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Nanofluids for solar collector applications: A Review

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Abstract

Nanofluids are embryonic fluids that exhibit thermal properties superior than that of the conventional fluid. The application of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentrations, by homogeneous dispersion and stable suspension of nanoparticles in the host fluids. Nanofluids plays vital role in various thermal applications such as automotive industries, heat exchangers, solar power generation etc. Mostly heat transfer augmentation in solar collectors is one of the key issues in energy saving, compact designs and different operational temperatures. In this paper, a comprehensive literature on thermophysical properties of nanofluids and the application of solar collector with nanofluids have been compiled and reviewed. Recent literatures indicate the conventional heat transfer using nanofluids and their specific applications in the solar collector.

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Keywords: Heat transfer; Thermal conductivity; Solar collector; Convective heat transfer; Nanofluid and Nano particle.

1. Introduction

Solar energy is the most copious of all energy forms. Renewable sources of energy from sun are fairly non-polluting and considered clean. Solar energy as the green and environmental friendly energy has produced energy for billions of years. Solar energy that reaches the earth is around $4x10^{15}$ MW and it is 200 times as large as the global utilization. Solar power generation grew even more rapidly (+86.3%), but from a smaller base. Renewable forms of energy accounted for 2.1% of global energy consumption, up from 0.7% in 2001. Consequently the utilization of solar energy and the technology of nanofluids attracted much more attention. Heat transfer nanofluids were first developed by Choi [1] of the Argonne national laboratory, USA in 1995.

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Nanofluid suspensions containing particles <100nm and have a bulk solids thermal conductivity order of magnitudes higher than the base fluids [2, 3]. Experimental studies conducted by [4-6] shows that the effective thermal conductivity increases under macroscopically stationary conditions. Since then, a number of studies have been conducted on the thermal properties (mainly thermal conductivity) viscosity and convective heat transfer performance. It have been demonstrated that nanofluids can have significantly better heat transfer characteristics than the conventional fluids depending upon the nano particle used, size of nano particle and concentration of colloidal suspension. Several quality comprehensive reviews summarized the thermo physical studies on nanofluids [7-9]. This article provides a sandwich approach on thermo physical properties of different nanofluids and their applications on solar collectors significantly.

1.1 Green Energy Technologies

Green energy is renewable and sustainable. It is renewable because it does not deplete easily and is obviously replenished. Solar, hydro, wind, geo thermal, bio fuels and tidal power are some of the green energy sources that can be used as an alternative to our conventional sources of energy. Specifically the solar energy technologies produce electricity from the energy of the sun. However, the energy recurring from solar through two significant modes of technologies one is solar Photovoltaics and another solar thermal collectors.

1.2 Solar Photovoltaics

French physicist Edmond Becquerel discovered how to produce electric current in a solid material with the help of sunlight as early as 1839. The photovoltaic effect cause certain materials to convert light energy into electrical energy at the atomic level, which was first studied in 1876 by Adam and Day, who made solar cell from selenium that had an efficiency of 1-2%. The photovoltaic effect was explained by Albert Einstein in 1904 via his photon theory [10]. A noteworthy breakthrough related to modern electronics was the invention of a process to produce pure crystalline silicon by Polish scientist Jan Czochralski in 1916 [11]. The efficiency of first generation silicon cells was about 6% [12], which is substantially lower than that of current solar cells (about 14-20%). Early efforts were made to make the photovoltaic cells viable for generating electricity for worldly applications were unsuccessful due to the high device costs. The lower prices of these photovoltaic cells and need for green technology gained interest in employing this technology.

1.3 Solar Thermal Collectors

Solar thermal collectors can also be considered legendary based on the type of heat transfer liquid and their construction used (water, non-freezing liquid, air, or heat transfer fluid) and whether they are covered or uncovered. Solar flat plate collectors are used for water heating applications and the efficiency of these systems are around 70% which is very high as compared to solar direct energy conversion systems having efficiency around 17% [13].These collectors are useful for domestic applications, space heating and industrial low temperature applications. Currently a large number of solar collectors are available on the market based on concentrating solar power (CSP) systems which use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam, which is then used as a heat source for a conventional power plant. Extensive ranges of concentrating technologies developed are the parabolic trough, the concentrating linear Fresnel reflector, the concentrating Sterling dish and the solar power tower collectors. Recently, the solar thermal configuration system combined with the emerging technologies of nanofluids and different nano particle suspensions to develop an innovative approach of nanofluid based solar collectors.

2. Nanofluids

Nanofluids demote to a solid-liquid mixture or suspensions produced by dispersing tiny metallic or non-metallic solid nano particles in liquids. Nanofluids are a new class of fluids engineered by dispersing nanometer sized materials (Nano-particles, Nano-fibers, Nano-tubes, Nano-wires and Nano-rods) in base fluids. The size of nanoparticles (usually less than 100nm) in liquids mixture gives them the ability to interact with liquids at the molecular level and so conduct heat better than today's heat transfer fluids depending on nano particles. Nanofluids can display enhanced heat transfer because of the combination of convection & conduction and also an additional energy transfer through γ-particles dynamics and collisions. Metallic nanofluids have been found to possess enhanced thermo physical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients compared to those of base fluids like oil or water. In current years, nanofluids established greater potential in many fields like solar collector and solar thermal storage. Even though some review articles involving the progress of nanofluids investigations were published in the past several years [14,15], most of the reviews are concerned with the experimental and theoretical studies of the thermophysical properties or the convective heat transfer of nanofluids.

2.1 Classification of Nanofluids

Nanofluids can be normally classified into two categories metallic nanofluids and non-metallic nanofluids. Eastman et al, [16] theoretically studied the atomic and microscale-level characteristic behavior of nanofluids. The result shows that the enhancement of thermal conductivity, temperature dependent effects and significant raise in critical heat flux. Metallic nanofluids often refer to those containing metallic nanoparticles such as (Cu, Al, Zn, Ni, Si, Fe, Ti, Au and Ag), while nanofluids containing non-metallic nanoparticles such as aluminium oxide (Al_2O_3), copper oxide (CuO) and silicon carbide (SiC, ZnO,$TiO_{2)}$ are often considered as non-metallic nanofluids, semiconductors (TiO_2), Carbon Nanotubes (SWCNT, DWCNT and MWCNT) and composites materials such as nanoparticles core polymer shell composites. In addition, new materials and structure are attractive for use in nanofluids where the particle liquid interface is doped with various molecules.

2.2 Thermophysical Properties of Nanofluids

Metallic nanofluids clearly exhibit improved thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity, convective heat transfer coefficient, emissivity and optical absorption. The property change of nanofluids depends on the volumetric fraction of nanoparticles, shape and size of the nanomaterial's as revealed in [17]. Increased thermal conductivity of nanofluid in comparison to base fluid by suspending particles is shown in Table 1.

Table 1, Thermal conductivity of various solids and liquids.

Material	Specification	Thermal Conductivity (W/m-K)
Metallic Solids	Copper	401
	Aluminum	237
	Silver	429
Nonmetallic Solids	Silicon	148
	Alumina	40
	CNT	2000
Nonmetallic liquids	Water	0.613
	Ethylene Glycol	0.253

2.3 Thermal Conductivity

Theoretical study on nanofluids containing Al_2O_3, CuO and Cu particles were investigated [18]. The results showed 60% improvement in heat transfer is observed corresponding to the base fluid HE-200 oil/water, with 5% volume dispersion. Further investigations on CuO, Al_2O_3 suspension on water/ethylene glycol [19] showed 20% improvement in heat transfer with 4% volume dispersion. Similar results were observed in steady state parallel plate technique by Xuan and Li, where 12% enhancement in effective thermal conductivity is observed. Further researches showed 20% [20] and enhancement by various researchers [19-21]. Cu nano particles suspended with transformer oil and water was investigated by Eastman et.al and results showed promising results. SiC nano particles of 26nm are suspended on deionized water/ ethylene glycol (EG) was investigated using transient hot wire method by [22-24]. Fe based nanofluid was investigated [25], by dispersing Fe nano particles of 10nm in ethylene glycol. The results showed that Fe, SiC nanofluid is not promising compared to the base fluid even though Fe is a good thermal conductive material. The many investigators reported that agglomeration of particles plays a vital role in the study of thermal conductivity of the material. From the aforementioned discussion, we find that the existing experimental and numerical data from different research communities vary extensively, as shown in Table 2. In context to the above discussions, the international nanofluid property benchmark exercise (INPBE) also justified the thermal conductivity of the nanofluids based on the experimental and theoretical studies [26]. The major results reported are there is an enhancement of 5% to 10% of thermal conductivity of nanofluids based on the base fluid (water, PAO). Also it is reported that there is no significant improvement in the thermal conductivity compared to the conventional base fluid, which depends on particle size and base fluid thermal conductivity. From the above discussions, we summarized results for thermal conductivity enhancement with different nanofluids as shown in Appendix A.

2.4 Viscosity

Viscosity is another parameter under study for determining the characteristics of nanofluid. The SiO_2 nanofluid was investigated [27] and reported that nanofluid viscosity depends on the volume fraction. Another set of researchers [28] studied commercial engine coolants dispersed with alumina particles. They found that the nanofluid prepared with calculated amount of oleic acid (surfactant) was tested to be stable. While the pure base fluid displays Newtonian behaviour over the measured temperature, it transforms to a non-Newtonian fluid with addition of a small amount of alumina nanoparticles. From the above mentioned discussion, we come across that the existing data from different research groups vary widely, as shown in Appendix B.

2.5 Convective Heat Transfer

In the past decade, many research activities in the experimental heat transfer characteristics of various nanofluids have been studied on forced convective heat transfer behaviour in parallel channels and straight tube using an unspecified nanofluid. It is observed that reduction in thermal resistance by factor of two was studied by various researchers [29,30]. Experimental investigation [30] on Cu/water based nanofluids showed substantial enhancement of heat transfer and also reported that friction factor does not play any role in the application. Similarly Al_2O_3 based nanofluids were investigated by Wen et.al and found that addition of Al_2O_3 enhance the convective heat transfer coefficient. Another set of researchers [31] revealed that a systematic and definite deterioration of the natural convective heat transfer occurs for the forced convection which was dependent on the particle density, solution concentration and the aspect ratio of the cylinder. Experimental investigation on Al_2O_3 nanofluids using water as base fluid was studied by various research groups and they concluded that the heat transfer coefficient in laminar flow [32-35] increases up to 12 to 15% and in the case of turbulent flow its ranges upto 8% [36,37]. The other factors which influenced the heat transfer coefficient are concentration, particle size and particle migration [32-35]. In contrary to the above statement, another set of researchers reported that low concentration rate in nanofluid produce no or less effects in the increase in heat transfer coefficient rate by (INPBE). They reported that this contrary can be overcome by increasing the volume fraction. Apart from these factors, chaotic movement of the particles and particle interactions produce significant on the heat transfer coefficient. Similarly CNT, CuO, SiO and TiO_2 nanofluids using base fluid as water was investigated [38-40]. Among these, CNT nanofluid produced similar results to that of Al_2O_3 nanofluid. Ding et.al [41] reported that the enhancement of heat transfer can be achieved by varying the flow condition, concentration of the fluid. Alternatively CuO was experimented for various wall boundary conditions and it holds good result [42]. The increase in the concentration of the nanofluid on contrary produce very weak effect on the heat transfer coefficient for volume fraction greater than 0.3% [43]. The heat transfer coefficient enhancement can be achieved in the range of 2% to 5%.

3 History of Solar Energy

The solar industry started in the early 1920s and growth lasted until the mid-1950s when low-cost natural gas became the primary fuel for heating. Today, people use solar energy to heat buildings, heat water and to generate electricity. The spectral distribution is determined by the 6000K surface temperature of the Sun shown in (Sukhatme, 1999) Fig (a).

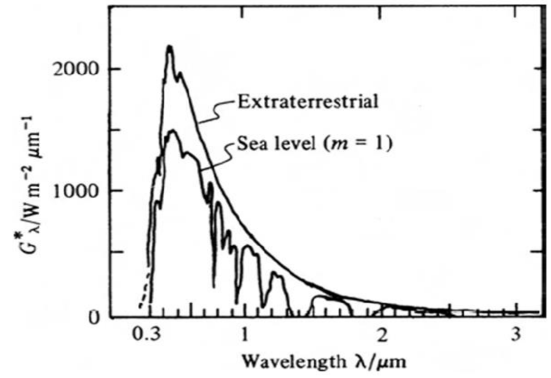
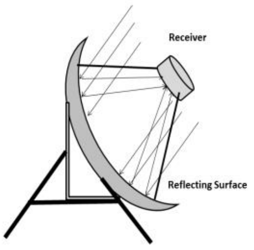


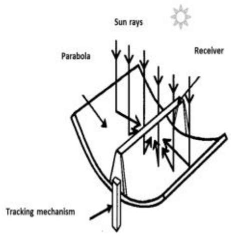
Fig (a) Spectral distributions of solar irradiance

This is an energy flux of very high thermodynamic quality, from an accessible source of temperature very much greater than from conventional engineering sources. The temperatures of the Earth's atmosphere, at about 230 K, and the Earth's surfaces, at about 260–300 K, remain in equilibrium at much less than the 6000K temperature of the Sun. Solar short wave radiation passes through the Earth's atmosphere, a complicated set of interactions occurs. The interactions which include absorption, the conversion of radiant energy to heat and the subsequent re-emission as long wave radiation: scattering, the wavelength dependent on change in direction, so that usually no extra absorption occurs and the radiation continues at the same frequency and reflection, which is independent of wavelength. From the natural heat flux, the solar collector allows sunlight through receiver glass tube before it strikes the absorber tube. The glass tube or plate traps most of the solar radiation inside collector using greenhouse effect. The Solar energy (sun) irradiance is about 63 MW/m^2. However, Sun–Earth geometry dramatically decreases the solar energy flow down to around 1 kW/m^2 on the Earth's surface. Nevertheless, under high solar flux, this disadvantage can be overcome by using dissimilar types of concentrating solar systems which transform solar energy into alternative form of solar thermal energy.

3.1 Classification of Solar Collectors

Solar radiation is converted into thermal energy in the focus of solar thermal concentrating systems. These systems are classified by their focus geometry as either point-focus concentrators (central receiver systems and parabolic dishes) or line-focus concentrators (parabolic-trough collectors (PTC) and linear Fresnel collectors). Most popular types of solar collectors are parabolic Dish, Parabolic Trough and Power Tower system. Firstly, the parabolic dish system Fig (b) uses a computer to track the sun and concentrate the sun's rays onto a receiver located at the focal point in front of the dish. Parabolic dish systems can reach 1000 °C at the receiver, and achieve the highest efficiencies for converting solar energy to electricity in the small-power capacity range. Secondly, the parabolic troughs concentrate sunlight onto a receiver tube that is positioned along the focal line of the trough Fig (c). Occasionally a transparent glass tube envelops the receiver tube to reduce heat loss. Parabolic troughs often use single-axis or dual-axis tracking system which permits temperatures at the receiver can reach 400 °C and produce steam for generating electricity. Thirdly, the heliostat uses a field of dual axis sun trackers that direct solar energy to a large absorber located on a tower Fig (d). A solar power tower has a field of large mirrors that follow the sun's path across the sky. The mirrors concentrate sunlight onto a receiver on top of a high tower and computer tracks the mirrors aligned consequently the reflected rays of the sun are always aimed at the receiver, where temperatures reach above 1000°C and produce high pressure steam for generating electricity. Finally, this categories of collectors were used which reduces heat losses and increases efficiency at high temperatures and thermal detoxification.





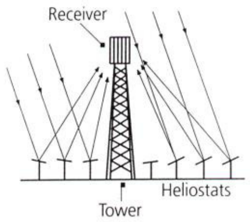


Fig (b) Parabolic Dish Collector, Fig (c) Parabolic Trough Collector, Fig (d) Power Tower System

3.2 Application of Nanofluids in Solar Collectors

For energy applications, two remarkable properties of nanofluids are utilized, one is the thermo-physical properties of nanofluids, enhancing the heat transfer and another is the application of nanofluids in solar collectors. The conventional direct absorption solar collector is a well-established technology, and it has been proposed for a variety of applications. However, the efficiency of these collectors is limited by the absorption properties of the working fluid. This technology has been combined with the emerging nanofluids technologies prepared by liquid-nanoparticle suspensions. The previous researchers review by Omid mahian et.al [44] gives a noble awareness about enhanced the efficiency and performance of the solar thermal system, solar water heater, thermal energy storage, solar cells and solar stills, there is a very limited number of research works in the area of solar collectors augmented with nanofluids. Basically, low temperature nanofluids based direct absorption solar collectors (DASC) were investigated theoretically by Tyagi et.al [45]. They studied Al_2O_3 water based nanofluids was used for the investigation where the particle volume fraction (0.1% to 5%) influenced the collectors efficiency. Significant increase in the collector's efficiency was observed not only varying the particles volume fraction, but also the glass cover transmissivity & collector height. It is reported, efficiency increases by 8% for volume fraction ranging from 0.8% to 1.6% and the effect of size of nano particles in increasing efficiency is marginal.

Taylor et.al [46] investigated experimentally, by using graphite/ therminol VP-1 nanofluids for 10-100MW solar power tower collectors and observed potential improvement in efficiency. Theoretically 10% in efficiency can be observed when compared with the conventional solar collectors, when using solar concentration ratio of 10-1000. Experimental results shown that 5-10% increase in efficiency can be achieved while using the nanofluids in the receiver section. The authors also estimated that $3.5 million/year more revenue can be attained by proper implementation.

Li et.al [47] carried out studies similar to Taylor et.al [46] by using three different nanofluids (Al_2O_3/water, ZnO/water & MgO/water) on the tubular solar collectors. The performance results showed that 95% of the incoming sunlight can be absorbed effectively while using the nanofluid of volume fraction less than 10 ppm. Efficiency of the flat plate solar collector was experimentally investigated by Yousefi et.al [48] using Al_2O_3 /water nanofluid with weight concentration of 0.2% & 0.4% and particle size of 15nm. The investigation was carried out with Triton X-100 as surfactant as well as without it. The results presented 28.3% increase in the efficiency is obtained with 0.2% weight fraction nanofluid. Additionally 15.63% increase in efficiency is observed by increasing mass flow rate and using the surfactant. The researchers further investigated MWCNT/water nanofluids in the flat plate solar collector with 0.2% weight fraction, pH of 3.5, 6.5 & 9.5 respectively and Triton X-100 as surfactant by [49]. The results revealed that the surfactant influences the efficiency and pH of isoelectric point enhances the efficiency of the collector. Finally, the review of all existing experimental and numerical data results for the prediction of the solar collector with different nanofluids is observed in Appendix C.

Khullar et.al [50] investigated aluminium based nanofluid both theoretically & experimentally on concentrating parabolic solar collector (CPSC). The aluminium based nano particles were suspended in Therminal VP-1 base fluid with 0.05% volume concentration. The results were compared with the conventional concentric parabolic solar collector which reveals that increase in 5-10% of thermal efficiency was observed.

Currently, Titan C.Paul,et.al [51] summarized their experimental investigation on next generation solar collectors (CSP) using NEILS (Nanoparticle Enhanced Ionic Liquids) as working fluids their results revealed that thermal conductivity was enhanced around 5% depending on the base fluid and ionic concentration. The heat capacity of nanofluid using Al_2O_3 nano particles was enhanced by 23% and 26% for nanofluids using silica nano particles and similarly 20% enhancement in convective heat transfer capacity was also observed.

Nanofluids (CNT, Graphite & Silver) based direct absorption solar collectors (DASC) were studied experimentally and numerically by Otanicar et.al [52], the effects of nanofluids on the efficiency improvement up to 5% were observed, using nanofluids as the absorption medium. The author compared the experimental data's with their respective numerical data. The results revealed that 3% efficiency increase can be achieved by using graphite nanoparticles of size 30nm, 5% efficiency increase can be achieved by using silver nanoparticles of size 20 to 40nm, where a 6% efficiency enhancement was observed when the particle size is halved. Also light heat conversion characteristics of two different nanofluids (TiO_2/water & CNT/water) were studied experimentally using vacuum tube solar collector in different weather patterns by He et.al [53]. The result shows excellent light heat conversion characteristics while using CNT/water nanofluids with 0.5% weight concentration. However, the temperature of CNT/water nanofluid is observed to be greater, which shows the CNT/water nanofluid is more suitable for vacuum tube solar collector application comparatively. Recent investigation on flat plate solar collectors using MWCNT nanofluids studied by M.Faizal, et.al [54]. The study is focused on reducing the size of flat plate solar collector when MWCNT nanofluid is used as working fluid. It is reported that 37% size reduction is possible by employing MWCNT as working fluid.

Remarks and Future Scope

Rising global population and living standards concerns over climate change, secure and safe low carbon energy supplies. Over the next 40 years, in order to sustain life and standards of living to which have grown accustomed, we must develop deep solutions for massivity scaling terawatts of affordable sustainable energy and develop means to reduce on CO_2 emissions. A pivotal future research should be determining the energy transport mechanism and green energy (solar thermal) in nanofluids. The solar thermal based engineering as well as many other industries has specific needs to increase heat transfer rates under a variety of constraints. Nanofluids have to satisfy many such needs and constraints. For solar thermal applications, the important features of nanofluids are the high transfer coefficients for liquids with high boiling points and medium pressures. Increased heat transfer rates in solar collectors could reduce the pumping power needs. However, ideal or even optimized nanofluids for solar thermal applications do not exist yet. The above review shows that the application of nanofluids in solar energy applications is still in its early stages so far, theoretical investigations have been reported on parabolic trough collectors; subsequently experimental studies can be performed. Practical implications of nanofluids are influenced by major factors such as production cost, synthesis methods, physical & chemical parameters. The evolvement of nanotechnology in future may overcome these factors.

This paper presents overview about nanofluid with solar collector applications, an existing emerging class of heat transfer fluid, in terms of barriers, future research and environmental challenges. Nanofluids are used to increase the performance of many thermal engineering systems. The use of nanofluids in the solar collectors may raise the effectiveness of the collectors using both experimental and theoretical investigations subjected to certain limitations. Experimental works encountered the major limitations, such as particle agglomeration, stability, erosion and corrosion of the heat transfer equipment's. Numerical simulations requires more exact models such as two phase mixture models need to be done for various solar collector applications. Based on the recent investigations, it was observed that the volume fraction and particle size plays a major role in determining the effectiveness [48]. Further the nanofluids concentration by weight percentage [48,53], volume percentage [48,50] and also pH [49] plays a vital role in the performance of the solar collector. Future studies are exposed widely on the application of nanofluids for high temperature applications and energy storage devices by having experimental and theoretical investigations. The nanofluids for any real applications can be made viable practically by undergoing study under different environment, geographical conditions testing its viscosity, fluid properties and thermo-physical properties on different thermal applications. Researchers on using the nanofluids on solar collector applications are at its fundamental level. Using the solar fuel with nanotechnologies in solar collector application have enormous potential in the future and is under global focus to attain clean and green energy.

LIST OF ABBREVIATION

CSP - Concentrating Solar Power
DASC - Direct Absorption Solar Collector
CNT - Carbon Nano Tube
SWCNT - Single Wall Carbon Nano Tube
DWCNT - Double -Walled Carbon Nano Tube
MWCNT - Multi Wall Carbon Nanotube
INPBE - International Nanofluid Property Benchmark Exercise
DASC - Direct Absorption Solar Collector
NCPSC - Nanofluid based Concentrating Parabolic Solar Collector
PAO - Poly-Alpha Olefins

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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Appendix A- Summarized results for thermal conductivity enhancement with different nanofluids.

Investigator / Year [Reference]	Nanofluids (Particle/Base fluid)	Particle Size	Volume (%) Concentration	Maximum Enhancement	Type of Study	Methodology
Masuda, et al.(1993)	$Al_2 O_3$- H_2O (46.85^{0}C)	13	1.30- 4.30	1.100-1.296	Experimental	Two Step Method
	$Si O_2$- H_2O (66.85^{0}C)	12	1.10- 2.40	1.005-1.007		
Ref [20]	$Ti O_2$- H_2O (86.85^{0}C)	27	3.10- 4.30	1.075-1.099		
Lee, et al. (1999)		38.4				
	$Al_2 O_3$- H_2O	23.6	1.00-4.30	1.03-1.10	Experimental	Two Step Method
Ref [4]	Cu O- H_2O	38.4	1.00-3.41	1.03-1.12		
	$Al_2 O_3$- EG	23.6	1.00-5.00	1.03-1.18		
	Cu O- EG		1.00-4.00	1.05-1.23		
Wang, et al. (1999)	$Al_2 O_3$- H_2O	28	3.00-5.50	1.11-1.16		
	$Al_2 O_3$- EG	28	5.00-8.00	1.25-1.41		Two Step Method
Ref [5]	$Al_2 O_3$- Engine oil	28	2.25-7.40	1.05-1.30	Experimental	
	Cu O- H_2O	23	4.50-9.70	1.17-1.34		
	Cu O- EG	23	6.20-14.80	1.24-1.54		
Xuan & Li (2000)	Cu (+laurate salt)- H_2O	100	2.50-7.50	1.22-1.75	Experimental	Two Step Method
Ref [7]	Cu (+oleic acid)- Transformer oil	100	2.50-7.50	1.12-1.43		
Choi, et al.(2001)	MWCNT(+dispersant)- Polyalphaolefin	25x50000	0.04-1.02	1.02-2.57	Experimental	Two Step Method
Ref [8]						
Eastman, et al.(2001)	Cu (old)- EG	<10	0.10-0.56	1.016-1.100	Experimental	One-step physical method
Ref [9]	Cu (Fresh)- EG	<10	0.11-0.56	1.031-1.140		
	Cu (+ Thiglycolic acid)- EG	<10	0.01-0.28	1.002-1.410		
Xie, et al. (2002) (a)						
	SiC- H_2O					
Ref [22]		26 (sphere)	0.78-4.18	1.03-1.17	Experimental	Two Step Method
	SiC- EG	26				
			0.89-3.50	1.04-1.13		

Xie, et al. (2002) (b)	Al_2O_3- H_2O	60.4	1.80-5.00	1.07-1.21		Two Step Method
					Experimental	Solid crystalline phase Effect
Ref [23]	Al_2O_3- EG	60.4	1.80-5.00	1.10-1.30		Morphology Effect
						pH value Effect
	Al_2O_3- pump oil	60.4	5.00	1.39		Base Fluid Effect
Xie, et al. (2002) (c)	Al_2O_3- H_2O	60.4	5.00	1.23		
	Al_2O_3- EG	60.4	5.00	1.29	Experimental	Two Step Method
Ref [24]	Al_2O_3- pump oil	60.4	5.00	1.38		Base Fluid Effect
	Al_2O_3- glycerol	60.4	5.00	1.27		
Das, et al. (2003) (a)	Al_2O_3- H_2O (36^{0}C)	38.4	1.00-4.00	1.07-1.16		
	Al_2O_3- H_2O (51^{0}C)	38.4	1.00-4.00	1.10-1.24	Experimental	Two Step Method
Ref [14]	Cu O- H_2O (36^{0}C)	28.6	1.00-4.00	1.22-1.26		Temperature Effect
	Cu O- H_2O (51^{0}C)	28.6	1.00-4.00	1.26-1.36		
Patel, et al. (2003)	Citrate reduced Ag- H_2O(30^{0}C)	60-70	0.001	1.030	Experimental	Two Step Method
	Citrate reduced Ag- H_2O(60^{0}C)	60-70	0.001	1.04		Temperature Effect
Ref [15]	Citrate reduced Au- H_2O(30^{0}C)	10-20	0.00026	1.05		
	Citrate reduced Au- H_2O(60^{0}C)	10-20	0.00026	1.05		
	Citrate covered Au- Toluene(60^{0}C)	3-4	0.011	1.09		
Xie, et al. (2003)		15x30000	0.40-1.00	1.03-1.07	Experimental	Two Step Method
	MWCNT- H_2O	15x30000	0.23-1.00	1.02-1.13		Nitric Acid Treatment
Ref [55]	MWCNT- EG	15x30000	0.25-1.00	1.04-1.20		
	MWCNT(+oleylamine)-decene					
Assael, et al.(2004)	MWCNT(+sodiumdodecyl sulfate)- H_2O	100x>				Two Step Method
		500000	0.60	1.07-1.38	Experimental	Treatment Effect
Ref [56]						Dispersant concentration Effect
						Sonication Time Effect

Wen & Ding (2004a,b)	Al_2O_3 (+sodium dodecylbenzene)- H_2O	42	0.19-1.59	1.01-1.10	Experimental	Two Step Method Temperature Effect
Ref [2,3]	MWCNT(+sodiumdodecyl Benzene)- H_2O (45^{0}C)	20-60 (diameter)	0.04-0.84	1.05-1.31		
Assael, et al.(2005)	DWCNT(+hexadecyltrimethyl ammonium bromide)- H_2O	5 (diameter)	0.75	1.03	Experimental	Two Step Method Dispersant Effect Sonication Time Effect
Ref [57]	MWCNT(+hexadecyltrimethyl ammonium bromide)- H_2O	130x>10000	0.60	1.34		
	MWCNT(+Nanosperse AQ)- H_2O	130x>10000	0.60	1.28		
Chon, et al.(2005)	Al_2O_3- H_2O (21^{0}C)	47	4.00	1.08	Experimental	Two Step Method Temperature Effect
	Al_2O_3- H_2O (71^{0}C)	47	4.00	1.29		
Ref [58]	Al_2O_3- H_2O (21^{0}C)	150	1.00	1.004		
	Al_2O_3- H_2O (71^{0}C)	150	1.00	1.09		
Hong, et al.(2005)	Fe- Ethylene glycol	10	0.20-0.55	1.13-1.18	Experimental	Two Step Method Sonication Time Effect
Ref [17]						
Liu, et al.(2005)	MWCNT- Ethylene glycol	20-50 (diameter)	0.20-1.00	1.02-1.12	Experimental	Two Step Method
Ref [59]	MWCNT(+N-hydroxysuccinimide)- engine oil	20-50 (diameter)	1.00-2.00	1.09-1.30		
	TiO_2(+cetyltrimethylammonium bromide)- H_2O	15 (Sphere)	0.50-5.00	1.05-1.30		
Murshed,et al.(2005)	TiO_2(+cetyltrimethylammonium bromide)- H_2O	10x40 Rod	0.50-5.00	1.08-1.33	Experimental	Two Step Method
Ref [60]						

Chopkar, et al.(2006) **Ref [61]**	Al_{70} Cu_{30}- Alloy-Ethylene glycol	20-40	0.19-2.50	1.05-2.25	Experimental	Two Step Method Crystallite size Effect
Hong, et al.(2006) **Ref [25]**	Fe- Ethylene glycol	10 (Cluster)	0.10-0.55	1.05-1.18	Experimental	Two Step Method Cluster size Effect
Kang, et al.(2006) **Ref [62]**	CuO- H_2O Si O_2- H_2O Diamond-Ethylene glycol	8-15 15-20 30-50	0.10-0.39 1.00-4.00 0.13-1.33	1.03-1.11 1.02-1.05 1.03-1.75	Experimental	Two Step Method
Lee, et al.(2006) **Ref [63]**	CuO- H_2O (pH=3) CuO- H_2O (pH=6)	25 25	0.03-0.30 0.03-0.30	1.04-1.12 1.02-1.07	Experimental	Two Step Method pH value Effect
Li & Peterson (2006) **Ref [64]**	Al_2 O_3- H_2O (27.5^0C) Al_2 O_3- H_2O (32.5^0C) CuO- H_2O (28.9^0C) CuO- H_2O (33.4^0C)	36 36 29 29	2.00-10.00 2.00-10.00 2.00-6.00 2.00-6.00	1.08-1.11 1.18-1.29 1.35-1.36 1.38-1.51	Experimental	Two Step Method Temperature Effect
Liu, et al. (2006) **Ref [65]**	CuO- H_2O CuO- H_2O CuO- H_2O CuO- H_2O	100-200 100-300 130-300 250 200x500	0.05 0.10 0.20 0.20 0.20	1.12 1.11 1.10 1.04 1.13	Experimental	One Step Chemical Method Settlement Time Effect
Yang, et al. (2006) **Ref [66]**	MWCNT(+polyisobutene succinimide)-polyalphaolefin		0.04-0.34	1.06-3.00	Experimental	Two Step Method Dispersing Energy Effect Aspect Ratio Effect Dispersant concentration Effect
Yang & Han (2006) **Ref [67]**	Bi_2 Te_3- Hexadecane oil(20^0C) Bi_2 Te_3- Hexadecane oil (20^0C) Bi_2 Te_3- perfluoro-n-hexane (3^0C) Bi_2 Te_3- perfluoro-n-hexane (50^0C)	20x170 20x170 20x170 20x170	0.8 0.8 0.8 0.8	1.06 1.04 1.08 1.06	Experimental	Two Step Method Surfactant

Appendix B - Summarized results for volume fraction dependent viscosity with different nanofluids.

Investigator / Year [Reference]	Nanofluids (Particle/Base fluid)	Particle Size	Volume (%) Concentration	Maximum Enhancement	Type of Study	Methodology
Masuda et al. Ref [68]	TiO_2- H_2O	27	1-4.3	11-60	Experimental	Two Step Method
Wang et al. Ref [69]	$Al_2 O_3$- DW	28	1-6	9-86	Experimental	Two Step Method
Wang et al. Ref [69]	$Al_2 O_3$- EG	28	1.2-3.5	7-39	Experimental	Two Step Method
Prasher et al. Ref [70]	$Al_2 O_3$- PG	27	0.5-3	7-29	Experimental	Two Step Method
Prasher et al. Ref [70]	$Al_2 O_3$- PG	40/50	0.5-3	6-36/5.5-24	Experimental	Two Step Method
He et al. Ref [71]	TiO_2- DW	95/145/210	0.024-1.18	4-11	Experimental	Two Step Method
Nguyen et al. Ref [72]	$Al_2 O_3$- H_2O	36	2.1-13	10-210	Experimental	Two Step Method
Nguyen et al. Ref [73]	$Al_2 O_3$- H_2O	47	1-13	12-430	Experimental	Two Step Method
Chevalier et al. Ref[74]	SiO_2- Ethanol	35	1.2-5	15-95	Experimental	Two Step Method
Chevalier et al. Ref[74]	SiO_2- Ethanol	94	1.4-7	12-85	Experimental	Two Step Method
Chevalier et al. Ref[74]	SiO_2- Ethanol	190	1-5.6	5-44	Experimental	Two Step Method
Chen et al. Ref [75,76]	TiO_2- EG	25	0.1-1.86	0.5-23	Experimental	Two Step Method
Murshed et al. Ref [77]	$Al_2 O_3$- DIW	80	1-5	4-82	Experimental	Two Step Method
Garg et al. Ref [78]	Cu-EG	200	0.4-2	5-24	Experimental	Single Step Method
Anoop et al. Ref [79]	$Al_2 O_3$- H_2O	45	2-8 wt%	1-6	Experimental	Two Step Method
Anoop et al. Ref [79]	$Al_2 O_3$- H_2O	150	2-8 wt%	1-3	Experimental	Two Step Method
Anoop et al. Ref [79]	$Al_2 O_3$- H_2O	95	0.5-6	3-77	Experimental	Two Step Method
Anoop et al. Ref [80]	$Al_2 O_3$- H_2O	100	0.5-6	3-57	Experimental	Two Step Method
Anoop et al. Ref [80]	$Al_2 O_3$- EG	100	0.5-6	5.5-30	Experimental	Two Step Method
Anoop et al. Ref [80]	Cu- EG	152	0.5-6	8-32	Experimental	Two Step Method
Chen et al. Ref [76,81]	TNT- EG	~10,L=100	0.1-1.86	3.3-70.96	Experimental	Two Step Method
Chen et al. Ref [75,81]	TNT- H_2O	~10,L=100	0.12-0.6	3.5-82	Experimental	Two Step Method
Chandrasekar et al.	$Al_2 O_3$- H_2O	43	1-5	14-136	Experimental	Two Step Method
Ref [82]	$Al_2 O_3$- Car Engine coolant	<50	0.1-1.5	4-136	Experimental	Two Step Method
Kole & Dey. Ref [83]	$CaCO_3$ -DW	20-50	0.12-4.11	1-69	Experimental	Two Step Method
Zhu et al. Ref [84]						
Lee et al. Ref [85]	SiC-DW	<100	0.001-3	1-102	Experimental	Two Step Method

Appendix C - Summarized results for solar collector enhancement with different nanofluids.

Investigator / Year	Type of Collector	Nanofluids (Particle/Base fluid)	Particle Size	Type of Study	Remarks
Yousefi et.al .(2012) Ref [48]	Flate plate	$Al_2 O_3$ / H_2O Triton X-100 is used as surfactant	15nm	Experimental	Efficiency of the collector with 0.2% (wt) nanofluids is higher than that with water by 28.3%. Surfactant leads to a 15.63% enhancement of the efficiency.
Yousefi et.al .(2012) Ref [49]	Flate plate	MWCNT / H_2O Triton X-100 is used as surfactant	10-30nm	Experimental	Efficiency of the collector increases extremely with 0.4% (wt) nanofluids, whereas with 0.2 % (wt) the efficiency decreases compared to water. Surfactant leads to enhancement the efficiency of collector.
Taylor et.al.(2011) Ref [86]	Direct Absorption	Graphite/ H_2O & VPI, $Al_2 O_3$ / H_2O & VPI, Cu / H_2O & VPI, Gold , Silver/VPI	5nm	Theoretical Experimental	Around 95% of incoming sunlight can be absorbed for nanofluid thickness ≥ 10 and nanoparticles volume fractions less than $1x10^{-5}$
Taylor et.al (2011) Ref [46]	Concentrating direct Absorption	Graphite/ H_2O & VPI, $Al_2 O_3$ / H_2O & VPI, Cu / H_2O & VPI, Gold , Silver/VPI	5-10nm 10-100nm	Theoretical Experimental	Efficiency increases up to 10% by using a Nanofluid in the receiver.
Otanicar et.al (2010) Ref [52]	Non-Concentrating direct absorption	Graphite/ H_2O & Silver / water & CNT / water 1000-5000 nm length	30nm 20nm	Theoretical Experimental	Efficiency considerably increases for volume fractions less than 0.5%, Efficiency increases by 6% with decreasing size of particle in silver/ water nanofluid.
Li et.al (2011) Ref [47]	Tubular	$Al_2 O_3$ / H_2O & ZnO/ H_2O& MgO/ H_2O	<20nm	Experimental	ZnO / water nanofluid with 0.2% volume concentration is the best selection for the collector.
Khullar and Tyagi (2012) Ref [50]	Concentrating direct absorption	Aluminum / water	<20nm	Theoretical	Using this type of collector leads to fewer CO_2 emissions by $2.2x10^3$ Kg in 1 Year.
Tyagi et al. (2009) Ref [45]	Non-Concentrating Direct Absorption	Aluminum / water	(0-20nm)	Theoretical	Efficiency extremely increases for volume fraction less than 2% and Efficiency increases slightly using an increase in the size of nano particles.
Faizal et.al (2013) Ref [54]	Flate Plate	MWCNT / Absorbing medium and used as surfactant	0.2 wt% and 0.4 wt%	Experimental	Flat plate solar collector when MWCNT nanofluid is used as working fluid. It is reported that 37% size reduction is possible by employing MWCNT as working fluid.