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Photothermal Convergence Performance of Mono and Hybrid Nanofluids in Solar Systems

Roy J. Issa
West Texas A&M University
Canyon, Texas, USA
rissa@wtamu.edu

Abstract - The global warming associated with fossil fuels have placed a concerted effort on exploiting other forms of energy resources that are sustainable, environmentally friendly, and abundantly available. Solar energy can be easily harvested and primarily converted into electrical and thermal energy forms. The efficient harvesting of direct solar energy is a key element in maximizing the utilization of solar energy. As working fluids, nanofluids are shown to exhibit outstanding photothermal conversion in the harvesting of direct solar energy. The paper explores experimental data from various research studies conducted on the photothermal conversion of nanofluids in direct absorption solar systems, and presents a comparison in the performance of mono and hybrid nanofluids. Hybrid nanofluids are shown to exhibit much greater thermal performance than mono nanofluids due to their synergistic thermal properties. Certain hybrid nanoparticles are shown to manifest captivating results for their photothermal conversion efficiency enhancements.

***Keywords*:** Mono Nanofluids, Hybrid Nanofluids, Photothermal Conversion Efficiency, Optical Absorption

1. Introduction

Over the past decade, a concerted effort has been made to utilize nanofluids in thermal systems for their enhancement of the thermal performance of the systems while reducing the operating costs. Altering the thermophysical properties of the original base fluid by adding dispersed nanoparticles has been shown to tremendously enhance the convective heat transfer capability of the bulk fluid, while a slight enhancement is seen in the bulk fluid thermal conductivity. In addition to their enhanced heat transfer capability, certain types of nanofluids also exhibit outstanding photothermal conversion performance in harvesting direct solar energy. The purpose of this paper is to perform a review of the photothermal conversion enhancement of mono and hybrid nanofluids, and compare the capability of the two kinds of nanofluids as function of the nanoparticles concentration.

2. Parameters Influencing Photothermal Conversion Process

Photoexcitation is the mechanism that drives photothermal energy conversion process resulting in buildup of heat by the material. Based on light absorption range, the photothermal energy conversion process is classified as either plasmonic localized heating, non-radiative relaxation in semiconductors, or thermal vibration in molecules [1]. Plasmonic localized heating occurs when metallic nanoparticles are irradiated at their resonance wavelength causing oscillation of the electron gas that leads to a rapid increase in the localized temperature. When semiconducting materials are irradiated, excited electrons generate energy similar to the bandgap, where the energy is released either in the form of photons or phonons (heat). For the case of thermal vibration in molecules, organic materials convert the absorbed solar energy to lattice vibration.

When a nanofluid is irradiated, the presence of the nanoparticles reduces the transmittance of the photons due to the absorption and scattering of the photons by the nanoparticles (Fig. 1) [2]. Transmittance decreases with the increase in nanofluid concentration while optical absorption of the nanoparticles increases. Compared to the base fluid, the optical absorption wavelength range of the nanofluid is much wider than that of the base fluid [2]. This results in the nanofluids exhibiting much higher optical absorption and photothermal conversion efficiency than the base fluid. Optical transmittance, T(λ), is calculated from Beer-Lambert law [3]:

$$T(\lambda) = e^{-K_\lambda d} \tag{1}$$

where K_λ is the extinction coefficient and d is the penetration distance in the fluid. Optical transmittance can also be related to the light radiation power before, P_o, and after the absorption, P:

$$T(\lambda) = P/P_o \tag{2}$$

The absorption, $\alpha(\lambda)$, can then be calculates as [2]:

$$\alpha(\lambda) = LOG_{10}[1/T(\lambda)] \tag{3}$$

Several important factors affect the photothermal energy conversion process such as the bulk fluid color, particles morphology, nanoparticles size and concentration in the base fluid. Studies show photon scatter increases with the increase in nanoparticle size but declines as particles starts aggregating [2]. Optical absorption is seen to be higher in darker than light-colored fluids. In addition, absorption fraction is seen to be dependent on both the light penetration distance in the fluid and on the nanoparticles concentration [4]. Nanoparticles with asymmetric structures, elongated (nanorods), and structures with sharp tips tend to exhibit a noticeable increase in their photothermal conversion efficiency due to the significantly enhanced electromagnetic fields caused by the increase of the plasmonic localized heat generation at the sharp tips and edges [5].

Optical absorption is seen to be enhanced by nanofluids that are formed from hybrid nanoparticles possessing either complementary or synergetic optical properties that lead to an increase in photon scatter. Hybrid nanofluids with enhanced photothermal conversion include bimetallic, metal-organic materials and metal-semiconductor materials.

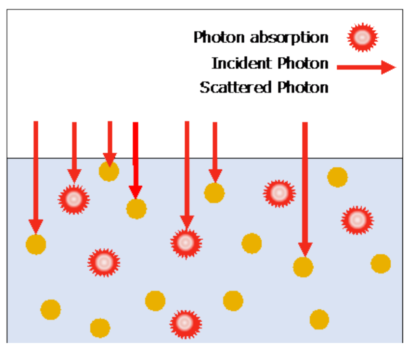

Fig. 1: Light scattering and absorption (Adapted from [2]).

3. Photothermal Conversion Performance of Mono and Hybrid Nanofluids

The majority of the research performed on nanofluids has been associated with a single nanoparticle type. However, recent studies [6-32] have shown tremendous improvement in the performance of thermal systems with the use of hybrid nanofluids, dispersion of two types of nanoparticles in a base fluid. Such systems include photovoltaic thermal systems, flat plate solar collectors, direct absorption solar collectors, and evacuated tubes solar collectors. Figure 3 shows a comparison in the photothermal conversion efficiency between mono and hybrid nanofluids, and Table 1 presents the details of various studies. The photothermal conversion efficiency, η, is calculated as:

$$\eta = \frac{(c_b m_b + c_n m_n)\Delta T}{GA\Delta t} \tag{4}$$

where c_b and c_n are the specific heat of the base fluid and nanoparticles respectively, m_b and m_n are the masses of the base fluid and nanoparticles respectively, ΔT is the temperature rise of the bulk fluid in a time interval of Δt. A is the illumination area of the fluid and G is the incident solar flux.

Studies conducted on mono nanoparticles (shown in Fig. 3) include: Al_2O_3 (alumina) [19, 20, 27], Au [6, 18, 21, 23, 24, 30], Ag [7, 12, 18-20, 26], TiN (titanium nitride) [22], MWCNT (multi-walled carbon nanotubes) [28, 31, 19] , Fe [20], Fe_3O_4 [11], TiO_{2-x} (oxygen deficient titanium dioxide) [16, 19], Si [20], SiO_2 [19], Gr (graphene) [31], GrO (graphene oxide) [8, 17, 32], SLGr [17], Cu [19-20], CuO [15], and CuO-MS [15]. Au, Ag, Gr, GrO-based nanofluids are among the mono nanofluids exhibiting high photothermal conversion efficiencies with enhancements exceeding 100%. In those studies, the concentration by volume for gold nanoparticles in a water-based fluid ranged from 10^{-5} to 0.018%, while for silver nanofluids it ranged from 10^{-4} to 0.3%, and for Gr and GrO nanofluids it ranged from 0.001 to 0.01%. For the majority of these nanoparticles, it is shown that the photothermal conversion efficiency increases with the increase in volume concentration up to a certain limit.

Figures 4-a through 4-d show the effect nanoparticles volume concentration has on the photothermal efficiency enhancement for mono and hybrid nanofluids. The results are based on experimental data compiled from the various studies mentioned above. For example, the efficiency enhancement of Al_2O_3 nanofluids is shown to saturate around 50% at 2% volume concentration [19] (Fig. 4-a), while MWCNT nanofluids saturates around 76% at a concentration of 1% by volume [28] (Fig. 4-a). On the other hand, silver nanofluids exhibits a decrease in its photothermal efficiency with the increase in nanoparticle concentration. Data analyzed from the review of literature show the enhancement in the photothermal conversion efficiency to reach 275% at 0.01% volume concentration [12], but continues to decline with the increase in concentration until reaching saturation of 13% at a concentration of 0.3% [7] (Fig. 4-b). Gold nanofluids present good photothermal conversion characteristics as well [6, 18, 21, 23, 24, 30]. Data show its photothermal efficiency enhancement increases with concentration and reaches 300% at a merely 0.018% volume concentration [30] (Fig. 4-c).

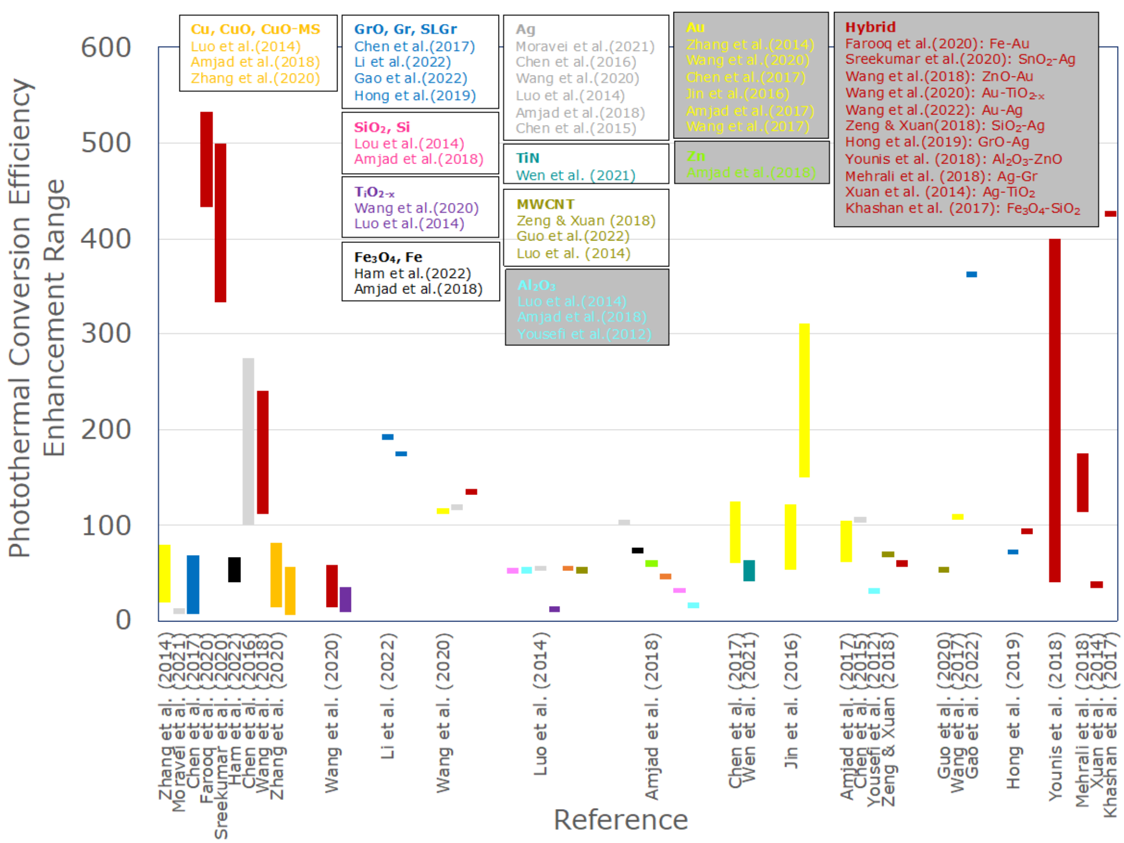

Fig. 3: Photothermal conversion efficiency of mono and hybrid nonfluids (comparison between various studies).

Hybrid nanofluids are shown to manifest captivating results in solar energy systems for their photothermal conversion efficiency enhancements. Figure 3 also presents data from studies on solar thermal systems using hybrid nanofluids. The variety of hybrid nanoparticles used include binary combinations of Fe-Au [9], SnO_2-Ag [10], ZnO-Au [14], Au-TiO_{2-x} [16], Au-Ag [16], SiO_2-Ag [28], GrO-Ag [32], Al_2O_3-ZnO [33], Ag-Gr [34], Ag-TiO_2 [35], and Fe_3O_4-SiO_2 [36]. Complied data shows the photothermal conversion efficiency of the nanofluid to reach an enhancement of 533% with 0.001% volume concentration of Au-Fe nanoparticles [9], an enhancement of 500% with 0.2% concentration by mass of SnO_2-Ag [10], an enhancement of 241% with 1 mg/ml of ZnO-Au [14], an enhancement of 423% with 1 mg/ml of Fe_3O_4-SiO_2 [36], an enhancement of 400% with 1% concentration by mass of Al_2O_3-ZnO [33], and an enhancement of 114% with 0.001% by volume of Ag-Gr [34]. It is obvious that hybrid nanofluids exhibit much greater thermal performance than mono nanofluids due to their synergistic thermal properties. For hybrid nanofluids (Fig. 4-d), the photothermal efficiency tends to increase with the concentration of the hybrid nanoparticles and reach saturation at relatively low critical concentrations compared to the mono nanofluids.

Table 1: Experimental studies carried out on the use of nanofluids in solar energy absorption.

Researcher	Year	Nano-Particle type	Particle size (nm)	Concentration	Base Fluid	Solar Intensity (W/m^2)	Efficiency Enhancement (%)
Zhang et al.	2014	Au	10-30	0.00028-0.0112 wt%	water	1,000	20-80%
Moravej et al.	2021	Ag	5-8	0.1, 0.2, 0.3 wt%	water	732-832	7.4-13%
Chen et al.	2017	GO	nanosheets 0.55-1.2 nm in thickness, 0.5-3 μm in size	0.001, 0.005, 0.01, 0.02, 0.05, 0.1 wt%	water	2,571	7-68%
Farooq et al.	2020	Fe-doped Au Nanoshells	60	0.001 v%	water	1,000	433-533%
Sreekumar et al.	2020	ATO, ATO/Ag	20-50	0.01-0.2 wt%	water	900 max	333-500%
Ham et al.	2022	Fe_3O_4	6-10	0.01, 0.05, 0.1 wt%	water	718	40-67%
Chen et al.	2016	Ag	53	0.001-0.1 v%	water	200-1,200	100-275%
Duan et al.	2018	Au, SiO_2/Au Nanoshells	15, 20/30	0.0008-0.2 v%	water	1,000	63-82%, 73-82% (actual efficiency)
Wang et al.	2018	ZnO-Au	rods: 0.75 μm length, 0.08 μm dia.	0.1, 0.5, 1 mg/ml	silicone oil	1,000-10,000	112-241%
Zhang et al.	2020	CuO-MS, CuO	—	10-100 ppm	water	1,000-3,000	CuO-MS: 14-82% CuO: 6-56%
Wang et al.	2020	TiO_{2-x}, Au/TiO_{2-x}	Au (14.8 nm), TiO_{2-x} (40-50 nm)	100 ppm	silicone oil	1,000 & 4,000	Au/TiO_{2-x}: 14-59% TiO_{2-x}: 8.6-36%
Li et al.	2022	SLG, GO	—	10, 30, 50, 70, 100 ppm	water	2,000	SLG: 189%, GO: 172%
Wang et al.	2020	Au, Ag, blended	triangular sheets (60 nm length, 5 nm height), rods (40 nm dia, 68 nm height)	0.0001 v%	water	1,000	Au nanorods: 112%, Ag nanosheets: 116%, blended: 132%
Luo et al.	2014	SiO_2, Al_2O_3, Ag, TiO_2, Cu, C, CNT	SiO_2: 30 nm, Al_2O_3: 20 nm, Ag: 50 nm, TiO_2: 10 nm, Cu: 50 nm, C: 35 nm, CNT: 10-20 nm OD	SiO_2: 2 v%, Al_2O_3: 2 v%, Ag: 0.1 v%, TiO_2: 1,3 v%, Cu: 1 v%, C: 0.05-5 v%, CNT: 1 v%	oil	750-8,000	@4,000 W/m^2, SiO_2: 49%, Al_2O_3: 50%, Ag: 52%, TiO_2: 9%, Cu: 52 ppm52%, C: 50%
Amjad et al.	2018	Ag, Fe, Zn, Cu, Si, Al_2O_3-γ	Ag: 50-60 nm, Fe: 50-80 nm, Zn: 40-60 nm, Cu: 35-45 nm, Si: 30-50 nm, Al_2O_3-γ: 40-80 nm	0.01 wt%	water	11,638	Ag: 100%, Fe: 70%, Zn: 57%, Cu: 44%, Si: 29%, Al_2O_3-γ: 13%
Chen et al.	2017	Au	10	0.5, 1.0, 1.5, 2.5 ppm	water	3,000, 5,000, 10,000	60-125%
Wen et al.	2021	TiN	20	10-50 ppm	glycol ethanol	1,000	41-63%
Jin et al.	2016	Au	9 nm-120 nm	0.36, 0.72, 1.45, 5.8 ppm	water	600, 950	@ 600 W/m^2: 53-122%, @ 950 W/m^2: 150-311%
Amjad et al.	2017	Au	20-30	0.008, 0.016, 0.024, 0.032, 0.04 wt%	water	280,000	61-105%
Zeng and Xuan	2022	Fe_3O_4, TiN, Fe_3O_4-TiN	Fe_3O_4: 100 nm, TiN: 15 nm	0.005 – 0.04 v%	ethylene glycol	1,000	(actual eff.) TiN: 58%, Fe_3O_4: 60%, Fe_3O_4-TiN: 62%
Chen et al.	2015	Ag	49 nm	20.24 – 80.94 ppm	water	450	103% @ 80.94 ppm
Yousefi et al.	2012	Al_2O_3	15 nm	0.2, 0.4 wt%	water	1,000	28.3% @ 0.2 wt%
Zeng and Xuan	2018	MWCNT, SiO_2/Ag	MWCNT: 8-15 nm (dia.), 3-12 μm (length) SiO_2/Ag: 150 nm	MWCNT: 0.001-0.1 v%, SiO_2/Ag: 0.001-0.1 v%	water	1,000	67% @ 0.1 v% MWCNT, 57% @ 0.1 v% SiO_2/Ag
Guo et al.	2020	MWCNT	—	0.005, 0.01, 0.05 wt%	water	2,000	51% @ 0.01 wt%
Wang et al.	2017	Au	13 nm	5 – 178 ppm	water	1,000	106-300%
Gao et al.	2022	Gr	0.55-3.74 μm (thick), 0.5-3 μm (dia.)	10, 30, 40, 50, 100 ppm	water	1,000	360% @ 40 ppm

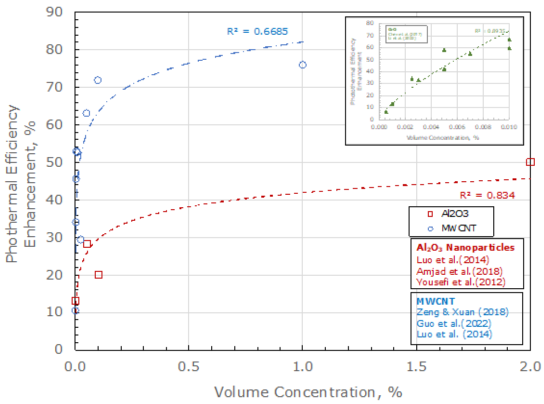

Fig 4-a: Effect of volume concentration on photothermal conversion efficiency for Al_2O_3 and MWCNT nanofluids.

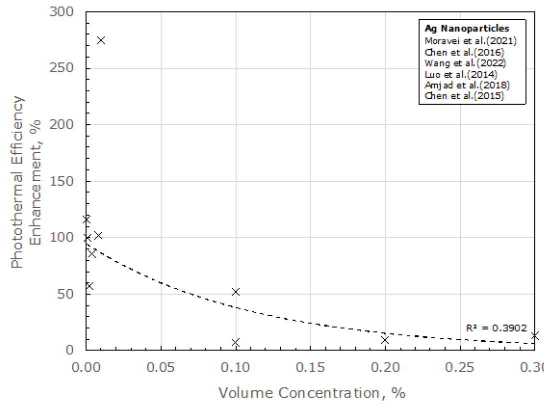

Fig 4-b: Effect of volume concentration on photothermal conversion efficiency for Ag nanofluids.

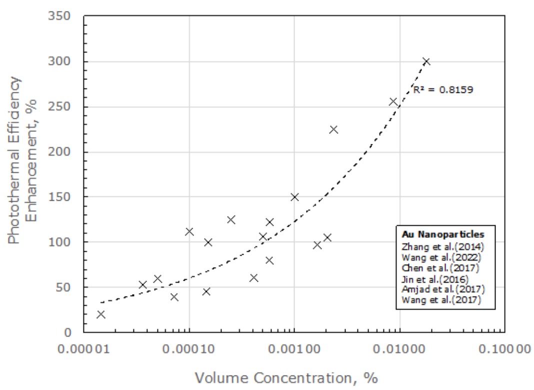

Fig 4-c: Effect of volume concentration on photothermal conversion efficiency for Au nanofluids.

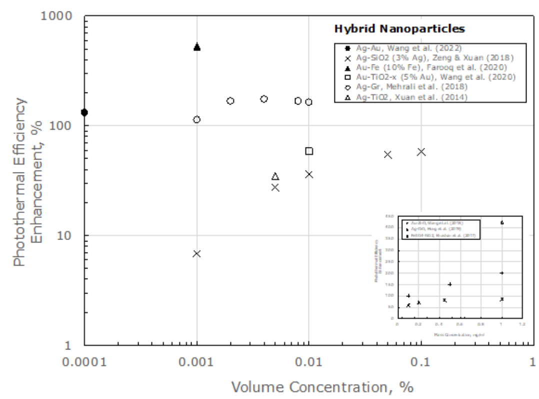

Fig 4-d: Effect of volume concentration on photothermal conversion efficiency for hybrid nanofluids.

4. Conclusion

A review was performed on the utilization of mono and hybrid nanofluids in solar systems. The paper compiles experimental data from several studies to examine the photothermal convergence performance of the two kinds of nanofluids.

Hybrid nanofluids are shown to exhibit much greater thermal performance than mono nanofluids due to their synergistic thermal properties. Results show Au, Ag and Gr-based nanofluids are among the mono nanofluids that exhibit high photothermal conversion efficiency enhancement that can exceed 100%, while hybrid nanofluids can reach outstanding enhancement that exceeds 400% as in the case of Fe-Au, SnO_2-Ag and Fe_3O_4-SiO_2 nanofluids. The majority of the mono and hybrid-based nanofluids, with the exception of Ag mono nanofluids, exhibit an increase in the photothermal conversion efficiency with the increase in nanoparticles concentration.

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