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ENHANCEMENT OF THERMAL EFFICIENCY OF NANOFLUID FLOWS IN A FLAT SOLAR COLLECTOR USING CFD

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Abstract

Flat plate solar collector (FPSC) is popular for their low cost, simplicity, and ease of installation and operation. In this work, FPSC thermal performance was analyzed. It's compared to diamond/H2O nanofluids. The volume percentage and kind of nanoparticles are analyzed numerically that validation with experimental data available in the literature. The hot climate of Iraq is employed to approximate the model. The numerical study is performed by using ANSYS/FLUENT software to simulate the case study of problem. Due to less solar intensity after midday, temperatures reduction. The greatest collector thermal efficiency is 68.90% with 1% ND/water nanofluid, a 12.2% increase over pure water. The efficiency of 1% nanofluid is better than other concentrations because of a change in physical properties and an increase in thermal conductivity. Since the intensity of radiation affects the outlet temperature from the solar collector and there is a direct link between them, this increases the efficiency of the solar collector, especially around 12:30 pm at the optimum efficiency.

Keywords: solar collector flat-plate; diamond/H_2O nanofluids; thermal performance, computational fluid dynamics.

Nomenclature

A_C - The solar collector's surface area (m^2)
cp_{bf} - The base fluid's specific heat (J/kg K)
cp_{nf} - The nano fluid's specific heat (J/kg K)
cp_{np} - The nano particle's specific heat (J/kg K)
F_R - Factor of heat removal
kG_T - Total irradiance of the sun(Wm2)
h_b - The back of the collector's convection heat transfer coefficient
K - Thermal conductivity(W/m. K)
L - length of the tube m
Q_u - Gained usable energy rate(W)
Q_{in} - The rate of heat transmission into the system (W)
R_a Rayleigh number
t - Time(s)
T_a - Air temperature(K)
T_c - Temperature of the glass cover (K)
T_i - Temperature of the solar collector's inlet fluid (K)
T_o - The temperature of the solar collector's outlet fluid (K)
T_s - Sky temperature (K)
$\dot{m}$ - The mass flow rate of fluid flow (kg/s)
N_u - Nusselt number
P -fluid pressure (Pa)
P_r - Prandtl number
Q_{out} - The rate of heat movement out of the system (W)
U - Velocity components in X directions (m/s).
V - Velocity components in Y directions (m/s).
W - Velocity components in Z directions (m/s).
U_L - The solar collector's overall loss coefficient (W/(m^2 K))

Greek symbols

ρ - Reflectivity for glass and absorber, and fluid density (kg/m^3)
φ - Particle concentration
τ_α - Absorptance-transmittance product
μ - The viscosity of the fluid (pa. s)
ε_p - Absorber plate emittance
ρ_{nf} - Density of nanofluid, kg/m^3
ε_g - Glass cover emittance
η_i - Collector thermal efficiency
α - Absorptivity
τ - Transmissivity

Abbreviations

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers
H_2O - Pure water
FPSC - Flat plate solar collector
ND - Nanodiamond

1. INTRODUCTION

Electricity and fossil fuels as major energy sources are becoming scarcer. To meet their growing energy demands, all countries must research renewable energy. The most significant renewable energy source is solar power since it's long-term. Solar energy is needed to meet the world's expanding energy demands. All common uses and desalination systems need a lot of energy. By boiling water with solar energy, this much energy may be saved Danook et al. [1], Hussein et al. [2] and Elghamry et al. [3]. FPSC, heat pipes, and evacuated tubes are kinds of collectors. FPSC is cost-effective in Installation, operation. FPSC uses direct and diffuse sun radiation to heat water and requires little cleaning and maintenance. FPSC doesn't need a sun tracking system because it's tilted. These characteristics make the flat plate collector popular in household water heating systems. The FPSC loses heat through radiation and convection, reducing its thermal efficiency. Duffie and Beckman [4] studied the improvement of the FPSC's thermal performance. Choi and Eastman [5] initially reported the influence of nanofluids. Maxwell [6] provided the first theoretical foundation for forecasting suspension conductivity. Solid particles are suspended in water and nanofluid. Dispersing nanoparticles in a heat transfer fluid creates nanofluids. The theory predicts nanofluid's thermophysical characteristics. Gupta et al [7] explore that adding high-conductivity nanoparticles to a fluid increases thermal efficiency. Nanoparticles have superior thermal conductivity compared to heat transfer fluids, which enhances heat transfer. Nanoparticle density increases nanofluid viscosity, Power, pressure drop in forced conventional heat transfer systems, Said et al. [8]. Physically, they're different from conventional fluids. Temperature, density, and viscosity change. Solids have a higher specific gravity than liquids, hence nanofluids should be denser. Said et al. [9] examined the effect of utilizing TiO_2-water nanofluid on flat plate solar collectors' quality. Nanoparticles' volume percentage ranged from 0.1 to 0.3 percent, and nanofluid flow rates were 0.5 to 1.5 kg/min. As a dispersion, ethylene glycol, poly (PEG 400) helped achieve the thermo-physical properties of the TiO_2 nanofluid and reduce sedimentation. The condition with 0.1% volume fraction and 0.5 kg/min flow rate had the highest exergy efficiency at 16.9%. The experiment yielded these values. Pumping power and pressure drop were equal to base fluid for 0.1 to 0.3 percent TiO_2 nanofluid. The TiO_2 nanofluid has remained stable for a month. Heat conductivity improves by 6 percentage points with 0.3% TiO_2. TiO_2-H_2O nanofluid increases solar collector exergy and energy efficiency over pure water. Nanofluids are one way to improve the FPSC's thermal characteristics and performance.

Researcher Sundar et al. [10] has used nanofluids to augment the FPSC's thermal efficiency. Zhang et al. [11] and Xie et al. [12] they proved that nanoparticle thermal diffusivity and surface area promote heat transfer. Choi [13] proposed adding nanoparticles to nanofluids to boost heat conductivity and to increasing the nanoparticle concentration by 1 percent by volume doubles the fluid's thermal conductivity. Other studies Trisaksri and Wongwises [14], Wen et al. [15] and Murshed et al. [16] validated Choi [17] findings. Even a minimal quantity of solid nanoparticles improved a base fluid's thermal conductivity and overall characteristics. Nanofluids have gained interest in recent decades due to their improved thermal suspension properties. Keblinski et al. [18] found that adding carbon nanotubes or copper nanoparticles to oil or ethylene glycol at a volume fraction of less than 1% increased nanofluids' thermal conductivity. Hwang et al. [19] explored convective heat transfer and pressure drop in aluminum oxide nanofluid flow and Al_2O_3 nanoparticles enhanced alumina nanofluids' thermal conductivity by 44%. Terekhov et al. [20] proved that Alumina nanoparticles boost the nanofluid thermal conductivity as well as Three percent of alumina increases the heat conductivity by 10%. Maïga et al. [21] utilized a single-phase model to explore nanofluid thermal characteristics in a tube and revealed that nanoparticles increase the Reynolds numbers and heat transfer coefficients. Chandrasekar et al. [22] studied the improvement in Alumina nanofluids thermal conductivity with varied volume fractions. Yu and Xie [23] revealed that the stable nanofluids need nanoparticle dispersion physical and chemical treatments, so several nanofluid preparation methods exist. Yousef et al. [24] explored the effect of introducing Alumina nanoparticles on FPSC efficiency at varied mass flow rates of the base fluid for example 0.2% weight fraction of alumina nanoparticles boosted collector efficiency by 28%.

Nanofluid's thermal influence on FPSC can be analyzed by CFD (Computational Fluid Dynamics) based on FVM (finite volume method) so that scientist and researchers mostly conducted this technique. Therefore, this research conduct and develop a complete thermal analysis for the FPSC using several nanofluids with varying nanoparticle concentrations. Different diamond/water nanofluid and nanoparticle volume fractions were analyzed.

2. PHYSICAL MODEL

Fig. 1. Flat solar collector parts include, the absorber plate, tubes, cover the glass, the air space between the glass and the absorber plate, the pump working at 12 volts, the storage tank, the safety valve, the flowmeter and the water. The working fluid enters from the tube and passes through the tubes under the absorber plate to transfer heat between the working fluid and the plate. The temperature at the outlet is higher than the temperature at the intake during absorption and output.

Fig. 2. The dimension of FPSC (exactly the absorption plate) consist of length 980 mm, height of 1000 mm and thickness of 2 mm.

The absorber's top half is directly exposed to the sun's heat, resulting in heat loss because of the lack of perfect insulation and the exposure to the wind from the glass cover, these values fluctuate every hour from nine in the morning until four in the

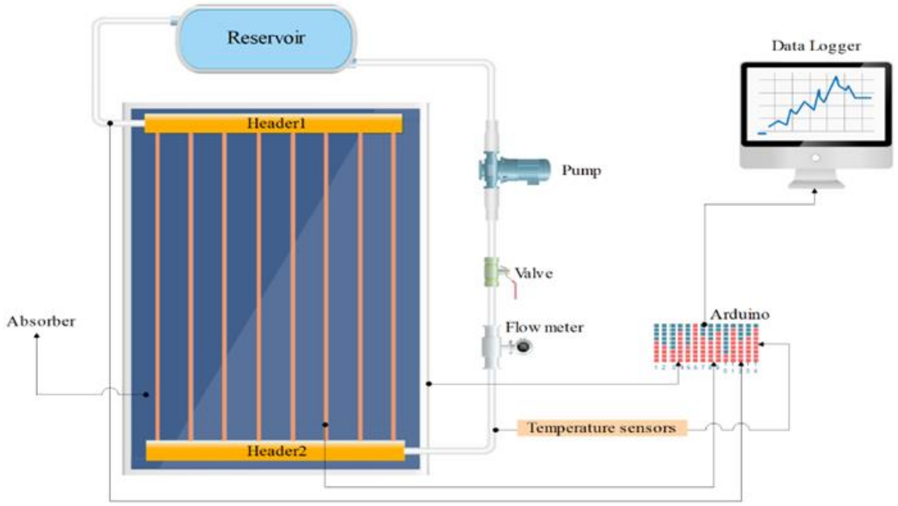


Fig. 1. Flat solar collector parts

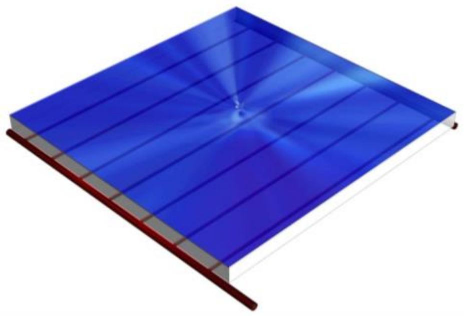


Fig. 2. The absorber of FPSC

afternoon. The upper wall is subject to convective heat loss and radiation between the absorber plate and glass, glass cover and ambient were assumed from the front and the sides and back, the facility is completely sealed as described in Yu and Liu [25]. One number changes every eight hours. The assumption of geometrical model is summarized as: (a) Solar collector elements were designed to have isotropic physical qualities. (b) The nanofluid flow is shown as a single component based on nanoparticle type, base fluid parameters, and nanoparticle volume percent. (c) The simulation considers water's temperature. (d) Suspended nanoparticle sedimentation is neglected. Using surfactants and mixing the nano fluid during fluid flow in the flat plate solar collector can achieve this assumption. The FPSC borders and sides are insulated, finally the surface temperature in front and backend of the FPSC is the same.

3. MATHEMATICAL MODEL

3.1. Governing equations

A working fluid Q_u absorbs usable energy according to Colangelo et al. [26].

$$Q_u = \dot{m} C_p (T_o - T_i) \tag{1}$$

C_p denotes the heat capacity of the working fluid.

It is also possible to determine the useful absorbed energy by subtracting the collected energy from the collector heat losses.

$$Q_u = A_c F_R [G_T(\tau\alpha) - U_L(T_i - T_a)] \tag{2}$$

(F_R) and total thermal losses factor (U_L). A_c is calculated using solar radiation, as well as G_T $(\tau\alpha)$, and T_a according to García et al. [27].

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

$$\eta_i = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_a}{G_T} \tag{4}$$

Using continuity, momentum conservation and energy equations, the fluid outflow temperatures were calculated. For the boundary condition parameters includes air temperature, and air speed are considered as model inputs. Each collection glass plate, absorber plate, and airgap are energy-analyzed as well as fluid flow and collector insulation. The working fluid solved by applying momentum conservation equations. CFD technique was also utilized to examine the collector's pipe network for pure water and other nanofluids. Gallavotti [28] explains water and nanofluid steady flows exposed to induced convection in three dimensions.

3.2. Mass Conservation

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{5}$$

where u, v, and w are the speeds (m/s) in the x, y, and z directions.

3.3. Momentum Equation

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{6}$$

$$\rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \mu \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right] \tag{7}$$

$$\rho u \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} + \rho w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right] \tag{8}$$

3.4. Balanced Energy

Heat transfer equation applied for each collector layer's:

$$\frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) = q \tag{9}$$

T and k are measured in degrees Kelvin and cubic feet per square inch. The heat transfer coefficients of the glass cover, collector back, and air gap are convective (h_b,h_g). Collect characteristics and wind speed (v_w).

$$h_g = 5.28 + 4.07V_w \quad (10)$$

$$h_b = 0.5h_g \quad (11)$$

$$h_a = \frac{Nu_a K_a}{\delta_a} \quad (12)$$

Air thermal conductivity (K_a) and the air gap Nusselt number (Nu_a) can be calculated from the thickness of the air gap as explored in Hollands et al. [29].

3.5. Nanofluids Properties

Researchers and scientist suggested to identify the amount and type of nanoparticles, as well as the thermophysical properties of the fluid, therefore all play a role in utilization of FPSC. The following formulas can be used to compute a substance's density, specific heat, viscosity, and thermal conductivity according to Ibrahim et al. [30], Hussein et al. [31] and Saleh et al. [32].

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \quad (13)$$

$$cp_{nf} = \frac{(1-\varphi)(\rho cp)_{bf} + \varphi(\rho cp)_p}{\rho_{nf}} \quad (14)$$

$$\mu_{nf} = (1 + 2.5\varphi + 6.5)\mu_f \quad (15)$$

$$\mathrm{K_{nf}} = \frac{K_{bf}\left(K_{nf} + 2K_{bf} - 2\varphi(K_{bf} - K_{np})\right)}{K_{np} + 2K_{bf} + \varphi(K_{bf} - K_{np})} \quad (16)$$

Thermophysical properties of nanoparticles can be identify as; Nanoparticles have diamond/water nanofluids, Size of particles Less than (20nm), Particles' Spherical shape, Density 3510 (kg/m^3), Conductivity1000 (W/m. k), Specific heat 497.26 (J/kg. k).

3.6. Mesh Generation

Grid-independent tests help balance accuracy and speed. The number of elements affects computing time. Model outputs 1.5 million cells. Since there are so many components, it doesn't matter how long computations take. Fig. 3 show the mesh. Fig. 4 illustrates that the simulation matched the experiment. If nonphysical events are predicted, coarse meshes will be implemented for this kind of calculation. Where header tubes link to riser pipes and fluid enters and exits.

The model's solution was done using ANSYS 2022 R1, Fluent function solver. Solar collector flat plate geometry was designed and implemented in OpenFOAM toolbox and applied appropriate mesh. The characteristics of a mesh for current model as follows; The maximum sizing was 0.14962 m and high smoothing were selected, the number of statistics nodes were 330910, the number of elements were 1416020 and fife layers of inflation with smooth transition were selected. The ratio of change was 0.272 and rate of growth was 1.2. The setup introduced the physical properties of glass, aluminum, copper, air and the flat solar collector's boundary conditions. The collector positions and flow rates are allocated. G_T,T_a , T_i, V_w, and $\dot{m}$. Original: To compute the glazing absorption plate's temperature theoretically, the solver applied continuity, momentum, and energy conservation equations on the modal. The solver updates nanofluid thermophysical properties automatically. The main porpose of the solver is to calculate the thermal performance of the FPSC. Fig. 4, shows results from postprocess of the software. The analysis consist of the complex zones include the absorber plate and tubes.

4. THE VALIDATION OF SOLVER RESULTS

The present model's correctness was implemented using CFD approach of pure water and diamond/H_2O nanofluids with 1% volume fractions. The numerical data is compared to Alklaibi et al. [33] results for validation, and the divergence was less than 3%. Fig. 8 shows the comparison between solar collector thermal efficiency and model predictions using pure water and diamond/H_2O nanofluids. Dispersion and thermophysical property predictions make diamond/H_2O nanofluids better than water.

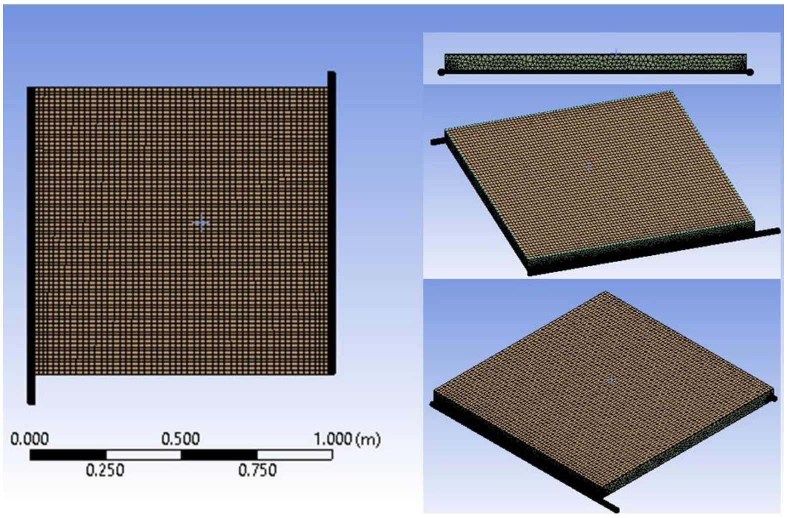
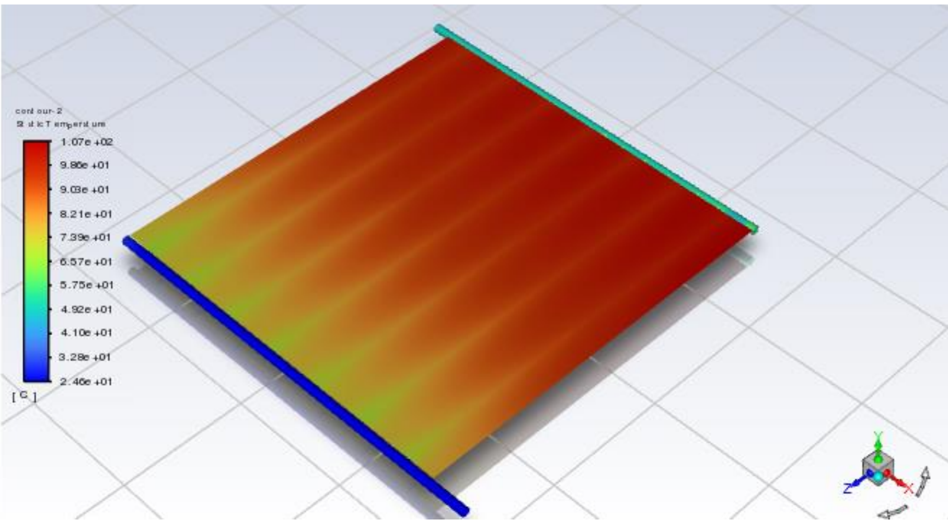
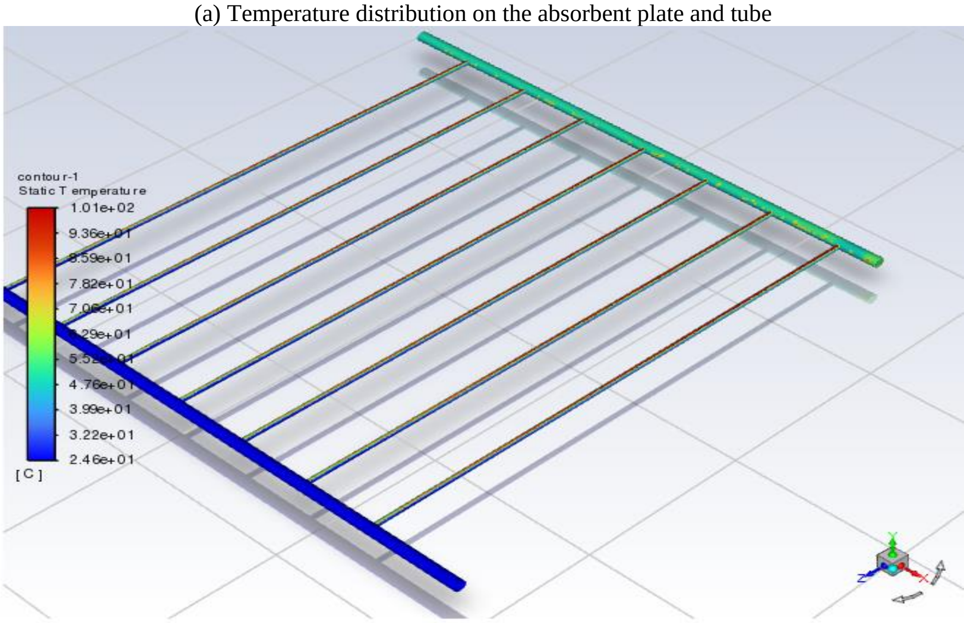


Fig. 3. Mesh generation of FPSC and the tubes



(a) Temperature distribution on the absorbent plate and tube



(b) Temperature distribution on the tubes and headers

Fig. 4. The FPSC physical contours

5. EXPERIMENTAL RESULTS

The experiment and testing of solar collector has been conducted under the climatic conditions of Kirkuk city of republic of Iraq. It was observed that the outlet temperature is entering the solar collector in 25ºC and the flowrate is 0.009 kg/sec for pure water as shown in Fig. 6. The results of outlet temperature are numerically recorded along one month June 2022 and reduced for four days: 01/06, 10/06, 21/06, and 27/06 as average from nine o'clock A.M until four o'clock P.M. It can be seen that the temperature is increased from the sun rise and the recording data from 9 A.M. till the mid-day at 12.30 P.M. which is represented the optimum solar intensity. The behavior of temperature was decreased after mid-day due to reduce the intensity solar.

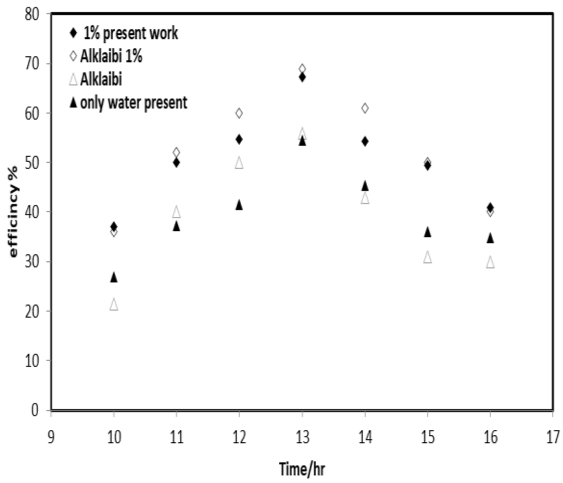


Fig. 5. Time-depend thermal efficiency validation of FPSC

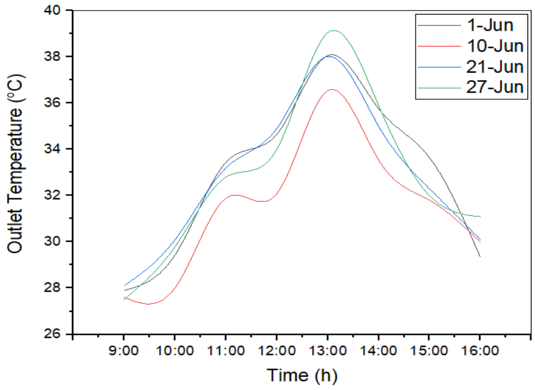
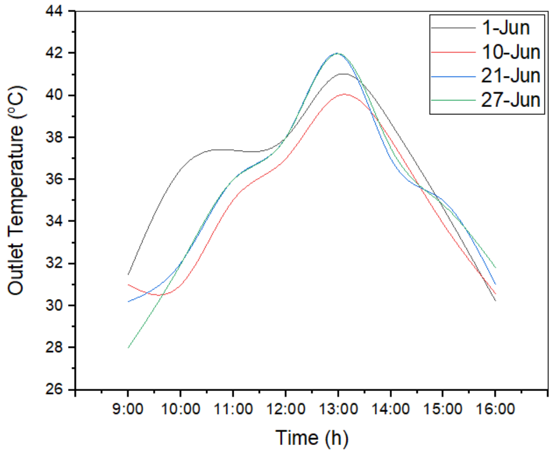


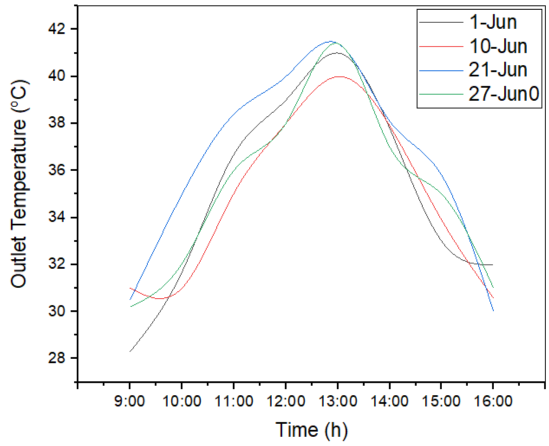
Fig. 6. Outlet temperature with time for pure water

The time-depended of the outlet temperature for water and diamond nanofluids are utilized at concentrations of 0.1%, 0.5 %, and 1 % respectively, as seen in fig.7. The outlet temperature is determined using smart thermometer. It was observed that the outlet temperature of nanofluids has the same behavior with using pure water along June 2022 with different values. The reason for elevated the values of outlet temperature was due to improvement of thermal nanofluid characteristics as compared to base fluid. It can be seen that the 0.1 and 0.5 percent is enhanced the outlet temperature by 8.05% and 8.65% respectively as compared to pure water then the 1 percent has the highest values of outlet temperature as compered the pure water with 10.5%. For the pure water, the results of efficiency were numerically monitored along one month June 2022 and reduced for four days: 1/6, 10/6, 21/6, and 27/6 as average from 9:00 a.m. to 4:00 p.m. It can be seen from fig.8. The efficiency increases with the rising of the sun and the recording of data from 9 a.m. to mid-day at 12.30 p.m., which represents the optimum solar intensity. The solar intensity decrease, therefore, efficiency decreases after midday, also cause slight difference between the temperature entering and exiting the flat plate solar collector**.** Fig. 8 shows how the efficiency of water and diamond nanofluids changes over time when they are utilizing at concentrations of 0.1 percent, 0.5 percent, and 1 percent, respectively. The experimental study was used to establish how efficient the system is. Along June 2022, it was noticed that the efficiency of using nanofluids has the same behavior as using purified water, but with different values.

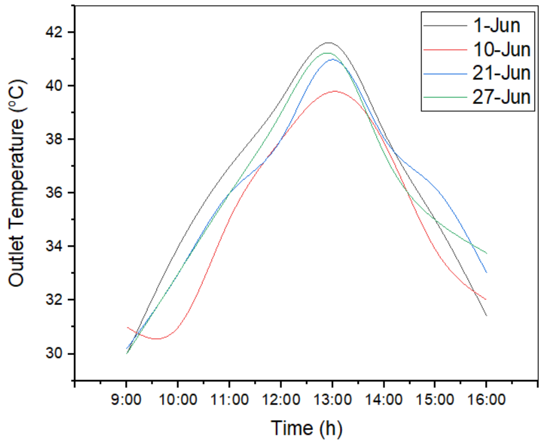
The improvement of thermal Nanofluids vs. basic fluids are the cause of the rising values of outlet temperature. This is because nanofluids have a smaller thermal expansion coefficient, when compared to pure water, it is clear that a concentration of 0.1 and 0.5 percent produces an increase in outlet temperature of 8.75 and 9.5 percent, respectively; however, a concentration of 1 percent produces the highest values of outlet temperature, up to 12.02 percent higher than that of pure water.



a: Nano 1%



b: Nano 0.5%

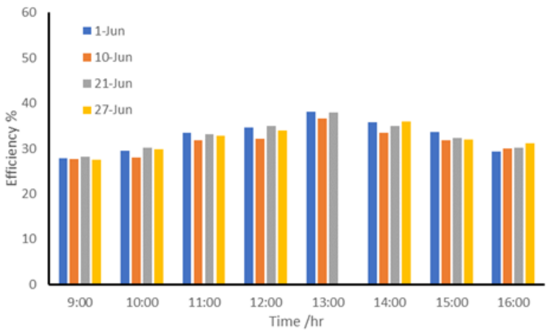


c: Nano 0.1%

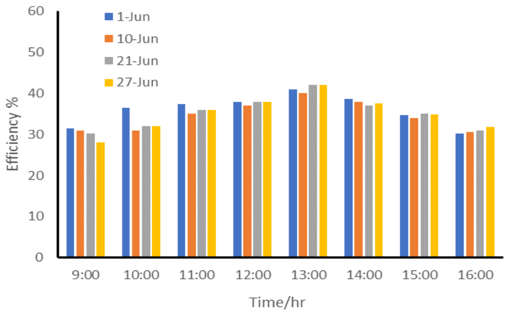
Fig. 7. Outlet temperature of nanofluids over the time

6. CONCLUSIONS

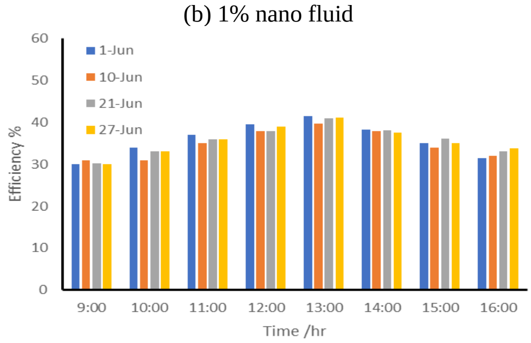
The FPSC's thermal performance was analyzed using pure water and nanofluids with variable nanoparticle composition. The experimental data and theoretical results from CFD were validated and it was in good agreement. The sun irradiation steadily climbs to its highest point at 12:30 p.m., when it reaches its maximum value, and then it begins to gradually fall until the conclusion of the test interval. The amount of 1.0 vol% of nanofluid with pure water as the working fluid reaches the



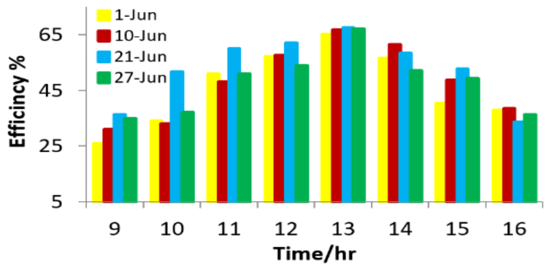
(a) Pure water



(b) 1% nano fluid



(c) 0.5% nano fluid



(d) 0.1% nano fluid

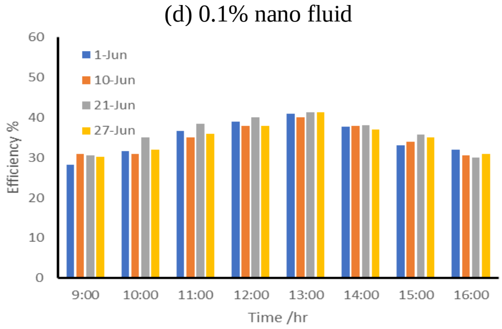


Fig. 8. Collector efficiency of nanofluids over the time

greatest thermal efficiency possible, which is 69.06%. In this case up to 12.02% improvement were done over the previous level. Generally, the nanofluids with 1% higher concentration have better efficiency. The results show up the Diamond/H_2O nanofluids was better than pure water due to their dispersion and thermophysical property predictions.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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