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NUMERICAL AND EXPERIMENTAL STUDY OF HEAT TRANSFER ENHANCEMENT FOR DIFFERENT BASE FLUIDS USING AL_2O_3 ON F.P.S.C UNDER SOLAR SIMULATION

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ABSTRACT

In this research paper, the solar irradiance of flat plate solar collector was evaluated using experimental and numerical analysis. In the experiment, an automatic solar simulator was designed and built to simulate the solar irradiance. The simulator was controlled by an Arduino board. The light source and fabrication of the simulator were used for a wide range of testing and the comparison was made between different cases. The test was performed on a flat plate double glazing solar collector with different base fluids; ethylene glycol (EG), glycerine, and water. To enhance the heat transfer, Al_2O_3 nanoparticles having a diameter of 20 nm were added. In order to investigate the effect of volume fraction on the heat absorption, three-volume fractions, 0.2%, 0.45, and 0.6%, were used in this study. Laminar flow was considered with a flow rate of 1 L/min. Solar irradiance was measured from 11:00 to 13:00 on September 25th, 2016. COMSOL 5.2a was used in a numerical analysis of flat plate solar collector. A good agreement between numerical and experimental for all cases was observed. The maximum temperature difference between inlet and outlet was found when the (water/ Al_2O_3) was used as a working fluid at a volume fraction of 0.6%.

KEYWORDS: Flat plate solar collector, solar simulator, Base fluids, Nanoparticles, volume fraction Al_2O_3, COMSOL.

1. INTRODUCTION

Finding other resources to produce energy rather than relying on conventional fossil fuels are very important for many reasons. First, economic prospects are very important in energy production, reducing the cost of producing energy can improve the economy of a country or a company. Second, it has been relied widely on fossil fuels in energy production in the last two centuries. Human daily uses of fossil fuels are greater than those compensated from geological processes (Hussein et al., 2014). So, a large amount of fossil fuels has been spent to produce energy. Thus, the amount of fossil fuel reserves is decreasing day by day. Finally, for environmental concerns, many countries have set regulations to produce energy with lower impact on the environment. For all the aforementioned reasons, it is necessary to find alternatives to fossil fuels. Solar energy has been used successfully instead of conventional fossil in many fields. Solar power is considered the cleanest and most reliable form of renewable energy. In solar systems, sun rays are converted into heat energy or electricity by photovoltaic (PV) panels (Kandasamy et al., 2014) and (Shan et al., 2014). The amount of energy that can be achieved from sun rays is more than enough for human use throughout the year (Choi, 1995). However, heat transfer in solar PV panels needs to be improved to ensure the highest amount of sun's energy converted to another form of energy (Beckman, 1991).

Nanofluid is a mixture of a base fluid with nanoparticles. Nanoparticles are dispersed in a base fluid for heat transfer enhancement (Zawrah et al., 2015). The usual size of the nanoparticles is below 100 nm. The conventional base fluids used in solar systems are water, (EG), and oil. Nanoparticles that are usually used in solar systems are made of metals, oxide, carbide, or carbon nanotubes (Demirbas et al., 2006). There are two main advantages of nanofluids to be used in solar systems. First, it is used to increase the heat transfer, which it is, in consequence, lead to increase the thermal conductivity of nanofluids. The other advantage is to improve the absorption properties of nanofluids (Tooraj et al, 2012). The effect of (Al_2O_3/water) nanofluid, as working fluid, on the performance of a flat-plate solar collector was investigated experimentally. The used weight fraction was (0.2%, and 0.4%) and the nanoparticles size was (15) nm. The flow rate of nanofluid was in the range of 1 to 3 L/min. ASHRAE standard was used to calculate the efficiency. In comparison to using water only as a working fluid, adding 0.2% wt nanoparticles to water led to increasing the efficiency by 28.3%. Saleh et al., 2012 employed implicit finite difference method and wrote a MATLAB code containing the necessary equations and information of this method to simulate the flat plate solar collector. A transient process was assumed in this research paper. They found that the temperature difference between inlet and outlet was 3 °C at the solar irradiance of 849.6 W/m^2 and flow rate 1.5 GPM and a 3.5 °C at a solar irradiance of 891 W/m^2 with the same flow rate. (Gupta, H. K.et al, 2015) investigated the effect of using (Al_2O_3/water) nanofluids as heat transfer fluid with various flow rates, 1.5, 2, and 2.5 L/min, and volume fractions of 0.005%. The nanoparticles size was 20 nm. The area of solar collector was 154 x 90 cm^2 and absorber area was 144 x 80 cm^2. The results showed that the enhancement in collector efficiency for 1.5 and 2 L/min flow rate of nanofluid was 8.1% and 4.2% respectively. Jamal-Abad.M.T.et al 2013 examined the effect of nanoparticles on the base fluid by using (Cu–water) on the flat-plate collector by investigation experimental performance. The volume fraction was 0.05% and 0.1 %, and the nanoparticles average size was (35 nm). The collector area was 670 cm^2. The results showed that the efficiency of the collector at 0.05 % wt. is 24% more than that of the pure base fluids and the maximum efficiency was observed during the solar noon for all samples.

2. EXPERIMENTAL WORK

In this work, flat plate solar collectors were tested using nanofluid under automatic solar simulator and it was designed and built to simulate the solar irradiance which is controlled by Arduino board. The measured solar irradiance was recorded from 11:00 to 13:00 on September 25th, 2016 at a latitude of 32.546° and a longitude of 44.237° (Karbala - Hindayai city). The rig was tested under a controlled environment. Collectors are made of aluminum and they were painted black to enhance heat absorption (Khudhair, 2012) and double glazing cover type window glass having thickness 0.04cm. The flat plate solar collector is insulated from all sides. This work includes studying the effect of volume fractions of nanoparticles on base fluid. Table 1 shows the specifications of the solar collector using the solar power meter device to measure solar irradiance, an anemometer to measure wind speed, thermometer (data logger by a computer), and thermocouple type k to measure temperature from different locations. All measuring instruments were calibrated. The schematic experimental rig system is shown in Fig. 1 and the photograph of the experimental rig is shown in Fig. 2.

Table 1. The specifications of solar collector

No.	Components	Remarks
1	Collector	The dimension of the collector is (width 70cm, length 100cm, and thickness 14.8cm).
2	Absorber plate	Made of aluminum, the dimensions are (80cm length, 50 cm width, and 0.02cm thickness).
3	Header	The header has two pipes, the inner diameter is 2.3cm, the thickness is 0.02 cm, and the length is 62 cm.
4	Riser	The risers own six pipes, the inner diameter is 1 cm and the thickness is 0.02 cm and the length is 64 cm.
5	Cover	The number of covers is two glass window types having a thickness of 0.04 cm.
6	Painted	The plate was painted black type (Matt 890) with 50% by weight river sand.
7	Insulation	The collector is insulated from all sides with 10 cm insulator, and the bottom is 9 cm.
8	Tilt angle	The tilt angle of heat flux is (22°).

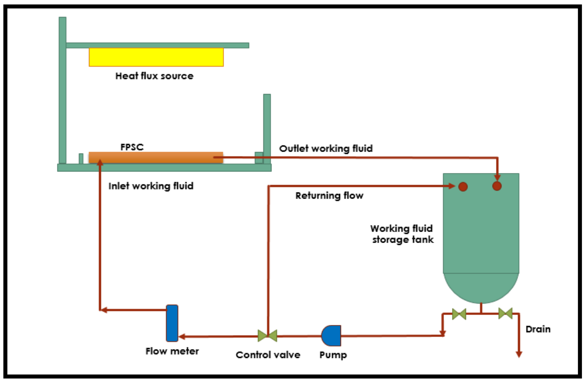

Fig. 1. The schematic experimental rig.

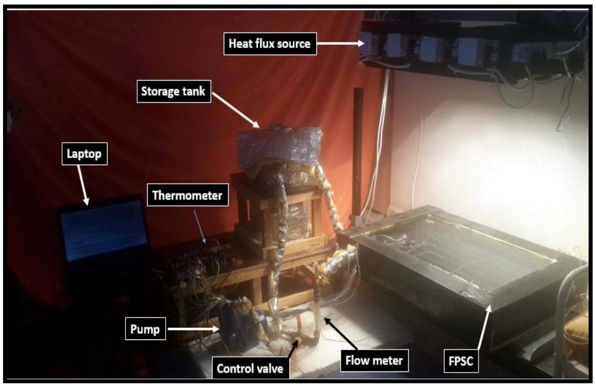

Fig. 2. The photograph experimental rig.

2.1. Nanofluids Preparation

Nanofluid used in this work has been prepared by following two steps. Nanoparticle powder (Al_2O_3) was added to the base fluid (EG, glycerine, and water) with volume fractions of 0.2%, 0.4%, and 0.6%. Physical properties of Al_2O_3 are given in Table 2. In the first step, the mixture of Al_2O_3 and the base fluid was placed in a magmatic stirrer for 30 mins. In the second step, the mixture was put in ultra-sonication having a power of 1200W for 150 mins as shown in Fig. 3 (Khanafer, 2011).

Fig. 4 shows the scanning electron microscopy (SEM) image of Al_2O_3 and Fig. 5 shows the X-ray diffraction (XFD) of Al_2O_3 nanoparticles.

Table 2. Physical properties of Al_2O_3.

Properties	Al_2O_3
Crystal Form	Gamma
Purity	99+ %
Average particles Size	20 nm
Morphology	Nearly spherical
True density	3.89 g/cm^3
Specific heat capacity	880 J/kg.K
Color	White

Fig. 3. The ultrasonic crasher cell.

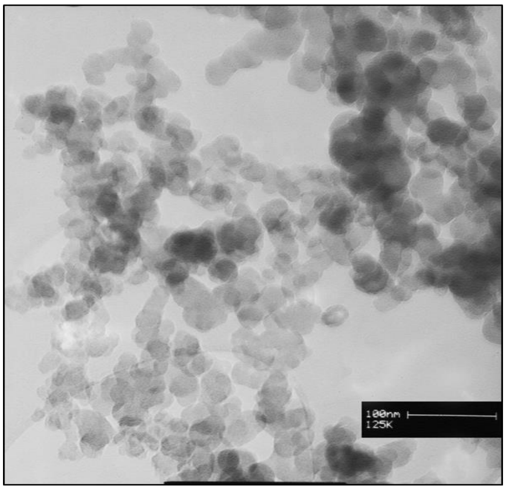

Fig. 4. The SEM of Al_2O_3Nanoparticles.

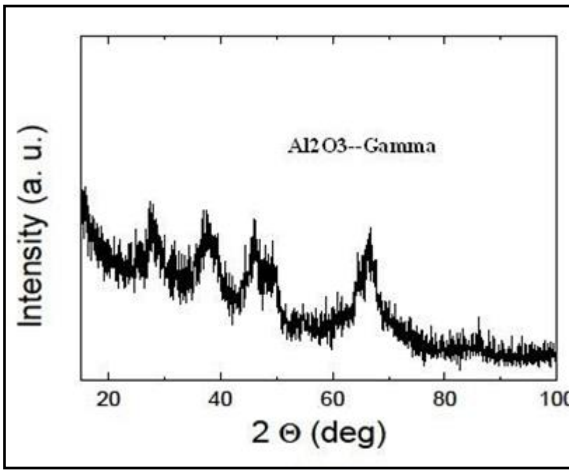

Fig. 5. X-Ray Al_2O_3-gamma Nanoparticles.

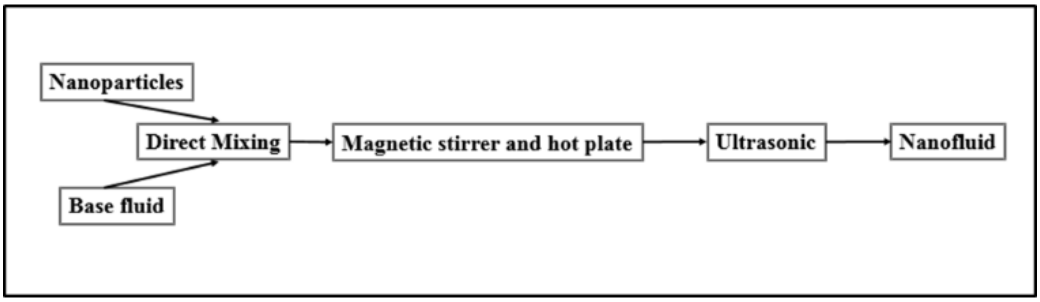

Fig. 6. Two-step preparation process of Nanofluids.

Equations (1) and (2) were used to calculate the amount of Al_2O_3 added to the base fluid (Duan, 2012).

$$\%\emptyset = \frac{V_{np}}{V_{np}+V_{bf}} \quad (1)$$

$$m_{np} = \rho_{np} V_{np} \quad (2)$$

Where: m and ρ is mass (g) and density (g/cm^3) of the nanoparticles respectively

Table 3. The Base fluids specification.

Physical Properties	EG	Glycerine	Water
Thermal Conductivity ($W/m^2.k$)	0.252	0.286	0.613
Density (kg/ m^2)	1111.4	1259.9	998.2
Viscosity (kg/m.s)	0.0157	0.799	0.001003
Specific Heat (J/kg.k)	2415	2427	4182

3. NUMERICAL INVESTIGATIONS

The 3D model of flat plate collector generated using COMSOL 5.2a software. The mesh of the 3D model is shown in Fig. 7.

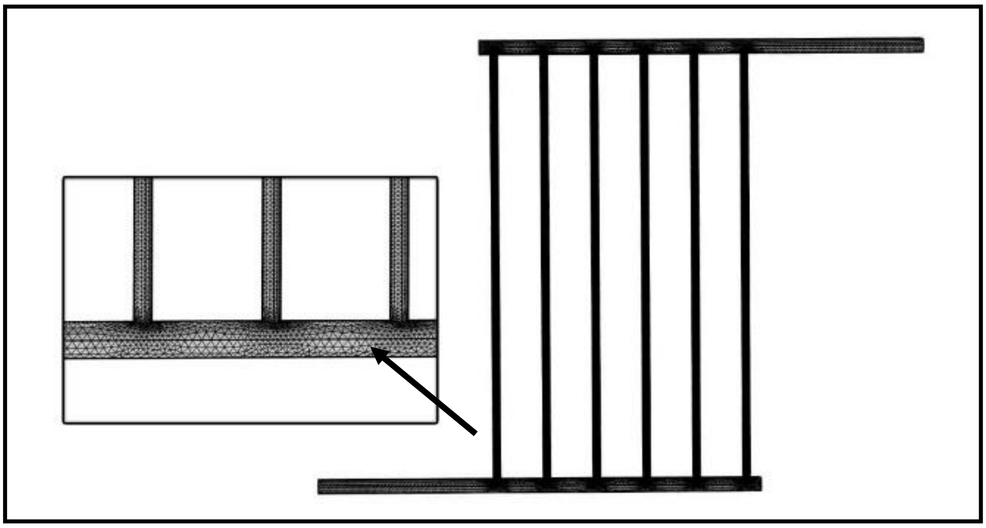

Fig. 7. Meshing the geometry.

3.1. Boundary Condition and Assumptions

The numerical results of flat plate solar collector were collected from COMSOL of interface between laminar flow and heat transfer in the fluid. Different volume fractions of nanoparticles in the study were used (0.2%, 0.4%, and 0.6%) and the flow rate of the base fluid is 1 L/min under laminar flow. The temperature was measured. No-slipping of wall and unsteady state flow within 120 mins, each step 5 min were considered in this study.

Assumptions:

- The flow is unsteady and has laminar, and incompressible flow.
- The outlet boundary condition is an outflow.
- The thermal physical properties of nanofluids, base fluids, absorber plate, and tube are dependent on temperature.

4. RESULTS AND DISCUSSIONS

The experimental work has been performed on a flat plate solar collector and tested under laminar (1L/min) with nanofluids. The main goal of doing the experiment is to validate the numerical results that were achieved from COMSOL. A good agreement between numerical and experimental for all cases was found.

4.1. Incident Solar Radiation Results

The solar irradiance was measured using digital solar power meter device, model-1333, Range-1 to 2000 W/m^2. The experiment was done on September 25th, 2016 and data were collected from 11:00 to 13:00. Fig.8 shows the recorded data.

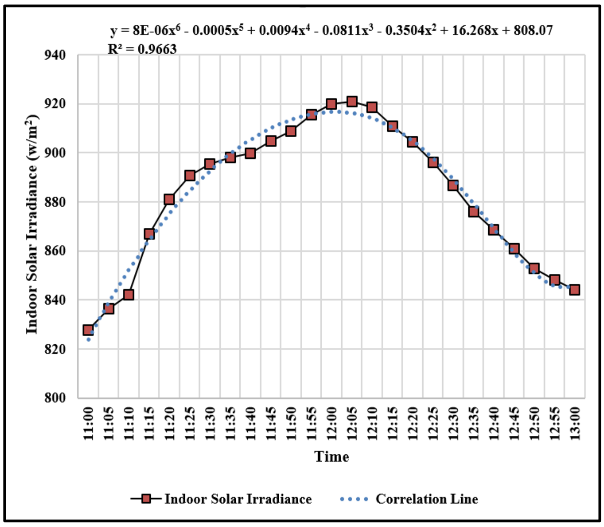

Fig. 8. The incident solar radiation

4.2. Temperature Difference Result

- The difference in temperature of working fluid between inlet and outlet was measured. It was found that adding nanoparticles and increasing the volume fraction led to enhance the heat transfer.
- The absorption of heat is highly dependent on the physical properties of base fluid.
- Adding nanoparticles to the base fluid led to enhance the heat transfer because of the physical properties of these particles are better than those of base fluids.

The following cases show the comparison between experimental and numerical results.

Case No.1 (Water and Al_2O_3):

Adding Al_2O_3 nanoparticles enhanced the heat transfer performance of the working fluid (water). It was observed that increasing the volume fraction of nanoparticles increased the temperature difference between inlet and outlet. Increasing the time of exposing the solar collector to sun lead to increase the temperature difference between input and output (70 mins).

The experimental and numerical comparisons for (water/Al_2O_3) are shown in Figs. below.

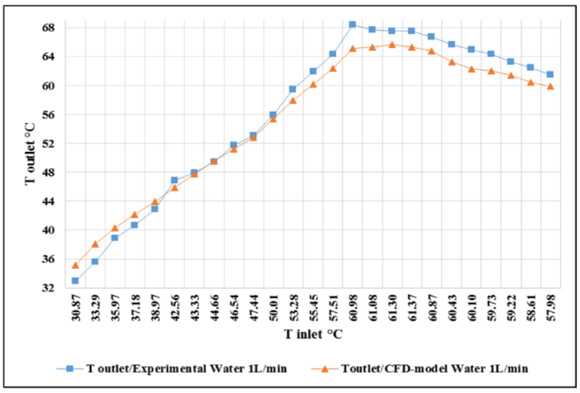

Fig. 9. The validation between Experimental (Water) and CFD-Model.

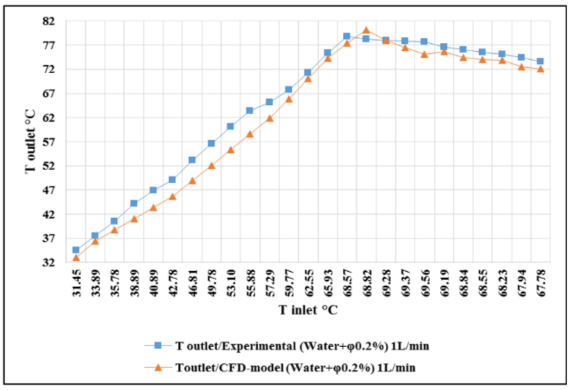

Fig. 10. The validation between Experimental (water+0.2%) and CFD-Model.

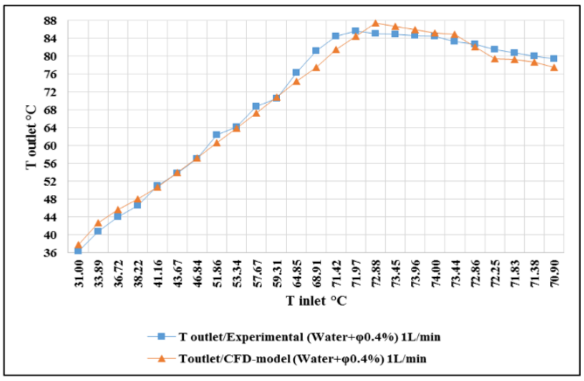

Fig. 11. The validation between Experimental (water+0.4%) and CFD-Model.

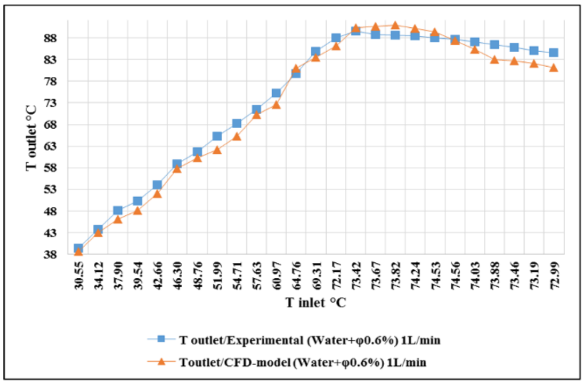

Fig. 12. The validation between Experimental (water+0.6%) and CFD-Model

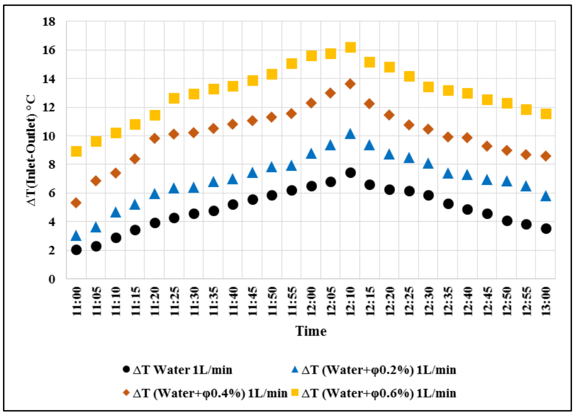

Fig. 13. The comparison between working fluids (water).

Table 4. The maximum experimental ΔT (inlet-outlet) and the error.

Case No.1	Max. ΔT °C	Error Range %
Water	7.466	-5.668 to +6.920
Water / Al_2O_3 : φ=0.2%	10.173	-7.174 to +4.546
Water /Al_2O_3: φ=0.4%	13.644	-4.529 to +5.008
Water /Al_2O_3: φ=0.6%	16.213	-8.774 to +6.271

Case No.2 (Glycerine and Al_2O_3):

Adding Al_2O_3 nanoparticles enhanced the heat transfer performance of working fluid (glycerine). It was observed that increasing the volume fraction of nanoparticles increased the temperature difference between inlet and outlet. Increasing the time of exposing the solar collector to sun lead to increase the temperature difference between input and output (70 mins).

The experimental and numerical comparisons for (glycerine/Al_2O_3) are shown in Figs. below.

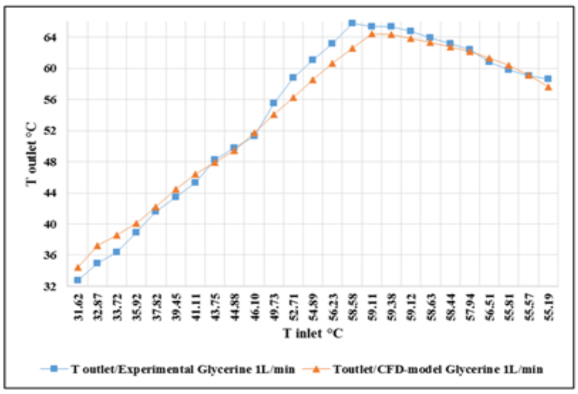

Fig. 14. The validation between Experimental (Glycerine) and CFD-Model

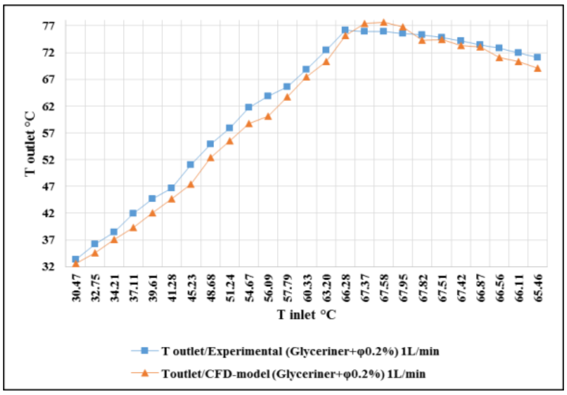

Fig. 15. The validation between Experimental (Glycerine+0.2%) and CFD-Model

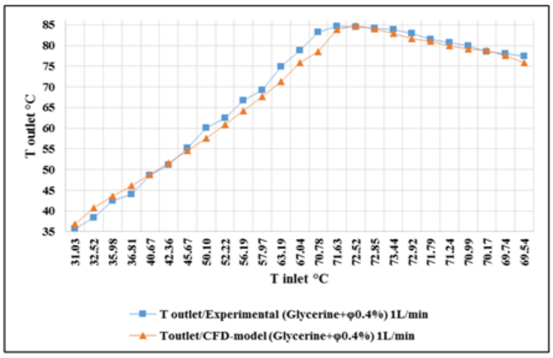

Fig. 16. The validation between Experimental (Glycerine+0.4%) and CFD-Model

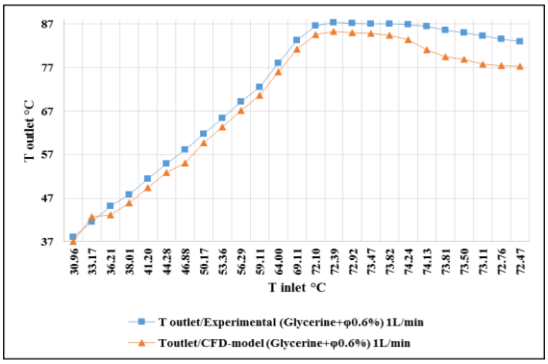

Fig. 17. The validation between Experimental (Glycerine+0.6%) and CFD-Model

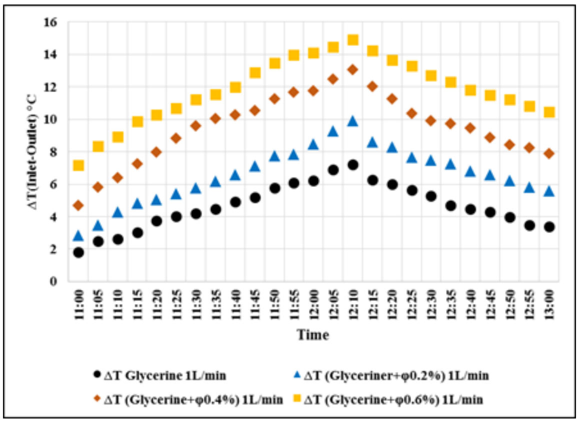

Fig. 18. The comparison between working fluids (Glycerine)

Table 5. The maximum experimental ΔT (inlet-outlet) and the error

Case No.2	Max. ΔT °C	Error Range %
Glycerine	7.221	-5.209 to +6.169
Glycerine/Al_2O_3: φ=0.2%	9.934	-6.015 to +3.772
Glycerine/Al_2O_3: φ=0.4%	13.088	-6.004 to +5.928
Glycerine/Al_2O_3: φ=0.6%	15.909	-5.048 to +7.887

Case No.3 (EG and Al_2O_3):

Adding Al_2O_3 nanoparticles enhanced the heat transfer performance of working fluid (EG). It was observed that increasing the volume fraction of nanoparticles increased the temperature difference between inlet and outlet. Increasing the time of exposing the solar collector to sun led to increase the temperature difference between input and output (70 mins).

The experimental and numerical comparisons for (EG/Al_2O_3) are shown in Figs. below.

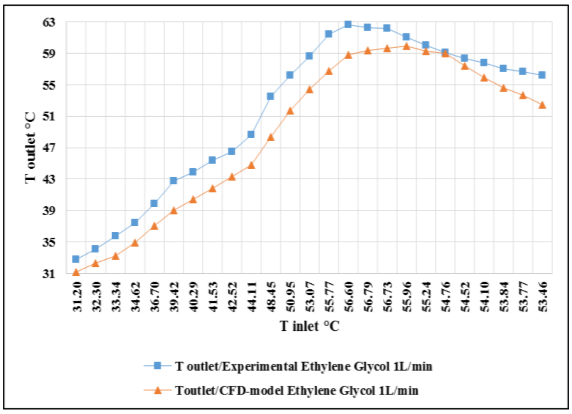

Fig. 19. The validation between Experimental (EG) and CFD-Model

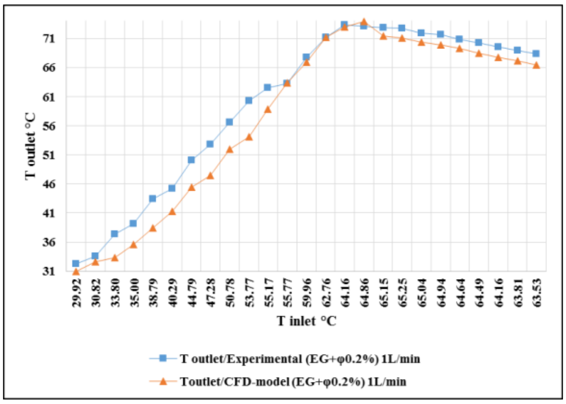

Fig. 20. The validation between Experimental(EG+0.2%) and CFD-Model

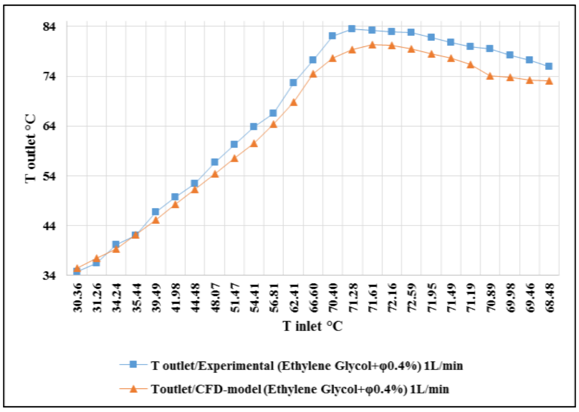

Fig. 20. The validation between Experimental(EG+0.4%) and CFD-Model

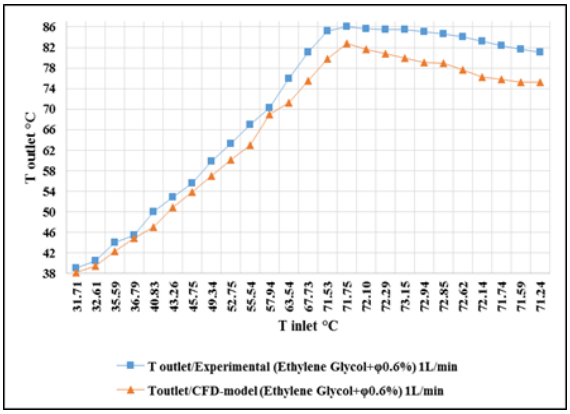

Fig. 22. The validation between Experimental(EG+0.6%) and CFD-Model

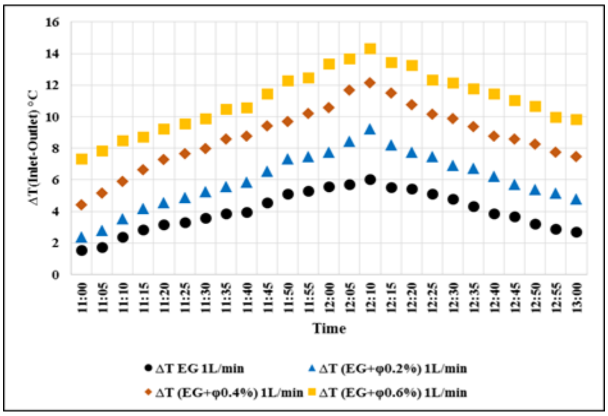

Fig. 23. The comparison between working fluids (EG).

Table 6. The max. Experimental ∆T (inlet-outlet) and the error

Case No.3	Max.∆T °C	Error Range%
EG	6.051	-3.985 to +4.873
EG/Al_2O_3: φ=0.2%	9.214	-4.893 to +5.544
EG/Al_2O_3: φ=0.4%	12.654	-8.351 to +1.791
EG/Al_2O_3: φ=0.6%	15.343	-7.269 to +5.360

5. CONCLUSION

Water showed better heat transfer performance than other working fluids because the thermal conductivity of water is greater than other working fluids used in this study.

Other observations are shown below:

- The physical properties of base fluids were enhanced by adding nanoparticles because the physical properties of nanoparticles are better than those of base fluids.
- Nanofluids showed better temperature difference between outlet and inlet than using base fluids alone. Also, increasing the volume fraction of nanoparticles led to an increase in temperature difference.
- The numerical CFD simulation can be utilized successfully to estimate the outlet temperature of the flat plate solar collector. A comparison was made between numerical and experimental results. A good agreement between experimental and numerical results was observed. A maximum discrepancy (8.77%) was found when (water / Al_2O_3) was used at a volume fraction of 0.6%.
- The solar simulator device is used for a wide range of testing and to ensure the comparison to be valid between different cases.

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