

Carbon-based Nanofluid Applications in Solar Thermal Energy

Nur Çobanoğlu¹, Ziya Haktan Karadeniz², and Alpaslan Turgut^{3,*}

¹Izmir Katip Çelebi University, Graduate School of Natural and Applied Science, Çiğli, İzmir, Turkey

²Izmir Katip Çelebi University, Department of Mechanical Engineering, Çiğli, İzmir, Turkey

³Dokuz Eylül University, Department of Mechanical Engineering, Buca, İzmir, Turkey

Abstract. Renewable energy sources such as solar, wind and geothermal are proposed as an alternative to fossil fuels whose excessive use causes global warming. The most popular one of the renewable energy sources is considered as solar energy due to the fact that required energy is provided by the sun entire year around the world. Solar energy systems convert the solar radiation to the useful heat or electricity. In order to achieve better performance in solar thermal systems many studies have been conducted. Some of these studies suggest that heat transfer fluid could be changed with the nanofluids which can be defined as new generation heat transfer fluid. Nanofluids are suspensions of nano-sized particles such as metals, metal-oxides, and Carbon-allotropes (C), in the conventional base-fluids (water, ethylene glycol and oil). Using nanofluid enhances the efficiency and thermal performance of solar systems due to their better thermophysical and optical properties. Recently, C-based nanofluids are getting attention due to their enhanced thermal conductivity and absorptivity at even low concentrations. The results show that C-based nanofluids have a potential to use in solar energy systems: solar collectors, solar stills, photovoltaic/thermal systems.

1 Introduction

After industrial revolution with the increase in energy demand, availability of the fossil fuels is decreasing gradually. Because of sharp increase in prices of fossil fuels and their harmful effects to environment, renewable energy sources, especially solar energy, is getting more attention compared to past years. Solar energy is the most popular one among renewable energy sources. It provides the required energy by the sun entire year around the world by conversion of solar radiation to useful heat or electricity. In order to obtain better performance with solar thermal systems, many studies have been conducted both experimentally and numerically. Some studies suggest that changing working fluid could improve the efficiency.

Nanofluids are determined as new type of heat transfer fluids and can be used as working fluid in thermal systems. The term of nanofluid was introduced for the first time by Choi [1]. Nanofluid is a suspension of nanosized particles (metals, metal oxides, carbon etc.) in a conventional base-fluid (water, oil, ethylene glycol). Addition of nanoparticles into base-fluid increases the thermal conductivity and viscosity of the nanoparticles. It has been reported that the improvement in thermal performance and efficiency of the system is related to enhanced thermal conductivity. Therefore there is an increasing attention on nanofluid topic. Comparison of the normalized numbers of publications in the fields of “nanofluid” and “heat transfer” is presented in Fig.1. 2016 values which are 2377 for the keyword “nanofluid” and 12293 for “heat transfer” are used for normalization. It can be said that nanofluids are getting popular as heat

transfer fluids by exponential increase of publications about them.

With the addition of nanoparticles, transmittance of the heat transfer fluid decreases and the sun light is absorbed by the nanoparticles.

Therefore, nanofluids are used in solar thermal applications due to their better optical properties and enhanced thermal conductivity. Recently, the nanofluids which are used as a heat transfer fluid in solar energy systems are called as solar nanofluids. The enhancement of utilization of nanofluids in solar applications is presented in Fig.2. by normalization of the keywords of “nanofluid” and “solar” in “nanofluid” for 2016 data.

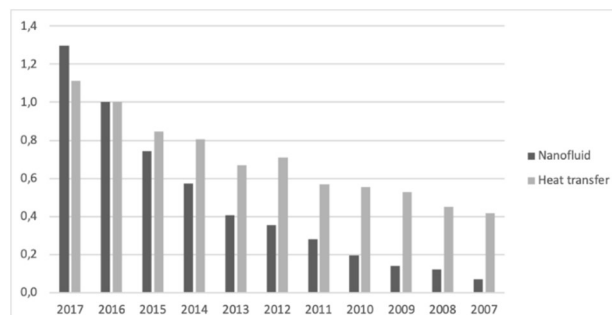


Fig. 1. Normalized numbers of publications in fields of nanofluid and heat transfer. Normalization is carried out with values of 2016. Data taken at 29.11.2018 from ISI WEB of KNOWLEDGE.

In solar thermal systems the solar energy is directly converted to the useful heat. It has been reported that nanofluids in solar thermal systems improves the

* Corresponding author: alpaslan.turgut@deu.edu.tr

efficiency of the system. The reason behind this enhancement is explained by the ability of nanoparticles on direct absorption of the sun light [2]. Utilization of nanofluids allow to use a volumetric receiver instead of a selective surface which has a narrower temperature profile and thus higher emissive losses. The particles can be selected with respect to their optical properties. This allows to design the systems with working fluid which has high absorption in the solar range and low emittance in the infrared. Absorptivity is affected by the size, type and concentrations of the nanoparticles for desired conditions. Size and concentration of the nanoparticles affects the uniformity and efficiency of receiver temperature. Moreover, receiver performance is improved by the enhanced heat transfer due to the better thermal conductivity compared to conventional base-fluids.

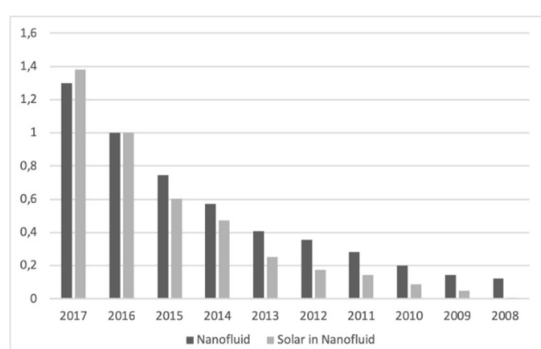


Fig. 2. Normalized numbers of publications in fields of nanofluid and solar in nanofluid. Normalization is carried out with values of 2016. Data taken at 29.11.2018 from ISI WEB of KNOWLEDGE.

Recent studies show that nanofluids have a potential to be used in solar energy systems such as solar collectors, solar stills, photovoltaic/thermal systems and thermal energy storage systems. Verma and Tiwari [3] have been reported that using nanofluids as a heat transfer fluid in solar thermal system (solar collectors, photovoltaic systems, solar thermoelectric and energy storage system) could be better solution to enhance efficiency. Shamshirgaran et al. [4] mentioned that definition of the key parameters such as nanoparticles size, concentration, shape and dispersion technology for the optimization of the solar thermal energy storage is important. Das et al. [5] reported that using nanofluids as a optical filter could contribute the evolution of solar PV modules which works in higher ambient temperatures and receives higher solar irradiance. Mahian et al. [6] reviewed the nanofluid based solar thermal systems. Nanofluid utilization in collectors increases the efficiency and performance and reduces the CO₂ emission. This paper overviews the potential applications of carbon-based nanofluids in solar thermal systems.

2 Carbon-based Nanofluids in Solar Thermal Systems

Among all types of nanoparticles, carbon nanoparticles are preferred to use in solar thermal applications and increase the overall efficiency due to their superior

thermal conductivity and absorptivity compared to others at even low concentrations. Hordy et al. [7] showed that denatured alcohol based functionalized MWCNTs could absorb almost 100% of incident solar light and exhibit excellent stability upon multiple cycles of boiling and condensation. Karami et al. [8] conducted experiments on thermophysical and optical properties of low-temperature direct absorption solar collectors. Seven different concentrations (0, 5, 10, 25, 50, 100 and 150 ppm) of water based functionalized MWCNT (10 nm diameter and 5-10 μ m) nanofluids used. At even low concentrations, light extinction level was improved compared to water. Thermal conductivity was also increased with the concentration and temperature and they reported 32% enhancement compared to water. Meng et al. [9] studied with ethylene glycol based CNT nanofluid. Strong optical absorption spectra ranged between 200-2500 nm. Moreover, insignificant increase in viscosity and 18% enhancement in photo thermal conversion efficiency was obtained for 0.5 wt.% nanofluid at room temperature. At 55°C, reduction in viscosity and 24.5% higher thermal conductivity was observed for 4.0 wt.%. Moreover, optical properties of carbon nanohorn based nanofluids have been studied [10–12]. It has been reported that carbon nanohorn based nanofluids have promising optical properties and enhanced thermal conductivity compared to base-fluid. With both these enhancements and chemical functionalization, new kind of nanofluids could be very promising to increase the overall efficiency of the solar device. Han et al. [13] studied with the carbon black nanofluid and reported that they had possibility to enhance solar absorption efficiency due to their good absorption ability. Significant enhancement in thermal conductivity could not be achieved due to the surface functionalization of carbon black particles and nanofluid exhibited surface thinning behavior. Ahmad et al. [14] reviewed the optical properties of various nanofluids (metals, metal oxides, carbon etc.) used in solar collector. Optical solar absorption increases with the size and the concentration of nanoparticles. However, they mentioned that some studies reported insignificant effect of particle size on absorption. Path length also have significant effect on optical absorption. Transmittance of nanofluids is indirectly related to volumetric concentration, size and path length. Light scattering is affected by concentration and size of metallic nanoparticles. Using nanofluid also increases the overall extinction coefficient.

2.1 Solar Collectors

Nanofluids have been used widely in solar collectors among the solar thermal systems. Absorbed solar energy is collected and converted to the heat by solar collectors, and the heat is transferred to the collector fluid which is in contact with the collector. There are many numerical and experimental studies on efficiency of nanofluids in the different types of solar collectors. In the literature, there are some reviews on nanofluid based solar collectors. Chamsa-ard et al. [15] reviewed the nanofluid types, synthesis, properties and applications in direct solar thermal collectors. They concluded that the stability and

thermal conductivity are important performance parameters for solar collectors. Raj and Subudhi [16] reviewed the flat-plate and direct absorption solar collectors using nanofluids to identify optimum working conditions and affecting parameters (surfactant, collector area, particle type, particle size and base-fluid). They have concluded that long-term stability of nanofluid and nanoparticle dispersion affects sunlight absorption and the solar collector efficiency. Solar collector efficiency increases with the increase in volumetric fraction at first, but then increase in viscosity due to the increase in concentration results in reduction in collector efficiency. Effective particle size, surfactant addition and suitable selection of pH affects the solar collector efficiency in positive way. Moreover, they reported that the main reason behind enhancement of collector efficiency was abnormal increment in thermal conductivity of nanofluid. Solar collectors using CNT or carbon nanohorn based nanofluids have highest efficiencies. At higher temperature, higher collector efficiency was found compared to water. Gorji and Ranjbar [17] presented a review study on optical properties and applications of nanofluids in direct absorption solar collectors. They reported that choosing nanofluid concentration has crucial importance to obtain maximum performance. Kim et al. [18] reviewed the performance of various nanofluids in evacuated tube solar collectors and showed that utilization of nanofluid increased the performance. Leong et al. [19] also reviewed the nanofluid based solar collectors. They concluded that direct absorption solar collectors and flat plates were studied more and concentrating solar collector was given less attention among the studies. The literature consists more review studies on solar collectors working with nanofluids [20], [21].

Said et al. [22] compared effects of different nanofluids (SWCNT, Al_2O_3 , SiO_2 and TiO_2) on performance of flat plate solar collector; and they found reduction of 4.34% in entropy generation and enhancement of 15.33% in heat transfer coefficient for SWCNT based nanofluid. Moreover, Said et al. [23] studied with SWCNT-water nanofluid with SDS surfactant in same type collector. The enhancement of thermal conductivity of 0.3 vol.% nanofluid was 91%. For 0.3 vol.% nanofluid at 0.5 kg/min mass flow rate, energy and exergy efficiency was found as 95.12% and 26.25%, respectively. Contrary to enhancement of efficiency with utilization of nanofluids Yousefi et al. [24] reported a reduction with water based MWCNT nanofluid (0.2 & 0.4 wt.%). However, using surfactant in nanofluid increased the efficiency. Moreover, they [25] reported that change in difference between pH of nanofluid and p*H* of isoelectric point affected the collector efficiency in positive way. Verma et al. [26] studied with water based MWCNT, graphene, CuO , Al_2O_3 , TiO_2 , and SiO_2 nanofluids and they presented the enhancements in the efficiencies as 23.47%, 16.97%, 12.64%, 8.28%, 5.09% and 4.08%, respectively.

Evacuated tube solar collectors have higher efficiency, ease of installation and transportation as well as considerably lower cost and heat losses compared to conventional flat plate solar collectors [27]. Tong et al. [28] used water-based MWCNT nanofluid (1 vol.%) in

custom-designed enclosed type evacuated U-tube solar collector and found 4% of increase in efficiency compared water. Moreover, Sabiha et al. [29] studied water based SWCNT in evacuated tube solar collector. They evaluated the performance of solar collector at different concentrations (0, 0.05, 0.1 and 0.2 vol.%) and at different flow rates (0.008 to 0.025 kg/s). Increase in mass flow rate and concentration improves the efficiency. Maximum efficiency was found as 93.43% (at 0.2 vol.% and 0.025 kg/s) which is 71.84% higher compared to water. Moreover, in terms of weather conditions, efficiency was found higher for 0.2 vol.% nanofluid at cloudy days compared to water in sunny days. Mahbubul et al. [30] found approximately 10% enhancement in efficiency by using 0.2 vol.% water based SWCNT nanofluid.

Ladjevardi et al. [31] reported that volumetric solar collector could absorb 50% of incident light with water-based graphite nanofluid (0.000025 vol.%) while only water can absorb 27%. And the thermal efficiency of the system was 88% higher when nanofluid was used.

Moreover, Kaseian et al. [32] used oil based MWCNT nanofluid (0.2 and 0.3 vol.%) in concentrating parabolic solar collector and they reported that 4-5% and 5-7% enhancement in collector efficiency compared to water for 0.2 and 0.3 vol.%, respectively. He et al. [33] studied to light-heat conversion with water based TiO_2 and CNT nanofluid in vacuum tube solar collector under two different weather conditions. It was reported that CNT nanofluid was suitable for vacuum tube solar collectors due to its better performance.

Loni et al. [34] used thermal oil based MWCNT nanofluid and reported that up to 13% enhancement in thermal efficiency of solar dish collector with a cavity receiver. Mwesigye et al. [35] found 4.4% enhancement in thermal efficiency therminol-VP1 based SWCNT nanofluid as a working fluid in parabolic trough collector. Bortolato et al. [36] have used water based single wall carbon nanohorn in direct absorption parabolic trough solar collector. After 8 hours later, the efficiency decreased from 87% to 69% due to the aggregation of nanoparticles. There was no significant difference between results of initial performance of nanofluid based volumetric receiver and surface receiver working with water.

Luo et al. [37] studied with solar collector based on direct absorption collection and with the various types of oil-based nanofluids: graphite, CNT, SiO_2 , Al_2O_3 , TiO_2 and Cu. And maximum photothermal efficiency was obtained as 122.7% with 0.01 vol.% graphite nanofluid.

Different from the conventional base-fluids, carbon nanomaterials were added into ionic liquids for investigation of suitability in solar thermal applications. Graphite nanoparticles, SWCNT and graphene was suspended into [BMIM] BF_4 ionic fluid by Zhang et al. [38]. Maximum photothermal efficiency was observed with 0.01 graphene nanofluid as 26.6% where as it was 18.2% for ionic fluid. Photothermal efficiencies of nanofluids ranged between 21.3% to 26.6%. They concluded that these nanofluids showed great potential to be used as heat transfer fluids in solar thermal applications.

Ahlatli et al. [39] investigated the influence of utilizing a water-based CNT nanofluid (0.01, 0.05, 0.1, 0.5 wt.%) in solar micro-channel collector. They observed enhancement in heat transfer coefficient 19.5% for 0.05 wt.% nanofluid and 25% for 0.5 wt.% nanofluid. Moreover, they reported that efficiency could be increased by using quartz instead of glass and high concentrated nanofluids have better performance when quartz was used at the top surface of the heat exchanger. Otanicar et al. [40] investigated the performance of micro scale direct absorptive solar collector working with water based silver, CNT and graphite nanofluids. The efficiencies were found as 57.5%, 50.5%, 55.5% and 54% for Ag nanofluids (0.25 vol.%) which had 20 and 40 nm particle diameter, graphite (0.5 vol.%) and (0.5 vol.%), respectively. For water, efficiency was 32.5%. Kullar et al. [41] studied the comparison of volumetric absorber system with surface absorption system employing TiNOX copper coated substrate under similar conditions by using ethylene glycol based amorphous carbon and water based MWCNT nanofluids. They found that volumetric absorption system have higher optical and photothermal conversion efficiency. MWCNT nanofluid had higher stagnation point compared to amorphous carbon nanofluid. Performance of the volumetric system was dependent on the concentration and optimum concentration for highest stagnation temperature must be chosen carefully. Delfani et al. used water/ethylene glycol (70:30 in volume) based MWCNT nanofluid in direct absorption solar collector and collector efficiency was increased 10-29% with increase in concentration compared to base-fluid. Gorji and Ranjbar [42] studied with water based graphite, Ag and Fe₂O₃ nanofluid in same type collector and found that all nanofluids have higher efficiency compared to base-fluid and maximum enhancement was observed for magnetite nanofluid. Dugaria et al. [43] studied numerically with water based single wall carbon nanohorn in direct absorption solar receiver. They found optical efficiency as 90.6% and higher than receiver with selective surface and aluminum receiver.

As an alternative to conventional solar thermal receivers, high-flux direct absorption solar collectors have been used. Heat transfer oils, molten salts and liquid metals have been used as heat transfer fluids. Taylor et al. [2] used Therminol VP-1 based graphite nanofluid (0.125 and 0.25 vol.%) in laboratory scale nanofluid dish receiver. Though 0.125 vol.% nanofluid exhibited 11% improvement in steady-state efficiency, 0.25 vol.% did not enhance the efficiency. Moreover, system was compared to Abengoa PS10 power tower, and graphite nanofluid with volume fractions equals to 0.001% or less were suitable due to their higher absorption and stability. In addition, Veeraragavan et al. [44] studied with the Therminol VP-1 based graphite nanofluid and found the maximum efficiency as 35% in volumetric collector at 1 cm deep channel with solar concentration of 10. Liu et al. [45] used ionic liquid ([HMIM]BF₄) based graphene nanofluid and they found that receiver efficiency decreased with the increase of graphene concentration. They concluded that they brought a new perspective to direct absorption solar collector working with ionic liquid

based graphene nanofluid. However, Li et al. [46] used water and Therminol as a base-fluid and MWCNTs as nanoparticles in nanofluid. Results of numerical study showed that surface absorber had 2 times higher efficiency compared to nanofluid-based absorber.

2.2 PV/T Systems

The second-most popular application of nanofluids in solar thermal systems can be considered as PV/T systems. PV/T systems convert the solar energy both thermal (by solar collector system) and electrical energy (by photovoltaic system). Yazdanifard and Ameri [47] reviewed the exergetic advancements of PV/T systems and mentioned the utilization of nanofluids. They reported that increase of nanoparticle concentration in the base-fluid increases the exergy efficiency of PV/T systems. Moreover, Said et al. [48] reviewed the performance and environmental effects of conventional and nanofluid based PV/T systems and they concluded that PV/T systems working with nanofluids had higher overall exergy and energy efficiency compared to conventional ones.

Nasrin et al. [49] conducted numerical and experimental study on water based MWCNT based cooling system of PV/T. They reported 89.2% and 87.65% of overall efficiency for 1000 W/m² in numerical and experimental results, respectively. Hjerrild et al. [50] investigated the enhancement in optical efficiency by using hybrid nanofluid (Ag nanodisc core in SiO₂ thin shell and MWCNTs). Addition of CNT causes reduction in electrical efficiency but significant enhancement in absorption. Hassani et al. [51] reported environmental and exergy analysis of nanofluid based hybrid PV/T systems by using different configurations. They observed approximately 1.3 MW h/m² of exergy annually with the smaller exergy payback time of 3 years when water based Ag nanofluid and CNT nanofluid were used as optical filter and coolant, respectively. Although, this configuration was the most pollutant because of the manufacturing, it may prevent emissions of about 448 kg CO₂ eq m⁻² yr⁻¹.

2.3 Solar Stills

Solar stills are mostly used in the distillation of impure water like brackish or saline water. The impure water is evaporated by heat due to the solar energy. Evaporated water goes up to cold glass ceiling and water droplets are formed. Since ceiling is angled the droplets go down to second through and collected. Because of the slow distillation process, various types of solar stills have been developed: solar stills with the dye in the basin, concentrator assisted solar still, tubular solar stills, spherical solar stills, etc. [52]. Arunkumar et al. [52] reviewed the nanofluid based solar stills in terms of system productivity and enhancement. They concluded that using nanofluid increases the productivity (produced pure water mass per area, kg/m²) as well as system thermal efficiency. Moreover, the distilled water productivity increases with the increase in concentration

and then at high concentrations productivity starts to reduce. Moreover Jani and Modi [53] and Bait and Si-Ameur [54] also published a review study on nanofluid based solar stills [53]. Gnanadeson et al. [55] studied with the water based MWCNT nanofluid in the modified vacuum solar still and reported that utilization of nanofluid increased evaporation rate and hence condensation rate on the cooler surface. Moreover, Gnanadeson et al. [56] investigated the new ways to improve efficiency of single basin solar still. Utilization of aluminium sheets, providing the insulation and painting the inside bottom of the solar still as black increased the efficiency as 55%, 20% and 15%, respectively. Efficiency was improved by 60% with using water based MWCNT nanofluid. Chen et al. [57] used water based magnetic MWCNT nanofluid ($\text{Fe}_2\text{O}_3/\text{MWCNT}$). The absorption band of nanofluid was broader than water and with the increase in concentration, more solar energy was harvested. Nanofluids at all concentrations could absorb almost 100% of solar energy when thickness was 4 cm. However, water could absorb almost 80% of solar energy when its thickness was 10 cm. Evaporation rate increased with the concentration (0-0.04 wt.%) from 24.91% to 76.65%.

3 Challenges of nanofluids

Although, nanofluids have better thermophysical and optical properties compared to base-fluid, the stability is the most important challenge of nanofluids for commercialization. Both reasons of instability and the ways to improve stability have been studied by different groups [57–60]. Instabilities in the nanofluid also causes inaccurate values for thermophysical properties. Generally, in order to improve stability, surfactants are used. But surfactants also affect the thermo-physical properties and heat transfer performance of the systems. For example, utilization of surfactant decreases the thermal conductivity and surface tension of the working fluid.

Moreover, with the addition of nanoparticles into base-fluid, viscosity increases. Increase in viscosity requires higher pump powers and results in reduction in efficiency and performance of the system. It can be said that utilization of nanofluids have more significant advantage in passive systems.

And C-based nanofluids have higher increment in performance of the systems compared to metals and metal-oxides. However, their high cost can be considered as the limitation.

4 Conclusions

Literature includes many studies on utilization of nanofluids in solar thermal applications. Among all type of nanofluids, C-based nanofluids generally have higher enhancement in efficiency in the system due to their excellent optical properties and enhanced thermal conductivity at even lower concentrations. Increase in concentration results in instabilities in the nanofluid which is considered as the biggest challenge. Therefore,

using C-based nanofluids at lower concentrations could give better performance compared to base-fluid or other type of nanofluids at higher concentrations.

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