO–water Al_2O_3–water	Thermal efficiency of CuO–water nanofluid were greater than other nanofluids
Theoretical	Mahian et al. [73]	2014	Al_2O_3–water	Entropy generation decreased with increasing the nanofluid concentration
Numerical	Nasrin and Alim [74]	2014	Alumina–water	When Reynolds number increased, the percentage of collector efficiency was enhanced by using nanofluid
Numerical	Kabeel and El-Said [75]	2014	Cu–water	Volume fractions of nanoparticles had a significant effect on increasing the fresh water production and decreasing its cost
Theoretical	Mahian et al. [76]	2014	Cu–water Al_2O_3–water TiO_2–water SiO_2–water	Efficiency decreased with increasing volume fraction of nanoparticles and SiO_2/water nanofluid gave the highest efficiency of the collector
Experimental	Moghadam et al. [77]	2014	CuO–water	Nanofluid with mass flow rate of 1 kg/min increased the collector efficiency by about 21.8%
Experimental	Zamzamian et al. [78]	2014	Cu-synthesized/EG	Efficiency of the collector was improved by increasing the nanofluid concentration
Theoretical	Said et al. [79]	2014	SWCNT–water TiO_2–water Al_2O_3–water SiO_2–water	SWCNT nanofluid reduced the entropy generation by 4.34% and enhanced the heat transfer coefficient by 15.33%
Theoretical	Mahian et al. [80]	2014	Boehmite alumina–water and ethylene glycol	1. Outlet temperature increased with an increase in volume fraction of nanoparticles 2. Entropy generation rate due to heat transfer was reduced for all shapes of nanoparticles
Experimental	Roy et al. [81]	2015	Silver–water	The maximum efficiency of the solar collector was found to be near 70% for 0.04% particle volume concentration at 6 L/min

Table 1 (*continued*)

Model	Reference	Year	Nanofluid type	Results and remarks
Experimental	He et al. [82]	2015	Cu–water	1. Cu–H_2O nanofluid was enhanced the collector efficiency by about 23.83% 2. Nanoparticle size had a major effect on collector efficiency
Theoretical and experimental	Shojaeizadeh et al. [83]	2015	Al_2O_3–water	Nanofluid was increased the maximum collector exergy efficiency by about 1%
Theoretical and experimental	Said et al. [84]	2015	TiO_2–water	Efficiency was increased by 76.6% for 0.1% volume fraction
Experimental	Michael and Iniyan [85]	2015	CuO–water	Nanofluid improved the thermal performance of the collector by 6.3%
Theoretical and experimental	Said et al. [86]	2015	SWCNT–water	Maximum energy and exergy efficiency of the collector was enhanced up to 95.12% and 26.25% respectively

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.

The above drawbacks can be solved efficiently by using the nanofluid, 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. Nanofluid can pass through pumps and pipes without adverse effects such as clogging and fouling. Therefore, it is very useful in microchannel applications.
8. The heat transfer increases as a result of increase in the heat transfer surface area between the particles and fluids.
9. 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 [7].
10. 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.
11. Nanoparticles dispersed fastly in liquids, so it reduce the friction and wear occur in the pipelines and pumps.
12. Nanofluid 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].
13. Nanoparticles increase significantly the mixing fluctuation and turbulence of the fluid [19].
14. The dispersion of nanoparticles flattens the transverse temperature gradient of the fluid.

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].

Table 2
Summary of investigations of nanofluid in the direct absorption solar collector.

Model	Reference	Year	Nanofluid type	Results and remarks
Theoretical	Tyagi et al. [87]	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. [88]	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. [89]	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. [90]	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. [91]	2012	Aluminum–water	1. Al–water nanofluid was a good option for improving the performance of the collector 2. Collector efficiency increased slightly with an increase in the particle size
Numerical	Moradi et al. [92]	2013	Glycol-based and water-based nanofluid	When the concentration of nanoparticles increased, the efficiency of the collector increased up to a certain limit and then decreased
Experimental	Kundan and Sharma [93]	2013	CuO–water	Efficiency of the solar collector was increased by 4–6% compared to conventional water-based solar collector
Experimental	Verma and Kundan [94]	2013	Al_2O_3–water	Collector efficiency was increased about 3–5% when nanofluid was used as compared to a simple water
Numerical	Ladjevardi et al. [95]	2013	Graphite–water	Nanofluid capable to absorb more than 50% of incident irradiation energy
Theoretical	Hector and Singh [96]	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. [97]	2014	Magnetic nanofluids	Both magnetic field and magnetic nanofluids enhanced the heat transfer efficiency of the collector
Experimental and theoretical	Lee et al. [98]	2014	MWNCTs–water	DASC concept can further improved the efficiency of conventional flat-plate solar collectors
Experimental and numerical	Luo et al. [99]	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. [100]	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. [101]	2014	Cu–water Ag–water	Collector efficiency enhanced about two times with increasing Reynolds number and solid volume fraction
Experimental	Hordy et al. [102]	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. [103]	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. [104]	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 [105]	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. [106]	2015	Carbon-nanohorn	Heat losses due to conduction, convection and radiation at the boundaries were computed
Theoretical	Cregan and Myers [107]	2015	Al–water	Efficiency was rapidly increased when the solid volume fraction was very small
Experimental	Gupta et al. [108]	2015	Al_2O_3–water	Collector efficiency was increased for all four concentrations of nanofluid than pure water

1.2. 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 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 [23]. In fact, classical solar thermal collectors have a metal sheet as an absorber, designed such that water has the minimum temperature in each transversal section, in order to collect heat as much as

Table 3
Summary of investigations of nanofluid in parabolic trough solar collector (PTSC).

Model	Reference	Year	Nanofluid type	Results and remarks
Numerical	Khullar and Tyagi [109]	2010	Al–water	Thermal and optical efficiencies and outlet temperatures of the collector was improved with using nanofluid
Numerical	Khullar et al. [110]	2012	Aluminum–Therminol VP-1	Nanofluid collector had about 5–10% higher efficiency as compared to conventional parabolic solar collector
Numerical	De Risi et al. [111]	2013	Ni–CuO	Maximum thermal efficiency was about 62.5%, for a nanofluid outlet temperature of 650 °C and a nanoparticles volume concentration of 0.3%
Experimental	Sunil et al. [112]	2014	SiO_2–H_2O	SiO_2–H_2O nanofluid had comparatively higher efficiency at higher volume flow rates
Numerical	Ghasemi and Ahangar [113]	2014	Cu-water	1. Thermal efficiency of the collector decreased with increase receiver length 2. By increasing volume fraction of nanoparticles, the performance of collector was enhanced
Numerical	Sokhansefat et al. [114]	2014	Al_2O_3–synthetic oil	Heat transfer coefficient of the working fluid in an absorber tube was enhanced with presence of nanoparticles
Numerical	Mwesigye et al. [115]	2015	Al_2O_3–synthetic oil	Nanofluid was improved the thermal efficiency of the receiver up to 7.6%
Experimental	Kasaeian et al. [116]	2015	MCNT–mineral oil	Global efficiency was enhanced about 4–5% at 0.2% and 5–7%, at 0.3% when MCNT/mineral oil nanofluid was used

Table 4
Summary of investigations of nanofluid in wavy solar collector.

Model	Reference	Year	Nanofluid type	Results and remarks
Numerical	Nasrin and Alim [117]	2013	Ag–water CuO–water	Better performance of heat transfer inside the collector was found by using the highest solid volume fraction of Ag–water nanofluid
Experimental	Alaeian et al. [118]	2014	MWCNT–Oil	Heat transfer coefficient was increased up to 56% compared to base fluid at highest concentration and lowest dimensionless curvature ratio

Table 5
Summary of investigations of nanofluid in heat pipe solar collector.

Model	Reference	Year	Nanofluid type	Results and remarks
Experimental	Lu et al. [119]	2011	CuO–water	Nanofluid significantly enhanced the thermal performance of the evaporator
Experimental	Moorthy et al. [120]	2012	TiO_2–water	The efficiency was enhanced by 16.7% by using nanofluid compared to pure water
Experimental	Chougule et al. [121]	2012	Carbon nanotube (CNT)	Nanofluid collector gave a better performance in all test conditions
Experimental	Senthil Kumar et al. [122]	2012	CNT–water	The nanofluid working fluid collector gave the better performance in all the operating conditions
Experimental	Chougule et al. [123]	2013	Carbon nanotube (CNT)	They obtained the optimal value of CNT nanofluid concentration for better performance of the heat pipe solar collector
Experimental	Liu et al. [124]	2013	CuO–water	Both the air outlet temperature and collector efficiency using nanofluid are higher than that using water
Experimental	Saravanan and Karunakaran [125]	2014	TiO_2–DI water	Thermal efficiency of the collector was increased by using nanofluid
Experimental	Aruna et al. [126]	2014	TiO_2–DI water	Nanofluid gave a better performance when compared to propanol

possible from the solar thermal energy. The performance of the solar collector mainly 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], Alkilani et al. [26], Hossain et al. [27], D'Antoni and Saro [28], Mathur et al. [29], Tian and Zhao [23], Shukla et al. [30], Devanarayanan and Murugavel [31] and very recently by Wang et al. [32].

1.3. Solar collector types

1. Conventional flat plate solar collector: It has a simple construction as shown in Fig. 1 (Kong et al. [33]) which consists of an absorber [a metal plate (Copper or Aluminum) coated with a black chrome layer] to collect the sun's heat energy which is then transferred to a fluid running in tubes attached to the underside of the collector. Insulation (mineral wool) surrounds the plate to prevent the heat loss due to the conduction. A glass plate is placed above the absorber plate to prevent convective heat losses. This collector is used for many technological applications such as hot water system, air heating and solar cooker. In this type, the fluid absorbs heat energy through a surface absorber (fluid flow through pipes). The absorber is a metal sheet designed such that the water has the minimum temperature in each transversal section, in order to collect as much as possible from the solar thermal energy. Flat plate solar collectors are used broadly to increase the working fluid temperature in the range of 30–100 °C above the ambient temperature. The performance of this collector depends on geographic factors, geometry and orientation of the collector. However, this type suffers from several defects which can be summarized as follows:
    1. The heat losses due to the conduction, natural convection and radiation from the collector surface due to the temperature difference between the plate and ambient air are considerably large which reduces its efficiency.
    2. The working life of the collector is some what short due to the pipe corrosion by the water [34].
    3. The water may freeze in cold days; therefore a pump is required to maintain the forced circulation of the water. This

Table 6
Summary of investigations of nanofluid in another solar collectors.

Model	Reference	Year	Nanofluid/collector type	Results and remarks
Experimental	Li et al. [127]	2011	Al_2O_3–water ZnO–water MgO–water Tubular solar collector	ZnO nanofluid with 0.2 vol% concentration was a good option in solar energy utilization
Experimental	Taylor et al. [128]	2011	Aluminum–Therminol VP-1 Copper–Therminol VP-1 Graphite–Therminol VP-1 Silver–Therminol VP-1 Power tower solar collectors	Efficiency improvement on the order of 5–10% was possible with a nanofluid receiver
Experimental	Gangadevi et al. [129]	2013	Al_2O_3–water PV/T solar collector	Both the electrical and thermal efficiencies of a hybrid solar system increased considerably by using the nanofluid
Experimental	Paul et al. [130]	2013	Ionic liquid–Al_2O_3 Concentrating Solar Power (CSP) system	Heat transfer performance was enhanced by 15% with using the nanofluid
Numerical	Hewakuruppu et al. [132]	2014	Not specified	A nanofluid with a short wavelength, optical depth of 3 with no scattering, and a long wavelength with optical depth of zero was required for optimum performance
Numerical	Rahman et al. [133]	2014	Cu–water Al_2O_3–water TiO_2–water Triangular solar collector with corrugated bottom wall	Cu–water nanofluid performed a better performance than other used nanofluids
Experimental	Goudarzi et al. [134]	2014	CuO–H_2O Cylindrical solar collector with receiver helical pipe	Maximum thermal efficiency was increased by about 25.6% by using 0.1 wt% nanofluid in 0.0083 kg/s mass flow rate of fluid
Numerical	Rahman et al. [135]	2014	CNT–water Quarter circular solar collector	Both solid volume fraction and tilt angle played vital roles for augmentation of heat transfer in solar collector
Experimental	Goudarzi et al. [136]	2015	CuO–water Al_2O_3–water Cylindrical solar collector	Efficiency of the collector was increased when there was more differences between pH of nanofluid and pH of iso-electric point
Experimental	Michael and Iniyan [137]	2015	CuO–water PV/T solar collector	Nanofluid was increased the collector efficiency up to 45.76%
Experimental and Theoretical	Tong et al. [138]	2015	MWCNT–water Evacuated U-tube solar collector	Nanofluid was improved the collector efficiency by 4%
Experimental	Colangelo et al. [139]	2015	Al_2O_3–distilled water Modified flat panel solar collector	1. Nanofluid was increased the efficiency up to 11.7% 2. Nanofluid was more effective than water at high temperature

   leads to increase the cost and the space required of the collector.
   4. The incident flux density in this collector is limited.
   5. The limited quantity of the heat transferred by the fluid.
   6. The outlet temperatures of this collector are low.
   7. The using of this type is limited in sunny and warm climates, while its performance is greatly diminished during cold, cloudy and windy days.

2. Uncovered or unglazed solar collector: It is one of various types of the flat plate solar collector. This type is usually the cheaper option, but still offers an effective solar thermal energy in applications such as water preheating for domestic or industrial use, heating of swimming pools, space heating and air heating for industrial or agricultural applications [35].
3. Direct absorption solar collector (DASC): This type was firstly proposed in 1975 by Minardi and Chuang [36] and used to enhance the efficiency of the flat plate collector by making the fluid to directly absorbs 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 [37]. 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.
4. Concentrating solar collector: This type is used in power generation plants, which heating the water with high mass flow rate. There are many types of concentrating solar collector such as Paraboloid Dish, Parabolic Trough and Heliostat. This type is more efficient than the direct absorption solar collector, but it has a high installation cost and needs a modern tracking system.
5. Parabolic trough solar collector (PTSC): This type of solar collector is one of the linear concentrating solar collectors which are appropriate for working in the range of 150–400 °C. It is straight in one dimension (*z*-direction) and curved as a parabola in the other two dimensions (*x*–*y* plane) as shown in Fig. 2 (Garcıa et al. [38]). It uses mirrored surfaces of a linear parabolic reflector to focus solar radiation into an evacuated tubular receiver placed along the focal line of the parabola. The receiver mainly includes an inner absorber tube surrounded by an outer glass cover and supported brackets [39–40]. This type can be used to drive machinery or to generate electricity. The largest solar power plant using a parabolic trough technology is called SEGS plants which is located in the California – United States and produces about 354 MW of electricity [39].Two important factors must be carefully considered in the construction of this collector which are the accuracy of the parabolic shape and the torsional resistance of the collector. Moreover, the stresses and deflections experienced by the receiver and the reflector must remain below specified levels under various thermal, wind and gravitational loads as indicated recently by Coccia et al. [41]. For further details about the parabolic trough solar collector, the

Table 7
Summary of review investigations of nanofluid in solar collector.

Reference	Number of reviewed papers	Year	Applications	Results and remarks
Sruthi [140]	5	2012	1. Solar water heater 2. Solar cell	Various advantages of using nanomaterials in solar water heater were presented
Khanafer and Vafai [141]	104	2013	1. Thermal energy storage systems 2. Photovoltaic systems 3. Direct absorption solar collectors 4. Solar desalination	For optimum performance of a solar collector, the solar radiation should be absorbed within a small wavelength range ($0.25\ \text{mm} < \lambda < 2.5\ \text{mm}$)
Javadi et al. [142]	134	2013	Direct absorption solar collector	Further researches must be focused on the two-phase analysis of nanofluids
Mahian et al. [143]	93	2013	1. Solar collectors and solar water heaters 2. Photovoltaic/thermal systems 3. Solar ponds 4. Solar cells 5. Thermal energy storage 6. Solar still	1. Different volume fractions should be tested to find the optimum volume fraction 2. Using of nanofluids in collectors led to a reduction in CO_2 emissions, annual electricity and fuel savings
Al-Shamani et al. [144]	100	2014	1. Cooling solar collector 2. Photovoltaic/thermal (PV/T) collector systems	Nanofluids could be used to cool photovoltaic/thermal (PV/T) collector systems
Chaudhari and Walke [145]	20	2014	1. Solar collector 2. Solar still 3. Thermal energy storage 4. Solar cell	Nanofluid minimized temperature difference between absorber and the heat transfer fluid
Nerella et al. [146]	15	2014	Solar collector	The improvements of solar collector efficiency by using nanofluids with base fluid were highly comparable with the solar collector efficiency when only base fluid was used
Kasaeian et al. [147]	127	2015	1. Solar collector 2. Photovoltaic systems 3. Energy storage system 4. Solar thermo-electrics devices 5. Solar cells	Development of the particle production and decreasing in costs was essential for the nanofluid research
Verma and Tiwari [148]	172	2015	Solar collector	Thermal efficiency of the PV/T systems was highly enhanced by using nanofluids
Hussein et al. [149]	48	2016	Direct absorption solar collector	Nanofluid improved the efficiency of the direct absorption solar collectors

Fig. 1. Photograph of the flat plate solar collector (Kong et al. [33]).

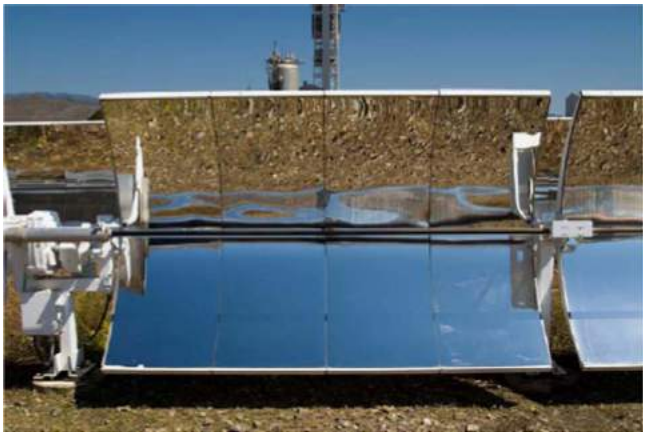

Fig. 2. Photograph of the parabolic trough solar collector (Garcıa et al. [38]).

reader can be returned to the comprehensive overview by Garcıa et al. [38].

6. Evacuated tube collector (ETC): This type depends on the concept of the heat pipe which transfers heat more efficiently than solid conductors as shown in Fig. 3 (Du et al. [42]). It uses a series of borosilicate glass tubes with each containing a finned heat pipes (typically made from copper). The fins are coated with a black chrome coating and pipes contain a liquid which undergoes an evaporating-condensing cycle of the pure working fluid as it is heated and cooled. The heat pipes are connected to a manifold which facilitates heat exchange from the liquid to a heat transfer fluid flowing through the manifold. The framework of the collector is made from stainless steel and rock wool is used for insulation [43]. A structure of this type is shown in Fig. 4 as explained by Wei et al. [34], while their components are illustrated in Fig. 5. This type of the solar collectors has a low thermal losses, low cost and high efficiency than the conventional collectors. In fact, heat pipes that working under gravity with the condenser above the evaporator does not require an external power or capillary action to return the working fluid from the condenser to the evaporator. This type of the heat pipe is known as a thermosyphon or wickless gravity assisted heat pipe. Common thermosyphon is a tubular construction and can be easily integrated into a flat plate or evacuated tubular solar heating systems. Fig. 6 illustrates an example of an evacuated tube collector which is called the solar heat pipe vacuum

Fig. 3. Photograph of the heat pipe solar collector (Du et al. [42]).

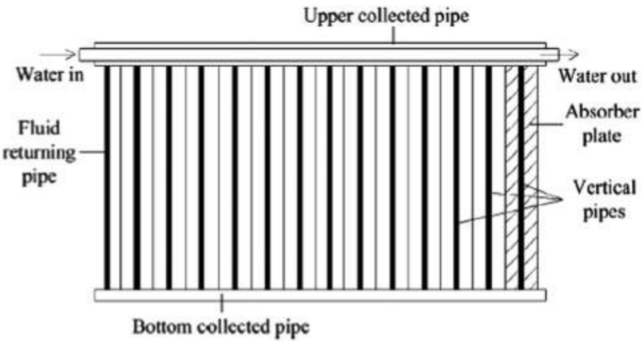

Fig. 4. Structure of solar heat collector with integrated heat pipe (Wei et al. [34]).

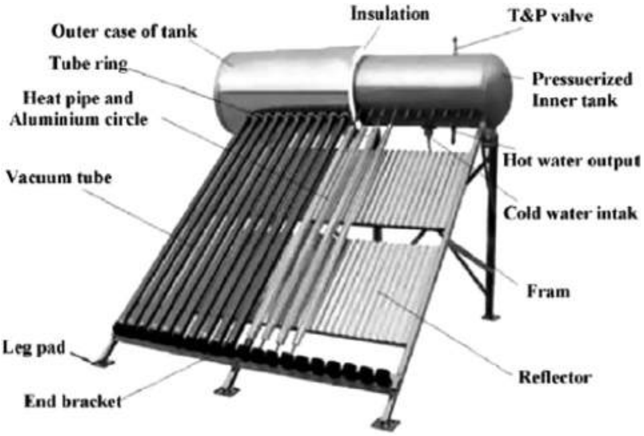

Fig. 5. Components of evacuated tube solar water heater collectors (Hossain et al. [27]).

collectors as given by Bourdoukan et al. [44]. For more details about the evacuated tube collector, the reader can be go back to the review by Shah et al. [45].

7. Cylindrical solar collector: it is a type of tubular solar collectors which has a copper coil in the shape of a helical pipe (Fig. 7) instead of absorbent coating in the cylindrical center and it has a high thermal efficiency than a flat plate type. The major advantage of this type is that it is not necessary to direct it to the sun because of its circular shape, while the flat plate collector should always be directed to face the sun with a certain tilted angle to get the best efficiency [46].

Fig. 6. Photograph of the solar heat pipe vacuum collectors (Bourdoukan et al. [44]).

Fig. 7. Photograph of the cylindrical solar collector (Sadhishkumar and Balusamy [46]).

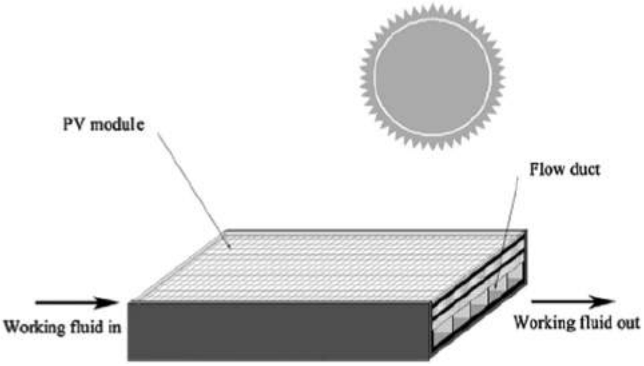

Fig. 8. The brief structure of a typical hybrid PV/T collector (Shan et al. [47]).

8. Hybrid photovoltaic/thermal solar collector (PV/T): This type can be considered as a thermal and electrical energy system which combines between a photovoltaic (PV) cell [which converts the electromagnetic radiation (photons) into electricity] with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module as shown in Fig. 8 (Shan et al. [47]). This combination of both electricity and heat make this collector more efficient than the conventional one [48]. The PV/T collector consists from a PV module and an attached pipe for flowing working fluid as shown in Fig. 9 (Ji et al. [49]). The two main goals of the PV/T solar collector are summarized as follows [50]:
    1. Thermal energy can be produced and used for heating purposes.

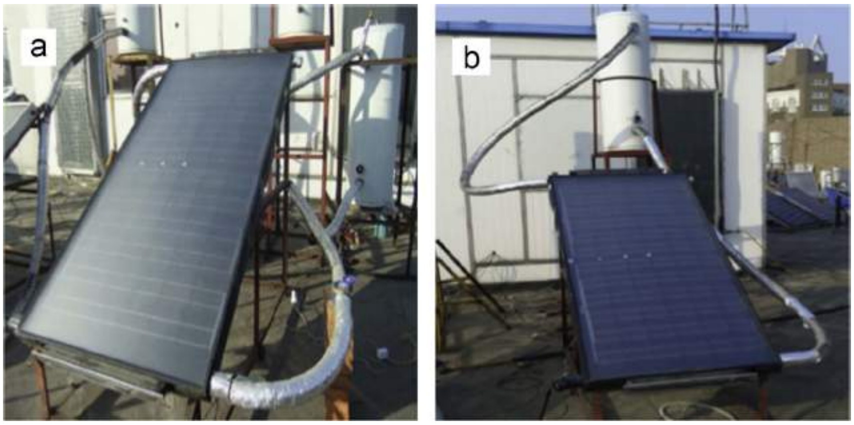

Fig. 9. Photograph of PV/T solar collector (Ji et al. [49]).

Fig. 10. Photograph of transpired solar collector (Shukla et al. [52]).

2. It cools the solar cell and decreases its temperature and as a result, the electrical conversion efficiency is increased.

For more details about the PV/T solar collector, the reader can be go back to the comprehensive review by Ibrahim et al. [51]

9. Transpired solar collector (TSC): This type is a highly efficient collector system particularly used for preheating the fresh air and was widely used in Canada and USA. It uses the solar energy to heat the absorber surface, which transmits the thermal energy to the ambient air. The absorber surface is generally a metallic sheet (usually made from steel or aluminum), which can be integrated to the building façade (Fig. 10). The contact surface between the metal skin and air is increased by drawing air through the multiple small perforations into the cavity between the skin and facade. Finally, the heated air is drawn into the building to provide space heating. During the summer season, the warm air in the cavity can be released using a bypass damper to avoid overheating inside the building or can be used for water heating in order to maximize the utilization of TSC. For additional informations about the transpired solar collector, one can be go back to the review paper by Shukla et al. [52]
10. Nanofluid-based solar collector: This new generation of solar collectors depends on the concept of nanotechnology where nanoparticles in a liquid medium can scatter and absorb solar radiation. It benefits from the efficiency improvements that arise from using a nanofluid as a working fluid in the collector. This collector have a layer of a nanofluid which lies on the top of the collector to directly absorbs the sun's radiation. Therefore, this nanofluid layer eliminates the need for the absorber plate and tubes which are found in the conventional solar collector as mentioned by Otanicar and Golden [53]. Fig. 11 shows schematics and materials for both conventional and nano collectors. Therefore, the main difference between the conventional and nanofluid-based collectors lies in the mode of the working fluid heating. In the conventional collector, the sunlight is absorbed by a surface and then transferred to the fluid. But, in the nanofluid collector the sunlight is directly absorbed by the working fluid through the radiative heat transfer.

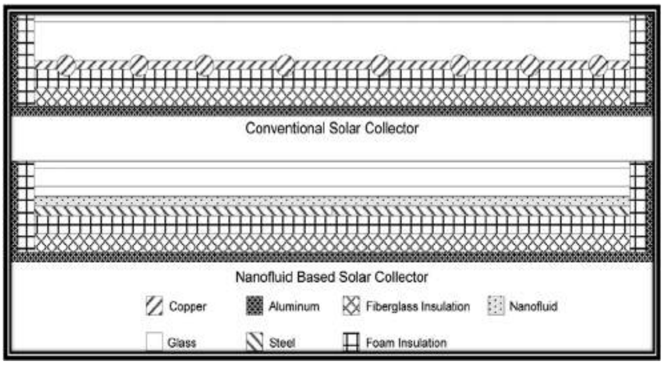

Fig. 11. Schematics and materials for both conventional and nano collectors (Otanicar and Golden [53]).

2. Benefits of using nanofluid in the solar collectors

Nanofluids have many advantages as compared to classical fluids which make them very efficient in solar collectors. Some of these advantages can be summarized as follows [1]:

1. The easy change in the shape, material, size and solid volume fraction of nanoparticles make them very effective to maximize the absorption of the solar energy.
2. The solid nanoparticles increase the surface area and the heat capacity of the fluid due to their very small particle size.
3. Nanofluid can be optically selective, it shows high absorption in the solar range and low emittance in the infrared range. Therefore, the optical characteristics (light absorption and emission behavior) of a base liquid such as the extinction coefficient are enhanced by using the nanofluid.
4. Solid nanoparticles increase dramatically the thermal conductivity of the base fluid and as a result increase the efficiency of solar collectors. Since, the thermal conductivity increases with increasing the concentration and the temperature of the nanofluid.
5. Nanofluid has a high absorption coefficient in comparison with the base fluid. Also, it has a good stability under moderate temperature gradients which makes it as a one of excellent absorbing fluids.
6. Nanofluids improve highly the radiative properties of the basic fluids and leading to increase the efficiency of solar collectors.

7. Nanofluid can be used to reduce the surface temperature by enhancing the fluid properties instead of pumping water at higher flow rate which is considered not advantageous as the overall efficiency of the solar collector is lowered.
8. Nanofluid has the ability to avoid the sedimentation, fouling, clogging of pumps and pipes due to its extremely small size.
9. Nanofluid was used efficiently to reduce the required heat transfer area of tubes and heat exchangers which were utilized in the parabolic trough collectors and as a result reduces the total cost of these collectors.
10. Nanofluids enhance the scattering and absorption of the incident radiation when passing through it. Also, it is found that the optical properties of the pure water are significantly improved by adding nanoparticles in it.
11. The using of nanofluid in the solar collector leads to increase the desired output temperature of the system which is required to increase the collector efficiency. While, in the conventional solar collector, the output temperature increasing requires an increase in the heat transfer area and this leads to increase the size and the cost of the collector.
12. The nanofluid can be used efficiently to reduce the size and cost of the solar collector system. This is due to the elimination of the complex manufacturing processes encountered in creating surface- absorbing plates.
13. The nanofluid increases the collector efficiency due to its high density, low specific heat of nanoparticles and high convective heat transfer coefficient.
14. The nanofluid can be used effectively to reduce the convection and emissive heat loss encountered in the conventional collector.

3. Applications of nanofluid in the flat plate solar collector

Otanicar and Golden [53] performed a comparative environmental and economic analysis of conventional and nanofluid solar hot water systems. They concluded that the nanofluid based solar collector had a slightly longer payback period, but at the end of its useful life had the same economic savings as a conventional solar collector. Also, the results showed that the nanofluid based solar collector had a lower embodied energy (about 9%) and approximately (3%) higher levels of pollution offsets than a conventional collector. Natarajan and Sathish [54] investigated experimentally the role of nanofluid (MWCNT–water) in the solar water heater. Thermal conductivities had been measured by the transient hot-wire method. The results proved that nanofluids were more effective than the conventional fluids and if were they used as a heat transport medium, it increased the efficiency of the traditional solar water heater. Polvongsri and Kiatsiriroat [55] investigated experimentally the performance of a flat-plate solar collector when silver–water nanofluid was used as a working fluid. The silver nanoparticle size was 20 nm with concentrations at 1000 and 10,000 ppm respectively. The experiments were undertaken with three identical flat-plate solar collectors each had an area of 0.15×1.0 m^2. They concluded that the nanofluid improved the thermal performance of the collector compared with water, especially at high inlet temperature. Yousefi et al. [56] investigated experimentally the effect of using the Al_2O_3–water nanofluid as an absorbing medium in a flat-plate solar collector (Fig. 12). The effect of mass flow rate, nanoparticles mass fraction and the presence of surfactant on the efficiency of the collector was studied. The weight fraction of nanoparticles were taken as 0.2% and 0.4%, while the particles dimension was considered as 15 nm. The results showed that using the 0.2 wt% of nanofluid increased the efficiency of the collector in comparison with water by about 28.3% as shown in Fig. 13. Yousefi et al. [57] investigated experimentally the effect of using the MWCNT–water nanofluid as an absorbing medium in a flat-plate solar collector. The effect of Triton X-100 as a surfactant on the stability of the nanofluid was studied. The weight fraction of CNTs were taken as 0.2% and 0.4%, while the mass flow rates of nanofluid were varied from 0.0167 to 0.05 kg/s. Results showed that by increasing the weight fraction from 0.2% to 0.4%, a substantial increase in the collector efficiency was observed. They concluded that using the 0.2 wt% MWCNT nanofluid without surfactant decreased the collector efficiency, while with surfactant increased it as shown in Fig. 14. Yousefi et al. [58] investigated experimentally the effect of pH variation of MWCNT–H_2O nanofluid on the efficiency of a flat-plate solar collector. The experiments were carried out using 0.2 wt.% MWCNT with various pH values (3.5, 6.5 and 9.5) and Triton X-100 as an additive. Results showed that by increasing or decreasing the pH values with respect to the pH of iso-electric point, more enhancement in the efficiency of the solar collector was observed. Tora and Moustafa [59] simulated numerically the heat transfer performance of an Al_2O_3–water-based nanofluid for the flat-plate solar collector. It was found that the thermal conductively of the nanofluid and the collector efficiency had better values with higher particle sizes. Also, the collector using an alumina–water nanofluid had higher efficiency than that using the water only. Jamal-Abad et al. [60]

Fig. 12. The experimental flat plate solar collector (Yousefi et al. [56]).

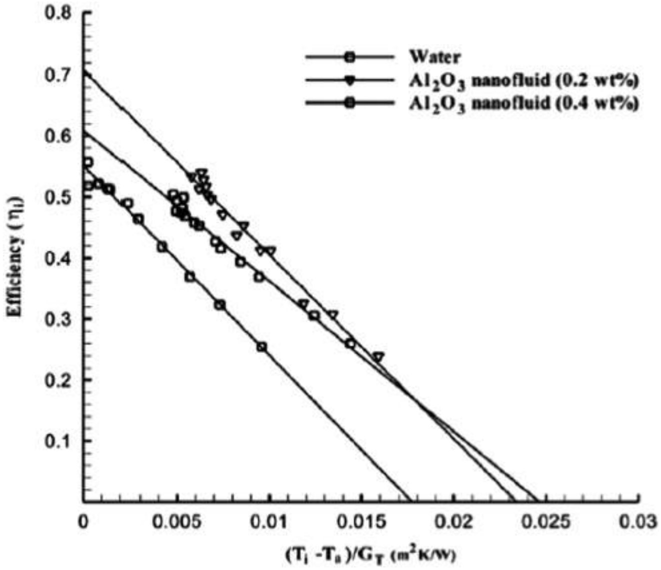

Fig. 13. The effect of mass fraction of Al_2O_3–water nanofluid on the efficiency of a flat-plate solar collector (Yousefi et al. [56]).

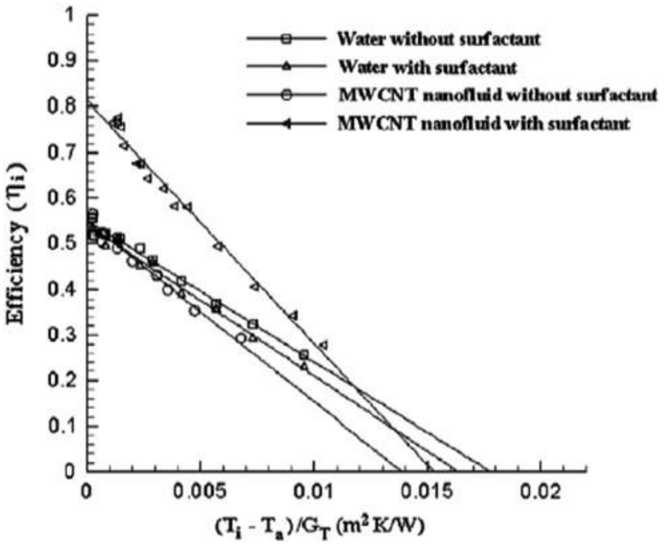

Fig. 14. The efficiency of the flat plate solar collector containing 0.2 wt% MWCNT nanofluid and pure water for both with and without surfactant cases (Yousefi et al. [57]).

examined experimentally the effect of Cu–water nanofluid on the performance of a flat-plate solar collector. The results showed that the collector efficiency was higher when the concentration of nanoparticles was raised. They concluded that the efficiency of the collector at 0.05 wt% was approximately 24% more than that of the pure base fluids. Faizal et al. [61] analyzed the potential of the size reduction of the flat-plate solar collector by using multi-walled carbon nanotube (MWCNT) as an absorbing medium. The analysis was based on different mass flow rate, nanoparticles mass fraction and presence of surfactant in the fluid. For the same output temperature, it was observed that the collector's size can be reduced up to 37% of its original size when applying MWCNT nanofluid and as a result decreased the overall cost of the system. They computed the reduction in the size of collector's area from the following equation:

$$A_c = \frac{\dot{m} C_p (T_{out} - T_{in})}{I_T \eta} \tag{1}$$

Gangadevi et al. [62] analyzed experimentally the performance of a thermal solar flat plate collector by using Al_2O_3–water nanofluid and used it to enhance the efficiency and decrease the electricity consumption of a solar assisted water heater. It was found that the efficiency of the solar collector was increased about 30% by using Al_2O_3–water nanofluid than that the water. Chaji et al. [63] fabricated and tested a small flat plate solar collector filled with TiO_2–water nanofluid (Fig. 15). Three flow rates (36, 72 and 108 l/m^2 h) and four particles concentration ratios (0, 0.1, 0.2 and 0.3 wt%) were investigated. It was found that the collector efficiency was improved between 2.6% and 7% by using the nanofluid compared to the base fluid. Tiwari et al. [64] analyzed theoretically the thermal performance of the flat-plate solar collector for water heating by using Al_2O_3/water nanofluid as an absorbing medium with different particle volume concentrations (0.5–2%). The effect of mass flow rate and particle volume fraction on the collector efficiency was investigated. The results showed that using 1.5% (optimum) particle volume fraction of nanofluid increased the thermal efficiency in comparison with water by about 31.64%. Faizal et al. [65] investigated numerically the energy, economic and environmental aspects of using metal oxides nanofluid in a flat-plate solar collector. It was estimated that 25.6%, 21.6%, 22.1% and 21.5% solar collector area reduction were achieved for using CuO, SiO_2, TiO_2 and Al_2O_3 water-based nanofluid respectively as shown in Fig. 16. Moreover, the average value of 220 MJ embodied energy was saved for each collector and around 170 kg less CO_2 emissions was reduced for the nanofluid solar collector compared to a conventional one. Said et al. [66] investigated experimentally the thermo-physical properties of ethylene glycol/water mixture and water-based alumina nanofluids and its effect on a flat plate solar collector. It was found that Al_2O_3–water nanofluid was more preferable against sedimentation and aggregation than Al_2O_3–ethylene glycol/water mixture nanofluid. They concluded that the pressure drop and pumping power of the nanofluid flows were very close to that of the base liquid for low volume concentration. Alim et al. [67] theoretically analyzed the entropy generation, heat transfer and pressure drop of (Al_2O_3, CuO, SiO_2 and TiO_2) nanoparticles suspended in water inside a flat plate solar collector. These nanofluids had different nanoparticle volume fractions and volume flow rates in the range of 1–4% and 1–4 L/min respectively. They concluded that, the CuO/water nanofluid was reduced the entropy generation by 4.34% and enhanced the heat transfer coefficient by 22.15% compared to the water as an absorbing fluid. Colangelo et al. [68] investigated experimentally the performance of the flat panel solar collectors (Fig. 17) using Al_2O_3–water nanofluid in order to avoid the effect of nanoparticles sedimentation. It was found that, the convective heat transfer coefficient was increased up to 25% at a concentration of 3% volume. The results showed that the main sedimentation parameter was the flow velocity and to better control it, a standard flat panel was modified by changing the cross-section of the lower and top header of the panel in order to keep the fluid axial velocity constant. Shankar and Manivannan [69] developed a numerical model

Fig. 15. The experimental flat plate solar collector (Chaji et al. [63]).

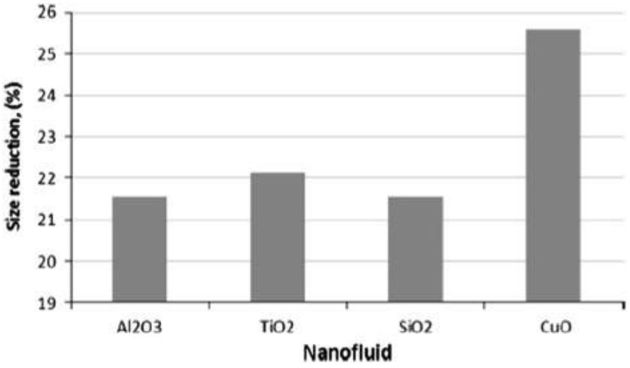

Fig. 16. Percentage of size reduction for solar collector by applying different nanofluids (Faizal et al. [65]).

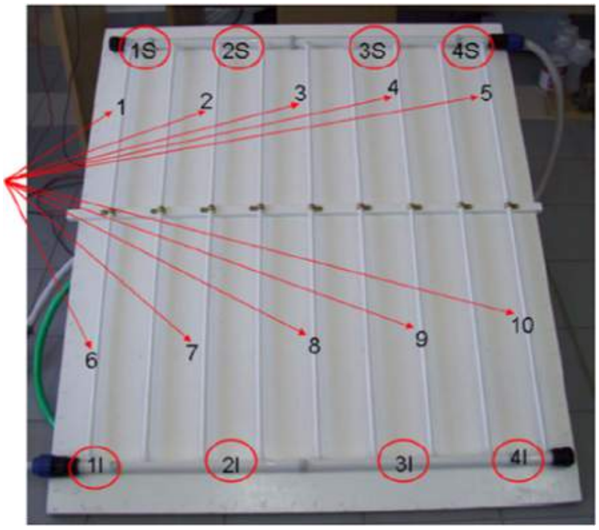

Fig. 17. Flat panel solar thermal collector (Colangelo et al. [68]).

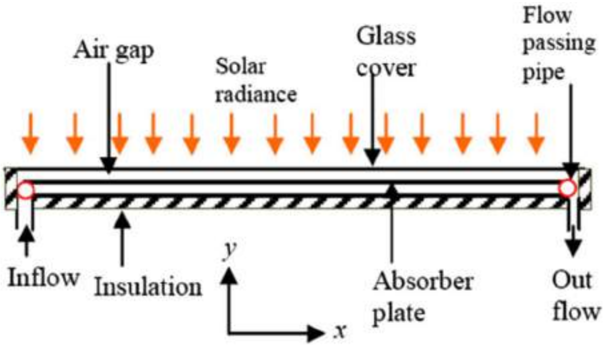

Fig. 18. Schematic of flat plate solar collector (Nasrin and Alim [70]).

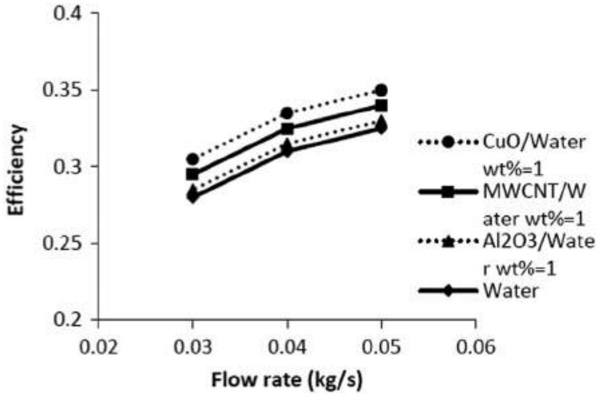

Fig. 19. Comparison between thermal efficiencies of various nanofluids under different mass flow rates (Ekramian et al. [72]).

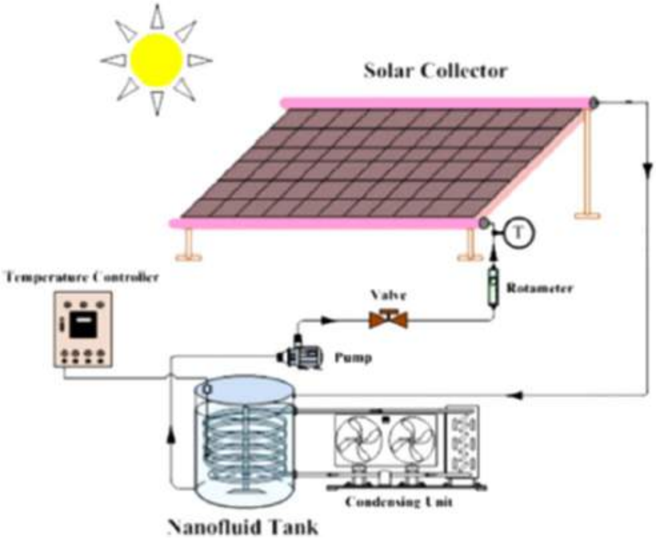

Fig. 20. A schematic of the nanofluid cycle in the flat plate solar collector (Mahian et al. [73]).

of the solar water heating system by using CuO–water nanofluid. The theoretical results showed that about (10.88%) of an improved efficiency was observed at (0.025%) volume fractions of the nanofluids. While the experimental results by using the water as a working fluid in the flat plate collector type was found to be with a maximum temperature of about (68.2 °C). Nasrin and Alim [70] investigated numerically the heat transfer by a water based nanofluid containing double nanoparticles (alumina and copper) and various nanofluids inside the riser pipe of a flat plate solar collector (Fig. 18). The results showed that the better performance of heat loss through the riser pipe of the flat plate solar collector was found by using the double nanoparticles (alumina and copper) than single nanoparticle (only alumina). They concluded that Cu–water nanofluid was more effective in order to promote heat loss system through the riser pipe of a flat plate solar collector. They stated that the actual useful energy gain in a solar collector was computed from the following equation:

$$Q_{usfl} = F_R A(I(\lambda\kappa) - h(T_m - T_a)) \tag{2}$$

Polvongsri and Kiatsiriroat [71] investigated experimentally the water solar collector performance with a silver–water nanofluid. In their study, a 20-nm silver particles mixed with water at concentrations of 1000 and 10,000 ppm were undertaken in a three small identical closed-loop flat-plate solar collectors, each with an area of (0.15 m × 1.0 m). It was found that the overall heat loss coefficient of the solar collector with nanofluid was reduced and more solar heat gain was obtained, especially with a high inlet temperature of the nanofluid. The results indicated also, that when the flow rate was different from the standard value, the solar thermal characteristics were also improved by using the nanofluid. Ekramian et al. [72] studied numerically the heat transfer performance of MWCNT-water, Al_2O_3–water and CuO–water nanofluids with mass percents of 1, 2 and 3 wt% in a flat plate solar collector. Effects of the inlet temperature, nanoparticle mass percent and mass flow rate on the heat transfer coefficients and thermal efficiency of pure water and nanofluids were studied. The results showed that the thermal efficiency of CuO–water nanofluid were greater than other nanofluids as shown in Fig. 19. Mahian et al. [73] performed an analytical study on the entropy generation and the heat transfer due to Al_2O_3/water nanofluid flow in a flat plate solar collector as shown in Fig. 20. Four different particle sizes, including 25, 50, 75 and 100 nm and volume concentrations up to 4% were considered. Effects of the tube roughness, nanoparticle size and different thermophysical models on the Nusselt number, heat transfer coefficient, outlet temperature of the collector, entropy generation and Bejan number were investigated. It was found that, the entropy generation was decreased with increasing the nanofluid concentration. Nasrin and Alim [74] investigated numerically the forced convection by a water–alumina nanofluid through the horizontal flat plate solar collector. Comprehensive average Nusselt number, average temperature, mean velocity, percentage of collector efficiency, mid-height temperature for both nanofluid and base fluid through the collector pipe were presented. The results showed that, when the Reynolds number

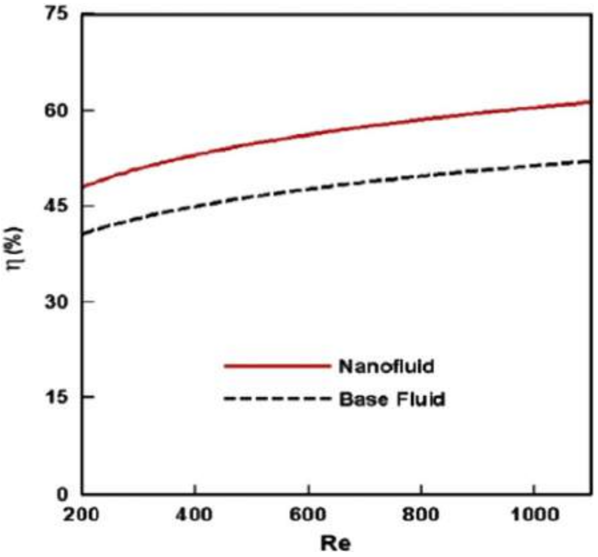

Fig. 21. The variation of percentage of collector efficiency as a function of Reynolds numbers (Nasrin and Alim [74]).

increased, the percentage of collector efficiency was enhanced by using the nanofluid as shown in Fig. 21. They suggested a semi-empirical correlation to compute the average Nusselt number through the riser pipe of the collector which was given by

$$Nu_{av} = (0.9223 + 0.2327Pr)(Re)^{0.2120} \tag{3}$$

When $4.2 \leq Pr \leq 10.2$ and $200 \leq Re \leq 1700$

Kabeel and El-Said [75] investigated numerically the applicability of flashing desalination technique for small scale needs using a novel integrated system coupled with Cu–water nanofluid in a flat plate solar collector. The thermal properties of the working fluid in the collector was improved by using different concentrations of Cu nanoparticles to determine the best volume fraction which gave a higher fresh water productivity. The results showed that the solar water heater collecting area was considered as a significant factor for reducing the water production cost. They concluded that, the volume fractions of nanoparticles had a significant effect on increasing the fresh water production and decreasing its cost. They computed the water production cost (C_{pro}) from the following relation by assuming 365 working days:

$$C_{pro} = \frac{TCO}{f \times CA \times 365} \tag{4}$$

Mahian et al. [76] performed a theoretical study to evaluate the performance of a minichannel-based flat plate solar collector using four different nanofluids including Cu/water, Al_2O_3/water, TiO_2/water, and SiO_2/water. The results were presented for volume fractions up to 4% and nanoparticle size of 25 nm where the inner diameter of the risers of the collector was assumed to be 2 mm. They concluded that the efficiency was decreased with increasing the volume fraction of nanoparticles and SiO_2/water nanofluid gave the highest efficiency of the collector as shown in Fig. 22. It was found also that the entropy generation was reduced by adding nanoparticles. They estimated the efficiency of the collector from the following equation:

$$Efficiency\ (\%) = \frac{Q_u}{A\ G_t} \times 100 \tag{5}$$

Moghadam et al. [77] investigated experimentally the effect of CuO–water nanofluid as an absorbing medium on the performance and the efficiency of a flat-plate solar collector as shown in Fig. 23. The volume fraction of nanoparticles was taken as 0.4%, the mean particle dimension was kept constant at 40 nm, while the working fluid mass flow rate was varied from 1 to 3 kg/min. The experimental results explained that the nanofluid with mass flow rate of (1 kg/min) increased the collector efficiency by about 21.8%. Zamzamian et al. [78] performed an experimental study to investigate the effect of Cu-synthesized/ethylene glycol nanofluid on the efficiency of a flat-plate solar collector (Fig. 24). The weight fractions of the tested nanoparticles with an average diameter of 10 nm, were taken as 0.2% and 0.3% of the nanofluid. The experiments were performed at different volume flow rates of the nanofluid ranging from 0.016 to 0.050 kg/s. It was found that by increasing the nanofluid concentration, the efficiency of the

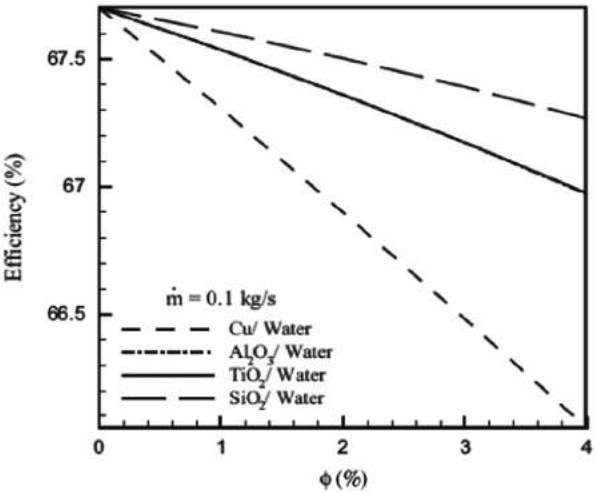

Fig. 22. Variations of efficiency with volume fraction for different nanofluids (Mahian et al. [76]).

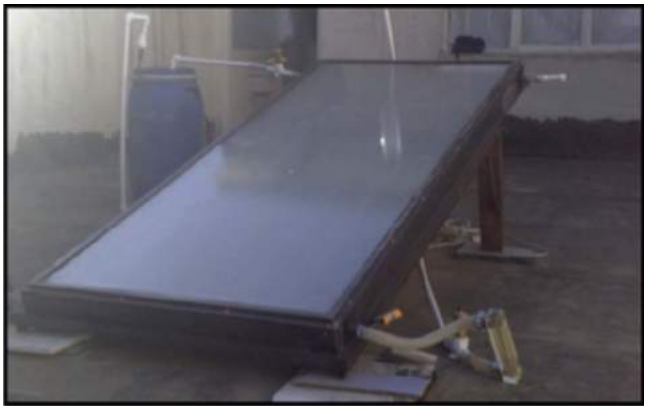

Fig. 23. The experimental flat plate solar collector (Moghadam et al. [77]).

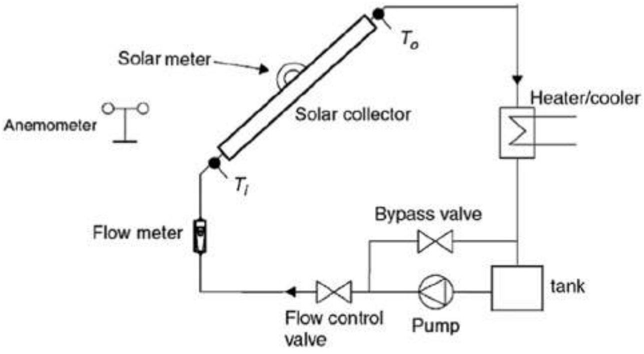

Fig. 24. Schematic of closed loop test system for flat-plate solar collector (Zamzamian et al. [78]).

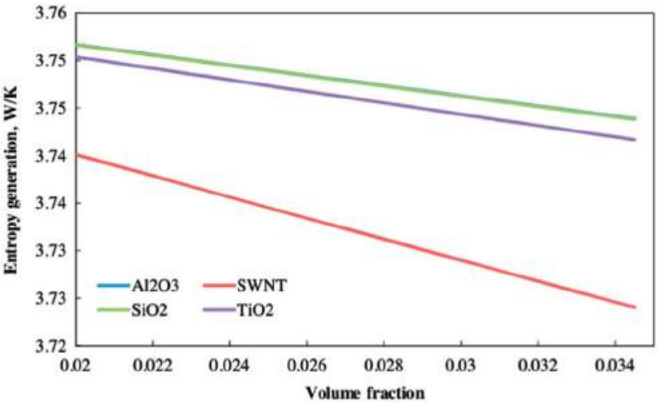

Fig. 25. The variation of the entropy generation with volume fraction in the flat plate solar collector (Said et al. [79]).

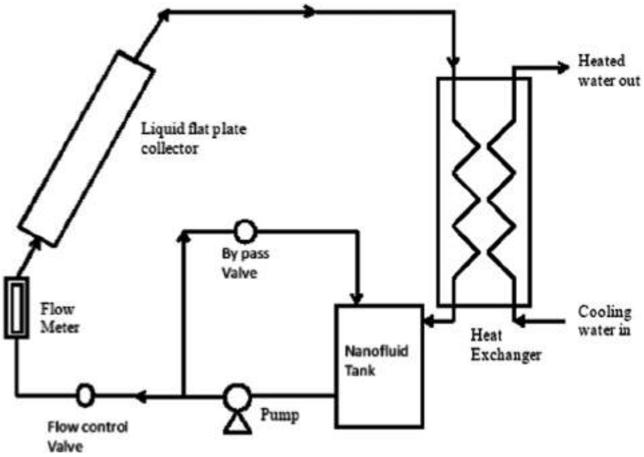

Fig. 26. Schematic of nanofluid-based liquid flat plate solar collector components used in (Roy et al. [81]).

Fig. 27. Photographic view of the test section (Roy et al. [81]).

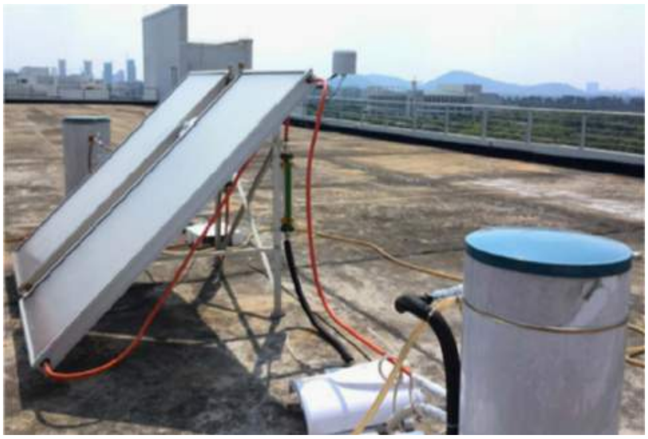

Fig. 28. The experimental flat plate solar collector (He et al. [82]).

collector was improved. Said et al. [79] analyzed theoretically the entropy generation, heat transfer enhancement and the pressure drop for a flat-plate solar collector operated with four different nanoparticles suspended in the water (single wall carbon nanotubes (SWCNTs), TiO_2, Al_2O_3 and SiO_2). It was observed that the SWCNTs nanofluid reduced the entropy generation by 4.34% as shown in Fig. 25 and enhanced the heat transfer coefficient by about 15.33%. Mahian et al. [80] examined theoretically the effects of different shapes of boehmite alumina nanoparticles suspended in a mixture of water and ethylene glycol together with the tube materials on the performance of a flat plate minichannel-based solar collector. Two different materials were considered for the solar collectors including copper and steel. It was found that the outlet temperature increased with an increase in the volume fraction of nanoparticles. They concluded that with an increase in the volume fraction of nanoparticles, the entropy generation rate due to the heat transfer was reduced for all shapes of nanoparticles. Roy et al. [81] investigated experimentally the heat transfer characteristics of silver/water nanofluid in a flat plate solar collector (Figs. 26 and 27). The solar radiation heat flux varied between 800 W/m^2 and 1000 W/m^2 respectively, while the particle concentration varied between 0.01%, 0.03%, and 0.04%. The fluid Reynolds number varied from 5000 to 25,000. The influence of radiation heat flux, mass flow rate of nanofluid, solar collector inlet temperature and volume concentration of the particle on the convective heat transfer coefficient and the collector efficiency were studied. They concluded that, the efficiency of the flat plate collector was increased with increasing particle concentration and flow rate. The maximum efficiency of the system was found to be near 70% for 0.04% particle volume concentration at 6 L/min. They computed the efficiency of the flat-plate collector from the following equation:

$$\eta_i = F_R(\tau\alpha) - F_R U_L \frac{T_{fi} - T_a}{I_T} \tag{6}$$

He et al. [82] investigated experimentally the effect of $Cu–H_2O$ nanofluid on the efficiency of the flat-plate solar collector (Fig. 28). The experimental results showed that the efficiency of the collector was enhanced by 23.83% by using the nanofluid (25 nm, 0.1 wt%) as an absorbing medium. It was found also, that the efficiency of the collector was decreased with the nanoparticle size increasing. Shojaeizadeh et al. [83] investigated the effect of various parameters like fluid mass flow rate, nanoparticle volume concentration, collector inlet fluid temperature, solar radiation and ambient temperature on the optimization and collector exergy efficiency of a flat-plate solar collector containing Al_2O_3–water nanofluid. They concluded that the nanofluid was increased the maximum collector exergy efficiency by about 1%. While, the optimum values of the fluid mass flow rate and collector inlet fluid temperature were decreased by about 68% and 2% respectively. Said et al. [84] studied experimentally and theoretically the performance of a flat plate solar collector by using TiO_2–water nanofluid of volume fraction of 0.1% and 0.3% respectively. The results illustrated that the energy efficiency was increased by

76.6% for 0.1% volume fraction in comparison to the water. They concluded that the pressure drop and pumping power of TiO_2–water nanofluid was very close to the base fluid for the considered volume fractions. Michael and Iniyan [85] investigated experimentally the effect of CuO–water nanofluid with 0.05% volume fraction on the flat plate solar water heater. It was found that the thermal performance of the collector was improved by 6.3% with using the nanofluid. They mentioned that the enhanced performance of nanofluid was due to the higher thermal conductivity of the nanoparticles, which caused a Brownian motion and led to absorb more solar energy. Very recently, Said et al. [86] studied experimentally and theoretically the effects of thermo-physical properties of short Single Wall Carbon Nanotubes (SWCNTs) suspended in water on the exergy efficiency of a flat plate solar collector. It was found that the maximum energy and exergy efficiency of the collector was enhanced up to 95.12% and 26.25% compared to water which was 42.07% and 8.77% respectively.

4. Applications of nanofluid in the direct absorption solar collector

Tyagi et al. [87] investigated theoretically the possibility of using water and aluminum nanofluid as an absorbing medium for a low-temperature ($< 100\,^{\circ}C$) 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. [88] 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 are graphite (30 nm diameter), 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. [89] 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. [90] 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. [91] 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. 29. Moradi et al. [92] 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. 30 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 [93] 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. Verma and Kundan [94] investigated experimentally the effect of Al_2O_3–H_2O based nanofluids as an absorbing medium in a direct absorption solar collector (Fig. 31). The volume fractions of Al_2O_3 nanoparticles used were 0.005% and 0.05% respectively. Efficiency of

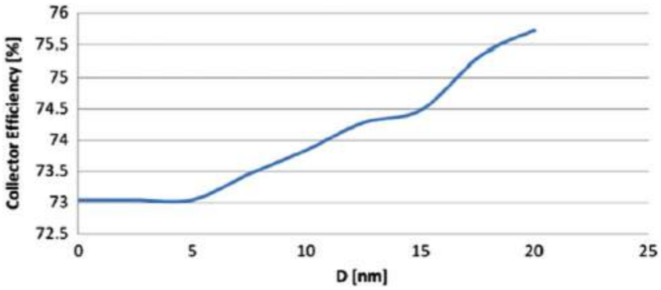

Fig. 29. Collector efficiency as a function of the particle size (D) (Saidur et al. [91]).

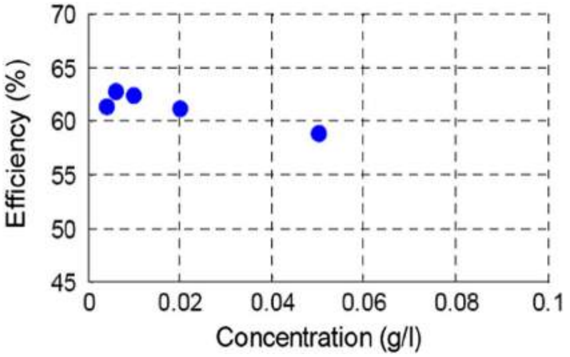

Fig. 30. The effect of nanoparticle concenteration on the efficiency of solar collector (Moradi et al. [92]).

Fig. 31. Direct absorption solar collector (Verma and Kundan [94]).

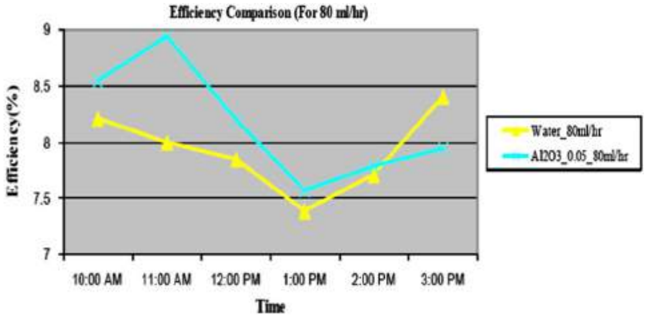

Fig. 32. Variation of efficiency of nanofluid and water for (80 ml/h) at different instants of time (Verma and Kundan [94]).

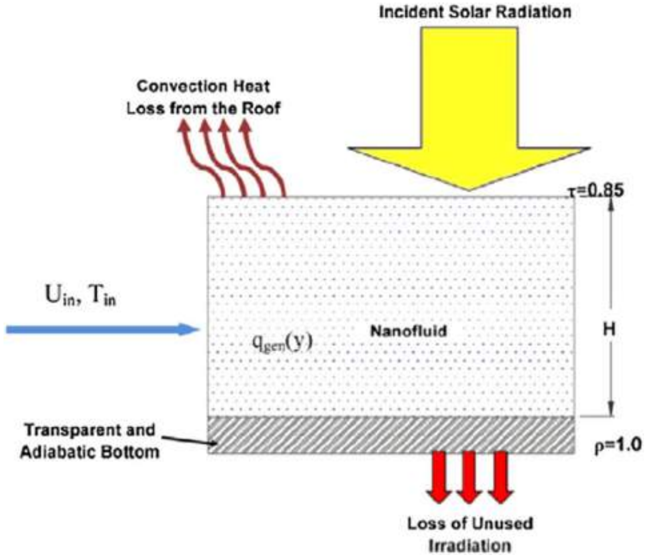

Fig. 33. The volumetric solar collector (Ladjevardi et al. [95]).

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. 32. They concluded also, that the collector efficiency depended on the size, shape and the volume fraction of nanoparticles. Ladjevardi et al. [95] investigated numerically the effects of using graphite / water nanofluid in the improvement of solar radiation absorption efficiency in a volumetric solar collector (Fig. 33) 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. Hector and Singh [96] 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. [97] 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. [98] 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. [99] 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. 34. Filho et al. [100] 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:-

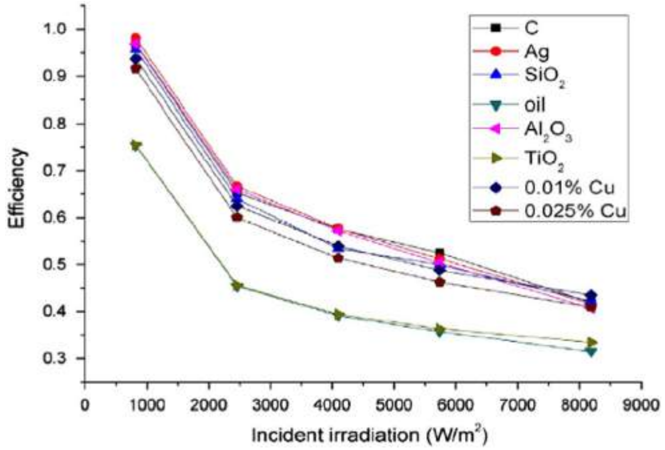

Fig. 34. Photo-thermal efficiency against the incident radiation intensity of the direct absorption solar collector (Luo et al. [99]).

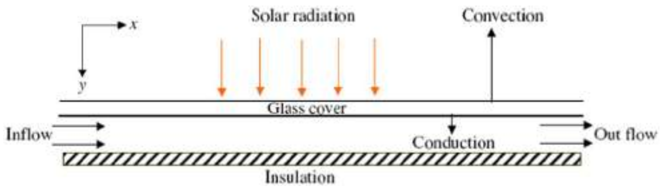

Fig. 35. Schematic of direct absorption solar collector (Parvin et al. [101]).

$$SAR = \frac{(m_w c_w + m_p c_p)\Delta T_n - m_w c_w \Delta T_w}{1000 m_p \Delta t} \tag{7}$$

Parvin et al. [101] 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. 35). 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

$$\eta = (2.488 + 0.327\varphi)(Re)^{0.4684} \tag{8}$$

When $0\% \leq \varphi \leq 3\%$ and $200 \leq Re \leq 1000$

Hordy et al. [102] 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. [103] 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 very recommended for increasing the overall efficiency of the direct absorption solar collectors. Zhang et al. [104] 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 [105] 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. [106] 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. Cregan and Myers [107] presented an approximate analytical solution to the steady state, two-dimensional model for the efficiency of an inclined nanofluid-based direct absorption solar collector working in the low to mid-temperature range. The nanofluid which was used in their modeling was Al–water. They assumed a constant fluid velocity profile in the collector and considered a low particle volume fractions. It was found that the efficiency did not vary with the collector angle of inclination. They concluded that the collector efficiency was rapidly increased when the solid volume fraction was very small. Very recently, Gupta et al. [108] investigated experimentally the thermal performance of the direct absorption solar collector by using a thin film of Al_2O_3–H_2O nanofluid. Four different concentrations (0.001%, 0.005%, 0.01% and 0.05%) of nanofluid were used in the test. They concluded that the efficiency enhancement of 22.1%, 39.6%, 24.6% and 18.75% was observed for 0.001%, 0.005%, 0.01% and 0.05% volume fraction respectively.

5. Applications of nanofluid in the parabolic trough solar collector (PTSC)

Khullar and Tyagi [109] analyzed numerically the heat transfer and fluid flow characteristics of the linear parabolic solar collectors. They added aluminum nanoparticles into the base fluid (water) to improve its absorption characteristics. The effect of various parameters such as concentration ratio, receiver length, fluid velocity and volume fraction of nanoparticles were studied. They concluded that nanofluid based collector was better than the conventional collector under similar working conditions. Khullar et al. [110] analyzed numerically the idea of harvesting solar radiant energy by using nanofluid-based concentrating parabolic solar collectors. It was observed that nanofluid collector had about 5–10% higher efficiency as compared to the conventional parabolic solar collector. They concluded also that nanofluid collector had the potential to harness the solar radiant energy more efficiently than a conventional one. De Risi et al. [111] investigated numerically the modeling and optimization of transparent parabolic trough solar collector working with gas-based nanofluid. It was found, that the transparent receivers combined with nanofluids were able to directly adsorb solar radiation due to the very high total surface of nanoparticles. They concluded that the maximum thermal efficiency was about 62.5%, for a nanofluid outlet temperature of 650 °C and a nanoparticles volume concentration of 0.3%. Sunil et al. [112] performed an experimental study to investigate the performance of a parabolic solar collector using SiO_2–H_2O based nanofluid (Fig. 36). Volumetric concentration of 0.01% and 0.05% were used in the experiment to prepare the nanofluid. Different volume flow rates employed in the experiment which varied as 20 L/h, 40 L/h and 60 L/h respectively. Magnetic stirrer with a hot plate system was used to mix the nanoparticles in water before sonication. It was found that SiO_2–H_2O based nanofluid had comparatively higher efficiency at higher volume flow rates. Ghasemi and Ahangar [113] studied numerically the effect of Cu–water nanofluid, as a heat transfer fluid, on the performance of a solar parabolic trough collector. The temperature field, thermal efficiency, mean-outlet temperatures were evaluated and compared with the conventional parabolic collectors and nanofluid based collectors. Also, the effect of various parameters such as fluid velocity, volume fraction of nanoparticles, concentration ratio and the receiver length were investigated. It was found that the thermal efficiency of the collector was decreased with the increase in the receiver length as shown in Fig. 37. The results explained also that, by increasing the volume fraction of nanoparticles, the performance of the collector was

Fig. 36. Schematic of parabolic solar collector (Sunil et al. [112]).

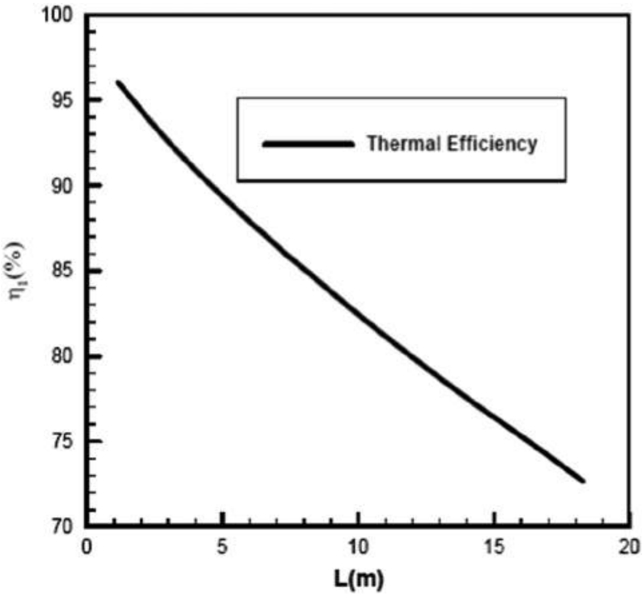

Fig. 37. Thermal efficiency variation with reciver length (Ghasemi and Ahangar [113]).

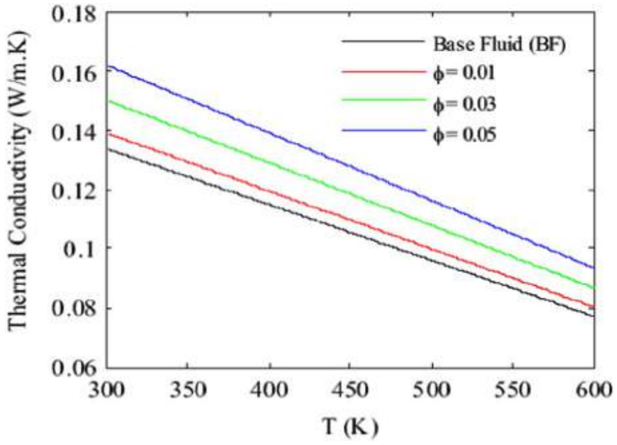

Fig. 38. The variation of thermal conductivity with the operational temperature (Sokhansefat et al. [114]).

enhanced. Sokhansefat et al. [114] investigated numerically the heat transfer enhancement in a parabolic trough collector tube by using Al_2O_3/synthetic oil nanofluid with a non-uniform heat flux. The effect of Al_2O_3 particle concentration in the synthetic oil on the rate of heat transfer from the absorber tube was also investigated. It was found that the heat transfer coefficient of the working fluid in an absorber tube was enhanced with the presence of nanoparticles. The results explained also that the thermal conductivity was remarkably improved by using a nanofluid as shown in Fig. 38. Mwesigye et al. [115] performed a thermodynamic analysis of the performance of a parabolic trough receiver using synthetic oil – Al_2O_3 nanofluid. A parabolic trough collector system with a rim angle of 80° and a concentration ratio of 86 was used in their study. They concluded that using nanofluid was improved the thermal efficiency of the receiver up to 7.6%. Very recently, Kasaeian et al. [116] investigated experimentally the performance of a solar parabolic trough collector (Fig. 39). The multi-walled carbon nanotube (MCNT)/oil based nanofluids with 0.2% and 0.3% were prepared as a working fluid. The results showed that, the global efficiency of a parabolic collector was enhanced about 4–5% at 0.2% and 5–7% at 0.3% when MCNT/mineral oil nanofluid was used instead of pure oil.

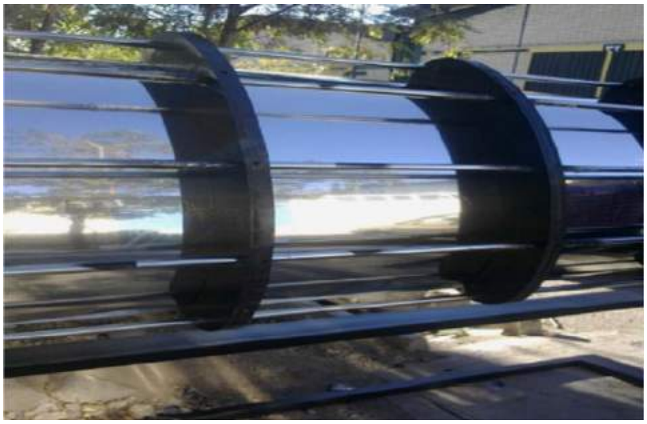

Fig. 39. Schematic of solar parabolic trough collector (Kasaeian et al. [116]).

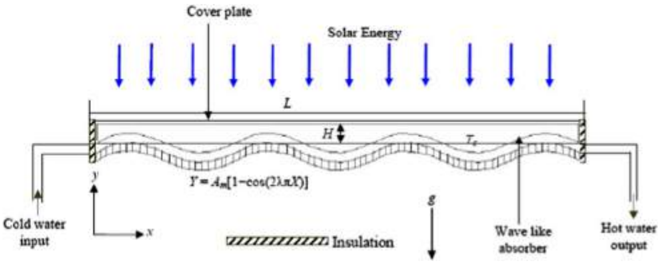

Fig. 40. Schematic of wavy solar collector (Nasrin and Alim [110]).

6. Applications of nanofluid in the wavy solar collector

Nasrin and Alim [117] investigated numerically the performance of Ag–water and CuO–water nanofluids on the heat transfer in a solar collector with a flat plate cover and a sinusoidal wavy absorber (Fig. 40). The behavior of both nanofluids related to performance such as temperature and velocity distributions, radiative and convective heat transfers, mean temperature and velocity of the nanofluid was investigated systematically. The results showed that the better performance of the heat transfer inside the collector was found by using the highest solid volume fraction of Ag–water nanofluid. Alaeian et al. [118] investigated experimentally the indirect absorption of the solar energy by MWCNT-oil nanofluid with mass fraction concentration of 0.1, 0.2 and 0.4% in wavy tubes for use in solar collectors. Different configurations of U-bend wavy copper tubes were investigated based on the dimensionless curvature radius and the number of sequences of U-bends in the laminar flow regime. It was observed that, the heat transfer coefficient was increased up to 56% compared to the base fluid at the highest concentration and the lowest dimensionless curvature ratio.

7. Applications of nanofluid in the heat pipe solar collector

Lu et al. [119] investigated experimentally the thermal performance of an open thermosyphon using both deionized water and CuO–water nanofluid for high-temperature evacuated tubular solar collectors (Fig. 41). Experimental results showed that the nanofluid significantly enhanced the thermal performance of the evaporator and evaporating heat transfer coefficients were increased by about 30% compared with those of the deionized

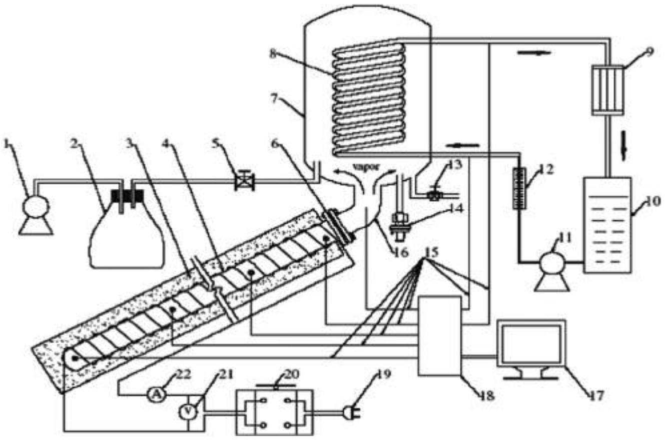

Fig. 41. Schematic of experimental apparatus. (1) Vacuum pump (2) regulators box (3) thermal insulator (4) evaporator tube (5) vacuum valve (6) flange plate (7) condenser box (8) condensing coil (9) heat exchanger (10) water tank (11) pump (12) rotermeter (13) water valve (14) relief valve (15) thermocouples (16) elbow tube (17) computer (18) data acquisition system (19) DC power supply (20) transformer (21) voltmeter and (22) ammeter (Lu et al. [119]).

water. It was found also, that the wall temperatures of the open thermosyphon using nanofluids decreased after substituting CuO nanoparticles into the water. Moorthy et al. [120] investigated experimentally the efficiency of the evacuated tube solar collector using water-based titanium oxide (TiO_2) nanofluid for conversion of the solar thermal energy. They concluded that the efficiency of the collector using TiO_2 nanofluid with 0.3% concentration was about 73%, compared to that using pure water which was about 58%. Chougule et al. [121] examined experimentally the performance of two identical flat plate collectors. In each collector, three identical wickless copper heat pipes were used. The working fluid used in one collector was a pure water and in the another a pure water with carbon nanotubes (CNT). Both collectors were tested using the solar tracking system. They concluded that the nanofluid collector gave a better performance in the all test conditions. Senthil Kumar et al. [122] performed an experimental analysis of nanofluid-charged wickless solar heat pipe collector by using the solar tracking system. In their work, two identical experimental set up of flat plate collectors with same dimensions, using heat pipes were fabricated. In each set up, three identical wickless copper heat pipes were used which having a length of (620 mm) and outer diameter of (18 mm). The working fluid used in one set up was the pure water and in the another was pure water with CNT nanoparticles. They concluded that the nanofluid collector gave the better performance in all the operating conditions. Chougule et al. [123] investigated experimentally the thermal performance of a solar wickless heat pipe collector at the outdoor test condition for pure water and carbon nanotubes (CNT) with various concentration (0.15%, 0.45%, 0.60% and 1% by volume) and various tilt angles (20 deg, 32 deg, 40 deg, 50 deg and 60 deg). They obtained the optimal value of CNT nanofluid concentration for better performance of the heat pipe solar collector. Liu et al. [124] designed experimentally an evacuated tubular solar air collector integrated with simplified CPC (compound parabolic concentrator) and an open thermosyphon (Fig. 42) using CuO–water nanofluid. The thermal performance of an open thermosyphon using nanofluid for this collector was evaluated. Experimental results showed that both the air outlet temperature and the collector efficiency using the nanofluid are higher than that using water. They computed the system collecting efficiency by using the following equation:

$$\eta_{net} = \frac{P_{net}}{nQ_{cpc}} \tag{9}$$

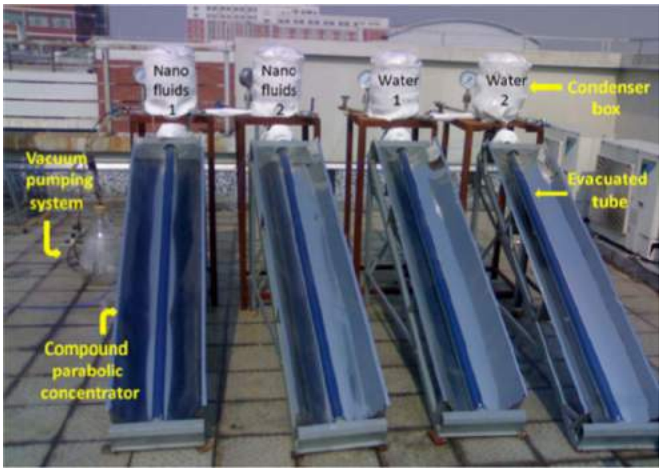

Fig. 42. Photograph of the evacuated tubular solar air collector (Liu et al. [124]).

Saravanan and Karunakaran [125] investigated experimentally the performance of V-type absorber plate solar collector with a heat pipe by using different working fluids such as nanofluid (TiO_2+DI water), methanol, ethanol and DI water. The results showed that there was a significant increase in the thermal efficiency of the collector by using the nanofluid. They concluded that the solar collector using V-type absorber plate with the heat pipe was recommended for domestic solar water heater applications due to its low weight, low cost and the long life. Aruna et al. [126] investigated experimentally the performance of the heat pipe solar collector by using two different working fluids (TiO_2+DI water nanofluid and propanol) with a constant concentration of nanoparticle and size as 80 ml/lit and 40 nm respectively. It was found that the nanofluid gave a better performance when compared to the propanol.

8. Applications of nanofluid in the another solar collectors

Li et al. [127] investigated experimentally the heat transfer performance of the tubular solar collector containing Al_2O_3, ZnO and MgO nanoparticles with distilled water as a base fluid. The experimental results showed that the heat transfer efficiencies of all types of nanofluids were increased in comparison to a distilled water. They concluded that according to the low viscosity and the excellent heat transfer performance, the ZnO nanofluid with 0.2 vol%. concentration was a good option in the solar energy utilization. Taylor et al. [128] investigated experimentally the applicability of using nanofluids in high flux solar collectors. In their experiments, they used the aluminum, copper, graphite and silver nanoparticles together with the Therminol VP-1 as a base fluid. Fig. 43 shows images of the reflective dish and the receiver with instrumentation used in their experiments. It was found that the efficiency improvement on the order of 5–10% by using a nanofluid receiver. They showed also, that graphite nanofluids with volume fractions on the order of 0.001% or less were suitable for 10–100 MW power plants. Gangadevi et al. [129] investigated experimentally the performance of the hybrid solar system (PV/T) which consisted from a flat plate solar collector attached to a solar photovoltaic cell by using Al_2O_3–water nanofluid. The results showed that both the electrical and thermal efficiencies of a hybrid solar system was increased considerably by using the nanofluid as a working fluid. Paul et al. [130] and Paul [131] investigated experimentally the thermal performance of ionic liquid-Al_2O_3 nanofluid as a heat transfer fluid in the solar collector. Viscosity, heat capacity and the thermal conductivity were measured and compared with

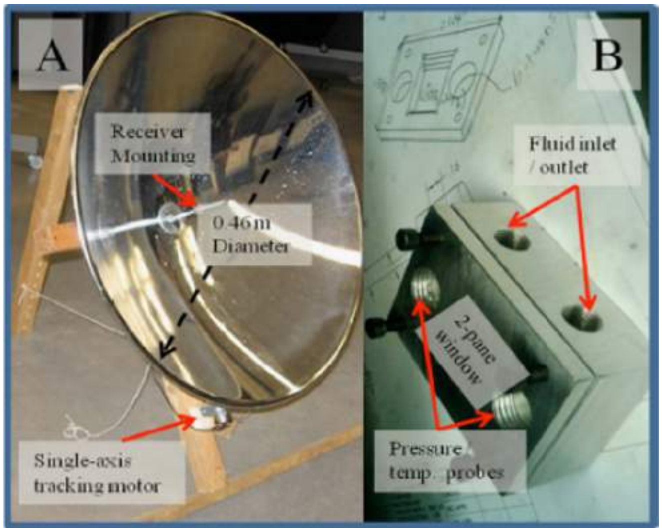

Fig. 43. Images of the reflective dish and receiver with instrumentation used by (Taylor et al. [128]).

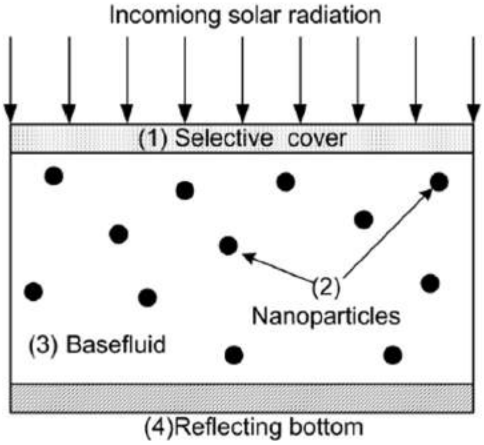

Fig. 44. Schematic of nanofluid-based direct absorption solar collector components used in (Hewakuruppu et al. [132]).

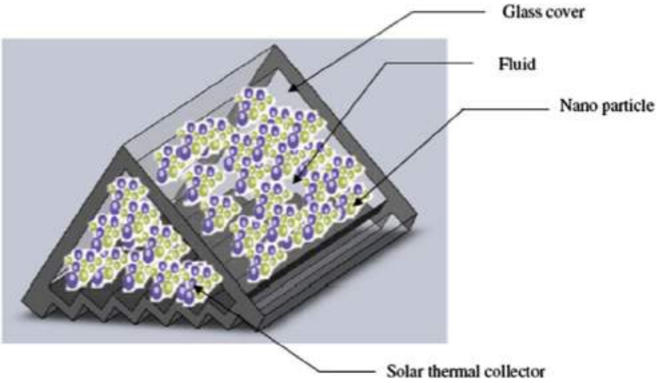

Fig. 45. 3D view of a triangular solar collector (Rahman et al. [133]).

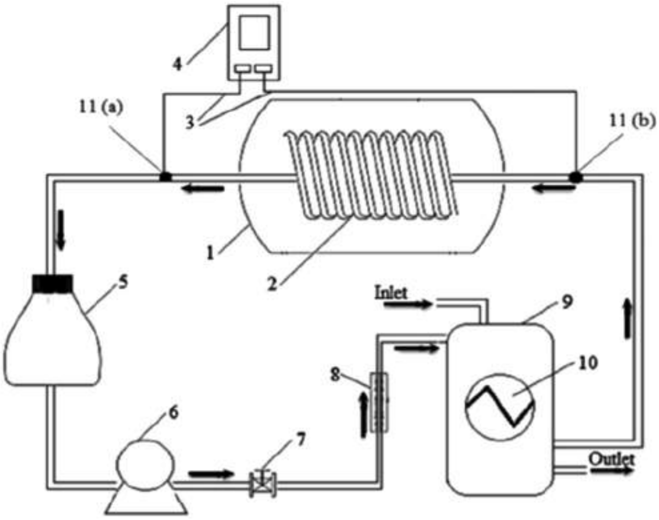

Fig. 46. Schematic of the cylindrical solar collector (1) cylindrical glass (2) copper coil (3) thermocouple wires (4) data logger (5) water supply and drainer (6) pump (7) line valve (8) rotameter (9) reservoir tank (10) heat exchanger (11a and 11b) thermocouples (Goudarzi et al. [134]).

existing theoretical models for liquid-solid suspensions. It was found that the heat transfer performance was enhanced by about 15% by using ionic liquid-Al_2O_3 nanofluid. Hewakuruppu et al. [132] investigated numerically the optical properties of nanofluid-based direct absorption solar collector components (Fig. 44), when they were optimized for selective absorption. It was found that a nanofluid with a short wavelength, optical depth of 3 with no scattering, and a long wavelength with optical depth of zero were considered for the optimum nanofluid. A cover of the solar collector which perfectly transmitted the short wavelength radiation and perfectly reflected long wavelength radiation was also required. Rahman et al. [133] studied numerically the heat transfer augmentation in a triangular solar collector with a corrugated bottom wall (Fig. 45) by utilizing water based nanofluids. They considered three types of nanoparticles (Cu, Al_2O_3 and TiO_2). It was found that Cu–water nanofluid performed a better performance from the heat transfer point of view than other used nanofluids. Also, they concluded that the heat transfer was increased up to 24.28% from the heated surface as the volume fraction was increased from 0% to 10%. Goudarzi et al. [134] investigated experimentally the effect of CuO–H_2O nanofluid and distilled water on the efficiency of a cylindrical solar collector with receiver helical pipe (Fig. 46). In their experiments, the mass flow rate of fluid was changed from 0.0083 to 0.033 kg/s while the weight fraction of nanoparticles were varied as 0.1%, 0.2% and 0.4% respectively. Results showed that the collector efficiency was enhanced by using nanofluid compared with the pure water. They observed also, that the maximum thermal efficiency was increased by about 25.6% by using 0.1 wt% nanofluid in 0.0083 kg/s mass flow rate of the fluid. They evaluated the performance of the collector by computing the instantaneous efficiency which was given by

$$\eta_i = \frac{Q_u}{A\ I_b} \tag{10}$$

Rahman et al. [135] studied numerically the effect of solid volume fraction and tilt angle in a quarter circular solar thermal collectors filled with CNT–water nanofluid. A wide range of solid volume fraction (0 to 0.12) and tilt angle (0–60°) was investigated for Rayleigh number ($Ra = 10^5$–10^8) and with various dimensionless times. It was found that both solid volume fraction and tilt angle played vital roles for the augmentation of heat transfer in the collector. Also, they concluded that the effect of inclination angle was more severe than the effect of solid volume fraction. Goudarzi et al. [136] investigated experimentally the effect of pH variation of two nanofluids (CuO–H_2O and Al_2O_3–H_2O) on the efficiency of a cylindrical solar collector. The collector consisted of a cylindrical glass tube with a helical pipe as a solar energy receiver as shown in Fig. 47. Their experiments were performed using 0.1 wt% CuO and 0.2 wt% Al_2O_3 with various pH values. The results showed that the thermal efficiency of the solar collector was increased when there was more differences between pH of nanofluid and pH of iso-electric point. This increasing in the efficiency was estimated respectively by about 52% for CuO nanofluid and 64.5% for Al_2O_3 nanofluid. Michael and Iniyan [137] investigated experimentally the performance of a solar photovoltaic thermal collector (Fig. 48) by using CuO–water nanofluid with 0.05% volume fraction. A copper sheet was laminated directly to the silicon cell in order to reduce the thermal resistance. It was found that the nanofluid was increased the collector efficiency up to 45.76%. Tong et al. [138] designed and constructed an enclosed-type evacuated U-tube solar collector (EEUSC) with low cost and high efficiency. A copper fin was employed in the U-tube to assume a constant heat flux. In order to increase the collector efficiency in the U-tube, the air gap was filled with a Multi-Walled Carbon Nanotube (MWCNT) – water nanofluid. It was found that the collector efficiency was increased by 4% with the use of the nanofluid. Very recently, Colangelo et al. [139] built a modified flat panel solar collector (Fig. 49) and its efficiency was measured by using a distillated water and Al_2O_3 – distillated water nanofluid with (3%) solid volume fraction. It was found that the collector efficiency was increased up to 11.7% by using the nanofluid compared with distillated water only. They concluded also that nanofluid was more effective than water at high temperature.

Fig. 47. Cylindrical solar collector and the experimental setup (Goudarzi et al. [136]).

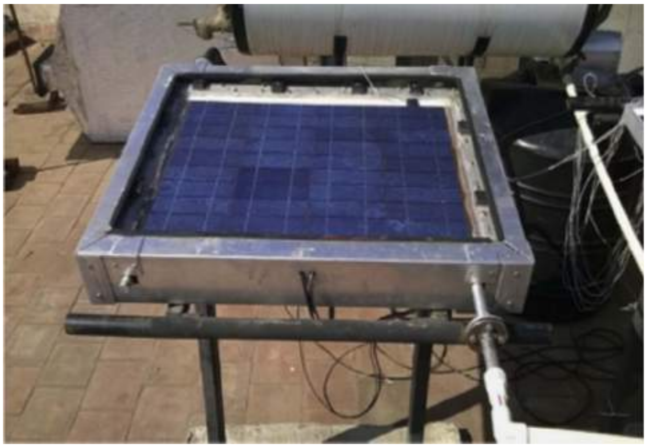

Fig. 48. Photovoltaic solar collector connected to the storage tank (Michael and Iniyan [137]).

9. Review papers related with application of nanotechnology in the solar collector

Sruthi [140] presented a review about the application of solar panels in water heater system and the use of nanotechnology in solar water heater (SWH). They presented various advantages of using nanomaterials in the solar water heater such as

1. Easy and safe to use.
2. Wide array of commercial applications due to its wireless capabilities.
3. Energy conserving and save money out of electricity.
4. Excellent thermal insulation in a thin layer system which does not increase the weight.
5. No moisture infiltration, which gives the insulation the benefits of corrosion resistance.
6. Easy installation and the high efficiency.

Khanafer and Vafai [141] presented an overview of the use of nanomaterials in solar energy and desalination sectors. They reviewed the most advances of the nanotechnology in thermal energy storage systems, photovoltaic systems, direct absorption solar collectors and solar desalination. They mentioned that, for an optimum performance of a solar collector, the solar radiation should be absorbed within a small wavelength range ($0.25\ \text{mm} < \lambda < 2.5\ \text{mm}$) and converted directly to a heat inside the working fluid to minimize the heat losses and the effect of both fouling and pumping cost. Javadi et al. [142] presented an overview of studies related with the performance of solar collector, especially the direct absorption solar collector by using nanofluid as a working fluid. They concluded that further researches must be focused on the two-phase analysis of nanofluids in order to find more accurate relationships between properties of

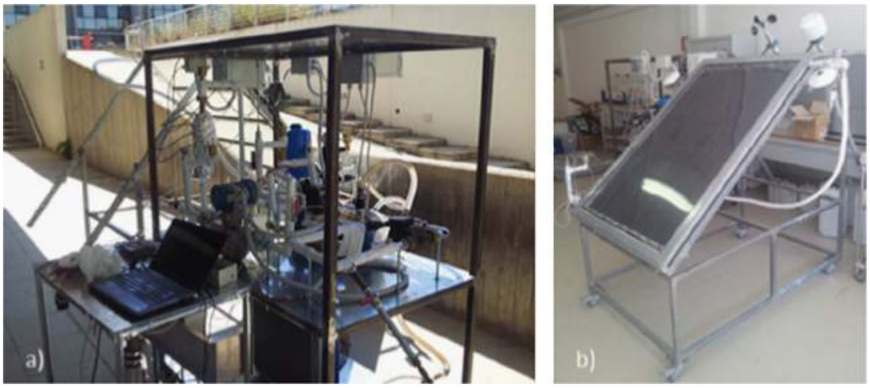

Fig. 49. Experimental setup (a) and flat panel solar thermal collector (b) (Colangelo et al. [139]).

nanoparticles and the nanofluid. Moreover, they indicated that there was a lack of study on the effect of nanofluid's optical properties such as transmittance and extinction coefficient on the performance of the solar collector. Mahian et al. [143] presented a review of the applications of nanofluids in solar thermal engineering. The papers related with the applications of nanofluids in solar collectors, solar water heaters, photovoltaic/thermal systems, solar ponds and solar thermoelectric cells were reviewed. They indicated that the experimental and numerical studies for solar collectors showed that in some cases, the efficiency could increased remarkably by using nanofluids. Moreover, the challenges of using nanofluids in solar energy devices were discussed. It was suggested that the nanofluids in different volume fractions should be tested to find the optimum volume fraction. They presented various suggestions such as

1. It was worth to carry out an experimental work on the effect of particle size on the collector efficiency.
2. From the economic and environmental point of view, the using of nanofluids in collectors led to a reduction in CO_2 emissions, annual electricity and fuel savings.

Al-Shamani et al. [144] presented an overview of the effects of nanofluids on the performance of cooling solar collectors from the considerations of efficiency and environmental benefits. Also, they presented an overview of the research, performance and development of photovoltaic/thermal (PV/T) collector systems. An efficiency fact was introduced in their paper to provide a general understanding for designers and researchers. They presented various conclusions such as

1. The thermal conductivity enhancement of nanofluids depended on the volume fraction, size, type of nanoparticles and the base fluid.
2. Suspended nanoparticles remarkably increased the forced convection heat transfer performance of the base fluid.
3. The sheet and tube collector was highly efficient and less expensive in practical application of the water-based PV/T, such as building-integrated systems.
4. Nanofluids could be used to cool photovoltaic/thermal (PV/T) collector systems.

Chaudhari and Walke [145] reviewed some studies related with the application of nanofluids in solar thermal engineering systems such as solar collectors, solar cells, thermal energy storage and solar stills. They suggested that, it was important to carry out an experimental work on the effect of particle size on the collector efficiency. They concluded that the volumetric absorption of nanofluid in solar collectors reduced the thermal resistance at interfaces and minimized temperature difference between the absorber and the heat transfer fluid and as a result the efficiency was increased. Nerella et al. [146] explained in their review paper that the efficiency of the solar collectors was limited by the absorption properties of the working fluid. The improvements of the efficiency in solar collectors by utilizing nanofluids with base fluid were highly comparable with the efficiency of solar collector when only base fluid was used. They indicated that the experimental and numerical results demonstrated an initial rapid increase in the solar collectors efficiency with volume fraction, followed by a leveling off in the efficiency as the volume fraction further increased. Kasaeian et al. [147] reviewed the applications of nanofluids on different types of solar collectors, photovoltaic systems, solar cells, energy storage system and solar thermoelectrics devices. They concluded that the volumetric absorption of nanofluid in solar collectors reduced the thermal resistance at interfaces and minimized the temperature difference between the absorber and the heat transfer fluid and as a result the efficiency was increased. They suggested that the development of the particle production and decreasing in costs were essential for the nanofluid research. Verma and Tiwari [148] presented a review about the application of nanofluids in solar collectors. It was found that the thermal efficiency of the PV/T systems was highly enhanced by using nanofluids. They recommended that a further researches were needed to investigate the effect of the nanofluid on the surface absorption capability of the absorbing plates in the flat plate solar collector. Also, additional experiments were required to study the optical property of nanofluids. Very recently, Hussein et al. [149] presented a comprehensive review about the recent advances related with the application of the nanotechnology in the direct absorption solar collectors. Their review including theoretical, numerical and experimental works related with the nanofluid applications in these collectors. It was found that the use of the nanofluid in the direct absorption solar collectors played a crucial role in increasing the efficiency of these devices.

10. Challenges and difficulties

The application of the nanofluid in the 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. Many studies [150] referred that the optimum heat transfer process requires that the working fluid have a high specific heat in order to exchange more heat.
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 boiling characteristics of the nanofluid are low. Therefore, when the concentration of nanoparticles increases, it leads to increase the surface temperature of nanofluid and make a severe overheating.
6. 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.
8. The utilizing of nanofluids suffers from some technical problems such as the nanoparticles sedimentation.
9. The cost of the nanofluid is high due to difficulties in its production and may causes an environmental damage when it is drained out after its usage.

11. Conclusions

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

1. Based on the reviewed papers, the nanoparticles must be dispersed uniformly in the base fluid to enhance the solar-weighted absorption and increase the efficiency of the solar collector.
2. Volume fraction of nanoparticles must be chosen accurately to enhance the performance of nanofluid collector. This is

because, the high volume fractions of nanoparticles increase the viscous force of nanofluids and reduce the heat transfer. While, the low quantity makes the nanofluid not able to absorb all of the incident solar radiation.

3. It is recommended to use carbon nanohorns (CNHs) as a nanoparticles to improve the optical properties of the direct solar collectors. This is due to their large surface area and large number of cavities.
4. It is found that the nanoparticle size has a major effect on the efficiency of the different kinds of the solar collectors.
5. It is very useful to invent a new design of solar collectors to capture and minimize the sedimentation phenomena in the solar collector pipes. Also, they have a high operating temperature and a high heat storage capacity.
6. More efforts are needed to study the reliability of using nanofluids in solar collectors from both environmental and economical point of view.
7. The future researches must be directed towards inventing efficient energy transport methods of nanofluid in solar collectors such as the enhancement of the heat transfer rate by studying the effect of particle shape on the thermal conductivity of nanofluid.
8. 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.
9. More researches are needed to study the effect of nanotechnology on both heat pipe and PV/T solar collectors, since the number of published papers related to these types are still limited compared with the corresponding papers related with the another types of the solar collector.
10. 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.
11. More efforts are needed to study the benefits of using nanofluids in order to develop the performance of the transpired solar collector since no paper exists up to date to consider this problem.
12. More researches are needed to study the effect of nanoparticles sedimentation on the performance of various types of the solar collectors.
13. Further researches are needed to study the effect of hybrid-nanofluids (a mixture of two or more different nanoparticles suspended in a base fluid) on the efficiency of different kinds of the solar collectors.

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