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Potential of Nanodiamond/Water Nanofluid as Working Fluid of Volumetric Solar Collectors

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ABSTRACT

In this study, the thermal efficiency of volumetric solar collector is experimentally compared using diamond nanofluid as the working fluid. First, the dispersion stability of prepared nanofluids is considered with zeta potential method. Then, the radiative properties of nanofluids, which affect directly the efficiency of volumetric collector, are experimentally determined using spectrophotometry method. Two setups for outdoor performance test of volumetric and surface solar collectors have been designed and built based on EN12975-2 standard. The tests were performed under different flow rate conditions and nanoparticle weight fractions. The thermal performance tests of volumetric collector reveals that using nanodiamond nanofluid (weight fraction of 0.001 wt%) enhanced the efficiency up to 19.6% compared to water-based one, at the mass flow rate of 0.0225 kg/s. In addition, at low reduced temperature difference, the efficiency of nanofluid-based volumetric collector is found to be 17.8% higher than that of a water-based surface solar collector, under similar operating conditions. Based on the experimental results obtained from this study, the nanofluid-based volumetric solar collector is suitable for utilization in water heating systems of residential buildings, but it will require new solar equipment like PCM or stratified storage tanks to be competitive with surface solar collectors.

1. Introduction

There is a direct relationship between development of a country and its energy consumption rate. Given the limited reserves of fossil fuels and increasing rate of energy consumption in nowadays, we can no longer be dependent of conventional sources of energy. Considering fossil fuels depletion and significant growth in energy demand over the last few decades in Iran, renewable energy sources should be used to protect the environment. Iran has a decent number of sunny days and ample sunshine in a calendar year, which makes it a great place to harness solar power for a clean and sustainable source of energy.

The most important elements of solar systems to absorb solar energy are solar collectors. There is a growing research interest in volumetric solar collector (VSC) due to their higher efficiency than the surface solar collector (SSC) [1]. Construction of solar collector aimed to absorb the solar energy by the working fluid, was first done in the mid. 1970s [2, 3].

In volumetric solar collectors, compared to conventional collectors, due to the removal of absorber plate, thermal resistance is less in the path of energy absorption [4]. In recent years, numerous theoretical and experimental researches have been conducted on the use of nanofluid as working fluid of solar collectors [5-7]. The first step to use nanofluid as a working fluid in solar collectors is to investigate their properties, i.e. stability, thermos-physical and optical properties. Remarkable attention has been given to the optical properties of various nanofluids as working fluid of VSC [8-13]. Karami et al. [8-10] separately examined the properties of nanofluids containing carbon nanotubes, carbon nanoball and copper oxide nanoparticles. They found out that using nanoparticles can improve the thermal and optical properties of the base fluid. Vakili et al. [11] suggested that the nanofluid containing graphene nanoplates can be used as the working fluid in direct absorption solar systems, because of increasing the extinction coefficient of the base fluid.

Diamond is an allotrope of carbon which has great properties such as superior hardness, high thermal conductivity (five times more than copper) and Young's modulus, high electrical resistivity, attractive optical characteristics, and excellent chemical stability and biocompatibility. Sundar et al. [12] reported that the thermal conductivity enhancements are 18.8%, 16.8% and 14.1% at 1.0% vol. of 20:80%, 40:60% and 60:40% PG/W for nanodiamond nanofluids at $60^{o}C$, respectively. The study done by Xie et al [13] showed that the thermal conductivity enhancement of the nanodiamond nanofluids increases with nanodiamond loading and the thermal conductivity enhancement is more than 18.0% for 2% volume fraction nanodiamond nanofluid.

In further exploring the potentials of nanofluids, Tyagi et al. investigated the performance of nanofluid-based VSC numerically [14]. They used aluminum nanoparticle suspensions in water as the working fluid and showed the efficiency enhancement of 10% in comparison with a conventional flat plate collector.

Otanicar et al. [15] numerically evaluated the performance of low temperature VSC based on Tyagi’s work [14]. They also reported the experimental results on micro solar direct absorption collector based on nanofluids made from a variety of nanoparticles and demonstrated the efficiency improvements of up to 5% by utilizing nanofluids as the absorption mechanism. Parvin et al. [16] numerically investigated the heat transfer performance and entropy generation of forced convection through a low temperature direct absorption solar collector. The results showed that both Nusselt number and entropy generation increase as the volume fraction of Cu nanoparticles and Reynolds number increase. Another numerical study of Parvin et al. [17] using four different nanofluid, showed that the higher absorption of solar radiation the more collector efficiency.

Muhan et al. [18] used hybrid nanofluid of CeO_2/CuO-water as working fluid of VSC. They reported that collector efficiency enhancement is obtained by increasing the nanofluid concentration and mass flow rate. Das et al. [19] considered the pressure difference and heat transfer in TiO_2 nanofluid-based VSC using FLUENT software. The results showed that Nusselt number on the collector is increased by increasing Reynolds number.

Gupta et al. [20] studied the effect of using aluminum oxide nanofluids on the performance of direct absorption solar collector. They built a sample collector with an area of $1.4m^2$ and observed the impact of the concentration of nanofluids and flow rate on the performance of the collector. Their test results showed that by using aluminum oxide nanofluid instead of the base fluid at the volume rate of 1.5 l/min, the collector efficiency would increase by 8%. Karami et al. [21] studied the impact of copper oxide nanoparticles on the performance of direct absorption solar collector with the aim of applying it in the domestic water heaters. They chose water and ethylene glycol mixture (70%:30% in volume) as the base fluid and after stabilization of the nanofluids, they studied the impact of volume fraction of nanofluids and flow rate on the performance of the solar collector according to the procedure of EN12975-2 standard. In a similar research, Vakili et al. [22] managed to increase the direct absorption of solar collector efficiency by using graphene nanoplates up to 23% as compared to the base fluid. According to their results, with nanofluid containing graphene nanoplates as working fluid, the efficiency of direct absorption solar collector reaches 93.2% at flowrate of 0.015 kg/s. Delfani et al. [23] examined the effect of applying MWCNT nanofluid as working fluid in VSCs. The results of this research showed that because of increasing the concentration of nanofluids, the efficiency of solar collector would be increased, as long as the collector efficiency would be 89.3% at the flow rate of 0.025kg/s.

The main aim of this research is the performance characteristics of nanodiamond nanofluid-based VSC to use it as the collecting device in a domestic solar water heater. To the best of the authors’ knowledge, no existing experimental study has addressed the use of nanodiamond nanofluid as the working fluid of VSC. In this study, the potential of using the nanofluids for absorbing solar radiation in VSC is evaluated using experimental method. Then, the thermal performance of nanofluid-based VSC is experimentally compared with water-based SSC using the experimental setups according to EN12975-2 standard.

1. Nanofluid preparation and properties

In this research, spherical diamond nanoparticles (Luoyang Tongrun Ino technology) with an average diameter of 10 nm and 98.3% purity were used as an additive to the water. Figure 1 shows a scanning electron microscope (SEM) picture of diamond nanoparticles

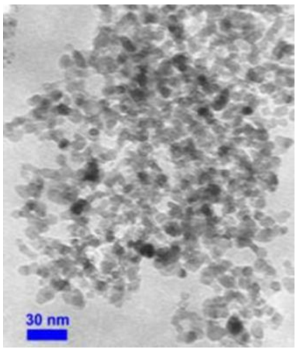

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Figure 1. SEM image of diamond nanoparticles

In this study, nanofluids were prepared with a two-step method. First, diamond nanoparticles were dispersed in deionized water (the base fluid) to form the nanodiamond–water nanofluid. Then an ultrasonic processor (UP400S) was utilized to deagglomerate and homogenize the suspensions. In order to gather more information about the agglomeration process and homogeneity of the suspension, experiments were carried out using three different surfactants: Polyvinyl Pyrrolidone (PVP), Sodium Dodecyl Sulfate (SDS), and Gum Arabic (GA). Agglomeration of nanodiamond nanofluids by adding SDS, PVP, and GA surfactants occurred after one day, 2 weeks, and four months, respectively. Based on these results, GA surfactant had the best stabilizing effect and was utilized as a main stabilizing agent.

To investigate the effect of nanofluid weight fraction on the efficiency of solar collectors, five different weight fractions of the nanodiamond–water nanofluid: 0.001 wt% (D1), 0.0005 wt% (D2), 0.00025 wt% (D3), 0.000125 wt% (D4), and 0.0000625 wt% (D5), were prepared. The above mentioned nanofluids were prepared first by adding diamond nanoparticles in deionized water and sonicate it for 15 minutes, and then adding GA surfactant and sonicating the suspension for 30 more minutes. Figure 2 shows the nanofluid samples

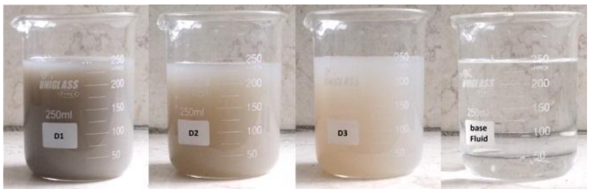

Figure 2. Three different weight fractions of diamond nanofluids

In order to characterize the stability of the suspensions further, zeta potential measurements were utilized. Zeta potential was measured using a Zetasizer Nano ZS manufactured by Malvern Instruments Ltd. The results revealed that the D1 sample had a negative zeta potential of -33.81 mV. These values indicate that the suspension has a good stability without any significant particle aggregation.

The thermal conductivity was measured based on transient hot-wire method using a KD2 Pro thermal properties analyzer (Decagon devices, Inc., USA) in the temperatures range from 25°C to 45°C. The method used in this instrument meets the standards of ASTM-5334 for thermal conductivity which is generally transient-heated needle method [24]. The thermal conductivity of nanodiamond nanofluids versus temperature for different weight fractions is shown in Figure 3. It is found that the thermal conductivity of nanofluids increases with the increase of diamond nanoparticle weight fraction due to higher thermal conductivity of diamond than that of deionized water. The thermal conductivity of nanofluids also enhances with temperature because of decrease of the viscosity of nanofluids which leads increase of the Brownian motion of particles. The best thermal conductivity in temperature of 45°C is related to D1 which is 0.77 W/m °C and increases 27.2% of deionized water as a base fluid.

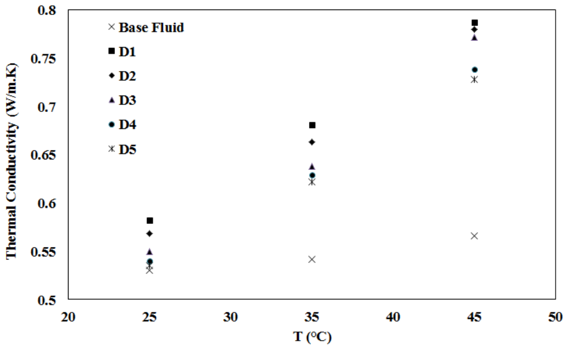

Figure 3. Experimental thermal conductivity of nanodiamond nanofluid at different particle weight fractions and temperatures

The amount of transmittance spectra are measured by using UV–Vis–NIR spectrophotometer (Cary5, Varian Inc., USA) in the range of 200– 3300 nm which conform to the solar radiation spectrum. According to the results of Figure 5, the diamond nanoparticles reduce the sample transmittance with respect to the base fluid considerably and enhance the amount of the captured light. The strong absorption bands exist for nanofluids at 950–1000 nm and again at 1400–1550 nm, which are because of water transmittance nature. After 1850 nm, these nanofluids are essentially opaque to incoming radiation. It can be seen from Figure 4 that the less transmittance takes place in the regions where a large portion of the incident sunlight energy is present.

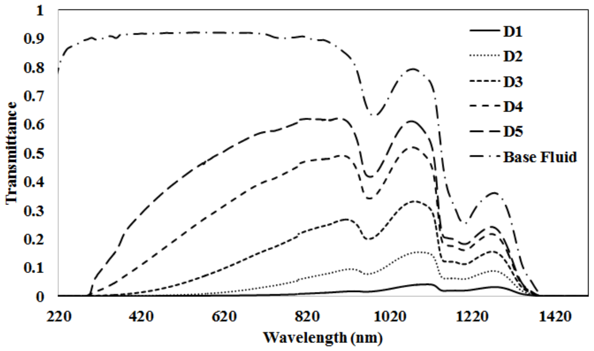

Figure 4. Transmittance spectra of nanodiamond nanofluid samples

For better studying the optical properties of samples, extinction coefficient ($K(\lambda)$) is calculated based on Beer- Lambert law ($T(\lambda)=e^{-K(\lambda).H}$) in which H is the length of the light path passing through the sample. The extinction coefficient of nanofluids with different weight fractions is shown in Figure 5. According to the results, diamond nanoparticles with a weight fraction of 0.001 wt%, lead to the increase in the extinction coefficient of the base fluid to 11 cm^{-1} at wave length of about 1385 nm, which is greater than increase in extinction coefficient of 150 ppm carbon nanotube nanofluid (4.1 cm^{-1}) [8] and of 0.005 wt% graphene nanofluid (6.48 cm^{-1}) [11].

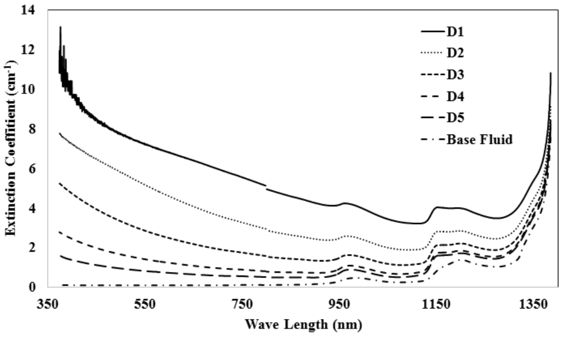

Figure 5. Extinction coefficients of nanodiamond

nanofluid samples

3. Test setups of VSC and SSC

In our previous studies, we have addressed the design and the procedure of thermal performance test of a residential-type volumetric absorption-based solar collector using different nanofluids as working fluid [21]. In this study, we have also designed and built a surface absorption-based solar collector to compare the efficiency of collectors experimentally. As shown in Figure 6, the experimental rig consists of two full-scale solar collector prototypes, two expansion tanks, two pumps and flow control valves, a refrigerated circulating bath (RCB), several measurement instruments such as temperature and flow sensors, pyranometers and anemometer, and a data acquisition system (DAQ). The specifications of collectors are summarized in Table 1. The detailed features of VSC design was reported in our earlier studies [21].

The collectors were experimentally investigated at the Road, Housing and Urban Development Research Center of Tehran, Iran (latitude is 35.69611N and longitude is 51.42311E) and were mounted by tilt angle of 35° to receive maximum solar energy (regarding Tehran latitude).

Table 1. Specification of VSC and SSC

	VSC		
	Dimension	**Unit**	**Material (Type)**
Occupied area	60 × 60 × 1	cm	-
Absorption area	0.36	m^2	-
Glass	t = 4	mm	Toughened
Header pipe	-	-	-
Fluid tubes	-	-	-
Frame	-	-	Al
Insulation	t = 10	mm	Polyurethane
	SSC		
	Dimension	**Unit**	**Material (Type)**
Occupied area	60 × 60 × 10		-
Absorption area	0.36	m^2	-
Glass	t = 4	mm	Toughened
Header pipe	D=22, t = 1		cu
Fluid tubes	D=10, t = 1	mm	cu
Frame	-	-	Al6063 Extruded
Insulation	t = 10	mm	Polyurethane

4. Test procedure

The experiments were performed at the operating temperature range of the collector 35°C–50°C and at the mass flow rates of 0.0075, 0.015 and 0.0225 kg/s for four different working fluids including the base fluid and three nanofluids with different weight fractions (D1, D2 and D3) under clear sky conditions. The test conditions, according to EN 12975-2, are shown in Table 2.

The parameters shall not deviate from their mean values over the measurement period by more than the limits given in Table 2. The detailed test procedure was reported in our earlier studies [21]. The time constant of the collector is defined as the elapsed time in which the fluid outlet temperature arrives 63.2% of its final increase, was 3.53 min. Therefore, each test period (4 times of the time constant [25]) was about 14–15 min.

Figure 6. Test setups for the collector prototypes

3. Results & Discussion

The fraction (F) of absorbed energy by nanofluid is obtained using optical properties and the collector height:

$$F = 1 - \frac{\int I_{b\lambda}(\lambda) \exp(-K(\lambda).H)\, d\lambda}{\int I_{b\lambda}(\lambda)\, d\lambda} \qquad (1)$$

Table 2. Permitted values of measured parameters to establish steady-state conditions [25]

Parameter	**Value**
Minimum test solar irradiance	$700\ W/m^2$
Permitted deviation of test solar irradiance	$\pm 50\ W/m^2$
Permitted deviation of Surrounding air temperature	$\pm 1.5K$
Permitted deviation of Fluid mass flow rate	$\pm 1\%$
Permitted deviation of Fluid temperature	$\pm 0.1K$

at the collector inlet	
Wind velocity	$2 - 4\ m/s$

where the incident solar intensity ($I_{b\lambda}(\lambda,T)$) is calculated using the blackbody relation:

$$I_{b\lambda}(\lambda,T) = \frac{2hc_0^2}{\lambda^5\left[exp\left(\frac{hc_0}{\lambda k_B T_{solar}}\right)-1\right]} \qquad (2)$$

where T_{solar} is taken as 5800 K, h is the Planck's constant, k_B is the Boltzmann constant, and c_0 is the speed of light in a vacuum. The results of the calculation of fraction of absorbed energy, F, for various weight fractions of nanofluids are shown in Table 3. As can be seen, three samples D1, D2 and D3 has the absorbed energy fraction (F) higher than 50% and thus, are chosen for thermal performance test of VSC.

The collector efficiency (η) relates the useful energy to the total radiation incident on the collector surface (AG) by Eq. (3):

$$\eta = \frac{\dot{m}c_p(T_{out} - T_{in})}{AG} \qquad (3)$$

An instantaneous efficiency curve is obtained by statistical curve fitting of the experimental data, using the least squares method:

$$\eta = \eta_0 - a_1 T_m^* - a_2 G (T_m^*)^2 \qquad (4)$$

where T_m^* is the reduced temperature difference and calculated as:

$$T_m^* = \frac{T_m - T_{amb}}{G} \qquad (5)$$

Where T_m^* is the average of T_{in} and T_{out}.

Table 3. Absorbed energy fraction (F) of nanodiamond nanofluid

Nanofluid samples	Absorbed energy fraction (%)
D1	83
D2	75
D3	62
D4	47
D5	34
Base Fluid	13

The VSC and SSC collector efficiencies using different working fluids at different flow rates are shown in Figures 7-9. As can be seen, collector maximum efficiency using the base fluid is 50% and 69% at 0.0075 k/s and 0.0225 kg/s, respectively. It conform the increasing trend of efficiency by flow rate which is in harmony to results of other researches about VSC [21-23]. The main reason of this trend is the reduction of heat loss due to less temperature increase at higher flow rates.

To demonstrate the effect of adding nanoparticles to the base fluid, the thermal performance test of VSC was performed again with D1, D2 and D3 samples at different flow rates. It can be concluded from the results that the VSC efficiency is increased using nanofluid as working fluid due to absorption coefficient enhancement, at all flow rates. The collector maximum efficiencies using nanofluid (D1 sample) were found to be 10.7%, 12% and 19.6% higher than that using the base fluid for 0.0075 kg/s, 0.015 kg/s and 0.0225 kg/s mass flow rates, respectively

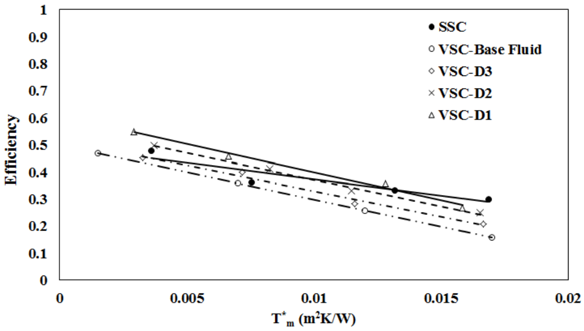

Figure 7. VSC and SSC efficiencies at 0.0075 kg/s flow rate

Additionally, it should be noted that the efficiency curve of nanofluid-based VSC has a greater slope compared to that of water-based VSC which is an indicative of the overall heat transfer coefficient (a_1 in Eq. 4), resulting from adding the nanoparticles. By increasing mass flow rate, overall heat transfer coefficient as a function of Reynolds number is increased. Therefore, at 0.015 kg/s and 0.0225 kg/s mass flow rate and values of T_m^* higher than 0.01 m^2K/W, utilizing nanofluid led to a decrease in the VSC efficiency compared to that of the base fluid. However, for the values of T_m^* less than 0.01 m^2K/W, the enhancement of solar energy absorption by nanodiamond nanofluid can dominate the deteriorating effect of increasing overall heat loss by flow rate, which results in higher efficiencies.

The profiles of Figures 7-9 also show the SSC efficiency using the base fluid. As can be seen, SSC has a higher efficiency than the water-based VSC at all flow rates, because of low absorption through water and high heat loss from VSC. This trend is also observed for the D3 nanofluid. Although the solar absorption is improved, the effect of heat loss is yet dominated. It reveals the importance of selecting the proper weight fraction of nanofluid for achieving the desirable performance of VSC.

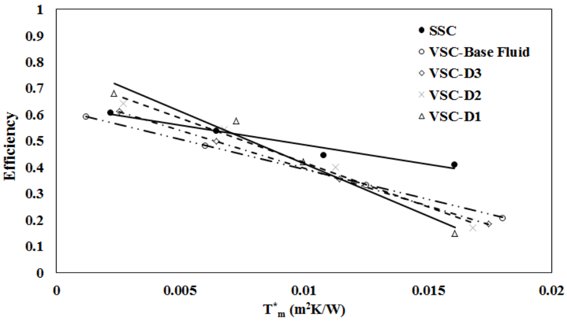

Figure 8. VSC and SSC efficiencies at 0.015 kg/s flow rate

In the lower inlet temperature, the efficiency of VSC by using D1 and D2 samples is higher than that of SSC at all flow rates. By increasing the T_m^*, especially at high flow rates, SSC experiences the higher efficiency. As mentioned above, the large heat loss from VSC, using the nanofluid with high weight fraction leads to smaller efficiency of collector. This fact was predictable because of removal of air gap.

This result show that at high temperatures (no hot water usage in building), the performance of VSC using the base fluid is much better than that of using nanofluids. Therefore, application of thermal storage systems such as PCM or stratified storage tanks with this new nanodiamond nanofluid-based collector is strongly recommended.

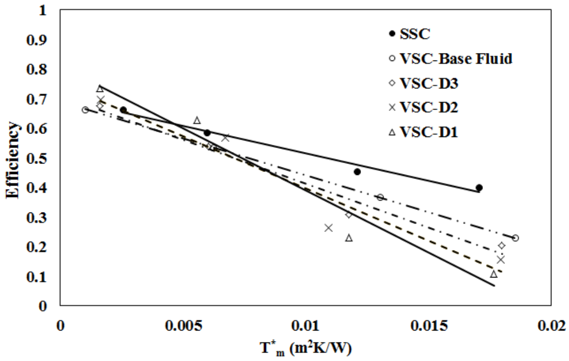

Figure 9. VSC and SSC efficiencies at 0.0225 kg/s flow rate

4. Conclusions

The following conclusions resulted from this work:

1- The experimental results on nanofluid stability showed that the GA is the best surfactant to disperse diamond nanoparticles in water.
2- According to the results, diamond nanoparticles with a weight fraction of 0.001%, lead to the increase in the extinction coefficient of the base fluid to 11 cm^{-1} at wave length of about 1385 nm and 27.2% increase in thermal conductivity of the base fluid.
3- Nanofluid samples with D4 and D5 weight fractions absorbed less than 50% of incident solar radiation.
4- Maximum efficiency of VSC using D1, D2 and D3 nanofluid samples is 11%, 5% and 1% higher than that of SSC at the same flow rates.

Because of higher heat loss of VSC at high reduced temperatures, the SSC has a better performance in comparison with VSC. Therefore, application of thermal storage systems such as PCM or stratified storage tanks with this new diamond nanofluid-based collector at high inlet temperatures is strongly recommended

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