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ORIGINAL RESEARCH PAPER

An experimental investigation on the performance of a symmetric conical solar collector using SiO_2/water nanofluid

A.R. Noghrehabadi[1,*], *E. Hajidavalloo*[1], *M. Moravej*[1]

[1] *Department of Mechanical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran*

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ABSTRACT: One of the effective methods to improve the thermal efficiency of solar collectors is using nanofluids as the coolant. The present study experimentally investigated the effect of SiO_2/water nanofluid with 1% mass fraction on the performance of a symmetric collector, i.e. conical solar collector. The conical solar collector with 1 m^2 area and normal to the earth was tested in Ahvaz, a city in the southwest of Iran. The experiments performed under ASHRAE standard without any surfactants based on the solar radiation, mass flow rate, and temperatures variation. Results demonstrated that the thermal efficiency and the temperature performance can be enhanced through SiO_2/water nanofluid in comparison with pure water. The maximum efficiency and outlet-inlet difference temperature of conical collector using nanofluid was about 62% and 6.8 ^{0}C respectively. Moreover, the collector behaviors are more efficient with the nanofluid than with pure water in the higher values of the flow rate and sun radiation.

KEYWORDS: *Conical solar collector; SiO_2/water nanofluid; Solar radiation; Flow rate; Efficiency*

Introduction

Solar energy is one the most popular renewable energy sources that can be used as a thermal or photovoltaic system. Solar collectors play a crucial role in the solar thermal systems; they convert solar radiation into heat and transfer the heat into the working fluids such as water or air. Stationary collectors such as flat plate collectors are the most common type of solar collector usually used as a water or air heater. These types of collectors have low efficiency and low outlet temperature [1-9]. Recently, many researchers have made an attempt to enhance the efficiency and performance of the collector through different methods. One of these methods is the use of nanofluids instead of the common fluids as working fluid [10-14]. Nanofluids are a suspension of base fluids such as water and nano particles with the size of 1-100 nm. These types of working fluids have more thermal properties compared to their base fluids. There are many studies throughout the world with regard to the using nanofluid in solar thermal systems. Otanicar et al. [15-16] studied the environmental, economic, and thermal influence of using nanofluids to improve the efficiency of solar collectors. As one of the first experimental studies on using nanofluids in solar collectors, Yousefi et al. [17] tested Al_2O_3/water as a coolant in the flat plate collector. They showed that nanofluid increases both the outlet temperature and the collector efficiency. Later, Yousefi et al. [18] studied the effect of pH of multi walled carbon nanotube/water nanofluid and showed that the optimum value of pH to maximize the collector efficiency.

Later, Yousefi et al. [18] studied the effect of pH of multi walled carbon nanotube/water nanofluid and showed that the optimum value of pH to maximize the collector efficiency. Lu et al. [19] investigated the thermal performance of an open thermosyphon for high temperature evacuated tubular solar collectors using deionized water and water-based CuO nanofluids as coolant respectively. They indicated that this nanofluid can enhance the collector performance and the evaporating heat transfer coefficients may increase about 30%.

In recent years, some researchers have examined the use of various nanofluids in solar collector. Mahian et al. [20] performed an analytical analysis to evaluate the performance of minichannel-based solar collector using four different nanofluids including Al_2O_3/water, T_iO_2/water, S_iO_2/water, and Cu/water. They revealed that the Cu/water is the best nanofluid providing the highest outlet-temperature and the lowest entropy. Nasrin and Alim [21] investigated numerically the natural convection of Ag/water and Cu/water nanofluids to employ in solar collector. They disclosed that these nanofluids can increase the collector efficiency.

Goudarzi et al. [22] experimented the effect of CuO/water nanofluid on the thermal efficiency of a cylindrical solar collector. They proved that this nanofluid can significantly enhance the efficiency of collector. Shojaeizadeh et al. [23] studied the exergy efficiency and optimization analysis of Al_2O_3/water nanofluid for flat plate solar collector. Their study indicated the effective parameter for exergy, the optimize value of mass flow rate, and the inlet fluid temperature.

✉ *Corresponding Author Email: *noghrehabadi@scu.ac.ir*
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Nomenclature

A_c	Surface area of solar collector (m^2)
C_p	Heat capacity(J/Kg k)
DT	Difference between inlet-outlet temperatures (^{0} C)
F_R	Heat removal factor
G_T	Global solar radiation (W/m^2)
$\dot{m}$	Mass flow rate (Kg/s)
Q_u	Rate of useful energy gained (W)
S_η	Uncertainty of efficiency (%)
T_a	Ambient temperature (K)
T_i	Inlet fluid temperature of solar collector (K)
T_o	Outlet fluid temperature of solar collector (K)
$T_{o,i}$	Collector outlet initial coolant temperature (K)
$T_{o,\tau}$	Collector outlet coolant temperature after time t (K)
U_l	Overall loss coefficient of solar collector (W/m^2 K)
	Greek Symbols
$\alpha\tau$	Absorption-transmittance product
η_i	Instantaneous collector efficiency
τ	Time constant of conical collector

Gupta et al. [24] investigated a low temperature of Al_2O_3/water nanofluid based on the direct absorption solar collector. They showed that the use of this nanofluid as coolant can improve the optical and thermo physical properties resulting in an increase in the collector efficiency.

Having all these in the mind, the purpose of the present study was to experimentally investigate the effect of one of the stable nanofluids on the efficiency of a symmetric collector. In so doing, water and S_iO_2/water nanofluid with 1% mass fraction tested on a symmetric collector as coolant. The symmetric collector was a 3-D collector with conical geometry having equal sides named Conical Solar Collector. The efficiency enhancement of the collector experimentally investigated and the effect of several conditions such as flow rate discussed.

Materials and methods

Experimental setup

The schematic of experimental setup is shown in Figure 1. Setup consisted of a square conical collector, piping, a pump, nanofluid storage tank, and some measurement instruments. The conical collector was built by the authors and tested at Shahid Chamran University of Ahvaz, Iran (latitude is $31^0\,19^{'}\,16^{"}$ N and longitude is $48^0\,40^{'}\,16^{"}$ E). The pictures of the solar collector and the setup are shown in Figure 2 and Figure 3. The specifications of the collector are illustrated in Table 1.

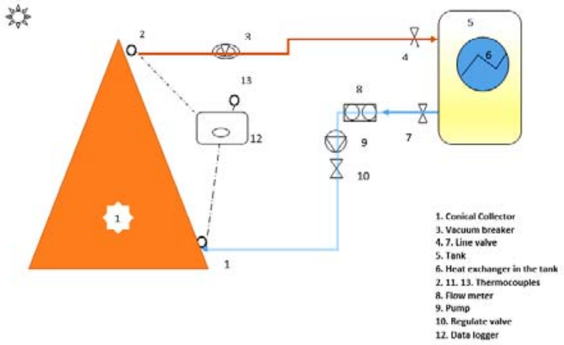

Fig. 1. The schematic of the experiment

Fig. 2. Piping and covering install on conical solar collector

Table 1

Specifications of the conical collector.

Specification	Dimension	Unit
Diameter of absorber (conical body)	0.6	m
Absorber area	1.0	m2
Absorber height (Con altitude)	1.07	m
Absorber thickness	1.5	mm
Frame (totally glass)	t= 4	mm
Pipe	D= 6.2, t=1.1	mm
Weight	34	Kg
Insulation (Polystyrene and wood)	t=20	mm

Fig. 3. The conical solar collector in setup

To measure the thermal efficiency of the collector, two K type thermocouples placed at the inlet and outlet of the collector and one K thermocouple used to log ambient temperature. The thermocouples connected to two data loggers (ktt310-kimo data logger). A diaphragm pump (Soft Water Pump) maximum mass flow rate 3 lit/min used to circulate the working fluid, i.e. water or nanofluid, inside the system. The solar radiation measurement implemented by a TES 132 solar meter type.

Preparation of nanofluid

The SiO_2/water nanofluid prepared in a two-step process so that nano particles were produced first and then the nanofluid. S_iO_2 nanoparticles (EVOTIK Industries) with 99.99% purity and average diameter about 12 nm employed. Figure 4 shows the TEM images of this nanoparticles. Following the process, these particles suspended in the water as the base fluid. According to the value of fraction, a certain amount of nano particles blended with fresh water in a vertical mixer without any surfactant. Later, the homogenizer device provided the homogeneous suspension of nanoparticles and water. At the end, the suspension was inserted in an ultrasonic bath for about 60 minutes to prepare the nanofluid with minimum aggregation of nano particles and to improve dispersion behavior.

All the preparation process was done in Nanofluid Laboratory of Shahid Chamran University of Ahvaz. Concerning the nanofluid stability during the operating time, the apparent of the nanofluid during the day test is taken into account. The nanofluid is prepared every day using ultrasonic bath to break down the agglomeration between nanoparticles and to minimize the sedimentation.

Testing method

To test the thermal performance of collector, ASHRAE Standard 93-86 [25] is certainly the one most often used to evaluate the performance of stationary solar collectors. The thermal performance of the solar collector is determined by obtaining the values of instantaneous efficiency for different combination of incident radiation, ambient temperature, and inlet fluid temperature.

This requires an experimental measurement of the rate of incident solar radiation as well as the rate of energy in addition to the working fluid as it passes through the collector, all under steady state or quasi-steady-state conditions [4].

Time constant

One of the collector specifications is time constant that can be used as a heat capacity of the collector. This parameter introduces the time reaction of the solar collector to evaluate the collector transient behavior. The time constant of a collector is the time needed for the coolant leaving the collector to reach 63% of its final steady state value after a step change in incident radiation [17], [26].

$$\frac{T_{O,\tau} - T_i}{T_{O,i} - T_i} = \frac{1}{e} \tag{1}$$

Where $T_{O,\tau}$ is the outlet coolant temperature of the collector after time t, $T_{O,i}$ is the outlet initial coolant temperature of the collector, and T_i is the inlet temperature of the collector.

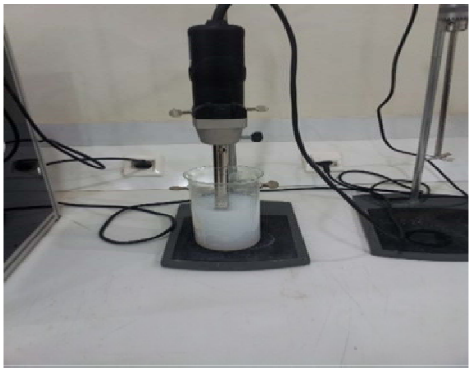

Figure. 4. Nanofluid preparation process

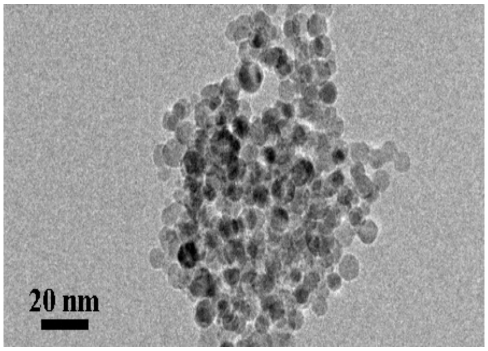

Figure. 5. TEM images of S_iO_2 nanoparticles

Time attempt

According to ASHRAE Standard 93-86, steady-state should be prepared during the data period and a specific time interval prior to the data period, which is called pre-data period [25, 26]. To reach the steady-state conditions, the mass flow rate and irradiation must be within ±1% and $\pm 50 W/m^2$ respectively. Besides, the outdoor ambient temperature must not be more than ±1.5K, and the inlet temperature must be within ±0.1K for the entire test period.

Governing equation

ASHRAE Standard 93-86 suggests performing the tests in various inlet temperatures. After the steady state conditions, the data for each test were average and used in the analysis as a single point while the other data rejected. As the inlet and outlet fluid temperatures and mass flow rate of the water were measured, the useful energy could be calculated using equation 2. The useful energy could also be expressed in terms of the energy absorbed by the absorber and the energy lost from the absorber as given by equation 3.

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{2}$$

$$Q_u = A_c F_R[G_T(\tau\alpha) - U_L(T_i - T_a) \tag{3}$$

Where Q_u is the rate of useful energy gain (W), $\dot{m}$ is the mass flow rate (Kg/s), C_p is the heat capacity of the coolant such as water or nanofluid (J/kg K), T_o is the outlet fluid temperature of solar collector (K), A_c is the surface area of solar collector (m^2), F_R is the heat remove factor, ($\tau\alpha$) is the absorption-transmittance product, G_T is the global solar radiation (W/m^2), U_L is the overall loss coefficient of the solar collector (W/m^2 K), and T_i and T_a are the inlet fluid temperature of the solar collector (K) and the ambient temperature (K) respectively.

The heat capacity of nanofluid determined by equation 4 [24, 27, 28].

$$C_{p,nf} = C_{p,np}(\varphi) + C_{p,bf}\,(1 - \varphi) \tag{4}$$

Where $C_{p,np}$ is the heat capacity of nanoparticles (for S_iO_2 is 765 J/kg K), φ is the volume fraction of nano particles and $C_{p,bf}$ is the heat capacity of water as the base fluid (4180 J/kg K) [29].

The instantaneous collector efficiency is calculated by relation between useful energy gained to the incident solar energy through the equation 5 and 6.

$$\eta_i = \frac{Q_u}{A_c G_T} = \frac{\dot{m}C_p(T_o - T_i)}{G_T} \tag{5}$$

$$\eta_i = F_R(\tau\alpha) - F_R U_L\left(\frac{T_i - T_a}{G_T}\right) \tag{6}$$

If the collector tested near the normal incident conditions, then $F_R U_L$ and $F_R(\tau\alpha)$ are constant for the range temperatures tested. According to equation 6, a straight line would be resulted when the efficiency values obtained from the averaged data plotted against $(T_i - T_a)/G_T$. In this line, $F_R(\tau\alpha)$ is the intersection of the line with vertical axis.

This point indicates the maximum value of efficiency occurring when the inlet fluid temperature of the collector is equal to the ambient temperature. The line slope is equal to $F_R U_L$ showing the energy loss from the solar collector. The intersection of the line with horizontal axis is called stagnation point. At this point, the efficiency of the collector is zero happening when no fluid flows via the collector.

Experimental uncertainty analysis

According to ASME guidelines, there exist no absolute measurements and errors in every experimental measurement.

Some of the usual sources of error are: the errors of calibration, data recording errors, and the unsuitable instruments. The uncertainty of the experimental results was calculated by the following ASME guidelines on reporting uncertainties in experimental measurements based on the deviation in experimental parameters [24, 30]. Errors in the flow rate measurement, temperature measurement, and solar radiation measurement are the main components of uncertainty in the collector efficiency. The uncertainty results of the measurements including all the sources of errors are revealed in Table 2. It should be mentioned that the final calculated value of the uncertainty of ΔT is presented in percentage which is derived from inlet and outlet temperatures uncertainty.

Table 2
The uncertainty results of the study measurements.

Parameter	Uncertainty (%)
Volumetric flow rate	±1.6
Solar radiation	±6.5
Difference between inlet-outlet temperatures	±1.2

The combined uncertainty to calculate the collector efficiency, S_η, was determined by the root sum square method (RSS), based on equation 5.

This analysis is as equation 7. The errors in C_p and A_c are assumed negligible.

$$(S_\eta)^2 = \left[\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta((T_o - T_i))}{(T_o - T_i)}\right)^2 + \left(\frac{\Delta G}{G}\right)^2\right] \tag{7}$$

In the calculation of the collector efficiency, the maximum uncertainty was approximately 6.8% at several tests.

Results and discussion

The experimental results consist of performance, temperatures variation, and the effect of mass flow rates in the conical solar collector using pure water and SiO_2 /water nanofluid.

All the data tested in a quasi-steady state condition and the collector tilt angle was 90^0. The tests on the collector have been taken place for many days from 8 AM to 5 PM on the spring season, 2015 and the data have been logged every 15 minutes. The experimental results are presented in the form of graphs and tables describing the collector efficiency and temperatures.

Effect of incident solar radiation

As mentioned before, the experiments have been performed for many days but the data collected on those days when the sky was clear. The following chart is similar to some of the studied performed before by other researchers [31]. Figure 6 divulges the solar radiation on one of the test days that have suitable and normal radiation for the tests.

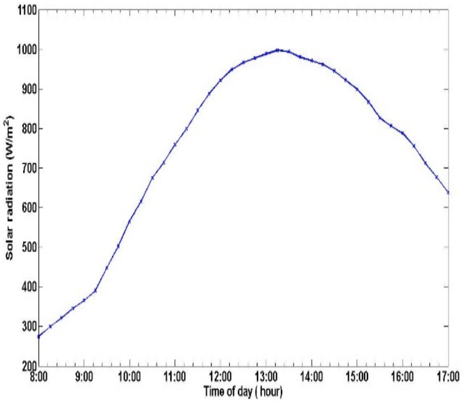

Fig. 6. The experimental data of solar radiation on one of the test days

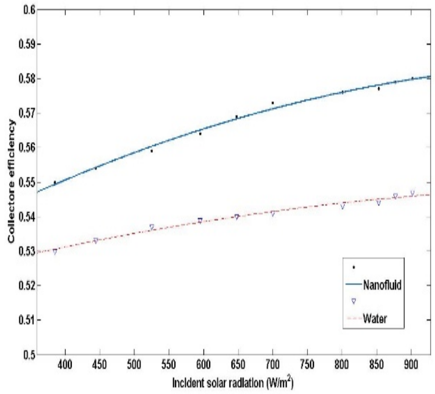

Figure. 7. The influence of incident solar radiation on the collector efficiency using SiO_2 /water nanofluid and water as coolant

Figure 7 illustrates the effect of incident solar radiation on the conical solar collector.

According to the figure, it is obvious that the efficiency of the collector is not sensitive to the incident solar radiation when the collector uses water as the coolant. On the other hand, the effect of the incident radiation is visible when the nanofluid is used as the coolant. This behavior can be explained by the properties of nanofluids such as brownian motion which can be explained as the more receivable energy in nanofluids causing the ability of heat transfer to be increased [32, 34].

Efficiency comparison between water and nano -fluid

Figure 8 indicates the efficiency of conical solar collector for two working fluids: pure water and SiO_2 /water nanofluid.

As shown in the figure, the collector efficiency is in the near range in both coolants.

Although SiO_2 /water nanofluid is more efficient than pure water, the difference is not that big; one of the main reasons is that the thermal conductivity of SiO_2 is not so larger than water [29, 32-34].

The values of F_RU_L and F_R ($\tau\alpha$) of the conical collector for water and nanofluid are shown in Table 3.

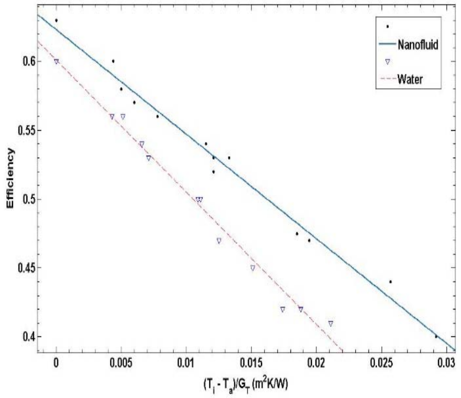

Fig. 8. Efficiency versus (T_i -T_a) /G_T curve for SiO_2 /water nanofluid and pure water

Table 3

F_RU_L and F_R ($\tau\alpha$) of the conical collector for water and nanofluid.

	coolant	F_R ($\tau\alpha$)	F_RU_L	R^2
1	water	0.601	9.601	0.989
2	nanofluid	0.623	7.598	0.986

The effect of the flow rate

Both water and SiO_2 /water nanofluid are tested for different mass flow rates to evaluate their influences. To control the flow rate of working fluid, a regulating valve was used.

The range of flow rate was 0.35 to 2.8 lit/min. To find the effect of flow rates on the collector efficiency, several tests were performed and the best experimental data was selected. The efficiency variation versus the flow rates for water and SiO_2 /water nanofluid, with 1% mass fraction, were presented in Figure 9.

According to the figure, the efficiency of the collector increases via increasing the flow rate using both coolants i.e. water and SiO_2 /water nanofluid. This trend is in line with the experimental works of Cristofari et al. [35] and Minsta et al. [31] in that they studied the influence of the mass flow rate on a solar collector. They concluded that the collector efficiency increases through increasing the higher mass flow rate. The figure also shows that the efficiency is more increased by the nanofluid than by the pure water. This trend can be described by the motion properties of nanofluids [36-38]. It is worth noting that the corresponding Reynolds number in this range of flow rates is between 2700-22000.

Figure 10 shows the difference between inlet-outlet temperatures (DT) while the flow rate is increasing. Moreover, it can be observed when the flow rate is increased, DT is decreased.

In the low values of the flow rate, the behaviors of pure water and S_iO_2/water nanofluid are similar; however, in higher values of the flow rate, the slope line of DT line for nanofluid is smaller than the pure water. Accordingly, it signifies that the collector with S_iO_2 /water nanofluid has better thermal behavior.

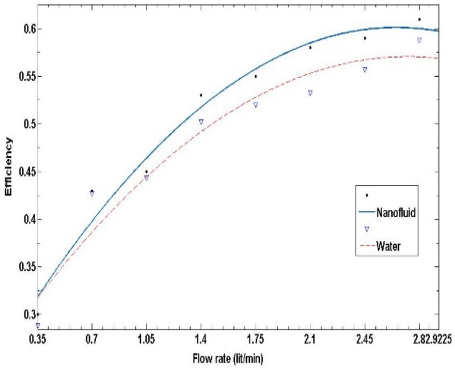

Fig. 9. The efficiency of conical collector with S_iO_2 /water nanofluid and pure water for various flow rates

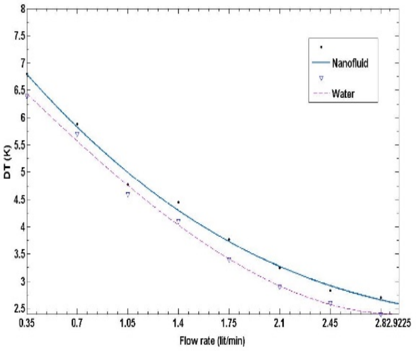

Fig. 10. The difference between inlet-outlet temperatures versus flow rate

Conclusions

As aforementioned, the present study experimentally investigated the performance of a 3-D symmetric conical solar collector with water and S_iO_2 /water nanofluid, 1% mass fraction without surfactant, as the working fluids. The experiments performed based on ASHRAE standard 93-86 and at different flow rates between 0.35-2.8 lit/min. The findings of the study are summarized in the following:

- S_iO_2 /water nanofluid increases the efficiency of conical solar collector compared to the pure water.
- When the incident solar radiation increases, the collector efficiency with water as the coolant does not have very sensitive variation; however, for the nanofluid, the collector efficiency increases with very low slope by increasing in the incident solar radiation.
- The efficiency of conical solar collector increases through adding the mass flow rate. This behavior is similar in both using water and S_iO_2 /water nanofluid; nevertheless, the nanofluid is more efficient than the pure water in the higher values of the flow rate.
- While the mass flow rate is increasing, the difference between inlet-outlet temperatures (DT) is decreasing. The decreasing trend of DT increasing in nanofluid is lower than that in the pure water.

Authors' contribution

The authors contributed equally to this work.

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