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ORIGINAL ARTICLE

Effect of Al_2O_3 and MgO nanofluids in heat pipe solar collector for improved efficiency

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Abstract
In this work, a heat pipe solar collector (HPSC) utilization system is proposed. An experimental system was designed to analyze the effect of nanofluid concentration on the efficiency of the solar collector. The HPSC system was investigated with low concentration of water-based Al_2O_3 and MgO as the working medium. To examine the structural and optical properties, the X-ray diffraction (XRD) and Fourier transform-infrared (FT-IR) were performed. The HSPC exhibited higher efficiency when they treated with MgO nanofluids. As the concentration of the nanofluid increases, the efficiency of the solar collector is increased irrespective of the working medium. Nevertheless, compared to the Al_2O_3, MgO reported superior efficiency irrespective of the concentration. Second, the entropy generation for MgO was lower and highest for the neat water. Further, the flow rate of the nanofluids increases the collector efficiency spikes. Experimental system shows that the maximum performance of the HPSC is possible by employing the nanofluids to the existing system in an optimized concentration.

Keywords Solar energy · Solar collector · Nanofluids · Heat pipe solar collector

Abbreviations

PV	Photovoltaic
Ti	Inlet temperature
Ta	Ambient temperature
ASTM	American Society for Testing and Materials
MgO	Magnesium oxide
Al_2O_3	Aluminium dioxide
XRD	X-ray diffraction
Lit/min	Liters per minute

Introduction

An environmental concern is mounting due to the uncontrolled use of the fossil fuel. Despite the technology like biodiesel, industrial gas turbines and fuel cells, solar is considered to be most renounced renewable energy source (Jandačka et al. 2017; Hadzima et al. 2007; Manigandan et al. 2021a). Solar energy is a promising source of renewable energy used to match the ongoing energy demand without causing any damage to the environment. Solar energy has numerous advantages such as eco-friendly, infinite and less maintenance (Maroušek et al. 2020a, b). Among several methods, the water heating solar collector is considered to be a sustainable option. Solar collectors are classified into flat-plate, evacuated tube, glass vacuum tube, parabolic and direct absorption technique (Maroušek et al. 2015, 2020a, b). Till date, increasing the collector efficiency is the greatest challenge for pioneers and policymakers. By focusing a vigorous research on the absorption, transmission and conversion, it is possible to increase the efficiency of the solar collectors (Bellila et al. 2021; Peters et al. 2020; Sangeetha et al. 2021). Many ideas have been proposed to enhance the efficiency of the system, among them, utilization of the nanofluids in the collectors is believed to be the most sustainable tool to increase the system reliability and the efficiency (Kosar et al. 2019; Sirignano et al. 2020; Caglar et al. 2021). Kutbudeen et al. analyzed the effects of Di water-based Al_2O_3 in the solar collector with strips. The experiments were conducted in the different volume of the concentration ranging from 0.15 to 0.35% (JaferKutbudeen et al. 2021). Further, the Reynolds number of the nanofluids was subjected to the range from 4000 to 15,000. With

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regards to the concentration, 0.35% reported the better heat transfer rate. At 0.35% nanofluid, 7.8% improvement in the heat transfer was observed. Furthermore, the Reynolds number also plays a key role in the heat transfer. The higher the Reynolds number, higher the heat transfer will be. On the other hand, the use of strips inside the solar collectors effectively improved efficiency of the collectors compared to non-strips. Kumar et al., investigated the efficiency of the heat pipe-based evacuated tube solar collector with the working fluid of ethylene glycol–water at the ratio of 60:40 (60% of ethylene glycol and 40% water). Besides, the graphene nanoparticles were mixed at various concentration of 0.025, 0.075 and 0.1 vol% which indeed generated the improved thermal conductivity of 21.9%, 25.8% and 28.7% respectively (Kumar and Kaushal 2020). Hussein et al. studied the effect of the multi wall carbon nanotubes and graphene nanoparticles–boron nitride on the flat solar collector. At 0.10 weight % the thermal conductivity of the collector was increased by 12–64%. Further, the use of the hybrid nanofluid generated the impressive outcome compared to the isolated nanofluid. Compiling all the findings together, it is very well-clear that usage of the hybrid nanofluids is sustainable compared to the conventional fluids (Hussein et al. 2020). In addition to the above, the similar trends were reported by other authors on the sustainability of the nanofluids in the solar energy production and utilization. Tong et al. performed the series of analysis on the flat plate solar collector with the water based nanofluids such as $Al_2O_3$and CuO. As mentioned above, the positive trends in the efficiency of the collector have been reported upon the introduction of the nanofluids to the system. To examine the effect of nanofluid concentration, the parameters such as energy efficiency and entropy generation were obtained. In addition to it, the exergy and energy analysis were also carried to witness the highest energy efficiency and exergy destruction. Employing the 1.0 vol% and 0.5 vol% of nanofluid enhanced the solar collector efficiency by 57% and 49.6% respectively. Among the two different nanofluids, Al_2O_3 reported higher exergy efficiency and improved thermal efficiency. Besides, compared to the water usage, drastic change in the thermal efficiency was viable by the application of the nanofluids (Tong et al. 2019). With regards to the entropy generation, the lowest value was obtained for the Al_2O_3 and the highest was observed for water. Dehaj, also exhibited the similar study on the evacuated heat pipe solar collector along with the nanofluids MgO. The two-step method was utilized by them to examine the performance of the nanofluids dispersed in the deionized water. On the other hand, the flow rate effects and nanofluid concentration were also obtained to examine the thermal performance. The higher thermal performance directly depends on the flow rate and the working medium. Increasing the flow rate resulted in the higher thermal performance. Higher the concentration of nanofluid higher the nanofluid efficiency will be (Dehaj and Mohiabadi 2019). Sarafraz et al. examined the thermosyphon heat pipe using the zirconia–acetone nanofluids. This specific study observed the stability of the nanofluids and they predicted that the nanofluids were stable up to 40–45 days at the weight % of 0.02–1%. High stability of the nanofluids depicts the strong attractive force between the nanoparticles. Further, the deposition of the nanoparticles in the inner wall was visible due to the agglomeration. Presence of the nanofluid typically reduced the thermal resistance and increased the heat transfer coefficient of evaporator section (Sarafraz et al. 2019). Ozsoy et al. performed the test to observe the effect of silver water-based nanofluid on thermosyphon heat pipe. From the series of findings, it is preeminent that, the use of the nanofluids increases the solar collector efficiency by 20% and 40% than neat water (Ozsoy and Corumlu 2018).

In addition to the above, the use of cascading solar hybrid system with the nanofluids also provides higher thermal efficiency by introducing the nanofluids. Introduction of the nanofluids increases the thermochemical process which indeed increases the sunlight concentration to the photovoltaic module. Further, the particle diameter which is less than 40 nm and 3 cm optical thickness were highly preferred and recommended for the PV/T systems for improved efficiency (Tang et al. 2019; Wang et al. 2021). Based on the above pre assumptions, it is evident that the utilization of the nanofluids increases the absorption capacity of the solar collector which indeed increases the efficiency of the system. Thus, this study examines the effect of nanofluid concentration of the solar collector (Bretado-de los Rios et al. 2021; Sheikholeslami et al. 2021; Manigandan and Kumar 2019). Although there are several notable existing works in the area of nanofluids, the studies of the nanofluid such as Al_2O_3 and MgO were very limited. Further, the study of the efficiency in the hot countries like India is limited. Keeping that in the mind, this study found that the effect of various parameters under the influence of the nanofluids.

Materials and methods

Experimental setup

Figure 1 shows the typical layout of the flat plate solar collector which is utilized in the current study. The test was conducted in Sathyabama Institute of Science and Technology, India (12.8° N, 80.2° E) from 9.30 a.m. to 5.00 p.m. The combined solar water/nanofluid tank collector capacity of 150 L was used in this study. To control the nanofluid, a circulating pump was installed in the inlet of the tank. The flows of the nanofluids were measured using the mass flow meter and they were controlled using the flow control valve.

Fig. 1 Experimental setup

Table 1 Specification of the flat plate solar collector

Details of parameters	Specification	Unit
Gross dimension (l*w*t)	1988 × 1010 × 89	mm
Empty weight	37.2	kg
Sealing and casing material	%Electrostatically painted (Black) and aluminium case	kg
Gross area	2.01	m^2
Aperture dimension	1960*960	mm
Transmittance of glass	Rockwool	mm
Cover thickness	3.2	mm
Insulation material	Glass wool	–

Table 2 Instrument's type and uncertainty

Instrument	Type	Accuracy (%)
Thermocouple	K-type (till 1200 °C)	0.80%
Flow meter	Electromagnetic (0–10 kg/s)	0.50%
Pressure	Differential transmitter	0.30%
Solar radiation sensor	Solarimeter (1500 W/m^2)	0.50%

Table 1 shows the specification of the solar collector used in the current study.

Uncertainty

According to the guidelines of the ASME, the measurement errors are possible due to the measurement of the experimental values. The errors can be calculated based on the deviation of the values and the systematic errors. Table 2 lists the types and accuracy of the errors usually takes place in the current study. The instruments used in the study were flow rate, temperature, solar radiation and data logger. All tests carried out in the non-cloudy days from 9.30 a.m. to 5.00 p.m. Further, the accumulation of the dust and cloud covers were not considered in the current investigation (Devi et al. 2020; Gurbuz 2020). To avoid the uncertainty in the weather, the test was conducted in the peak summer from July to September 2020.

Nanoparticles preparation and synthesis of nanofluids

The nanofluids Al_2O_3 and MgO were compared in the current study. Among different nanoparticles this study examines the above two nanoparticles since they possess high specific heat coefficient compared to other nanoparticles. Further they are relatively cheap compared to the other metallic and non-metallic nanoparticles. Meanwhile, the thermal conductivity of the above nanoparticles is good hence they were selected as the working medium in this study. The Table 3 shows the property of the nanoparticles. The concentration used in this study was ranged in three different fashion of 0.5%, 1.0% and 1.5% vol. Among several methods of nanoparticles preparation two step method was widely adopted due to high stability of the nanofluids. Initially, the nanoparticles were dispersed in pure water and sonicated for minimum 5 h using the ultrasonication apparatus (Praveenkumar et al. 2019; Siddiqui et al. 2016). After the dispersion of the nanoparticles, the distribution of

Table 3 Properties of nanoparticles

Type	Aluminum oxide (Al_2O_3)	Magnesium oxide (MgO)
Appearance	White	White
Morphology	Spherical	Multidimensional
Purity	99.9%	99%
Particle size	40 nm	20 nm
Thermal conductivity	33–35 W/mK	30 W/mK
Specific heat coefficient	880 J/kgK	880 J/kgK

the particles can be observed by the visualization and zeta potential process. Here the dispersion of the nanoparticles was observed only through the visualization instead of zeta potential. Further, the stability of the nanofluid was found to be 40–45 days.

Characterization of the nanofluids

Figure 2 illustrates the XRD patterns of the Al_2O_3 and MgO. XRD pattern of the Al_2O_3 and MgO calcined samples were compared to each other. The particle size was calculated based on the below equation (Manigandan et al. 2021b):

$$D = \frac{k\lambda}{\beta \cos\theta},$$

where D is the average crystallite size; K is the Scherrer constant (0.68–2.08); λ is the X-ray wavelength; β is the line broadening; θ is the Bragg's angle in degrees. Figures 2, 3 shows the XRD pattern of Al_2O_3 and MgO.

Results and discussion

Thermophysical properties of the nanofluids

The Fig. 4 shows the variation of the thermal conductivity for the tested nanofluids. As the temperature of the nanofluid increases the thermal conductivity was spiked due to the heat conduction. Compared to the MgO, Al_2O_3 reported the higher thermal conduction which accounts for the superior thermal efficiency. Further, another reason for the increase in the thermal efficiency at elevated temperatures is interfacial thermal resistance. In addition to the above, few literatures observed the effect of the thermal conductivity on the concentration of the nanofluids dispersed with the base water. Figure 5 represents the variation of the viscosity of the nanofluids at the temperature range from 20 to 60 °C. The viscosity of the fluid was measured using the typical instrument rheometer. Al_2O_3 reported higher viscosity despite the change in the temperature compared to MgO. The main reason for the lower viscosity values at the elevated temperature average efficiency was due to the weak adhesion between the molecules. As the temperature increases, the inter particle and molecular separate into individual phases due to poor bonding and attraction between the molecules. The amount of the heat supplied to the given mass can be measured using

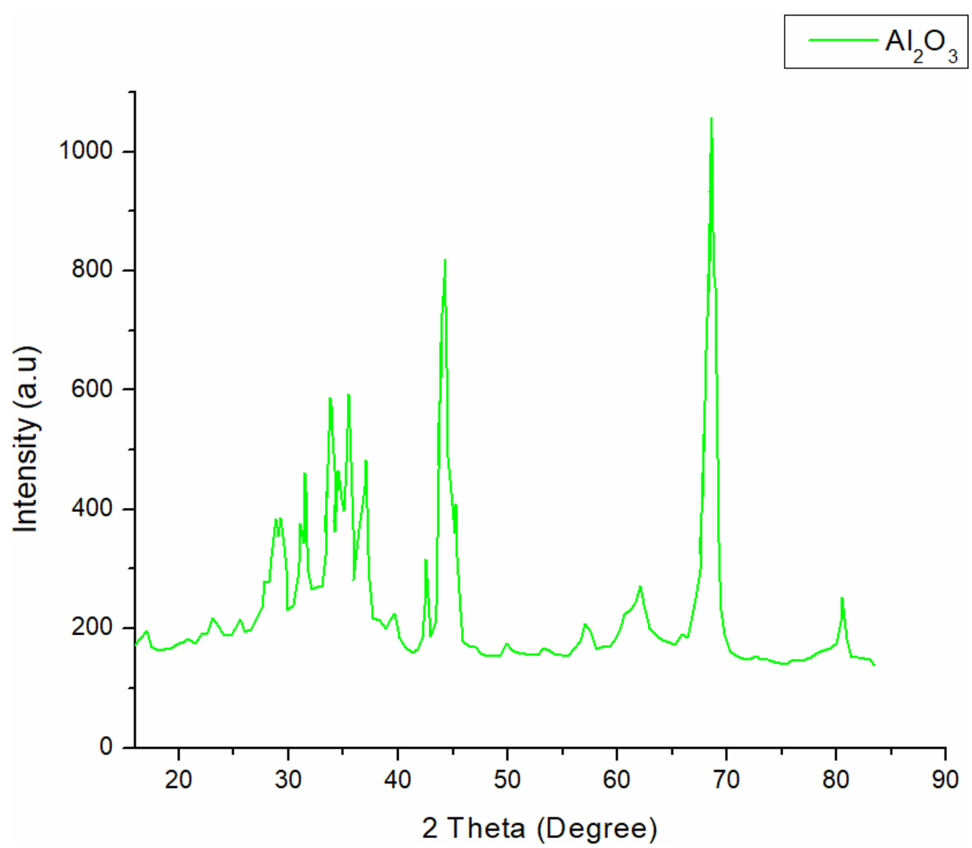


Fig. 2 XRD pattern for Al_2O_3

Fig. 3 XRD pattern for MgO

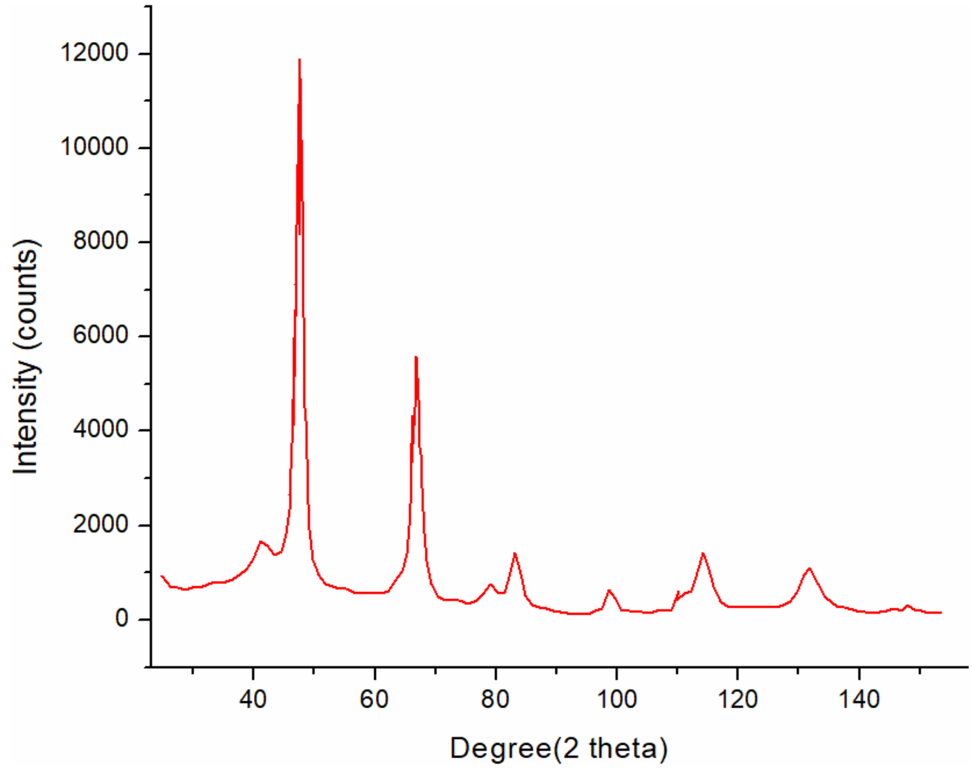
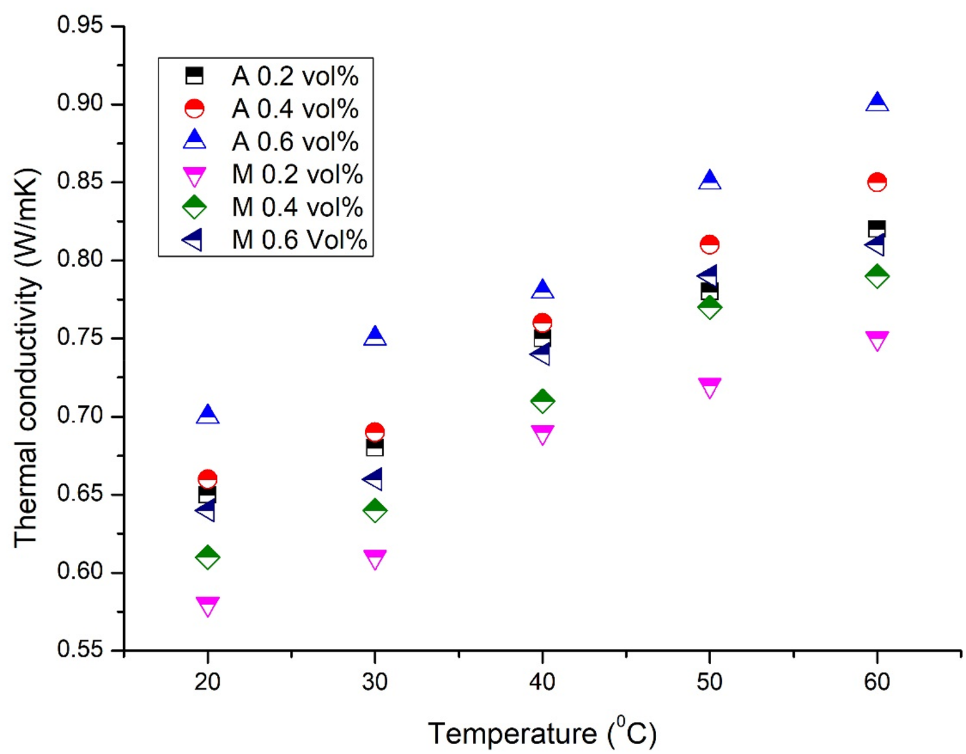


Fig. 4 Thermal conductivity for the different concentration of nanofluids



specific heat capacity. Figure 6 depicts the change in the specific heat capacity with respect to the temperatures based on the nature of the nanofluids (Xian et al. 2020; Shah et al. 2017). It is typical that as the concentration of the nanofluids increases, the heat capacity of the fluids will increase. The change in the specific heat increase was not profound due

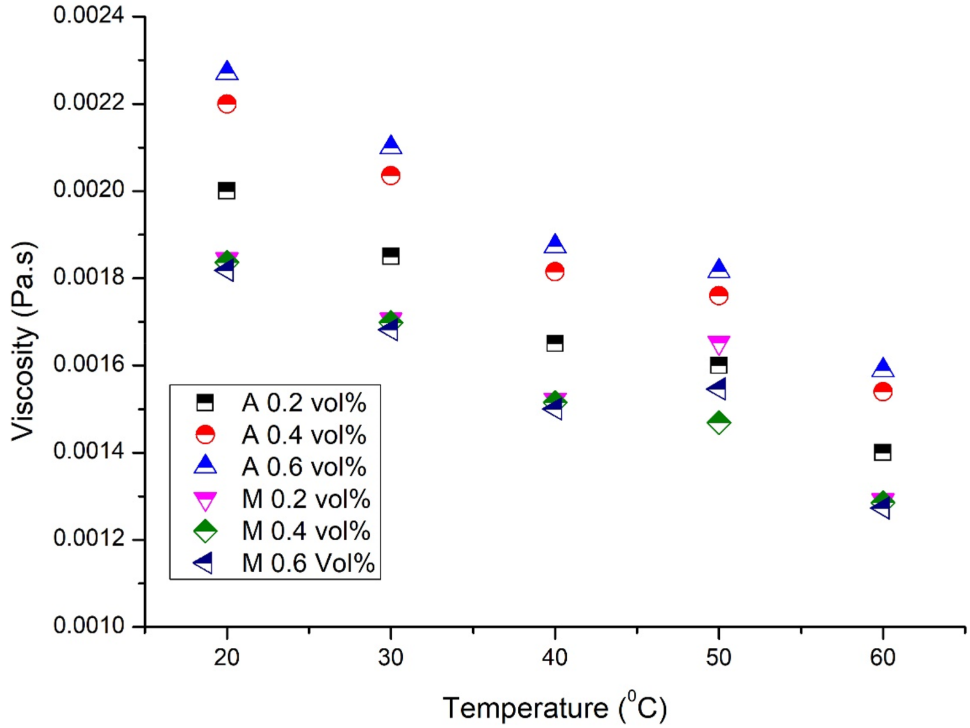


Fig. 5 Viscosity for the different concentration of nanofluids

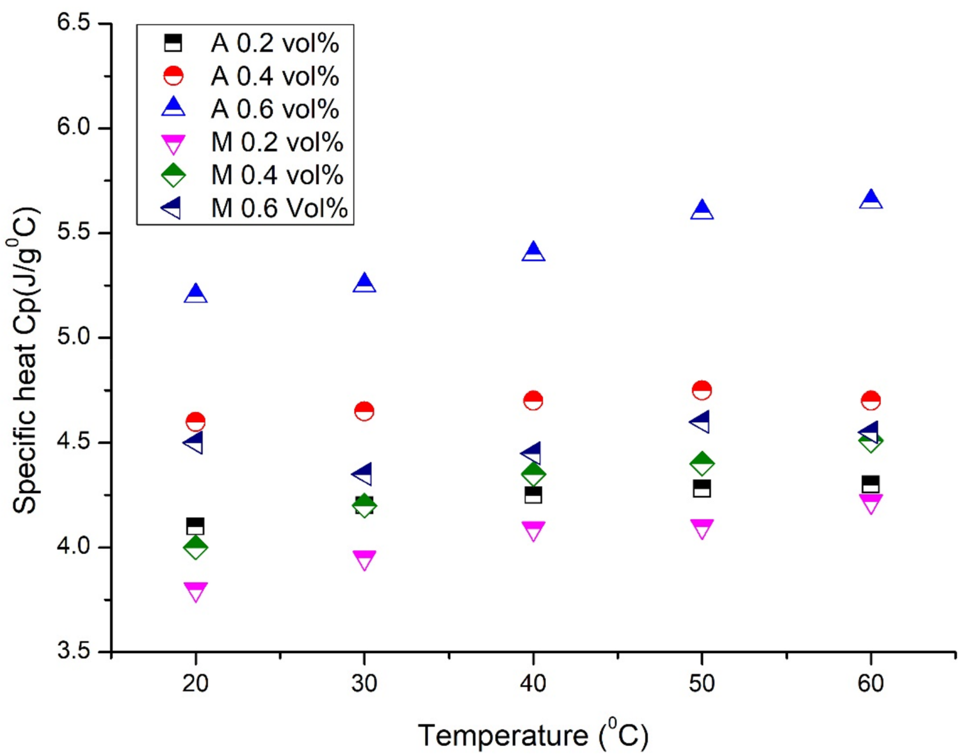


Fig. 6 Specific heat for the different concentration of nanofluids

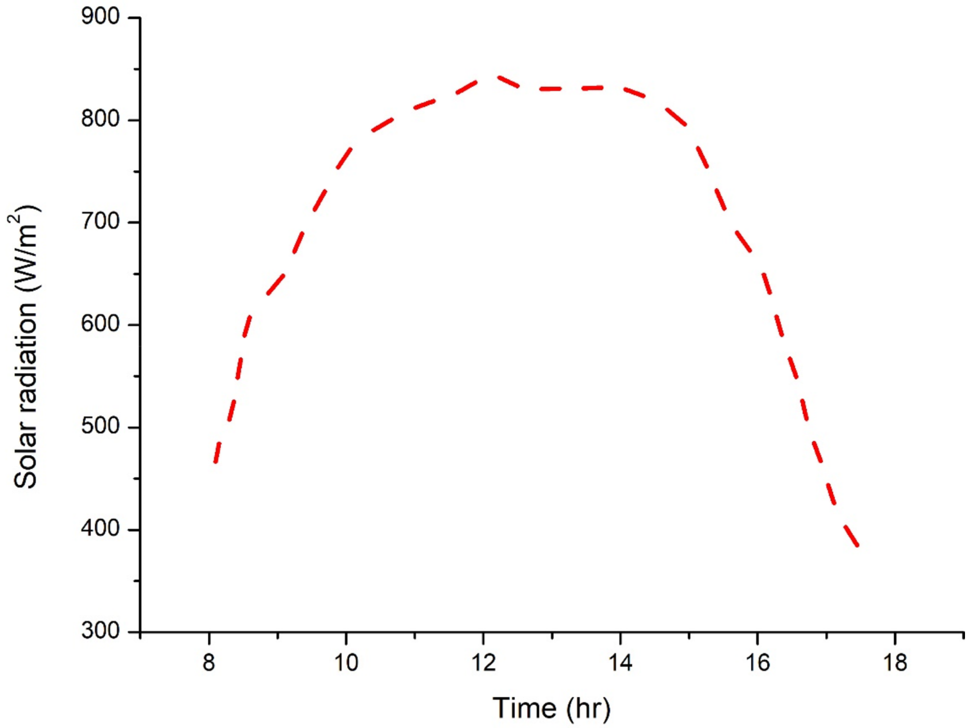


Fig. 7 Solar intensity radiation for the specific geographic location

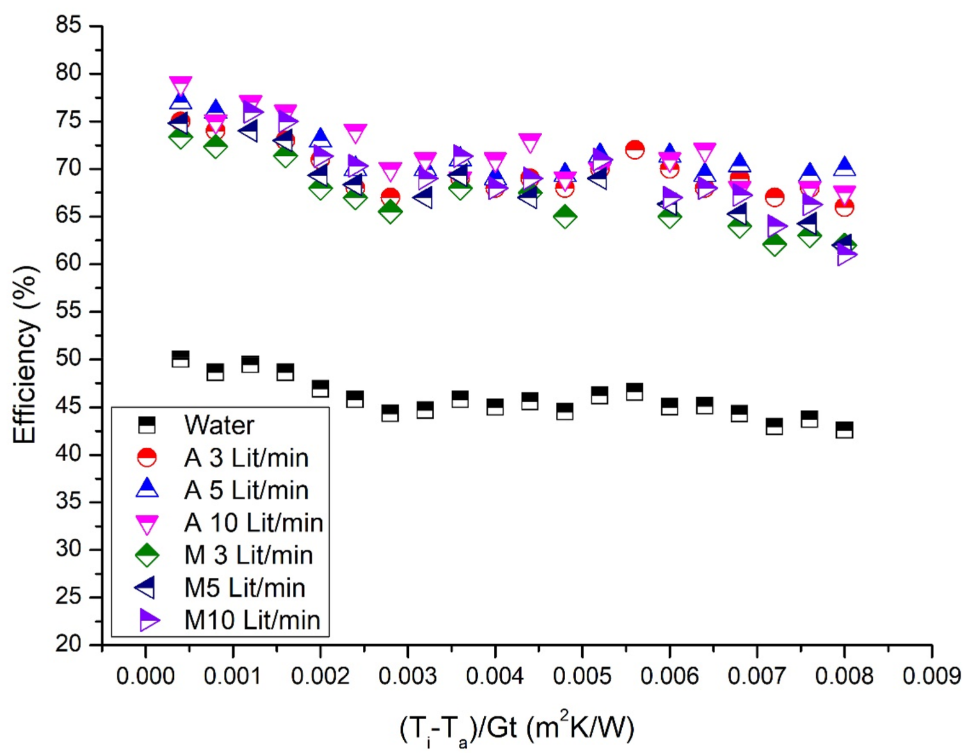


Fig. 8 Effect of mass flow rate on efficiency

to the interfacial free energy of the suspended nanoparticles in the fluids.

Solar intensity

The variation of the solar intensity is represented in the Fig. 7. Based on the figure it is clear that, as the day light increases the solar radiation increases. Initially at 8.00 a.m. the solar radiation was approximately466 W/m^2 and it reached the highest position of 831 W/m^2 at 13.10 p.m. and slowly the intensity of the solar radiation decreased marginally (Zayed et al. 2019). At the end of the study, the measured radiation was 374 W/m^2.The similar parabolic trend was used in our previous article (Ghaderian and Sidik 2017; Devaraj et al. 2018). The intensity was higher at the time line of 11.00 a.m. to 15.00 p.m.

Effect of mass flow rate

The nanofluid concertation on the maximum efficiencyof the solar collector and the average efficiency of the solar collector are illustrated in the Fig. 8. Mass flow rate was varied at three different fashions of 3 Lit/min, 5 Lit/min and 10 Lit/min for both Al_2O_3 and MgO nanofluids. Based on the observation it is clear that as the nanofluid concentration increases the maximum efficiency and the average efficiency of the solar collector increases. However, there was no notable change in the efficiency reported once the flow rate increased beyond 5 Lit/min. Further, irrespective of the nanofluid, the efficiency of the module is increasing with the mass flow rate. Even the neat water reported higher efficiency compared to the conventional collectors (Rejeb et al. 2020; Verma et al. 2018; Bhalla et al. 2019). This is mainly because of the convention and radiation loss due to the flow of nanofluids. With regards to the mass flow rate effect, the higher the flow rate, higher the efficiency of the solar collector will be. All nanofluids reported higher efficiency at 13.00 p.m. of 40%, 78%, 80%, 82%, 72%, 77% and 79% for A3 Lit/min, A5 Lit/min, A10 Lit/min, M3 Lit/min, M5 Lit/min and M10 Lit/min, respectively. As the solar radiation intensity decreased, the efficiency of the system dropped (Xian et al. 2020; Shah et al. 2017). For instance, compared to 13.00 p.m. At 17.00 p.m. the efficiency of the collector was reduced drastically to 27%, 42%, 48%, 58%, 37%, 51% and 51%.

Thermal efficiency

The thermal efficiency of the solar collector was measured for different concentrations of the nanofluids and compared with the baseline fluid water. Figure 9 represents the variation of the thermal efficiency for 0.2 vol%, 0.4 vol% and 0.6 vol% of Al_2O_3 and MgO nanofluids. Based on the predicted results it is very prominent that higher the concentration, higher the efficiency will be. Considering the nanofluids, 0.6 vol% reported higher efficiency related to Al_2O_3 (Ghaderian

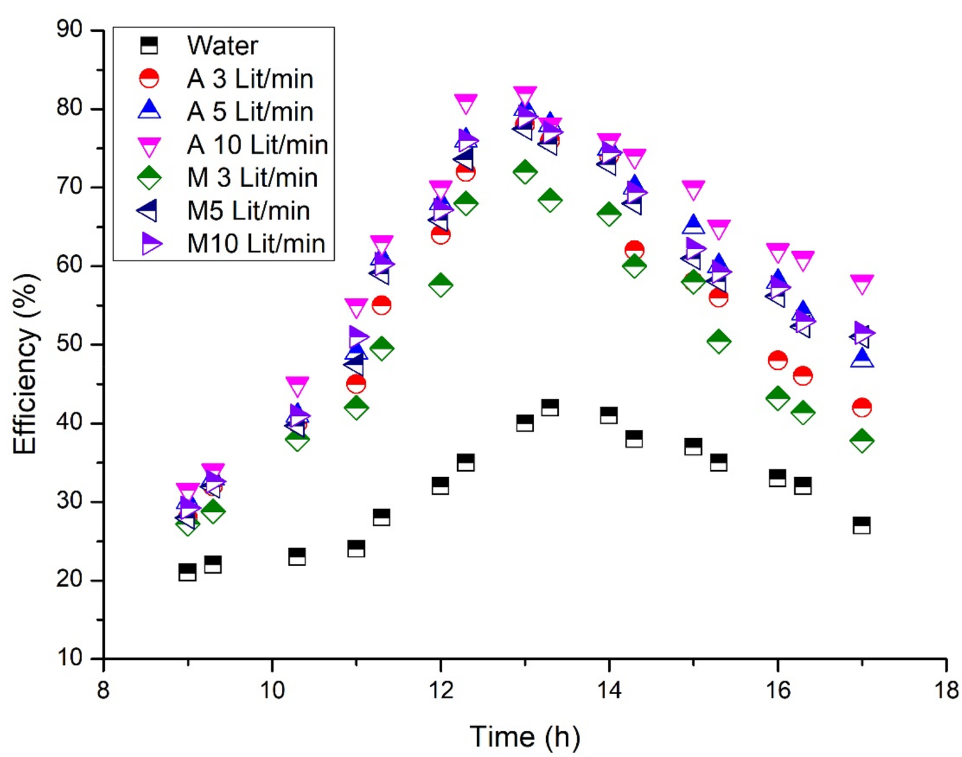


Fig. 9 Effect of solar radiation on the efficiency

and Sidik 2017; Rejeb et al. 2020). On the other hand, 76% of the thermal efficiency was reported by MgO. The maximum efficiency of system reported by the test nanofluids such as A0.2vol%, A 0.4vol%, A 0.6vol%, M 0.2vol%, M 0.4vol%, and M 0.6Vol% was 75%, 77%, 79%, 73.3%, 74.8%, and 76%. The respective minimum efficiency was 68%, 70%, 67.5%, 62%, 62% and 61%, respectively. Due to the increase in the concentration, the thermal conductivity of the nanofluids increases which leads to the superior heat transfer (Eltaweel et al. 2020). However, increase in the concentration above the optimum range reduces the dispersion stability owing to the increase in aggregation. Thus, it is a mandatory requirement to predict the maximum usage of nanoparticles before dispersing them into the base fluids (Devaraj et al. 2019; Lenhard et al. 2019). Besides, above the optimum levels, the increase in the heat transfer and absorption were not impressive.

Conclusion

First, based on the thermophysical test, it is clear that the nanoparticles increase the thermal conductivity of the system compared to neat water. Further, compared to the MgO, Al_2O_3 nanofluid reported higher thermal conductivity. With regards to the viscosity, the MgO was less viscous compared to the Al_2O_3 due to the lower density and the higher response to the temperature variation. The specific heat capacity of the system increases based on the concentration of the nanofluid. The high concentration of the nanofluids reduces the degree of wettability by obtaining the low solid liquid contact angle. Based on the mass flow rate and thermal efficiency, Al_2O_3 was impressive due to the dominant Brownian motion effects. Due to the influence of the Brownian motion, the heat transfer rates were improved massively upon addition of the nanofluids than baseline water. Increased mass flow of nanofluid depicts the higher thermal efficiency for the system. On captivating the above, addition of the nanofluids increases the absorption of the solar radiation and increases the thermal efficiency of the working system. This ensures the suitability of the solar collector energy as the sustainable source of energy.

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Declarations

Conflict of interest No Conflict of interest.

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