Performance Investigation of a Solar Thermal Collector Based on Nanostructured Energy Materials

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The convective and conductive heat transfer between the solar collector and working fluids make photothermal performance limited, and result in a higher rate of heat loss from the surface of the conventional absorber to the surroundings. Direct absorption solar collectors (DASC) are a favorable alternative for their improved photothermal performance. In this study, a simulation based on the performance of a nanostructured solar collector has been carried out using TRNSYS. The connective and conductive heat transfer from direct solar collectors were improved by using nanofluids and three different nanostructured materials, CuO, GO, and ZnO, in this study. The analysis determines the outlet temperature of the working fluids that passed through the direct solar collector. The TRNSYS model consists of a direct solar collector and weather model for Lahore city, the simulations were performed for the whole year for 1,440 h. The stability of these nanostructured materials in the water was investigated by using a UV-Vis spectrophotometer. Various performance parameters of direct solar collectors were determined, such as variation in outlet collector temperature and heat transfer rates. The numerical model is validated with experimental results. A maximum outlet temperature of 63°C was observed for GO-based nanofluids. The simulation results show that for the whole year, nanofluids improved the performance of direct solar collectors. Significant improvements in the heat transfer rate of 23.52, 21.11, and 15.09% were observed for the nanofluids based on nanostructures of CuO, ZnO, and GO respectively, as compared to water. These nanostructured energy materials are beneficial in solar-driven applications like solar desalination, solar water, and space heating.

Keywords: solar energy, performance investigation, hierarchical nanostructure, TRNSYS, direct solar collector

GRAPHICAL ABSTRACT
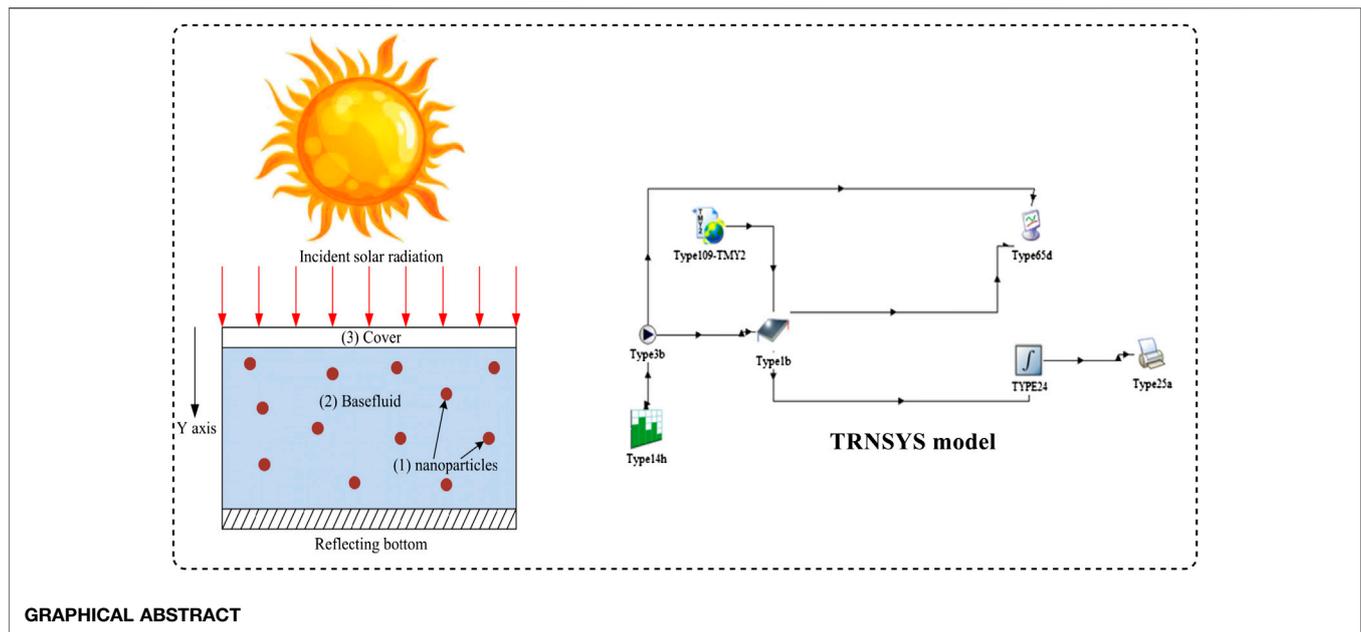
INTRODUCTION

Due to the rapid increase in population, energy demands are increasing day by day and fossil fuels are being widely used to meet this demand (Kriegler et al., 2017; Grubler et al., 2018). The burning of fossil fuels causes serious environmental issues (Ağbulut and Sarıdemir, 2019); to overcome these problems, alternative energy resources are being explored. Among alternative energy resources, solar energy has gained the attention of many researchers for differing reasons (Dudin et al., 2016; Oh et al., 2018; Guangul and Chala, 2019). The Sun is a universal renewable energy source (Moner-Girona et al., 2016). Solar energy utilization can be done by converting sun heat energy into a chemical form of energy, an electric form of energy, or a thermal form of energy. Thermal energy is the most commonly used among all of these. Solar collectors have been utilized for the converting of solar radiation into thermal energy (Conrado et al., 2017; Bellos and Tzivanidis, 2019). Solar energy is collected through flat-surface-based solar plates, converting this collected energy into heat and then delivering it to working fluid (Amjad et al., 2018a; Dehaj and Mohiabadi, 2019). However, the major drawback of this conventional surface base flat type is that, as the temperature of the flat plate increases, the radiant loss of heat occurs (Kılkış, 2000; Sint et al., 2017; Shafieian et al., 2019).

Therefore, it is necessary to exchange these typical solar collectors with directly absorbing solar collectors (Amjad et al., 2018b; Goel et al., 2020). Another way to increase photothermal conversion performance is through the use of composite nanofluids, which can be obtained by mixing binary nanoparticles. To abridge the collector and increase its efficiency, direct absorption solar collector (DASC) has been suggested. DASC absorbs large amounts of solar radiation from the Sun, meaning temperature distribution is uniform throughout the surface and results in a small amount of heat

loss as compared to surface-based collectors (Arefin, 2019; Poompavai and Kowsalya, 2020). The study of direct absorption solar thermal collectors has been carried out using a composite nanofluids solution (Gorji and Ranjbar, 2017; Wang et al., 2017). The application of nanoparticles in DASC is a relatively new concept (Pathak, 2020). Nanoparticles disseminate in the base fluids and offer the potential to improve the optical characteristics of their nanofluids. Nanofluids consisting of nanoparticles are the best medium for transferring heat in solar collectors; composite nanofluids can be obtained by mixing these absorbing dark nanoparticles into the working fluids, a method which has been broadly studied previously (Chamsa-ard et al., 2017; Olia et al., 2019), (Amjad et al., 2017a; Amjad et al., 2017b). In addition to this, direct absorption solar collectors show greater efficiency as compared to the conventional absorption of Al/H_2O nanofluids with that of pure water. Al/H_2O nanofluids have a high absorption capacity and are 10% more efficient with an indirect absorption solar collector using nanofluids than that of the typical type of flat plate collector (Salehi et al., 2020). Dark metal has a better absorbance rate (Zook et al., 2011). When the frequency of incident light becomes constant with the fluctuating frequency of electrons of dark nanoparticles, then localized surface Plasmon resonance will start occurring (Coronado et al., 2011; Yu et al., 2019), thus increasing absorption capacity in the spectral range of nanoparticles. Further, a binary combination of metal composite materials and nanostructures not only increases visual absorption (Basavarajappa et al., 2020), but also alters the spectral range properties to increase efficiency. Composite nanoparticles with different size range structures can achieve an effective capacity of absorption of solar energy, and studying the spectral properties revealed that the spectrum of absorption can be adjusted by changing the shape, size, and material of nanoparticles, so as to attain the most suitable solar

absorption (Li, 2012). The concentration of particles to some amount improves visual absorption, while changing to a higher rate of concentration will create some issues, such as flow viscosity increasing (Viamajala et al., 2009).

The solar irradiance of typical solar thermal collectors heats up the surface of an absorber by using the method of selective coating and, due to temperature differences, heat is transferred to the working fluid (Madhukeshwara and Prakash, 2012). Nanofluids containing nanoparticles that are efficiently absorbing solar rays promise to remove these difficulties in the conversion of photo thermal solar energy (Wang et al., 2017). Particularly, their higher level of visual and thermophysical properties, and thermal conductivity, play vital roles in increasing the capacity of solar energy absorption and its conversion (Mehrali et al., 2018).

Goudarzi et al. (Goudarzi et al., 2014) used CuO nanofluids in evacuated solar collectors and investigated its thermal performance; it was observed that the performance was enhanced by 30% when using CuO nanofluid as compared to water. Ghaderian et al. (Ghaderian et al., 2017) used nanoparticles for heat transfer; the thermal performance analysis of a solar thermal collector was investigated by deploying the finite difference method in MATLAB, the results of which exhibit in the temperature range of 30–100°C the radiant loss was increased from 26 to 58 W/m. With the addition of multiple wall carbon nanotubes into the base fluid, the convective heat coefficient increased, and a considerable improvement in coefficients of heat transfer was observed with increasing concentrations of nanoparticles. Bianco et al. (Bianco et al., 2018) carried out numerical simulations of Al_2O_3-based nanofluids in a flat plate photovoltaic cell; a two-dimensional model was developed in COMSOL and nanofluids of different concentrations (0%–6%) were passed through PV/T with laminar flow. The results show excellent improvement in the cooling of PV/T cell, which improves the overall efficiency of the cell.

In this present study, three different nanostructured materials, CuO, GO, and ZnO, were added into water, and these nanofluids were passed through a direct solar collector to absorb the heat of the solar collector. TRNSYS software was used in this study to simulate the heat absorbed by these nanofluids; the simulation was performed for Lahore city weather conditions for the whole year.

MATERIALS AND METHODS

Configuration of TRNSYS Model

The basic schematic diagram of the numerical model has been shown in **Figure 1**. The "Type 109" weather conditions were used for Lahore city. In TRNSYS there are built-in files saved for weather data of many cities across the globe, and it also has updated weather data in its database for Lahore. The direct solar collector of "Type1b" was used, which absorbed the incoming radiation of the sun for a time span of 12 h and transmitted these radiations directly to the working fluid, named "Type 14 h," for water mixed with nanoparticles. The remaining components interpolate the information of thermal heat absorbed by nanoparticles and transmit it to the water. The plotter was used to plot every millisecond of information in its database and then, after summarizing the result in the database of TRNSYS, "Type 25a" printer was used to represent the graphical results. The operating conditions of the TRNSYS model have been shown in **Table 1**.

The continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Momentum equations:

$$\rho_{wf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu_{wf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\rho_{wf}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial P}{\partial y} + \mu_{wf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\rho_{wf}\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z} + \mu_{wf}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$
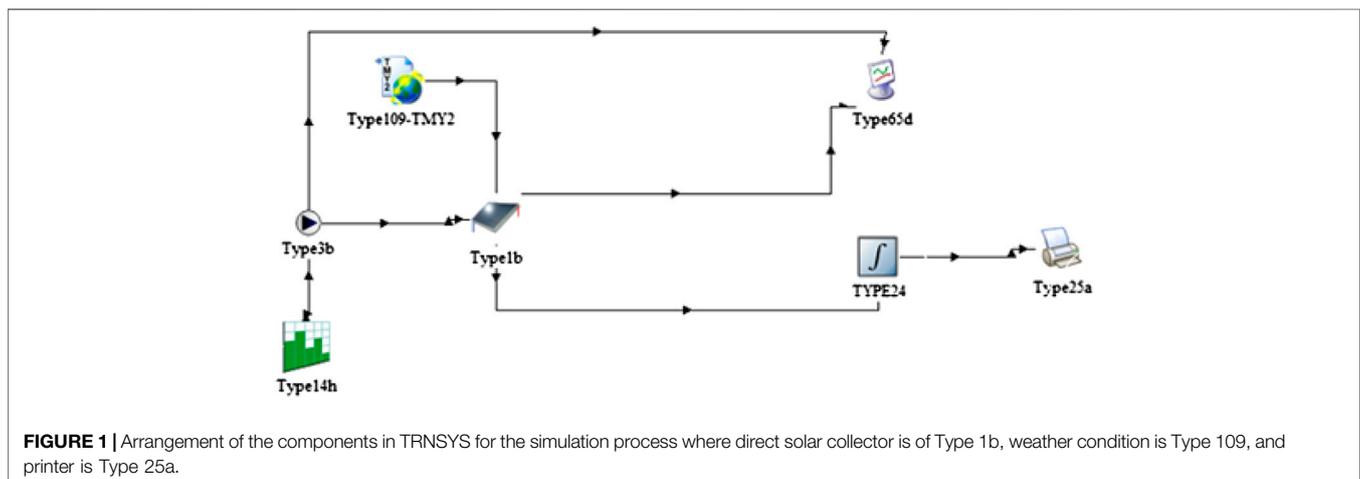

FIGURE 1 | Arrangement of the components in TRNSYS for the simulation process where direct solar collector is of Type 1b, weather condition is Type 109, and printer is Type 25a.

TABLE 1 | Specifications of TRNSYS model.

Parameter	Specifications	Parameter	Specifications
Inlet temperature	20°C	Ground reflectance	0.2
Inlet flow rate	100 kg/h	Incidence angle	45°
Ambient temperature	20°C	Number in series	1
Collector area	0.50 m²	Efficiency mode	1
Tested flow rate	40 kg/h·m²	Intercept efficiency	0.80
Efficiency slop	13 kJ/h·m²·K	Efficiency curvature	0.05 kJ/h·m²·K²
Maximum power of the pump	60 kJ/h		

Energy equations of working fluids:

$$\rho_{wf} C_{wf}\left(u\frac{\partial T_{wf}}{\partial x} + v\frac{\partial T_{wf}}{\partial y} + w\frac{\partial T_{wf}}{\partial z} \right)$$
$$= k_{wf}\left(\frac{\partial^2 T_{wf}}{\partial x^2} + \frac{\partial^2 T_{wf}}{\partial y^2} + \frac{\partial^2 T_{wf}}{\partial z^2} \right) \qquad (5)$$

Energy equations for walls of direct solar collector:

$$k_{cw}\left(\frac{\partial^2 T_{cw}}{\partial x^2} + \frac{\partial^2 T_{cw}}{\partial y^2} + \frac{\partial^2 T_{cw}}{\partial z^2} \right) = 0 \qquad (6)$$

Where, u, v, and w are the velocity components in the x, y, and z directions, respectively. T_{wf} and T_{cw} are the temperatures of working fluid and solar collector wall, respectively. ρ_{wf}, C_{wf}, k_{wf}, and μ_{wf} are the density, specific heat capacity, thermal conductivity, and dynamic viscosity of the working fluid (water and nanofluids), and k_{cw} is the thermal conductivity of the wall material of the direct solar collector.

Selection of Nanostructured Materials

Nanoparticles have gained the attention of many researchers due to their wide range of applications in the heat transfer process. The selection of nanoparticles depends upon their stability in base fluids; metal oxide and carbon-based nanoparticles, including ZnO, CuO, and GO, were used in this study due to their high stability, higher thermal conductivity, and high absorptivity as compared to others. The stability of these nanoparticles in water was checked by UV-spectrography and the kinematic viscosity of these nanofluids was determined by using a rheometer. The physiochemical characteristics of these nanoparticles were shown in **Table 2**. These nanoparticles were added to water to make nanofluids and passed from the bottom surface of the direct
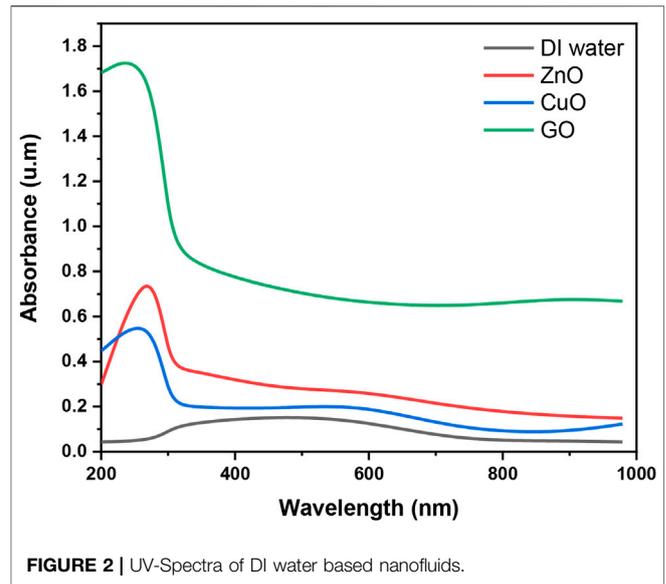

FIGURE 2 | UV-Spectra of DI water based nanofluids.

solar collector. All nanoparticles have different specific heat capacity values, due to which all nanofluids show a different rise in temperature and heat transfer rates. The simulation for these nanofluids was done daily for 4 h from 10:00 AM to 2:00 PM over a one-year time span. The stability of these nanoparticles has been shown in **Figure 2**. Water shows minimum absorbance as compared to all three nanofluids because water is a poor absorber of visible light. The solar absorbance of water can be increased by adding nanoparticles, due to their better absorptivity into visible light. The stability of these nanoparticles into base water was checked by using a UV-spectrometer. All nanofluids exhibited different absorption peaks at different wavelengths. The maximum absorptivity was shown by GO-based nanofluids at a wavelength of 270 nm. Both metal-based nanofluids exhibited lower absorbance as compared to GO nanofluids; the peaks for ZnO and CuO nanofluids were observed at a wavelength of ranges from 275 to 287 nm.

Simulation Model of the Solar Collector

The nanofluids that were passed through the directly absorbing solar collector were simulated using a component-based software known as TRNSYS, which simulates the performance of several transient systems. This software involves different options for different systems, which are referred to as "Type." In this present study, Type 1b system was used to model a direct solar collector with an entrenched layer of nanofluids passing from the

TABLE 2 | Characteristics of nanoparticles and water.

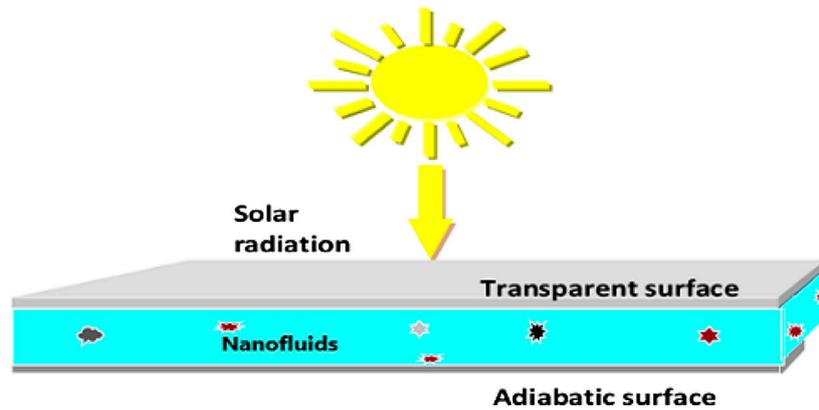| Substance	Specific heat value (kJ/kg-K)	Thermal conductivity (W/m-K)	Density (kg/m³)	Reference
Water	4.19	0.606	998	Barreneche et al. (2018)
CuO	0.531	33	6,310	Akbar et al. (2016)
ZnO	0.494	27	5,601	Cabaleiro et al. (2013)
GO	0.710	18	2,267	Esfahani et al. (2016)

FIGURE 3 | Schematic diagram of a direct solar collector with nanofluids (adapted from (Karami et al., 2014)).

bottom of this system. These nanofluids absorb the direct radiation that comes from the sun and transfer heat; in this study the overall solar collection has been calculated based on the intensity of sun radiation and cell temperature of the solar collector. Nanofluids configuration with a direct solar collector has been shown in **Figure 3**. The direct solar collector consists of transparent glass and adiabatic surfaces; the upper transparent glass surface absorbs the solar radiation directly from the sun, while the lower surface is adiabatic. Due to solar radiation, the temperature of the solar collector rises, which distinctly affects the photothermal efficiency of the solar collector. The photothermal efficiency of the direct solar collector can be improved to remove the absorbed heat; the conductive and convective heat generated in the direct solar collector were removed by passing nanofluids through the collector. Suspended nanoparticles in the base water absorb the heat from the upper surface of the solar collector and cool down the solar collector.
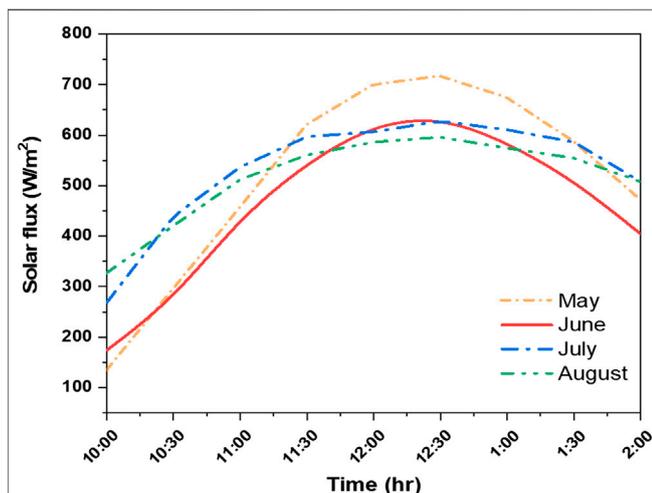
RESULTS AND DISCUSSION

The location used in TRNSYS for simulation was Lahore city and the coordinates are 31.695° North latitude and 74.244° East longitude at an elevation of 220 m above sea level. Type 109 weather condition model was used for the selected city for the whole year. The solar flux of four months from May to August has been shown in **Figure 4**; the maximum solar intensity was found in these four months in Pakistan. **Figure 5** represents the average change in day and nighttime temperature for Lahore city for the whole year. The peak temperature was observed from May to August 2020. The maximum daytime temperature of 41°C was observed in June, while at nighttime the temperature starts to decrease.
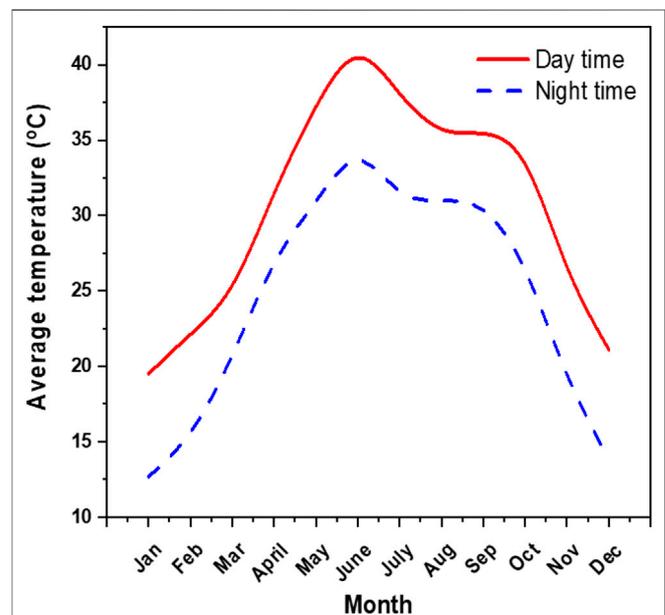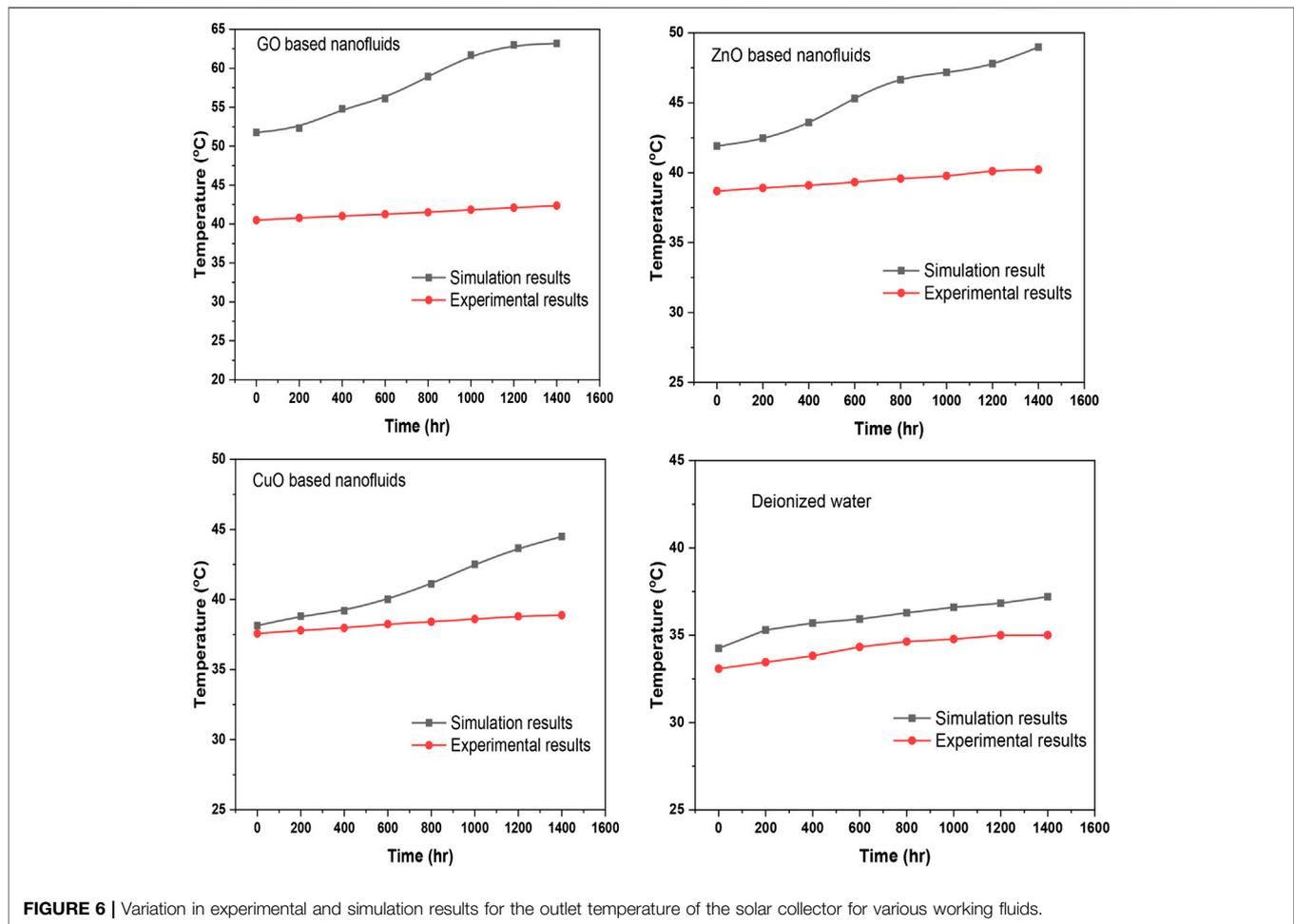

FIGURE 4 | Solar intensity of summer months.

FIGURE 5 | Average change in day and nighttime temperature for the year 2019 for the city of Lahore.

FIGURE 6 | Variation in experimental and simulation results for the outlet temperature of the solar collector for various working fluids.

Variation in Collector Temperature

The overall efficiency of direct solar collectors is adversely affected by increasing temperatures. Various techniques have been developed to reduce temperature; a coating of phase change was used at the backside of the PV cell to decrease the temperature, but very few studies have been done on aqueous nanofluids for direct solar collectors to reduce the temperature (Rezvanpour et al., 2020). As metal-oxide-based and carbon-based nanoparticles are better heat absorbers than water, a mixture of nanoparticles with water—termed as nanofluids—decreased the temperature of solar collectors effectively by absorbing the heat released by the collector. The simulation of nanofluids passed through the direct solar collector was performed for 4 h daily from 10:00 AM to 02:00 PM for the whole year. The direct solar collector absorbs the direct radiation from the sun and increases the inside temperature of the collector; four different working fluids were passed through the direct solar collector, including water and nanofluids consisting of three different nanoparticles (CuO, GO, and ZnO). The numerical results obtained from TRNSYS were compared with experimental results. The numerical results were linked with the experimental results observed by Sattar et al. (Sattar et al., 2020) and the variation in collector temperature (T_{col}) with simulation hours for the whole year has been shown in **Figure 6**.

The maximum temperature peaks for all working fluids were observed for summer hours. The maximum temperature was observed for GO-based nanofluids, followed by ZnO and CuO, and the minimum temperature was observed for pure water. Both numerical and experimental results show a similarity in behavior as time increases the temperature rises for all working fluids. For GO-based nanofluids, the difference between numerical and experimental results was observed at 20%. The difference between the experimental and numerical temperature results is associated with instrumental and human error and the heat leakage to surroundings with the increase in temperature may also contribute to this difference. Moreover, the TRNSYS model may also generate relatively smaller deviated results due to the difference in the characteristics defined in the numerical model than the actual physical properties, like specific heat value, thermal conductivity, and density. The maximum temperature shown by GO-based nanofluids was 63°C, followed by ZnO showing 49°C, CuO showing 45°C, and water showing 37°C. The temperature profile for all these working fluids for a specific day of the summer season for a time duration of 10:00 AM to 2:00 PM has been shown in **Figure 7**. The maximum temperature was observed in Lahore in June; during peak hours the temperature of the direct solar collectors also increased. The

FIGURE 7 | Temperature profile of all working fluids for a specific day of the summer season of June 2019.

FIGURE 9 | Heat transfer phenomenon in direct solar collector.
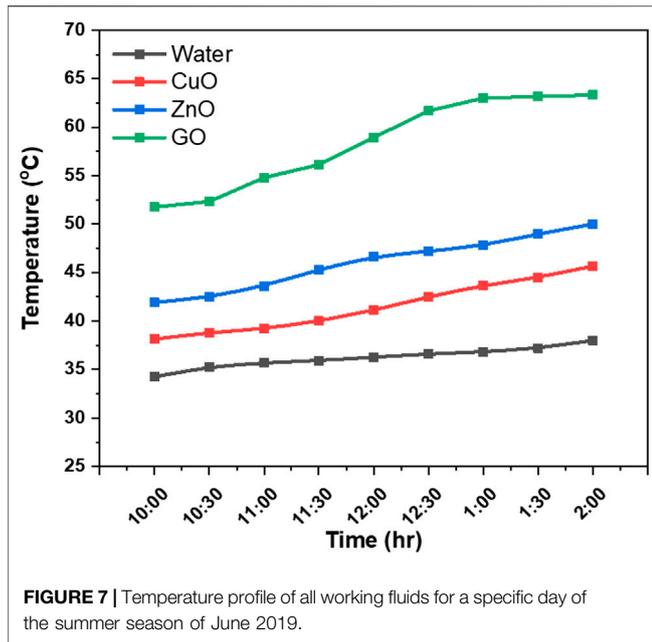
temperature profile of working fluids represents the heat absorption of these fluids which raises the temperature of the nanofluids passes through the solar collectors. The maximum temperature was shown for the GO nanofluid, followed by ZnO, CuO, and water. The maximum temperature of 63°C was observed during peak hours of the summer season (June 30, 2019). The temperature profile for all working fluids increased sharply from 10:00 AM to 01:00 PM and then started to decrease. Rezvanpour et al. (Rezvanpour et al., 2020) investigated the enhancement of conversion efficiency photovoltaic cell by using phase change materials and performed experimental and
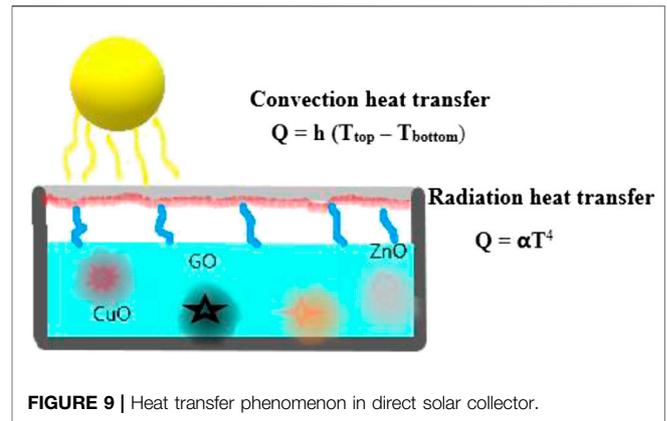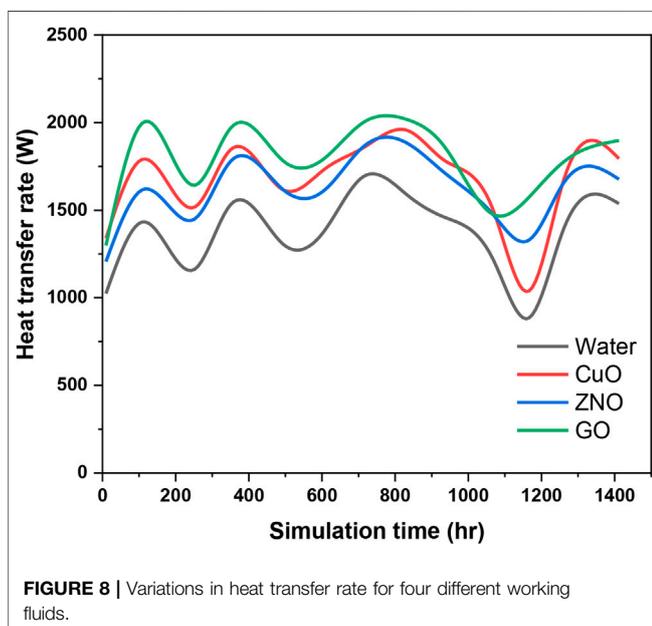
simulation analysis. A significant reduction of 26°C in temperature was observed with the use of phase change materials in a photovoltaic cell.

Heat Transfer Rate

The variation in heat transfer for four different working fluids has been shown in **Figure 8**. As the direct solar collector absorbs all radiation that comes from the sun and then heats up, this continued rise in temperature of the solar collector affects its overall efficiency. To improve the efficiency of the direct solar collector, different techniques are used for cooling purposes. One technique is to use pure water, but the use of metal-oxide-and carbon-based nanoparticles gain the most attention. The maximum heat transfer rate has been observed for GO-based nanofluids as, due to their black color, they absorb most of the heat that comes from the sun directly. Both metal-based nanoparticles, zinc oxide and copper oxide, due to their better thermal conductivities also absorb more heat as compared to basefluid. The heat transfer rate has been improved with the addition of nanoparticles in water; a significant improvement in the heat transfer rate of 11.33, 20, and 28.25% has been observed for GO, CuO, and ZnO nanofluids, respectively, as compared to basefluid (water) at a simulation time of 108 h.

The heat transfer modes in direct solar collectors are convective and radiate heat transfer; both modes of heat transfer have been shown in **Figure 9**. In convective heat transfer, the flowing fluid from the bottom surface of the solar collector absorbs the dissipating heat from the upper transparent glass and cools it down. The second mode of heat transfer is radiation in which no medium is required for heat transfer; anything that is above the absolute temperature emits radiation and this radiation is absorbed by nanofluids.

CONCLUSION

In this study, the solar energy captured using nanostructured energy materials in a direct absorption solar collector is simulated using TRNSYS. The performance of the direct solar collector was evaluated at various concentrations of nanostructured materials, including GO, CuO, and ZnO, where water was used as basefluid.

FIGURE 8 | Variations in heat transfer rate for four different working fluids.

The weather model used in TRNSYS was Type 109 model and the location of the selected model was Lahore, Pakistan. Photothermal performance of the dark-colored nanofluid GO was maximum due to its higher thermal conductivity and better absorption characteristics. The maximum outlet temperature of 63°C was observed for GO nanofluid during peak hours of the summer season (June 30, 2019). A significant improvement in the heat transfer rate of 23.52, 21.11, and 15.09% was observed for the nanofluids of GO, ZnO, and CuO, respectively, when compared with water as basefluid. The results showed that GO nanofluid is a potential candidate for solar thermal energy-based applications.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

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AUTHOR CONTRIBUTIONS

MZ and MA conceived the idea and planned work. MZ executed the work and drafted the manuscript in coordination with MA. MA and MF supervised the work, ZA and RS refined the draft and help explaining the underneath mechanism of enhanced photothermal performance. EF and XD reviewed the manuscript and refined the result interpretations with other authors. All authors contributed equally in the preparation of this manuscript to the submission phase.

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