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Research Article

Numerical investigation of direct absorption evacuated tube solar collector using alumina nanofluid

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ABSTRACT

Direct absorption evacuated tube solar collectors are a new type of collector that has great potential to use in a solar system. In the present work, energy analysis of the direct absorption evacuated tube solar collectors employing Al_2O_3 nanoparticles is investigated numerically. A three-dimensional computational fluid dynamics simulation model is developed in ANSYS-Fluent software. The working fluids which are selected in this study are Al_2O_3 nanoparticles dispersed in water and EG. The effect of the two volume fractions (0.04% and 0.06%) of the nanofluid is investigated on thermal performance of the DAETC. In addition, the temperature distribution of the system is examined based on different volume fractions of the nanofluids. The results show that the outlet temperature difference of 0.04% Al_2O_3/EG is improved by 19.34% with respect to 0.04% Al_2O_3/water and for 0.06% Al_2O_3/EG is improved by 16.45% with respect to 0.06% Al_2O_3/water nanofluid, respectively. The results also reveal that the collector efficiency of 0.04% Al_2O_3/water, 0.06% Al_2O_3/water, 0.04% Al_2O_3/EG, and 0.06% Al_2O_3/EG nanofluids are 69.77%, 71.39%, 66.68%, and 69.43%, respectively. The 0.06% Al_2O_3/water and 0.06% Al_2O_3/EG nanofluids have the highest collector efficiency and outlet temperature difference, respectively.

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INTRODUCTION

Energy demand is one of the main problems which are facing nowadays [1]. Among energy sources, renewable and clean energy has been considered due to the availability and lack of pollution. Solar energy is one of these essential resources that has numerous benefits. Solar thermal systems are widely utilized for capturing and converting solar energy to thermal energy. Conventional solar collectors have relatively high heat losses [2]. In the 1970s, volumetric solar collectors, also known as direct absorption solar collectors (DASC), were introduced in an effort to increase solar collector efficiency [3].

Various researches have been done on the subject of DASCs [2-4]. Gorji and Ranjbar [5] investigated a two-dimensional computational fluid dynamics simulation for

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different water-based nanofluids. They found that the thermal efficiencies are increased by 33-57% adding nanofluids.

Hooshmand et al. [6] studied a DASC using SiC/water nanofluid and porus foams experimentally. Through the addition of the porous foam and the nanoparticles, the thermal efficiency increased by a maximum of 14% and 37%, respectively. Hazra et al. [7] carried out an experimental work that considered the application of the carbon black/ethylene glycol (EG) nanofluid in the DASC. They concluded that 15 ppm carbon black/EG nanofluid improved efficiency by 27.90% with respect to using EG alone. Esmaeili et al. [8] used CuO nanofluid and metal oxide foams in the flat-plate DASC. Results indicated that employing CuO nanofluid and metal oxide foam improved the thermal efficiency by up to 26.8% and 23.8%, respectively.

The most common solar devices for low-temperature applications are flat-plate solar collectors; in contrast to evacuated tube solar collectors (ETCs), their efficiency and outlet temperatures are lower. Therefore, it is known that evacuated tube solar collectors are more beneficial than flat-plate collectors [9-10]. An experimental research was done by Kedar et al. [11] using an evacuated tube solar collector for solar desalination. They concluded that 27-28 lit/day of water were obtained, and the performance of the system was improved by incorporating this type of collector. Henein et al. [12] examined a performance of the ETC by considering MgO/MWCNT nanofluid as a working fluid. The results showed that the thermal energy absorbed improved from 240W to 495W using MgO/MWCNT nanofluid instead of water alone. Tong et al. [13] used different nanofluids in a ETC to investigate the energy and exergy efficiency of the system. According to the following, by using 0.01 vol%-MWCNT nanofluid, the ETC demonstrated the maximum energy and exergy efficiency, which was 33.1% higher than water. Moreover, Thota et al., [14] carried out an experiment in order to study the thermal efficiency of the ETC using MWCNT/water nanofluid. It is deduced that the maximum thermal efficiency of the ETC is 64.13% at flow rate of 1.4 LPM and 0.1% volume fraction.

Kasaeian et al. [15] examined the efficacy of the two types of nanofluids (silica and carbon nanotube) in a parabolic trough collector (PTC). They concluded that the best volume fraction for silica and carbon nanotube is 0.4 and 0.5, respectively. Hosseini and Dehaj [16] conducted an experimental investigation in a direct absorption evacuated tube collector which compared the optical characteristics and colloidal stability of 0.005%, 0.01%, and 0.02% volume fractions of Fe_2O_3 and Fe_3O_4 nanofluids. The collector results showed that the Fe_2O_3 nanofluids outperformed the Fe_3O_4 nanofluids in terms of improving energy conversion. In addition, another experimental work was done by Zheng et al. [17] scrutinizing PTC by using ferrous-ferric oxide/water nanofluids. According to the finding, compared to deionized water, a nanoparticle concentration of 0.20 wt% maximized the thermal performance of the collector. Moreover, Ram et al. [18] studied a PTC collector incorporating CuO/water nanofluid. It has been concluded that the efficiency of the collector increased by inserting different concentrations (0.05%, 0.075%, and 0.1%) of CuO/water nanofluid instead of using water alone.

According to the literature, nanoparticles have a remarkable ability to increase the thermal efficiency of solar collectors, which is the primary purpose of this paper. Most of the collectors discussed are flat-plate collectors; however, the evacuated solar collector is investigated in the present work.

MODEL DESCRIPTION

A 3-D model of a direct absorption evacuated tube solar collector (DAETC) is developed in ANSYS-Fluent 2021 R2 and shown in Figure 1. The thermophysical properties of the borosilicate glass of the collector are presented in Table

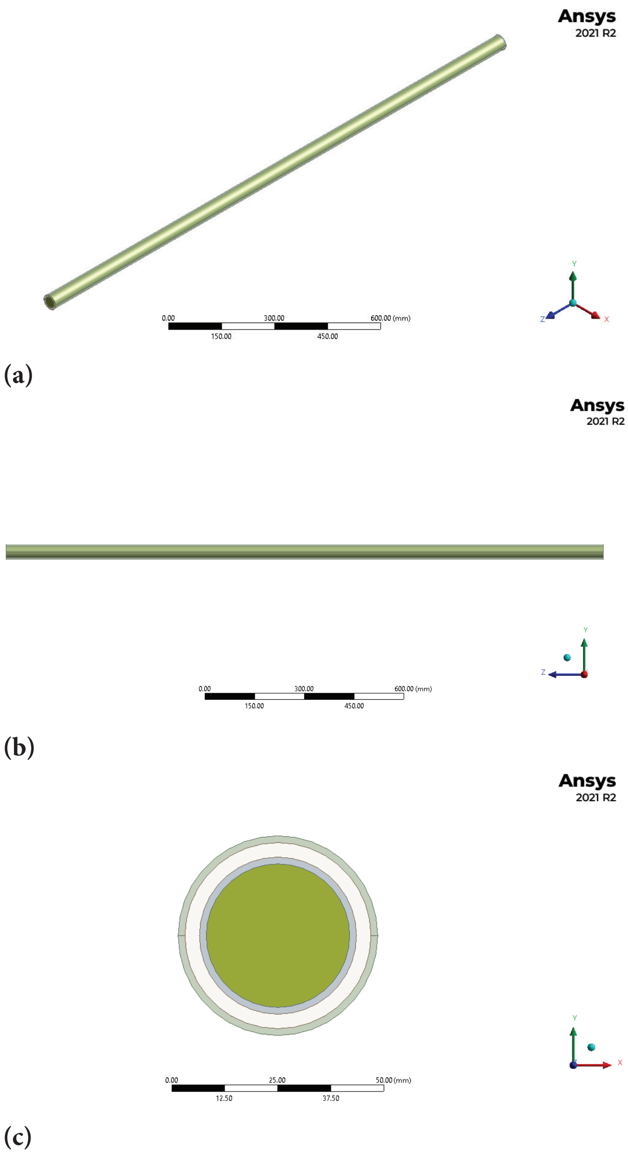


Figure 1. Geometry of the solar collector a) Isometric direction b) longitudinal direction c) transverse direction.

Table 1. Thermophysical properties of materials

Materail	Density (kg/m^3)	Thermal conductivity ($W/m.K$)	Specific heat ($J/kg.K$)
Water	998.2	0.6	4182
Ethylene glycol	1111	0.253	2415
Borosilicate glass	2124.9	1.1489	779.74

Table 2. Geometric specifications of collector

Parameter	Dimension
Length	1.8 m
Inner diameter of inner tube	33.8 mm
Outer diameter of inner tube	37 mm
Inner diameter of outer tube	43.8 mm
Outer diameter of outer tube	47 mm

Table 3. The operating condition of the simulation

Parameters	T_{amb}	T_{sky}	T_{in}	v_{in}
Value	288.15 K	270 K	293 K	0.001 m/s

1. Also, the collector specifications are presented in Table 2. The vacuum section acts as thermal insulation, and working fluid moves in the inner section of the collector. Also, the operating condition of the numerical simulation is shown in Table 3.

Governing Equations

A steady laminar, incompressible flow regime and fully developed is considered and the govering equations for fluid domain are given as follow [19]:

$$\nabla \cdot \left(\overrightarrow{V_f}\right) = 0 \tag{1}$$

$$\rho_f \left[(\overrightarrow{V_f} \cdot \nabla)\, \overrightarrow{V_f} \right] = -\nabla P + \nabla \cdot (\mu_f \nabla \overrightarrow{V_f}) \tag{2}$$

$$\rho_f C_{p.f} \overrightarrow{V_f} \cdot \nabla T_f = \nabla \cdot \left(k_f \nabla T_f\right) + q_s \tag{3}$$

where $\overrightarrow{V_f}$, μ and P are fluid velocity, viscosity and pressure. Also, T, k and q_s are the specific enthalpy, thermal conductivity and volumetric energy source term.

The Radiative Transport Equation (RTE) should be calculated to obtain the energy source term. The volumetric energy source term obtains as follows by neglecting emission, scattering coefficient, and using Beer-lambert law [20]:

$$q_s = I_0 K_{e\lambda} \exp\left(-(K_{e\lambda}) l\right) \tag{4}$$

where l refers to optical path in the collector and $K_{e\,\lambda}$ is an extinction coefficient of the nanofluid. Moreover, I_0 is the sun irradiation which is equal to 1000 W/m^2. The heat flux strikes the collector surface vertically, and the equations 1 to 3 are nonlinear equations that require boundary conditions to solve them. The corresponding boundary conditions considered for the numerical simulation take the following form:

$$T = T_{in}\ .\ \ v = v_{in} \tag{5}$$

$$P_{out} = 0 \tag{6}$$

$$u = v = 0 \tag{7}$$

where T_{in} and v_{in} are the entrance temperature and entrance velocity of the fluid. Also, transmissivity of the glass is assumed 0.9.

The primary purpose and focus of the current study are on the thermal efficiency of the collector, which can be obtained after solving the equations of mass, momentum, and energy with the radiation transfer equation.

It is essential to mention that the outlet temperature distribution is an effective parameter in computing the thermal efficiency. The following equation is used for calculating the thermal efficiency [17]:

$$\eta = \frac{\dot{m} c_p (T_{out} - T_{in})}{I_0 A} \tag{8}$$

Simulation Procedure

As mentioned, to perform computational simulation, ANSYS- Fluent 2021 R2 is used. The pressure and momentum equations are discretized using second-order upwind scheme. The equations for pressure and velocity are coupled utilizing SIMPLE scheme [19]. The convergence criterion occurs when the residual error of the governing Equations is less than 1e-7.

ANSYS-workbench 2021 R2 is applied for generating grids in the present study. In order to conform the simulation, the temperature distribution at the collector outlet for 0.06% Aluminium oxide is considered, and Figure 2 presents the independence of the grids applied. A structured mesh is used for the computational field of a solar collector, which can be seen in Figure 3. The boundary layer mesh near the inner surface of the tube has been used to get better and more precise results. From the various meshing, 1,300,000 elements are selected to continue the simulation. If the difference between each grid is less than 1%, optimal meshing can be expected [21].

The numerical study of Simonetti et al. [21] is employed to validate the present study. They divided the collector into two sections and considered that the upper half faces the sky, and the lower half is equal to ambient temperature. Simonetti et al. [21] studied the single wall carbon nanohorn (SWCNH) nanofluid in ethylene glycol with different concentration. Figure 4 presents the effect of the concentration of SWCNH on the collector efficiency. Validation

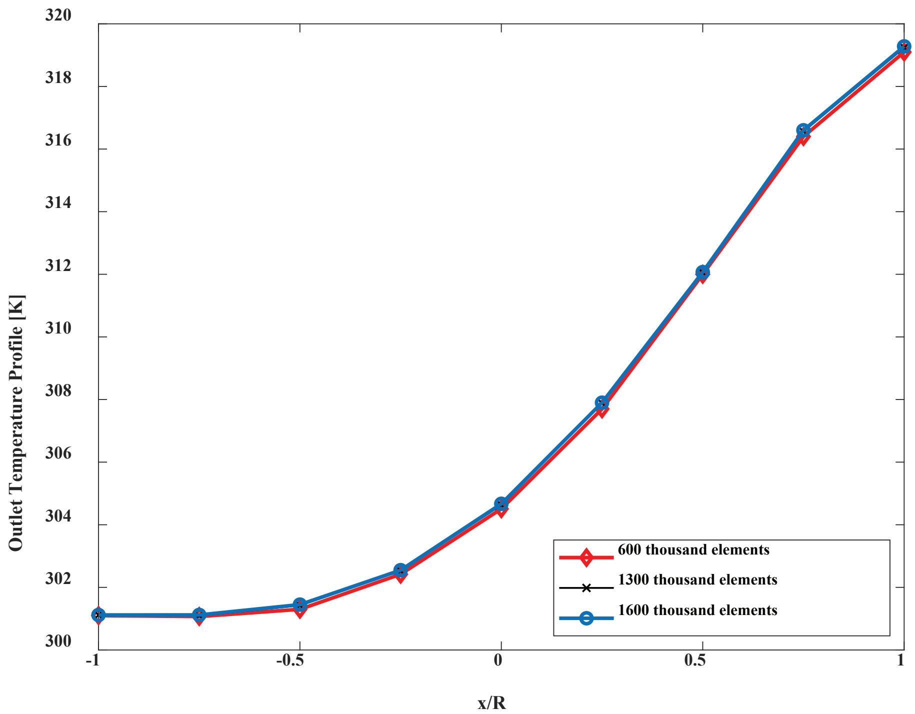


Figure 2. Grid independency.

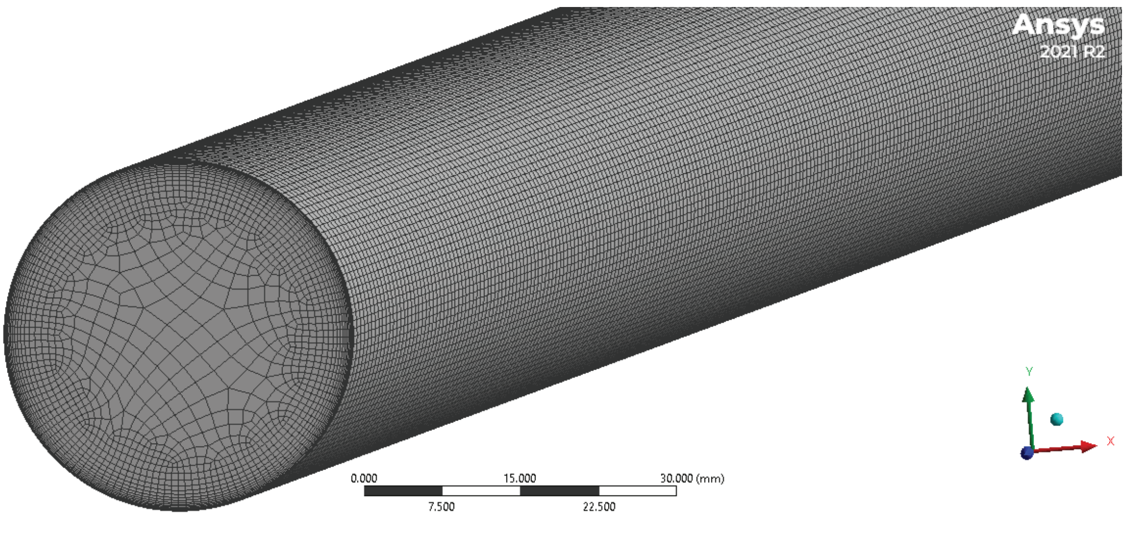


Figure 3. Grid distribution of evacuated tube solar collector.

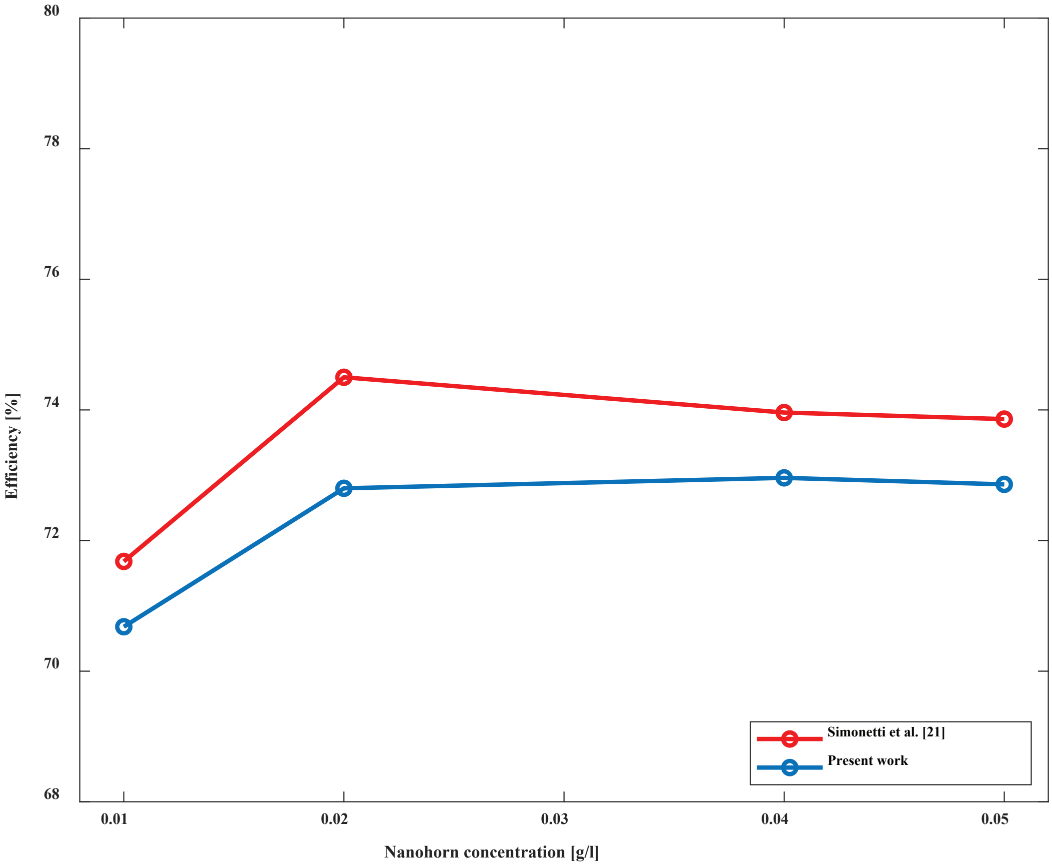


Figure 4. The validation of the present work compared with Simonetti et al. [21].

results show that the present study has a good agreement and an error value of 2.1%, which indicates the accuracy of the simulation.

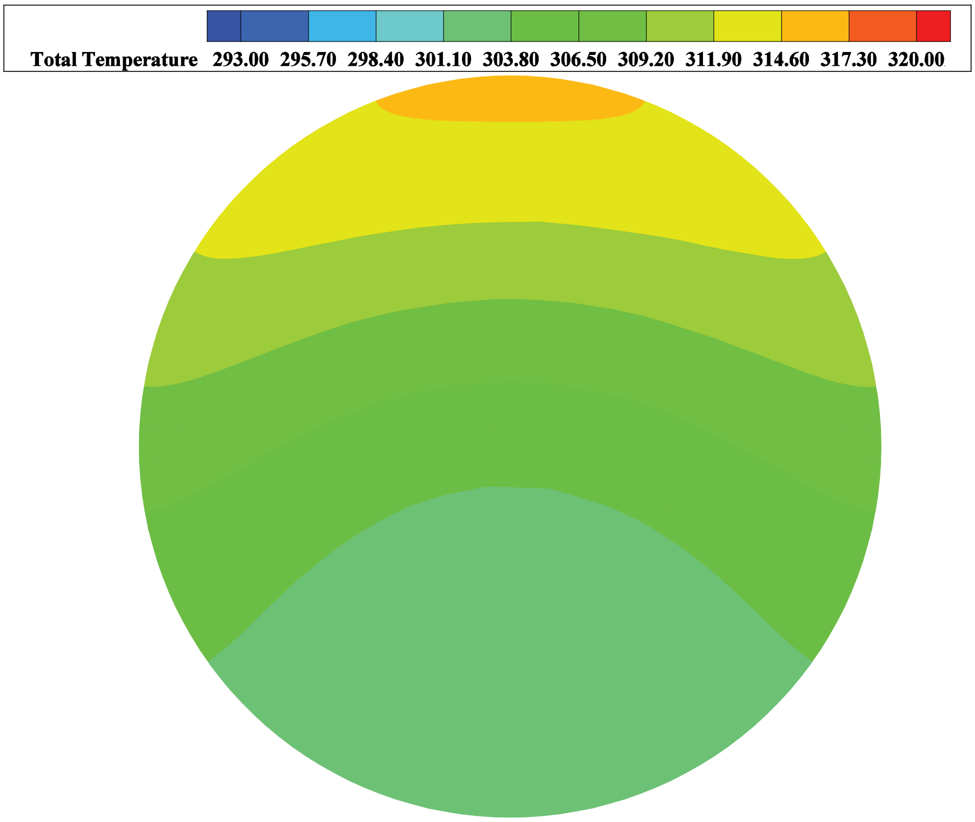
RESULTS AND DISCUSSION

The numerical simulation for investigating the impact of the nanofluid on the thermal performance of the evacuated solar collector under different conditions is developed. The working fluids are Al_2O_3/water and Al_2O_3/EG with 0.04% and 0.06% volume fractions. The effect of the volume fraction of nanofluid and base fluid type on the collector's efficiency is discussed. The optical properties of nanofluid for different base fluids are derived from the experimental works of Menbari et al. [22-23].

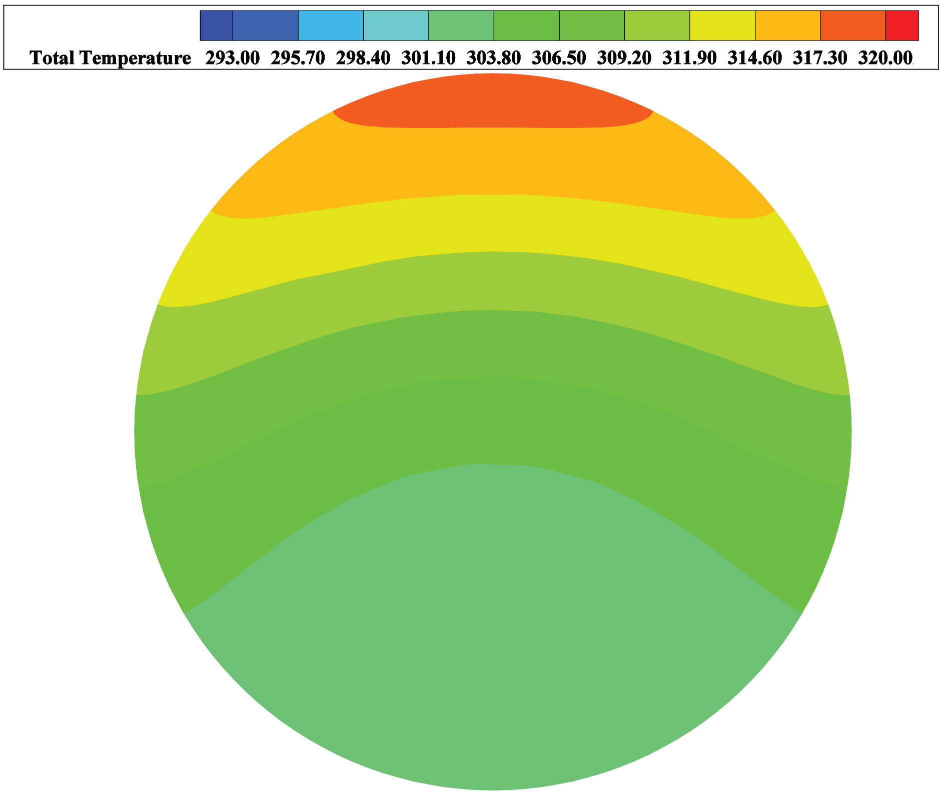
Temperature distributions of the collector outlet utilizing volume fractions of 0.04% and 0.06% of Al_2O_3/water nanofluid are shown in Figure 5 (a) and (b). By passing the working fluid into the collector, the nanofluid absorbs the solar energy, and the temperature of the working fluid has been increased gradually. According to Figure 5 (a), the temperature has improved by 22.02 K. Also, the maximum outlet temperature is 315.02 K.

By improving the volume fraction of nanoparticles of Al_2O_3 from 0.04% to 0.06%, the temperature difference at the outlet is elevated from 22.02 K to 25.28 K. The reason for this phenomenon is that by improving the volume fraction, the absorption coefficient of the nanofluid enhances. As a result, more heat is absorbed, which causes higher temperature differences in the working fluid. In addition, the collector efficiencies for 0.04% and 0.06% volume fractions equal 69.77% and 71.39%, respectively. Table 4 is summarized the results of the simulation for both mentioned volume fractions of Al_2O_3/water nanofluid.

Figure 6 (a) and (b) display the temperature contour along the collector tube employing 0.04% and 0.06% volume fractions of Al_2O_3/EG nanofluid, respectively. It is evident that the outlet temperature in the Al_2O_3/water nanofluid is fewer than the Al_2O_3/EG nanofluid by comparing the temperature contour of the two fractions of the same volume. The maximum temperature equals 315.02 K for 0.04% Al_2O_3/water nanofluid, although it equals 320.3 K for 0.04% Al_2O_3/EG nanofluid. Based on Figure 6 (b), the maximum temperature of 0.06% Al_2O_3/water is equal to 318.28 K; while for the EG-based fluid, it is equal to 323.26 K. Table 5 presents the results of adding Al_2O_3 nanoparticles for the mentioned volume fractions in EG-based fluid.



(a)

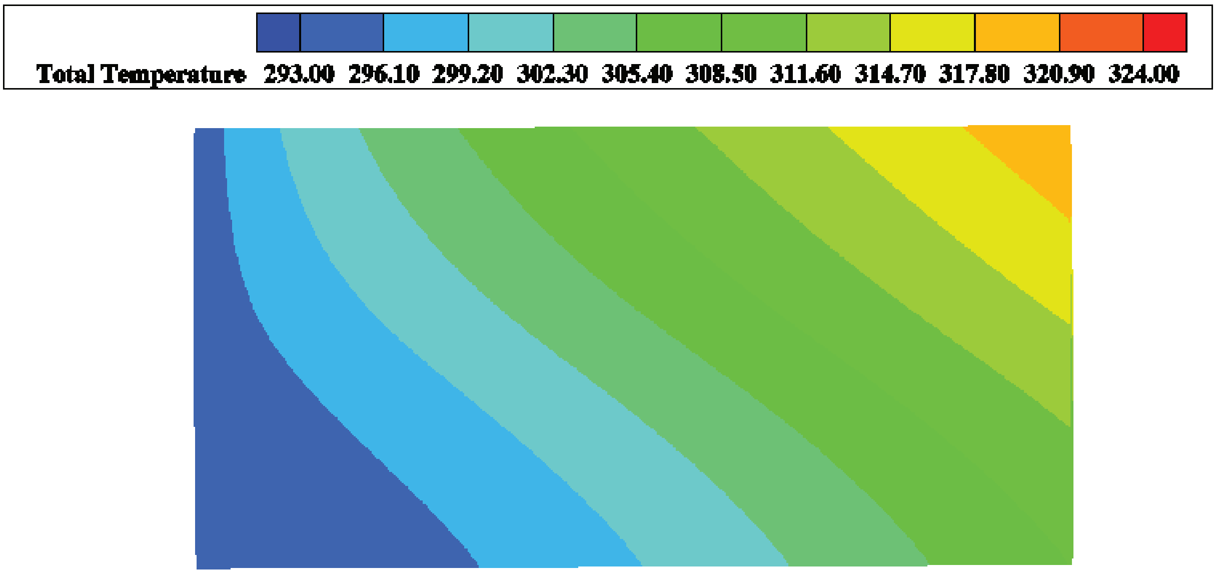


(b)

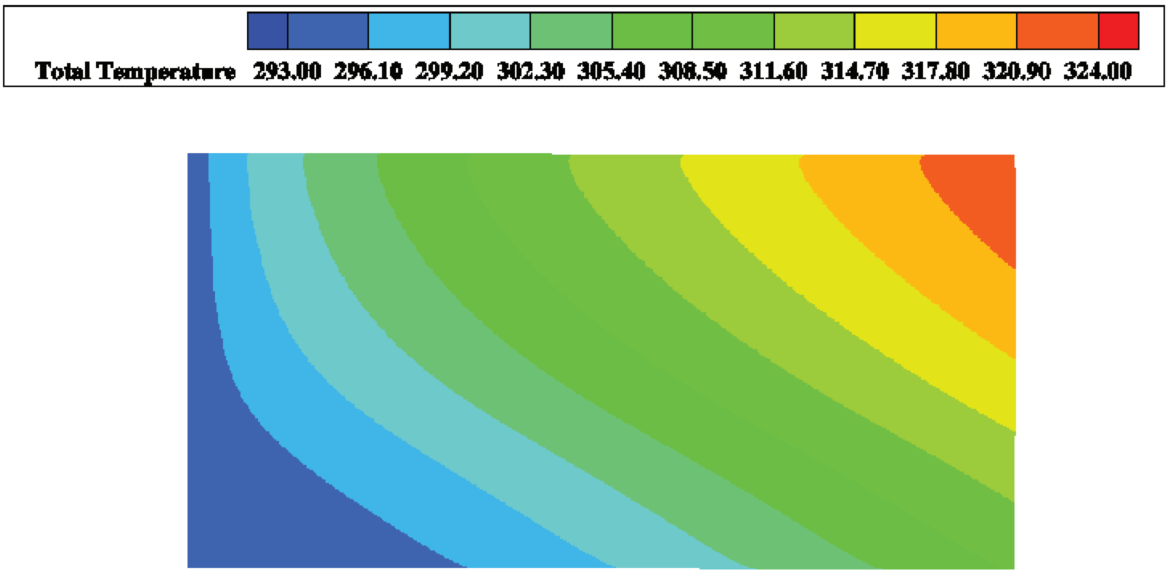
Figure 5. The temperature distribution of different volume fractions of nanofluid at the outlet of collector: (a) 0.04% Al_2O_3/water and (b) 0.06% Al_2O_3/water nanofluids.

Table 4. Simulation results of incorporating Al_2O_3/water nanofluid

Volume fraction	Maximum temperature (K)	Average temperature (K)	Temperature differences (K)
0.04% of Al_2O_3	315.02	306.03	22.02
0.06% of Al_2O_3	318.28	306.61	25.28



(a)



(b)

Figure 6. Temperature contour along the collector tube using (a) 0.04% Al_2O_3/EG and (b) 0.06% Al_2O_3/EG nanofluids.

Table 5. Simulation results of incorporating Al_2O_3/EG nanofluid

Volume fraction	Maximum temperature (K)	Average temperature (K)	Temperature differences (K)
0.04%	320.3	312.77	27.3
0.06%	323.26	313.58	30.26

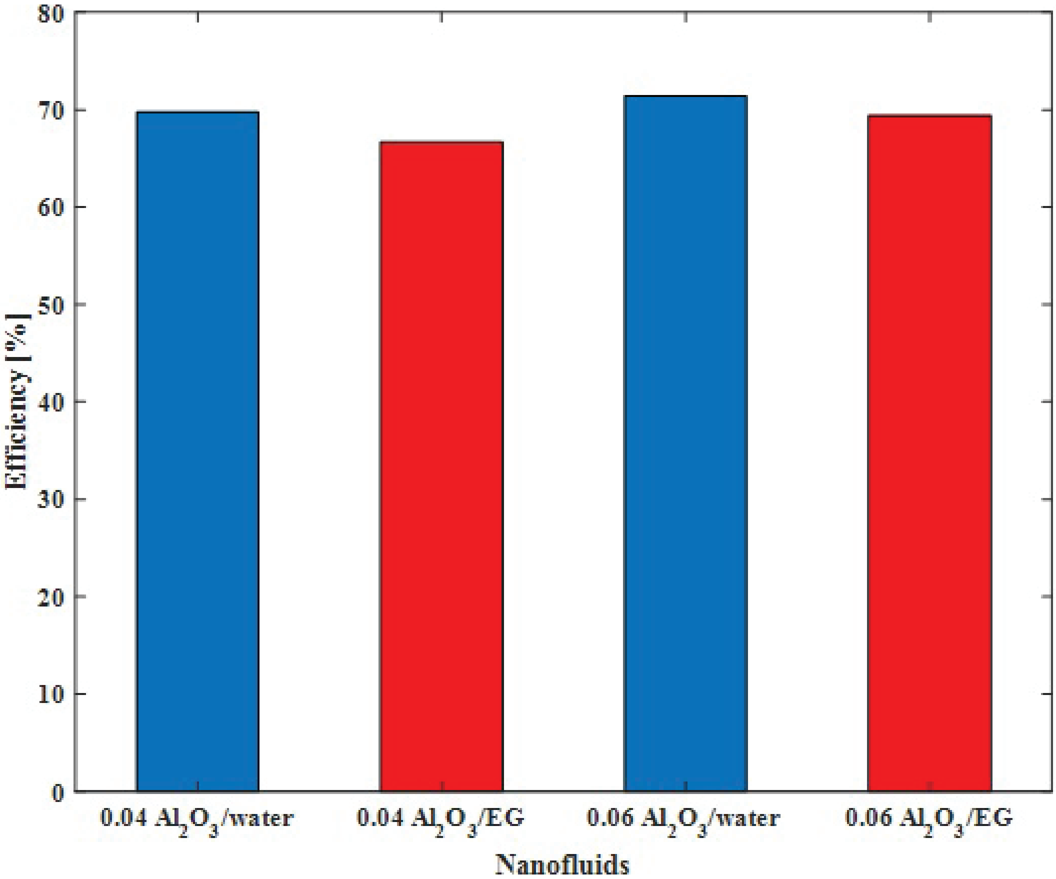


Figure 7. Comparison of the collector efficiency using different working fluids.

Also, the efficiency of the solar collector for 0.04% Al_2O_3/EG nanofluid equals 66.68% and for the 0.06% Al_2O_3/EG nanofluid equals 69.42%.

Figure 7 illustrates the efficiency of the collector for 0.04% Al_2O_3/water, 0.04% Al_2O_3/EG, 0.06% Al_2O_3/water, and 0.06% Al_2O_3/EG nanofluids. It is quite obvious that in the water-based fluid, collector efficiency is higher than the EG-based. The reason for this phenomenon is that the outlet temperature of EG-based fluid is higher than water-based one. Thus, more heat is lost in this case; therefore, it can be concluded that if water-based fluid is chosen, the collector efficiency is higher than EG.

CONCLUSION

In this numerical work, the thermal performance of the DAETC incorporating Al_2O_3 nanoparticles is investigated based on energy analysis. The impacts of the two volume fractions of nanofluids (0.04% and 0.06%) were employed. Besides, the base fluid is one of the factors that affect the outlet temperature of the collector; therefore, two different base fluids (EG and water) have been applied in the present work. The followings are itemized the results:

- By utilizing 0.04% Al_2O_3/water and 0.06% Al_2O_3/water nanofluids, the outlet temperature differential are 22.02 K and 25.28 K respectively; while for the 0.04% Al_2O_3/ EG and 0.06% Al_2O_3/ EG nanofluid are 27.3 K to 30.26K, respectively. It showed that the volume fraction of the nanofluids is a major factor which can affect the performance of the collector.
- In comparison to 0.04% Al_2O_3/water and 0.06% Al_2O_3/water nanofluids, the outlet temperature differences of 0.04% Al_2O_3/EG and 0.06% Al_2O_3/EG were improved by 19.34% and 16.45%, respectively.
- The collector efficiencies using 0.04% Al_2O_3/water, 0.06% Al_2O_3/water, 0.04% Al_2O_3/EG, and 0.06% Al_2O_3/EG nanofluids are equal to 69.77%, 71.39%, 66.68%, and 69.43%, respectively.
- The outlet temperature of the collector utilizing EG-base fluid is more remarkable than water-based fluid; while the thermal efficiency of the solar collector is higher selecting water-based. The reason for this phenomenon is that the heat loss of EG-based is much more than water-based fluid.

- The greatest collector efficiency and outlet temperature difference are achieved in the 0.06% Al_2O_3/water and 0.06% Al_2O_3EG nanofluids, respectively.

NOMENCLATURE

A	Collector net surface (m^2)
C_p	Specific heat at constant pressure ($J / kg\ K$)
I_0	Solar irradiation (W/m^2)
$K_{e\lambda}$	Mean extinction coefficient ($1/m$)
k	Thermal conductivity ($W / m\ K$)
l	length of the light path (m)
$\dot{m}$	Mass flow rate of the working fluid (kg/s)
P	Pressure (Pa)
q_s	Volumetric energy source term (W/m^3)
T_{amb}	Ambient temperature (K)
T_{in}	Inlet temperature (K)
$\bar{T}_{out}$	mean outlet temperature of the collector (K)
T_{sky}	Sky temperature (K)
u, v	x and y components of velocity (m/s)

Greek Symbol

η	Efficiency of the collector (-)
λ	wavelength (μm)
ρ	Density (kg/m^3)
μ	Viscosity ($Pa\ s$)
∇	Gradient

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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