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Experimental investigation on a flat plate solar collector using Al_2O_3 Nanofluid as a heat transfer agent

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Abstract

This work introduces experimental results of an Al_2O_3 -water based nanofluid as the working fluid for flat tube in plate type solar collector. Experimental test setup comprises a solar collector, closed working fluid system and measurement devices (flow meter, thermocouples, temperature meter and digital solar power meter). The Base case was experimented with di-ionized water with a flow rate of 1 lpm. In second case, Al_2O_3 nanoparticles are mixed in di-ionized water to get nanofluid of 0.5% volume fraction concentration. The maximum difference between outlet and inlet temperatures of the solar collector was 14.4°C with the solar irradiance of about 788 W/m^2 while in case of water the maximum temperatures difference was 10.7°C with a solar irradiance of about 781 W/m^2.

Keywords: Renewable energy; Flat plate solar collector; Nanofluid; Al_2O_3 nanofluid.

1. Introduction

Atmospheric and environmental pollution because of exhaustion fossil fuel in the world has led to some serious phenomena as ozone layer depletion, acid rain, and the greenhouse effect or (global warming). To prevent additional effects of these phenomena, there are two main alternatives: either to improve the fossil fuel quality and reducing harmful emissions or, the more significant option is to replace fossil fuel usage as possible with environmentally friendly, clean, and renewable energy sources. Solar energy heads these sources due to its availability and distribution in nature than other types of renewable energy [1].

Solar collectors are the key element in solar energy systems. It absorbs the solar radiation and converts it to thermal energy [2]. The most cost-effective solar collector is the “flat-plate” kind, but it suffers from relatively low efficiency and outlet temperature. Usual heat transfer fluid in solar collector; water has poor heat transfer performance due to its low thermal conductivity. Research and development activities are being carried out to develop the heat transport properties of heat transfer fluids.

so attempts to enhance the thermal conductivity by adding solid particles (metallic materials, such as silver, copper and iron, and non-metallic materials, such as alumina, CuO, SiC and carbon nanotubes) have much higher thermal conductivities than heat transfer fluids into these fluids since Maxwell commenced it in 1881 (Maxwell 1873). At first, solid particles of micrometer, millimeter amounts were blended into the base fluids to make suspensions or slurries. But, large solid particles cause difficult problems, like surface abrasion, microchannels clogging, and increasing pressure drop, which basically limits the practical applications [3].

The concept of nanofluids was first materialized by Choi [4] after performing a series of research at Argonne National Laboratory in USA. A nanofluid is a class of solid-liquid composite materials Formed by dispersing nanometer-sized solid particles (1-100nm) or droplets into heat transfer fluids [5].

Nanoparticles have exclusive properties, as large surface area to volume ratio, dimension-dependent physical properties, and lower kinetic energy, nanoparticles better and more stably dispersed in base fluids Compared with micro-fluids or milli-fluids because of the large surface area so nanofluids are promising for practical applications [3].

The first experiments were done by Masuda et al. [6] to show the extraordinary values of thermal conductivity of nanofluids. Where they distributed Al_2O_3 and TiO_2 with 4.3 wt% nanoparticles in water and found enhancement in thermal conductivity by 32% and 11%, respectively. Grim [7] dispersed aluminum particles (1-80nm) with 0.5-10wt% into a fluid and declared 100% increase in the thermal conductivity of the fluid.

Huaqing Xie et al. [8] experimentally prepared Various suspensions containing nanoparticles with specific surface areas(SSA) in a range of 5-124 and investigated their thermal conductivities using a transient hot-wire method. Nanoparticle suspensions have higher thermal conductivity than the base fluid, the enhancement increasing with the volume fraction and with an increase in the difference between the pH value of aqueous suspensions and the isoelectric point of particle. They found:

1. For the suspensions of the same base fluid, the thermal conductivity enhancements are highly dependent on (SSA) of nanoparticle, and the highest thermal conductivity with an optimal SSA.
2. The crystalline phase of the nanoparticles appeared to have no evident effect on the thermal conductivity of the suspensions.
3. Comparison between the experiments and the theoretical model shows that the measured thermal conductivity was much higher than the values calculated using theoretical correlation, indicating new heat transport mechanisms included in nanoparticle suspensions.

Otanicar [9] has studied experimentally the effect of different nanofluids on the efficiency in solar thermal collectors and found up to 5% improvement by utilizing the nanofluids as the absorption medium.

Sonawane et al. [10] investigated Aviation Turbine Fuel (ATF) of Al_2O_3 nanofluids for better heat transfer performance in a potential application of regenerative rocket engine thrust chambers. The volume concentration is varied between 0 and 1%. To ensure a factual evaluation, they measured experimentally all properties of the nanofluids. Using experimental set-ups fabricated in-house they measured separately thermal conductivity and specific heat but the viscosity was determined using a commercial viscometer and the heat transfer coefficient is determined using a horizontal double tube counter flow heat exchanger under turbulent flow conditions. They found the enhancement in the thermal conductivity and viscosity at 1% particle volume concentration was 40% and 38% respectively. The measured specific heats of the nanofluids do not show appreciable difference within the range of the particle volume concentrations they investigated. The increase of heat transfer coefficient is 30% at 1% particle volume concentration and that leads to an enhancement of 10% in the Nusselt number.

Khullara and Tyagia [11] presented an examination to the potential of the nanofluid based concentrating solar water heating system (NCSWHS) as an alternative to those based on fossil fuels. They reported a quantitative assessment to evaluate the potential environmental benefits obtained from NCSWHS if substituted for those using fossil fuels. Their analysis shows a considerable emission reductions (2.2 x 103kg of CO_2/household/ year) and fuel savings can be achieved.

Saleh Ahmad [12] presented a simulation of one-dimensional mathematical model for the transient processes happening in liquid flat-plate solar collectors. Taking time-dependent thermo-physical properties and heat transfer coefficients in consideration and solving equations of the energy conservation for the glass cover, air gap between cover and absorber, absorber, working fluid, insulation, and the storage tank. The differential equations were solved using the implicit finite-difference method in an iterative scheme and executed using the MATLAB. He verified the proposed method, by experiment was designed and conducted for several days with variable ambient conditions and flow rates. The efficiency of the proposed method was confirmed by experimental verification. The analysis shows a very good agreement between the measured and the numerically predicted values for different running conditions and flow rates. He found after fifty minutes of running the test temperatures difference about 3 ^oC at solar irradiance of 849.6 (W/m^2) and flow rate 1.5 GPM and a 3.5 ^oC after an hour with solar irradiance of 891 (W/m^2) with the same flow rate.

Yousefi et al. [13] studied experimentally the effect of Al_2O_3–water nanofluid, as working fluid, on the efficiency of a tube in plate type solar collector. The particles weight fraction of nanoparticles was 0.2% and 0.4% with the dimension of 15 nm. For varied mass flow rate of nanofluid from 1 to 3 Lit/min. their results show that, using the nanofluids increase the efficiency by 28.3% for 0.2 wt% in comparison with water as absorption medium. The efficiency was calculated by the ASHRAE standard.

Colangelo et al. [14] studied experimentally the performance of flat solar thermal collectors using nanofluids as new heat transfer fluids. They investigated the nanoparticles sedimentation both in standard solar flat and modified ones made from transparent tubes by changing the cross section of the lower and top header of the panel to keep the constant axial velocity of the fluid. After different nanofluids testes on the panel prototype, water–Al_2O_3 was chosen as heat transfer fluid. They prepared All tested nanofluids in batch and measured the thermal conductivity and convective heat transfer coefficient prior of using as heat transfer fluid in the solar panel. They observed an enhancement in thermal conductivity and convective heat transfer coefficient at a concentration of 3 vol% was up to 6.7% and 25% respectively.

Gupta et al. [15] investigated the effect of using Al_2O_3-H_2O nanofluid as heat transfer fluid in a prototype direct absorption solar collector at different flow rates. Study was carried out with distilled water and 0.005% volume fractions of 20 nm size Al_2O_3 nanoparticles at three flow rates of 1.5, 2 and 2.5 lpm. Calculation of instantaneous efficiency of solar collector followed ASHRAE standard 93-86. They observed an enhancement in collector efficiency by 8.1% and 4.2% for 1.5 and 2 lpm flow rate of nanofluid respectively.

Very few experimental studies on the thermal performance evaluation of flat plate solar collector with nanofluids as working fluid are available. Especially on tube in plate type solar collector under actual outdoor condition. An attempt has been made in the present paper, to experimentally study the effect of Al_2O_3-H_2O nanofluid as a heat transfer medium on the efficiency of a tilted flat plate solar collector under outdoor condition. Effect of 0.5% nanofluid concentrations was considered on the collector due to its sensible influence and cost effectiveness and performance was also compared with di-ionized water.

2. Flat plate solar collector experimental set-up

As the schematic diagram illustrate the work of Flat plate solar collector shown in Figure 1. Solar radiation passes through glass cover to absorbing plate and tubes which painted with matt black painting to enhance the absorption of short-wavelength sun radiation and reduce long wavelength radiation loss from the absorbing surface. This Solar radiation converts to thermal energy transferred by a heat transfer fluid. The fluid circulates in a closed system with a tank and submersible water pump.

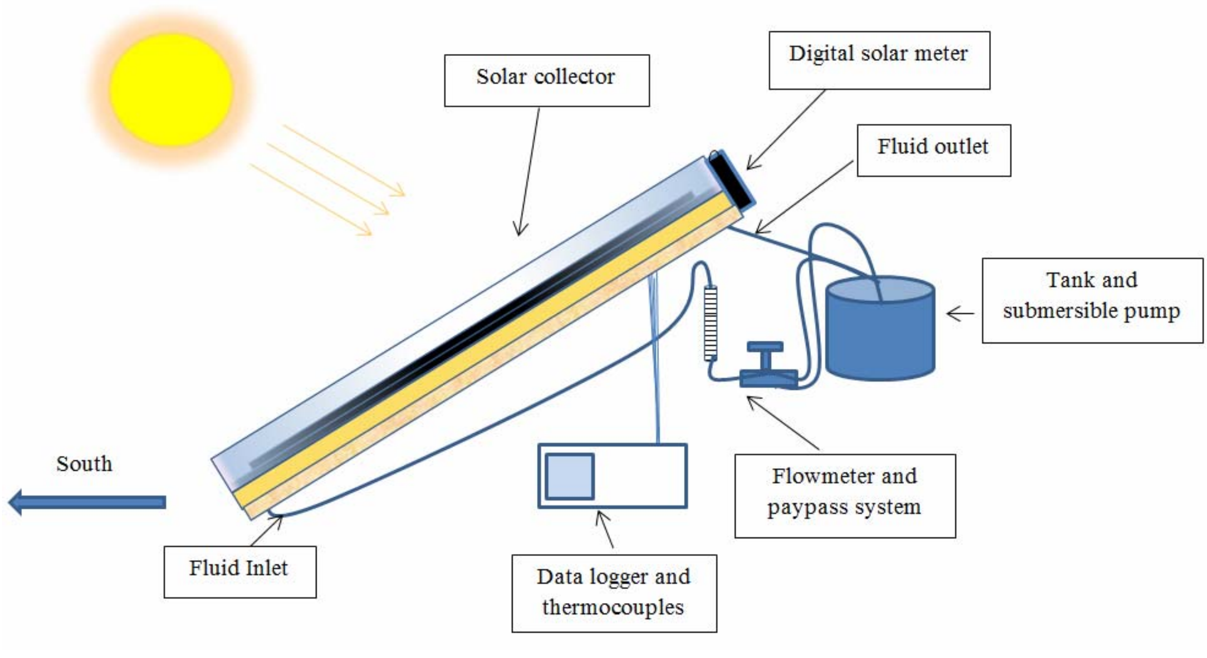


Figure 1. The schematic of flat plate solar collector

An experimental set up of Flat plate solar collector of size 1.04m x 0.64m has been developed as shown in Figure 2. Table 1 shows the components Specifications of the solar collector.

Figure 2. Experimental setup of flat plate solar collector

Table 1. The specifications of flat plate solar collector components

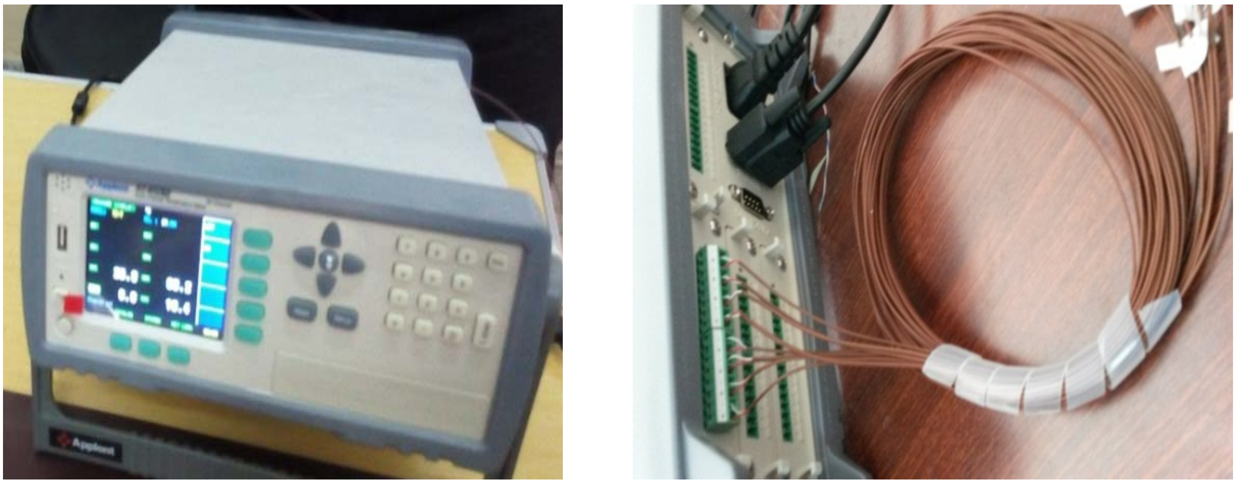
Component	Dimensions	Remarks
Collector	1.04mx0.64mx0.12m	Gross area=0.6656
Absorber plate	0.95mx0.526mx0.003m	Material: black painted stainless steel
Transparent cover	3mm thick	Material: window glass
header pipes	8mm inner diameter , 10mm outer diameter, 0.08m tube center to center distance 0.75m length,	Material: copper Number of tubes: six
Bottom insulation	0.045m thick	Material: glass wool
edges insulation	0.03m thick	Material: glass wool

2.1 Experimental apparatus and procedure

For current experimental study, a setup of flat plate collector was made in workshop and then erected at the roof top of Mechanical Engineering Department, Kufa University, an Najaf Alashraf (32.05° latitude and 44.25° longitudes). The collector was oriented due south (using a compass) with a tilt angle of 45°.

Photograph of experimental set up (Figure 2) show flat plate collector, tank and instruments used along Experiments. Specifications of the collector components used in Table 1. It simply consists of an absorber plate (0.95m long, 0.64m wide, 0.003m thick), mounted on a wooden box and insulated from bottom and edges of the box with a glass wool insulation to minimize conduction losses. Finley, the box closed from top with a sheet of glass to transmit about 90% of the incoming shortwave solar irradiation and transmitting none of the long wave radiation emitted outward by the absorber plate and to prevent convection losses with the environment.

Experimental test set up involves a solar collector, closed working fluid system and measurement devices. The working fluid system has a tank, a paypass pipes system and simple manual valves used to control flow rate of working fluid. The flow rate is measured with the help of flow meter (range 40-400 LpH, accuracy ±5%). A submersible pump circulates the collected fluid in the system. Eight T-type thermocouples were installed to measure collector inlet and outlet fluid temperatures, ambient, glass, tubes, absorber plate, and air gap between the plate and glass temperatures. The readings were collected and stored in a computer through a temperature meter (Make- Applent instruments, model- AT45xx, 8 channels, USB disk storage, Basic Accuracy 0.2% ±1° C). The software program of the temperature meter is AT45X_EN Software.exe. The temperature meter and thermocouples are shown in Figure 3.



(a) Temperature meter (b) Thermocouples type T

Figure 3. Temperature meter and thermocouples

The total solar irradiance measured in the plane which the collector stands using a digital solar power meter (Make-TES Electronical electronics, model- 1333, Range-1 to 2000 W/m^2, accuracy ±5 % of measurement). This manner removes cosine loss of the beam component since the collector is tilted from the horizontal. The digital solar meter is shown in Figure 4.

Figure 4. Digital solar power meter

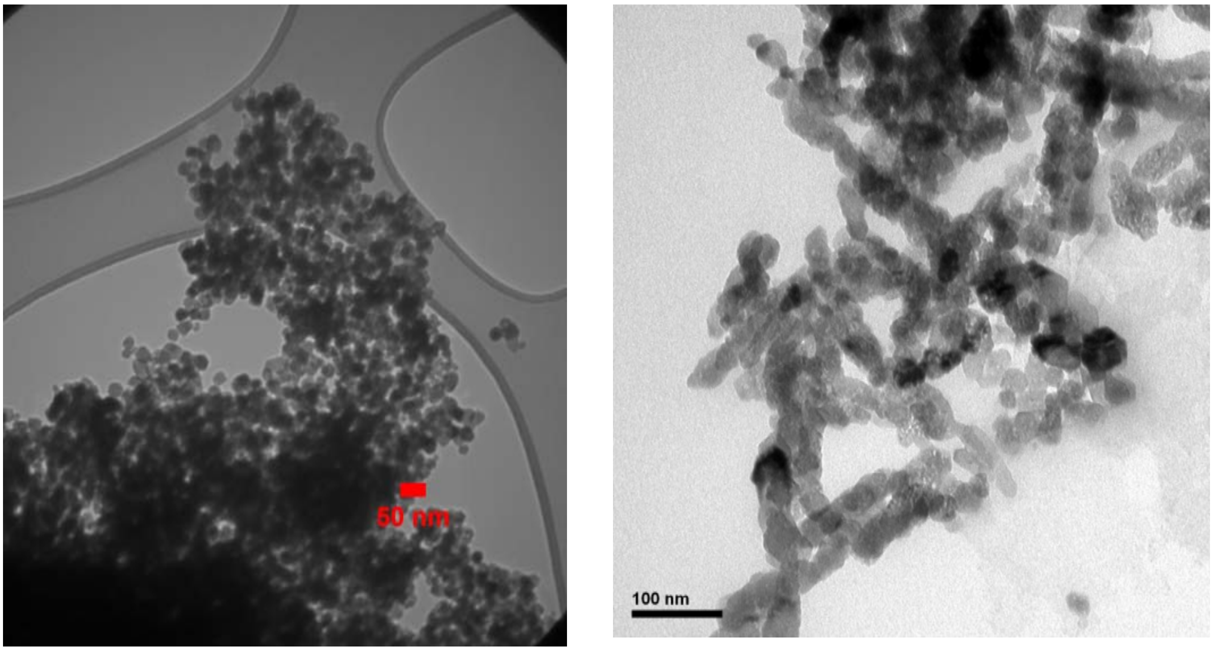
In addition to thermocouples measured temperatures an infrared camera (make-Flir systems, Model-E50) is used to take infrared images to the solar collector under testing. The camera is shown in Figure 5.

Figure 5. Infrared camera

2.2 Nanofluid preparation

Preparation of nanofluid with uniform dispersion and stability is necessary for enhancing heat transfer performance of conventional fluids. nanofluid must prepared in an orderly and protective method.

In this study ultrasonic vibration method is used for preparation of nanofluid. Dry powder from Al_2O_3 nanoparticles of 99.99% purity and average size of 20-40 nm (procured from US Research Nanomaterial, Inc. USA based company) are used with de-ionized water as base fluid in nanofluid preparation. Figure 6 shows the Transmission Electron Microscope (TEM) and scanning electron microscopy (SEM) analyzed images of the used (Al_2O_3) nanoparticles. Properties of the Al_2O_3 nanoparticles are tabulated in Table 2.



(a) TEM image of nano_Al_2O_3, size 20nm

(b) SEM image of nano_Al_2O_3

Figure 6. Analyzed images of transmission electron microscope (TEM) and scanning electron microscopy (SEM) of the used (Al_2O_3) nanoparticles

Table 2. Physical properties of Alumina (Al_2O_3) nanoparticles

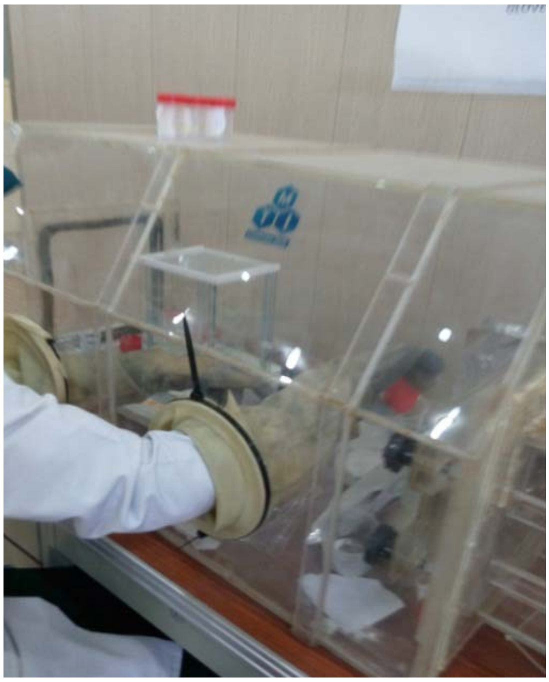
Al_2O_3 Content	99.99%
Crystal Form	Gamma
Size of particles	20-40 nm
Surface area per unit weight	10-30 m^2/g
Density	3890 kg/m^3
Morphology	nearly spherical

To weigh the Al_2O_3 nanoparticles very accurately a sensitive balance (make-Sartorius, model-224-1S, resolution-0.1mg) is used. Weighting of nanopowder is carried out in an acrylic vacuum glove box (Make-MTI corporation). As shown in Figure 7. The mass in grams of Al_2O_3 nanoparticles required for preparation of nanofluid with different volume concentrations is calculated using Equation (1), [16].

$$vol\% = \frac{m/\rho}{100mlwater + m/\rho} \tag{1}$$

where: m and ρ is mass (g) and density (g/cm^3) of the nanoparticles respectively. This equation calculates the mass of Al_2O_3 nanoparticles dispersed into 100 ml of water. A volume concentration of 0.5% was used in the study.

(a) the sensitive balance



(b) an acrylic vacuum glove box

Figure 7. The nanopowder mass evaluating instruments

Ultrasonic mixing was applied for one and half hour to disperse calculated amount of Al_2O_3 nanoparticles in de-ionized water using ultrasonic vibration mixer (Make- MTI corporation, model-SJIA, power-1200W, frequency-20 ±3 kHz,) as shown in Figure 8.

Figure 8. Ultrasonic cleaner apparatus for sonication process of Al_2O_3-water nanofluids

3. Results and discussions

Thermocouples are attached to the solar collector by putting the ball welded end of thermocouple wire in a direct contact with the surface wanted to estimate its temperature and covering this end with a high thermal conductivity dope to ensure the end insulating from environment and outside effects.
A sketch in Figure 9 and Table 3 illustrates the solar collector network of thermocouples distribution.

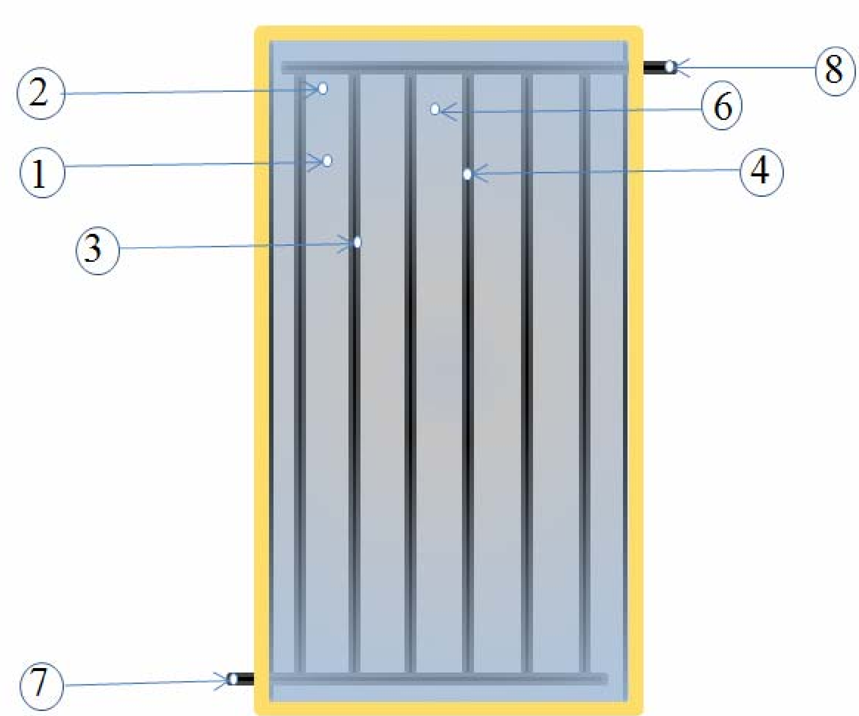


Figure 9.The solar collector network of thermocouples distribution.

Table 3.The solar collector network of thermocouples distribution in detailed location.

No.	location	notes
1	air gap between the plate and glass	
2	absorber plate	Thermocouple attached backside
3	Tube top surface	attached to second tube
4	Tube top surface	attached to forth tube
5	ambient	attached outside, not shown in figure above
6	Glass cover	attached inside collector
7	Inlet tube	
8	Outlet tube	

3.1 The water as working fluid (base case)

The Base case was experimented with di-ionized water on flat plate solar collector from 10 AM to 12 PM on May 29, 2015 with a maximum temperature of 44°C an average wind speed of 2.0mph. The flow rate of the working fluid was adjusted at 1 lpm, the solar collector was placed on the roof of Mechanical Engineering Department building. The inlet, outlet and all temperatures were measured every five seconds. Whereas the value of the solar radiation intensity was recorded as an average over 5 minutes intervals, the ambient temperature was with an average of about 42 ° C during the run with a small variation.

The measured data is presented in Table 4. As can be seen from the table the outlet temperature began to rise from inlet temperature as the water flows in pipes and collects thermal energy of solar radiation until that the difference between outlet and inlet temperatures reach its maximum value 10.7°C with the solar irradiance value of about 781 W/m^2 and an average of temperature difference is about 5.6 ° C. As observed from practical test when the solar irradiance decreased (because of passing cloud) the collector outlet temperature stopped increasing and decreased so the temperature difference reached from max value to 4.8°C and increased again as solar irradiance reaches about 847 W/m^2.

An infrared image shown in Figure 10, Is taken to the solar collector during the water test to show the real thermal distribution of the collector pipes and absorber plate.

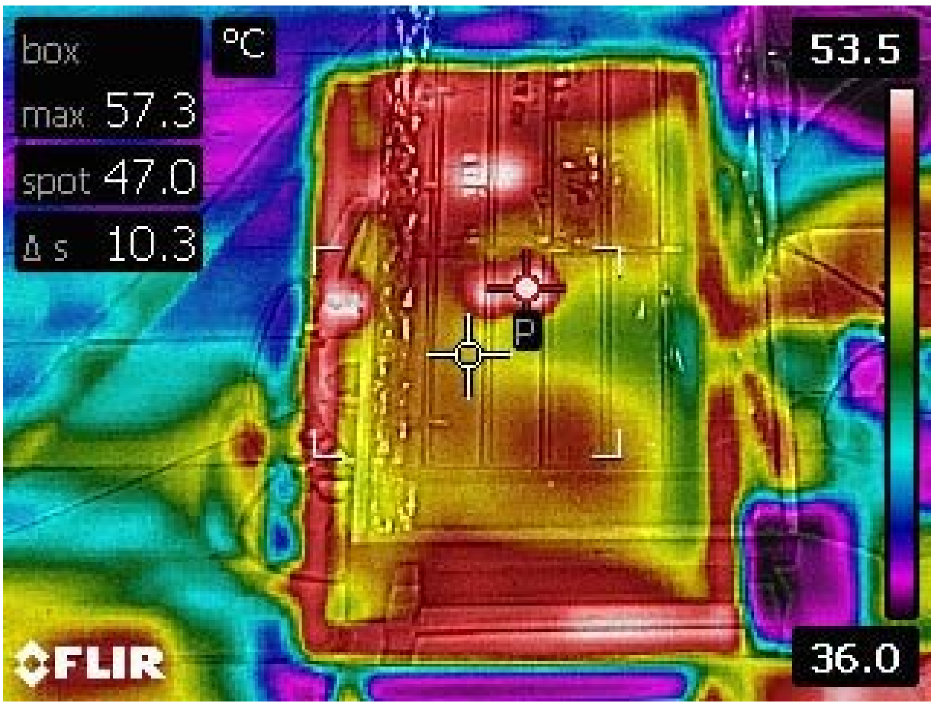


Figure 10. An infrared image of the solar collector with the water as working fluid

Table 4. The experimental results of the flate plate solar collector with the water as working fluid (base case)

TIME (minutes)	T1 [ºC]	T2 [ºC]	T3 [ºC]	T4 [ºC]	T5 [ºC]	T6 [ºC]	T7 [ºC]	T8 [ºC]	T8-T7 [ºC]	Solar radiation [W/m^2]
1	73.9	78.4	54.1	67	36.1	61	38.9	42.2	3.3	711.2
5	75.2	78.8	55.7	68.6	39.8	63	40.9	46.4	5.5	712.6
10	75.9	79.5	57	69.5	41.3	64.4	43.2	47.2	4	712.8
15	77.4	81.4	59.2	70.9	41	65	45.3	49.6	4.3	750
20	77.3	82.4	60.5	71.4	41.3	65.1	46.2	51.7	5.5	755.6
25	79.2	84.2	62.7	73.4	42.3	67	48.5	53.7	5.2	790
30	79.4	85.6	63.5	73.8	41.7	67.1	49.1	54.4	5.3	786.5
35	72	78.9	60.6	67.4	40.8	62.4	48.9	54.5	5.6	711.7
40	75.8	80.9	63.2	70.8	42.8	64.8	50.5	55.5	5	671.9
45	76.9	81.1	64.1	71.3	41.2	64.1	51.1	56.4	5.3	766.1
50	78.3	83.7	65.5	72.9	41.6	65.7	51.7	57.3	5.6	745.3
55	81.8	87.7	68.3	77.6	43	70.3	54	59.3	5.3	776.7
60	85.6	93.6	71.8	81.9	44.6	73.6	54.1	61.4	7.3	740
65	83.2	90	75	78.9	42.2	71.2	52.8	63.5	10.7	787.8
70	76.9	84.9	67.4	74.7	42.1	66.5	53.4	59.8	6.4	599
75	73.7	80.9	65.5	70.9	40.7	64.6	52.7	59.4	6.7	423
80	72.4	78.8	64.7	68.9	40.9	62.5	52.8	58.4	5.6	493.7
85	72.7	78.4	65.1	70	43	62.9	53.3	58.5	5.2	590.4
90	70.6	77.1	64.1	67.8	42.5	62	52.6	58.4	5.8	411.2
95	78.1	83.3	67.9	74.4	44.2	65.8	54.1	58.9	4.8	846.8
100	70.7	77.7	64.2	68.3	41.4	64.7	53.4	59.1	5.7	326.7
105	66.2	71.6	61.6	63.6	40.9	58.8	52.5	58.2	5.7	324.9
110	64.7	69.1	60.6	62.3	41.6	56.7	52	57.1	5.1	456.2
115	68.3	71.8	62.4	65.3	42.4	58.1	52.5	57.3	4.8	684.7
120	73.3	77.4	65.3	69.8	44.6	61.9	53.1	58	4.9	882.9

3.2 The nanofluid Al_2O_3-water as working fluid

Al_2O_3 nanoparticles are mixed in base fluid di-ionized water to get nanofluid of 0.5%volume fraction concentration and experiment is performed to determine the effect of using the nanofluid as a working fluid on the thermal performance of a flat plate solar collector. Same conditions and place of the base case was selected as the test from 10 AM to 12 PM on June 7, 2015. With a maximum temperature of 44°C and an average wind speed of 2.0mph. the ambient temperature was with an average of about 42.5°C. The flow rate of the working fluid was adjusted same at 1 lpm.

The measured data is shown in Table 5. As can be seen from the table the outlet temperature began to rise from inlet temperature as the nanofluid flows in pipes collecting the solar thermal energy. the maximum difference between outlet and inlet temperatures is 14.4°C were the solar irradiance value of about 788 W/m^2 and an average of temperature difference is about 7.8°C. Observetions from practical test show that the nanofluid outlet temperature and temperature difference increases higher than that of water. This can be ascribed to the enhancement of thermal conductivity of nanofluid due to adding Al_2O_3 nanoparticles to water.

As in water test an infrared image shown in Figure 11. is taken to the solar collector during the nanofluid test to show the real thermal distribution of the collector pipes and absorber plate.

Table 5. The experimental results of the flate plate solar collector with the nanofluid the nanofluid Al_2O_3-water as working fluid

TIME (minutes)	T1 [ºC]	T2 [ºC]	T3 [ºC]	T4 [ºC]	T5 [ºC]	T6 [ºC]	T7 [ºC]	T8 [ºC]	T8-T7 [ºC]	Solar radiation [W/m^2]
1	76.7	84.5	83.7	87	39.9	63.8	37.1	41.3	4.2	660.7
5	76.5	84.9	83.8	87.4	39.4	64	44.3	47.8	3.5	637
10	89.4	106.7	75.3	82	40.4	78.2	48.2	50.4	2.2	770.1
15	88.4	99.2	69.9	73.3	40.8	76.5	49.9	54.6	4.7	825.1
20	84.5	94	68.8	71.4	40.4	73.9	51.5	58.7	7.2	765.1
25	76.4	85.6	69.3	68.2	41.1	66.4	55.8	61.9	6.1	774.2
30	78	86	77.5	76	41.8	64.3	58.3	65.2	6.9	780.3
35	83.8	93.3	76.4	77.5	41.7	72.3	60.4	70.1	9.7	735
40	82.6	93.1	81.6	86.4	42.7	73.2	64.5	75	10.5	775
45	82.4	95.9	77.9	85.2	43.4	74.3	66.2	76.3	10.1	765
50	84.8	92.7	78.1	79.4	42.2	73.8	67.4	78.2	10.8	777.6
55	81.7	93.2	78.5	84	42.6	73.8	68.2	78.8	10.6	780
60	81.7	93	81.5	87.4	41.9	74.4	68.5	80.7	12.2	793
65	82.1	93.7	78.2	84	42.7	74.2	69.5	83.9	14.4	781.4
70	83.6	96.9	87.3	90.4	43.2	74	69.1	79.4	10.3	783.4
75	84.2	97.5	89.1	91.8	43.7	74.5	69.3	78.2	8.9	698
80	84.3	97.4	89	91.7	43.7	74.5	69.5	77.9	8.4	740.5
85	84.7	97.8	84.3	91.6	43.7	74.7	68.9	76.7	7.8	668.2
90	84.3	97.5	89.3	92	43.5	74.5	68.6	75.3	6.7	554.8
95	84.5	97.6	89.6	92.3	43.6	74.6	67.8	74.6	6.8	480
100	84.8	97.7	86.2	92.5	43.9	74.7	67.5	74	6.5	390.7
105	84.3	97.4	89	91.7	43.7	74.5	66.8	73.2	6.4	702
110	84.3	97.4	88.8	91.5	43.5	74.4	66.5	72.9	6.4	816.8
115	84.3	97.3	88.6	91.4	43.9	74.3	66.2	71.8	5.6	738.7
120	83.9	97.3	88.5	91.2	43.7	74.3	66.3	71.4	5.1	745.3

Figure 11. An infrared image of the solar collector with Al_2O_3 nanofluid as working fluid

4. Conclusion

The effect of using Al_2O_3-water nanofluid on the flat plate solar collector has been studied experimentally. The volume fraction of nanoparticles has been selected as 0. 5%. The collector outlet inlet temperatures difference increased with nanofluid than pure water for 1 lpm flow rates. Both the maximum and average temperatures difference observed to be increase when Al_2O_3-water nanofluid has been tested.

The solar radiation intensity has been recorded to observe its effect on the solar collector. Significant enhancement in solar radiation absorption and collector temperatures difference makes nanofluids as an appropriate heat transfer fluid for solar collectors and can be make a Significant develop in the solar renewable energy applications.

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