Incorporating nano-scale material in solar system to reduce domestic hot water energy demand

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ABSTRACT

With the aim of improving the usefulness of a solar system in energy-saving, the thermal behavior of the domestic hot water system was investigated. The energy/continuity equations were developed to investigate the transient analysis of a solar hot water system in three climatic regions in Saudi Arabia (Najran, Jeddah and Riyadh). By using a water-filled solar system, the energy consumption of the boiler reduced by 12478, 13,289 and 13,896 $\frac{\text{kWh}}{\text{year}}$ in Najran, Riyadh and Jeddah, respectively. With the addition of WO_3, CeO_2, Al_2O_3, Fe_3O_4, CuO and MWCNT nanoparticles, although the thermal conductivity increases (positive effect), but at the same time, the parameter of density × specific heat may be reduced (negative effect), hence using nanoparticles maybe not useful. In this study, it was found that increasing the conductivity has a greater effect and therefore for all nanoparticles, the collector heat gain increased. The best results were related to the collector equipped with MWCNT, so that this collector had more energy-saving than the water-based one by 9963 (for Najran), 10,000 (for Riyadh) and 10,379 kWh/year (for Jeddah).

Introduction

Buildings contribute a lot to pollution production and energy consumption [1–3]. Many solutions have been recommended by various researchers to reduce energy consumption [4–8]. Techniques include installing PCM in the building [9–17], heat recovery [18–20], using solar energy [21–33], other renewables such as wind [34–36], geothermal sources [37,38] and finally using nanofluid [39–43]. In the solar field, nanoparticles are used in two fields of photovoltaic cells (PVs) [44,45] and solar collectors [46]. Studies show that at best, PVs can convert up to 20% of the sun's radiation into electrical power. A large share of the input solar irradiance energy is converted into internal energy and increases the cell temperature (T_{PV}), which itself as an undesirable parameter reduces the electrical efficiency (η_e) [47]. There are several techniques for lowering T_{PV} [48–55]. Overall nanofluids have significant application in microchannel [56] and heat transfer [57,58]. In this section, focusing on nanofluid-based methods [59,60], PV, as well as PVT cooling, is investigated.

In an experimental study, Chandrasekar et al [61] evaluated the cooling of a PV device in three scenarios. In the first step, they added cotton wicks in water and revealed that this technique could reduce T_{PV} from 65 to 45 °C which is equivalent to a reduction of 20 °C. In the second scenario, they inserted Al_2O_3 nano-scale particles into the water and affirmed that T_{PV} lowered by 11 °C (from 65 °C to 54 °C). In the last scenario, loading CuO nano-scale particles led to 6 °C reduction in T_{PV}. Any decrease in T_{PV} improves η_{PV}. The use of the first, second and third scenarios increased η_{PV} by 15.5% (due to using cotton wicks filled with water), 7.7% (loading l_2O_3) and 5.5% (inserting CuO).

Hamdan and Kardasi [62] experimentally used CuO and Al_2O_3 nanoparticles to intensifies the electrical efficiency of a water-cooled PV. They first compared the cooling capacity of water with $CuO/water$ and $Al_2O_3/water$ and concluded that both nanofluids are more capable. Afterward, then challenged $CuO/water$ and $Al_2O_3/water$ and found that the former nanofluid was superior. In the case of $uO/water$, the parameters of η_{Elc} was 13.92% while in the case of water, η_{Elc} was 13.14%. Note that this figure was 12.99% for PV without cooling. In other words, loading CuO into water increased η_{Elc} by 5.9%. The nanofluids of $CuO/water$ and $Al_2O_3/water$ showed the best performance at 0.6 vol% and 0.4 vol%. Hasan et al., [63] compared the PVT cooling potential of $iC/water$, $TiO_2/water$ and $SiO_2/water$. The best results were related to $SiC/water$ so that

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Table 1
Studies on the usefulness of nanofluid in FPSCs.

References	Nanofluid	Findings
Hawwash et al. [65]	Loading Al_2O_3 at 0.1–3 vol%	At 0.5 vol%, the effectiveness was maximum
Ghasemi and Ranjbar [66]	Al_2O_3/waterCuO/waterAt 0.5, 1.5 and 3 vol%	$\frac{\eta_{Al_2O_3/water}}{\eta_{water}} = 1.28$ $\frac{\eta_{CuO/water}}{\eta_{water}} = 1.35$
Eltaweel and Abdel-Rehim [67]	Al_2O_3/water0.01, 0.05 and 1 wt%	For 0.01 wt% loading MWCNT led to $\frac{\eta_{MWCNT/water}}{\eta_{water}} = 1.16$ while for 0.05 and 0.1 wt%: $\frac{\eta_{MWCNT/water}}{\eta_{water}} = 1.21$ and $\frac{\eta_{MWCNT/water}}{\eta_{water}} = 1.34$
Said et al. [68]	TiO_2/water	$\frac{\eta_{MWCNT/water}}{\eta_{water}} = 1.766$
Sabiha et al. [69]	SWCNT/water	At 0.2 vol%: $\left(\frac{\eta_{SWCNT/water,max}}{\eta_{water,max}}\right) = 1.934$
Yousefi et al. [70]	Al_2O_3/water0.2–0.4 wt%	$\frac{\eta_{Al_2O_3/water}}{\eta_{water}} = 1.283$
Tiwari et al. [71]	Al_2O_3/water1.5 vol%	$\frac{\eta_{Al_2O_3/water}}{\eta_{water}} = 1.316$
Mirzaei [72]	CuO/water At 1,2 and 4 $\frac{lit}{min}$ 0.1 vol%	At 1 $\frac{lit}{min}:\frac{\eta_{CuO/water,max}}{\eta_{water,max}} = 1.1428$ At 2 $\frac{lit}{min}:\frac{\eta_{CuO/water,max}}{\eta_{water,max}} = 1.298$ At 4 $\frac{lit}{min}:\frac{\eta_{CuO/water,max}}{\eta_{water,max}} = 1.4310$ At 1 $\frac{lit}{min}:\frac{F_R U_{CuO/water}}{F_R U_{water}} = 1.3455$ At 2 $\frac{lit}{min}:\frac{F_R U_{CuO/water}}{F_R U_{water}} = 1.21$ At 4 $\frac{lit}{min}:\frac{F_R U_{CuO/water}}{F_R U_{water}} = 1.1622$ Taking to account the higher maximum efficiency and lower heat loss coefficient at higher mass flow rates, these results reveal that as the mass flow rate increses, the nanofluid efficacy on FPSC effectiveness becomes more usefulness.
Tong et al. [73]	Al_2O_3/*water*	For Al_2O_3 : $\left[\frac{\eta_{max,Al_2O_3/water}}{\eta_{max,water}} = 1.238 \quad \frac{F_R U_{Al_2O_3/water}}{F_R U_{water}} = 0.978\right]$
	CuO/*water*	For CuO : $\left[\frac{\eta_{max,CuO/water}}{\eta_{max,water}} = 1.181 \quad \frac{F_R U_{CuO/water}}{F_R U_{water}} = 0.732\right]$
	Fe_3O_4/*water*	For Fe_3O_4 : $\left[\frac{\eta_{max,Fe_3O_4/water}}{\eta_{max,water}} = 1.1463 \quad \frac{F_R U_{Fe_3O_4/water/water}}{F_R U_{water}} = 1.2144\right]$
	MWCNT/water	For MWCNT : $\left[\frac{\eta_{max,MWCNT/water}}{\eta_{max,water}} = 1.398 \quad \frac{F_R U_{MWCNT/water}}{F_R U_{water}} = 2.7\right]$ Note that the higher values of $\frac{\eta_{max,nanofluid}}{\eta_{max,basefluid}}$ as well as lower values of $\frac{F_R U_{nanofluid}}{F_R U_{basefluid}}$ are recommend.

this nanofluid was able to improve the parameters of η_{Th}, η_{Ele} and η_O by 12.75, 85 and 97.75%, respectively.

In another laboratory study, Ebaid et al. [64] prepared two nanofluids of $Al_2O_3/water$ and $TiO_2/water$ to improve PV cooling efficiency. Measurements of T_{PV} showed that both nanofluids could maintain cell temperature at lower values and were, therefore, better candidates than water. Although both nanofluids performed better in cooling at higher concentrations, $Al_2O_3/water$ cooling ability was better than $iO_2/water$.

In Solar collectors, nanoparticles are incorporated into water to increase the overall effectiveness. In a numerical study[41], it was found that the presence of CuO nanoparticles can increase the heat gain in collectors by 671 $\frac{kWh}{m^2}$. Many studies have been done in this field and for summary, we can refer to Table 1.

The idea of using solar energy to preheat the domestic hot water supply has been examined by many researchers and it was affirmed that the boiler energy damnd can be reduced owing to using solar energy. To further reduce energy usage, energy absorption in the solar system must be boosted. In this research, WO_3, CeO_2, Al_2O_3, Fe_3O_4, CuO and MWCNT nanoparticles are used to increase system efficiency. Although nanoparticles improve thermal conductivity, but they can reduce heat capacity. Decreasing the heat capacity rises the temperature in the collector and can itself increase the thermal losses. Therefore, it can not be claimed that the addition of nanoparticles and improvement in thermal conductivity improves performance and the heat capacity parameter should be included. In this study, considering the climatic conditions of Saudi Arabia, the question is answered whether the use of nanofluids in solar systems is beneficial?

Problem description

The solar system in Fig. 1 utilizes solar collectors, heat exchangers and storage tanks. The high cost of nanofluids makes it impossible to the whole system with nanofluids. Therefore, a heat exchanger is utilized to transfer thermal energy, so that the solar system is economically justifiable. The storage tank consists of two inlets and two outlets so that on one side, the cold drinking water and on the other side, hot water from the collector enters the tank. If the inlet energy from the hot water is not able to provide the proper temperature in the storage tank, an auxiliary electric heater should be used. The auxiliary heaters were used in this study because solar radiation is not always available.

Mathematical formulation

In a solar collector, only a part of the solar energy can be converted into thermal energy. This part of the energy can be obtained according to the collector efficiency:

$$\eta = \frac{\dot{Q}_{useful}}{A_c\ I_t(t)} = F_R(\alpha\tau) - F_R U_l \frac{T_i - T_a}{I_t(t)} \tag{1}$$

Note that $F_R(\alpha\tau)$ and $F_R U_l$ obtained using least square methodologies. To obtain solar intensity over tilted collector, at first, the solar intensity over the horizontal surface should be determined:

$$\underbrace{I_t(t)}_{\text{total radiation}} = \underbrace{I_b(t)}_{\text{beam radiation}} + \underbrace{I_d(t)}_{\text{diffuse radiation}} \tag{1}$$

where $I_b(t)$ is the beam radiation:

$$I_b(t) = I_0 \times \exp\left(\frac{-T_R}{0.9 + 9.4(\cos\varphi \times \cos\delta \times \cos\omega + \sin\delta \times \sin\varphi)}\right) \tag{2}$$

On the other hand, I_d is obtained from the following relation [74]:

$$\frac{I_d}{I(t)} = 1.0086 - 0.178 M_t \text{for} 0 < \kappa_T < 0.24 \tag{3}$$

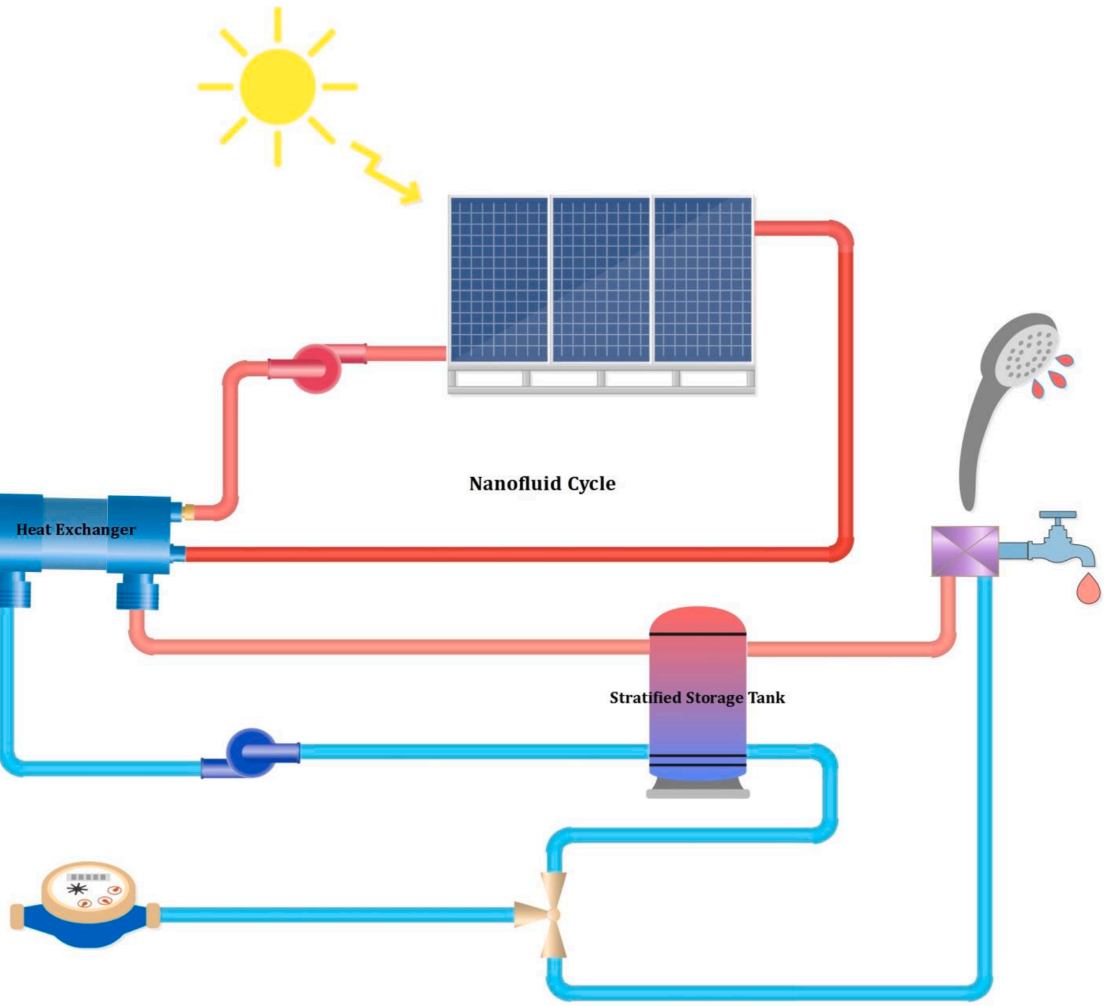

Fig. 1. A schematic of the solar system.

$$\frac{I_d}{I(t)} = 0.9686 + 0.1325M_t + 1.4183M_t^2 - 10.1862M_t^3 + 8.3733M_t^4 \text{for} 0.24 < \kappa_T < 0.8$$

$$\frac{I_d}{I(t)} = 1.0086 - 0.178M_t \text{for} 0.8 < M_t < 1$$

where clearness index parameter is defined as $M_t = \frac{I}{I_0}$. For any tilt surface, we have:

$$I_t(t) = \frac{\cos\theta_i}{\cos\theta_z} I_b(t) + \frac{1+\cos\theta}{2} I_d(t) + \rho\frac{1-\cos\theta}{2}(I_b(t) + I_d(t)) \quad (5)$$

where θ is the collector angle and $\cos\theta_i$ and $\cos\theta_z$ are obtained using the following equations:

$$\cos\theta_i = (\cos\varphi\cos\theta + \sin\varphi\sin\theta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\theta\sin\gamma + \sin\delta(\sin\varphi\cos\theta - \cos\varphi\sin\beta\cos\gamma) \quad (6)$$

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\delta\sin\varphi \quad (7)$$

Results

The energy required to supply the domestic hot water depends on many parameters. The first parameter is the amount of consumption that can not be discussed with certainty. In this study, hot water consumption for a hotel with a capacity of 30 people is discussed. The amount of hot water consumption per person in the hotel is approximately 90 L per hour. Therefore, the maximum consumption is 2700 L per hour. On the

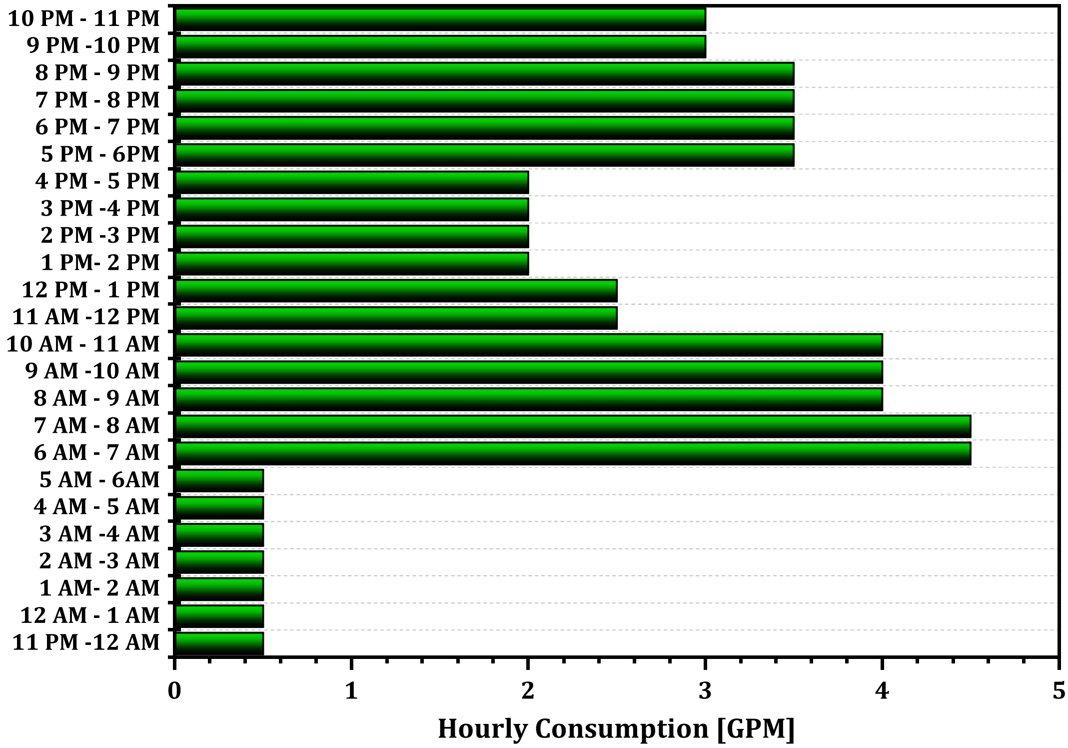

Fig. 2. Hot water demand profile (hourly consumption per person) [75].

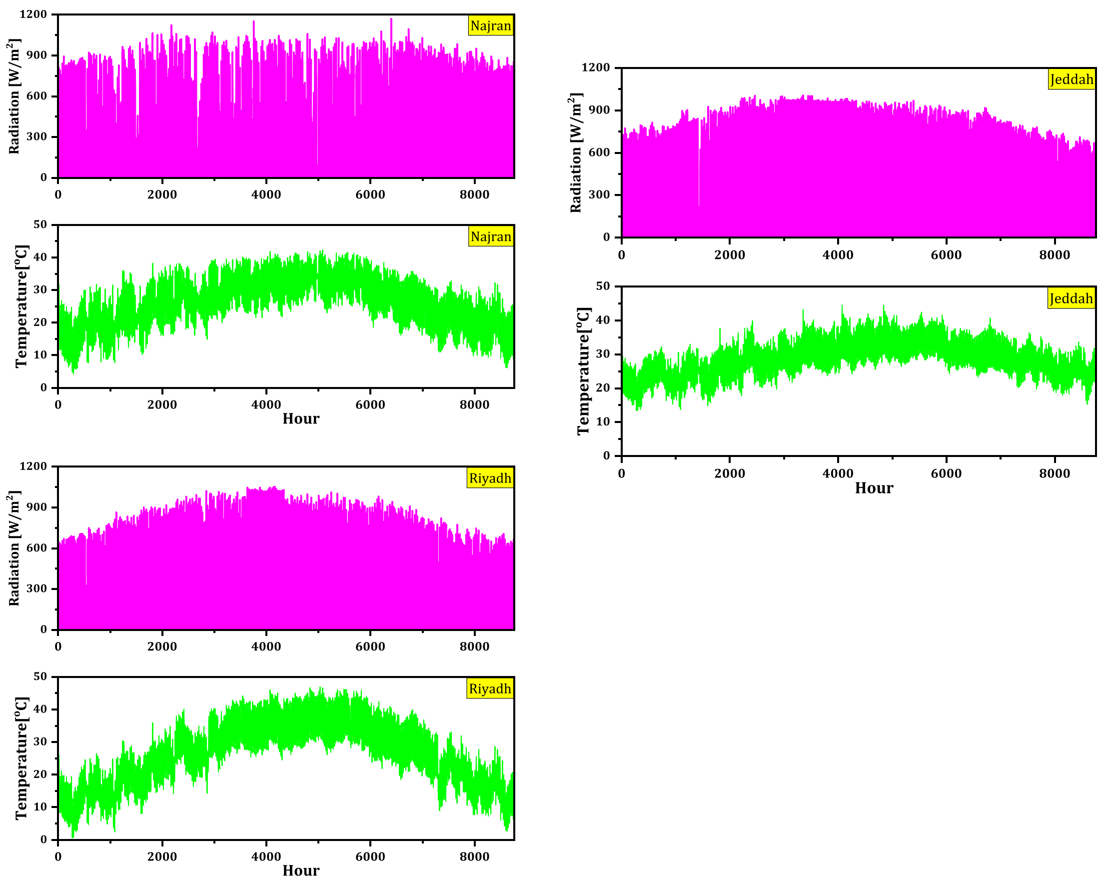

Fig. 3. The hourly variation in T_{amb} and Global radiation

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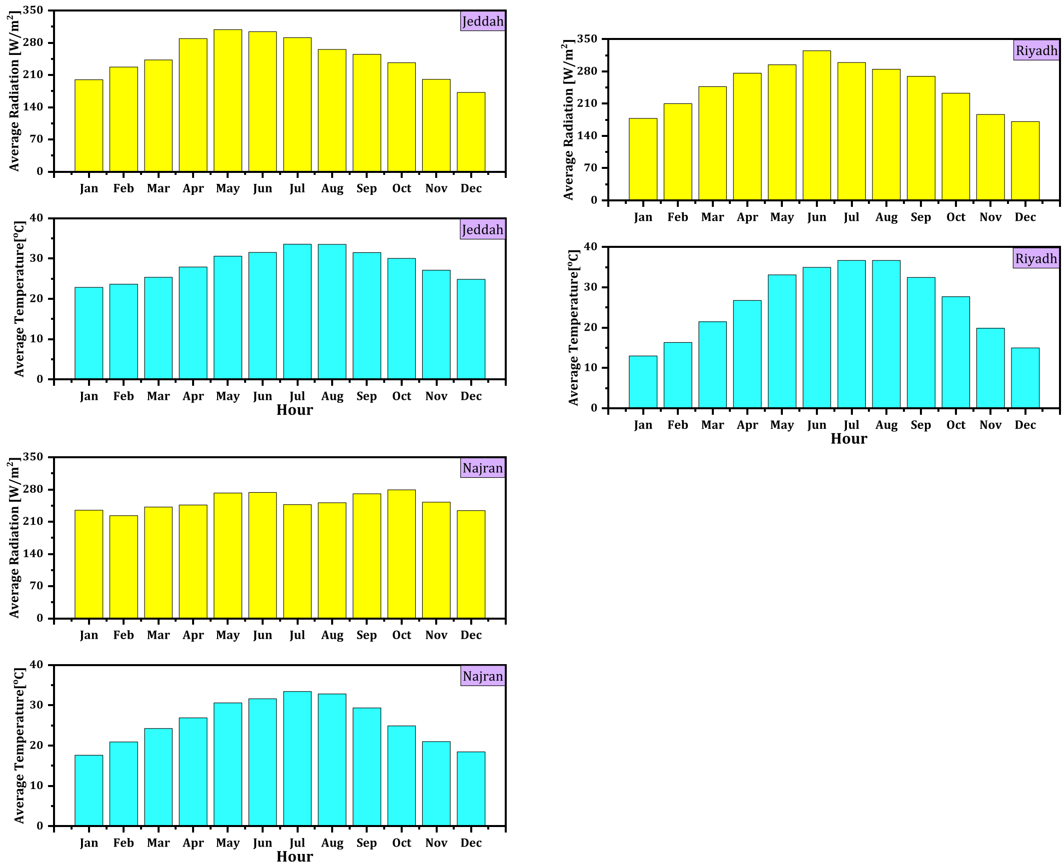


Fig. 4. The monthly average of T_{amb} and global radiation.

Table 2
annual variations in T_{amb} and global radiation.

Location	Average of radiation (W/m^2)	Average of temperature (°C)	Coordinates
Najran	252.31	26	17.5656° N, 44.2289° E
Riyadh	248	26.2	24.7136° N, 46.6753° E
Jeddah	250	28.5	21.4858° N, 39.1925° E

other hand, the amount of consumption is also time-dependent. To estimate the amount of DHW consumption in terms of hours, the pattern shown in Fig. 2 can be used.

The energy required to provide SHW is also dependent on the ambient temperature. Because of the temperature difference between the hot water and the outside, there is heat loss. In addition, solar radiation affects the amount of energy absorbed in the collector and therefore its amount must be determined. Using Meteonorm software, weather information is obtained for different regions.

Fig. 3 shows the weather data for the three regions of Jeddah, Najran and Riyadh. All three regions are located in Saudi Arabia and have a large population. Therefore, the use of solar systems in these areas can greatly reduce energy consumption.

Fig. 4 shows the average monthly temperature and radiation in all three areas.

Table 2 reports the annual variations in T_{amb} and global radiation.

Another important parameter in collectors is the properties of the working fluid. The presence of nanoparticles in the base fluid will modify the thermophysical properties of the base fluid. The thermal conductivity (k) of nanoparticles is higher than that of base fluids,

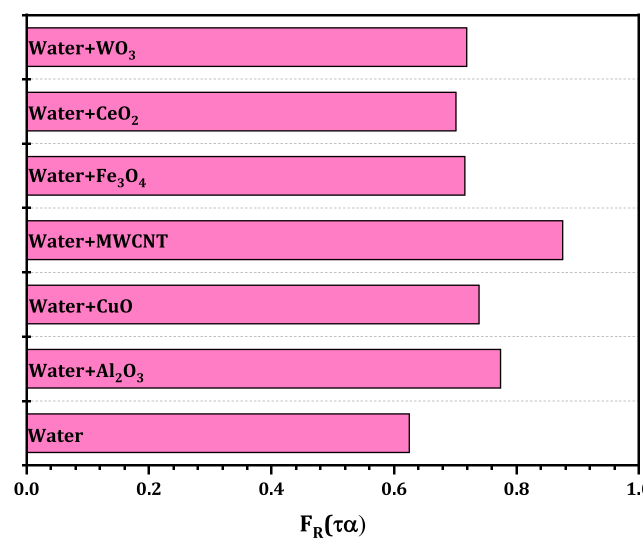


Fig. 5. The value of $F_R(\tau\alpha)$ for various nanofluids (Eq. 1) [73].

thereby improving it. The density of nanoparticles is higher than the base fluid, while the specific heat of the nanoparticles is less than the base fluid. The thermal performance of the collector depends on (k) and (ρc_p). Improvements in thermal conductivity and increases in ρc_p can lead to improvements in nanofluid thermal performance. The performance of the collector in the presence of nanofluid is compared with that of the water-based collector in Fig. 5 and Fig. 6.

Fig. 5 shows that the addition of nanoparticles significantly improved the parameter of $F_R(\tau\alpha)$. This improvement can be attributed

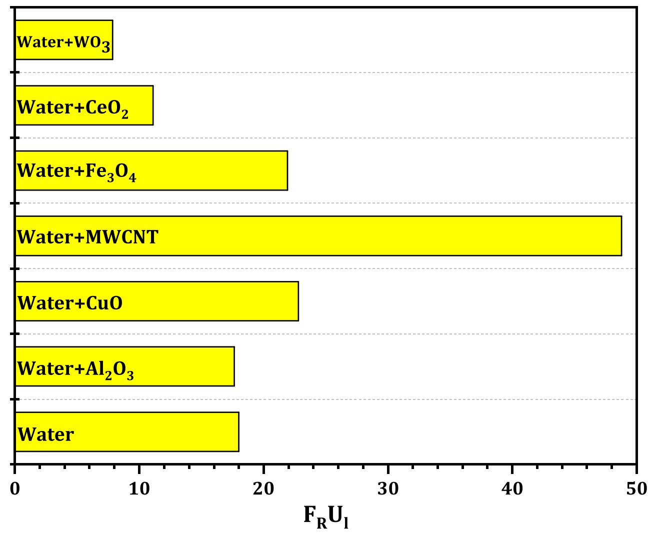


Fig. 6. The value of $F_R U_l$ for various nanofluids (Eq. 1) [73].

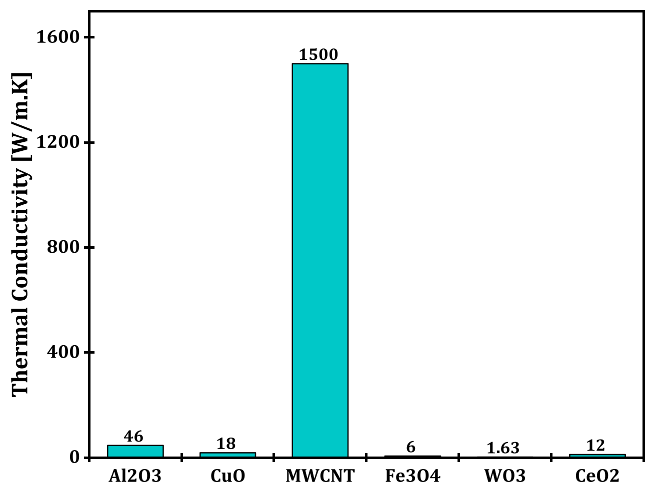


Fig. 7. Thermal conductivity of various nanoparticles in this study.

to the improvement that has been made in k_{bf}. The characteristic curve of the collectors shows [41] that in the case where the flow rate is zero, the efficiency is maximum. In this case, the convection does not affect the heat transfer rate and only thermal conductivity can affect the heat transfer. On the other hand, as has been proven in many studies, the presence of nanoparticles improves thermal conductivity. The addition of nanoparticles of Al_2O_3, CuO, MWCNT, Fe_3O_4, CeO_2 and WO_3 increases k_{bf} due to the increase in intermolecular collisions and thus improves this parameter. As the mass flow rate of the operating fluid in the collector increases, the momentum effect on the heat transfer rate increases. The presence of nanoparticles in this case reduces the momentum. Because nanoparticles are heavier than water and therefore require more momentum to move. It should be noted that the lower the parameter of $F_R U_l$, the better in terms of heat transfer. However, the presence of nanoparticles increases $F_R U_l$ and this may lead to a decrease in solar system performance (Fig. 6).

In Fig. 7, to compare the thermal conductivity of different nanoparticles, their thermal conductivity is compared. The greatest thermal conductivity is related to MWCNT. This nanoparticle has a high thermal conductivity and therefore seems to have a greater impact than other nanoparticles.

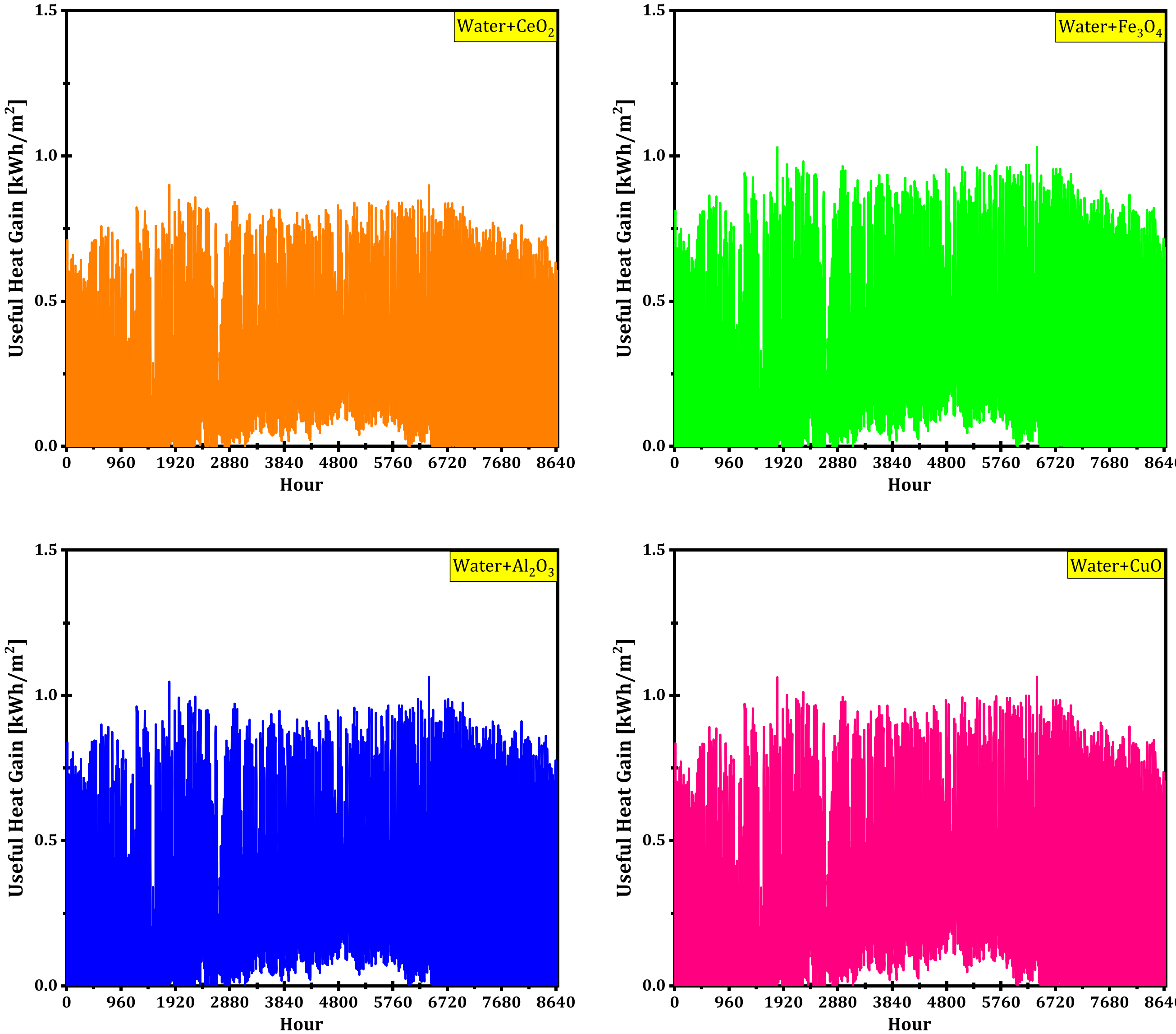
The heat gain variations per collector area which is filled with nanofluid are shown in Fig. 8.

According to Fig. 8, it can be seen that the heat gain variations correspond the radiations variations. Usually, after 8 a.m. and when the water inside the collector heats up, some energy is stored in it. By integrating form Fig. 8, the total energy which is stored in each collector can be obtained annually. For collectors filled with water, the heat gain per area collector was 1835 kWh. For collector filled with WO_3, it was 1931 kWh. For eO_2, Al_2O_3, Fe_3O_4, CuO and MWCNT this figure was 2049, 2306, 2343, 2414 and 3300 kWh.

Fig. 9 shows the amount of improvement in heat gain by adding different nanoparticles. As expected, the greatest improvement is related to MWCNT. This nanoparticle improves the amount of heat gain by 79.8% considering Najran climate zone.

Due to the fact that k_{WO_3} is very low (in compassion with other nanoparticles shown in Fig. 7), so it is not expected that this material can significantly boost the heat gain. This material enhances the heat gain by 5.25%.

The effect of nanoparticles on other regions is now being evaluated. Fig. 10 shows that nanoparticles were useful for both Jeddah and Riyadh. In addition, by comparing Fig. 9 and Fig. 10, it can be seen that the results are better for Riyadh is better than that of Najran. On the other hand for Jeddah; compared to Najran and Riyadh, the results are


Water+CeO2
Water+Fe3O4
Water+Al2O3
Water+CuO
Useful Heat Gain [kWh/m2]
Hour
0
960
1920
2880
3840
4800
5760
6720
7680
8640
0.0
0.5
1.0
1.5

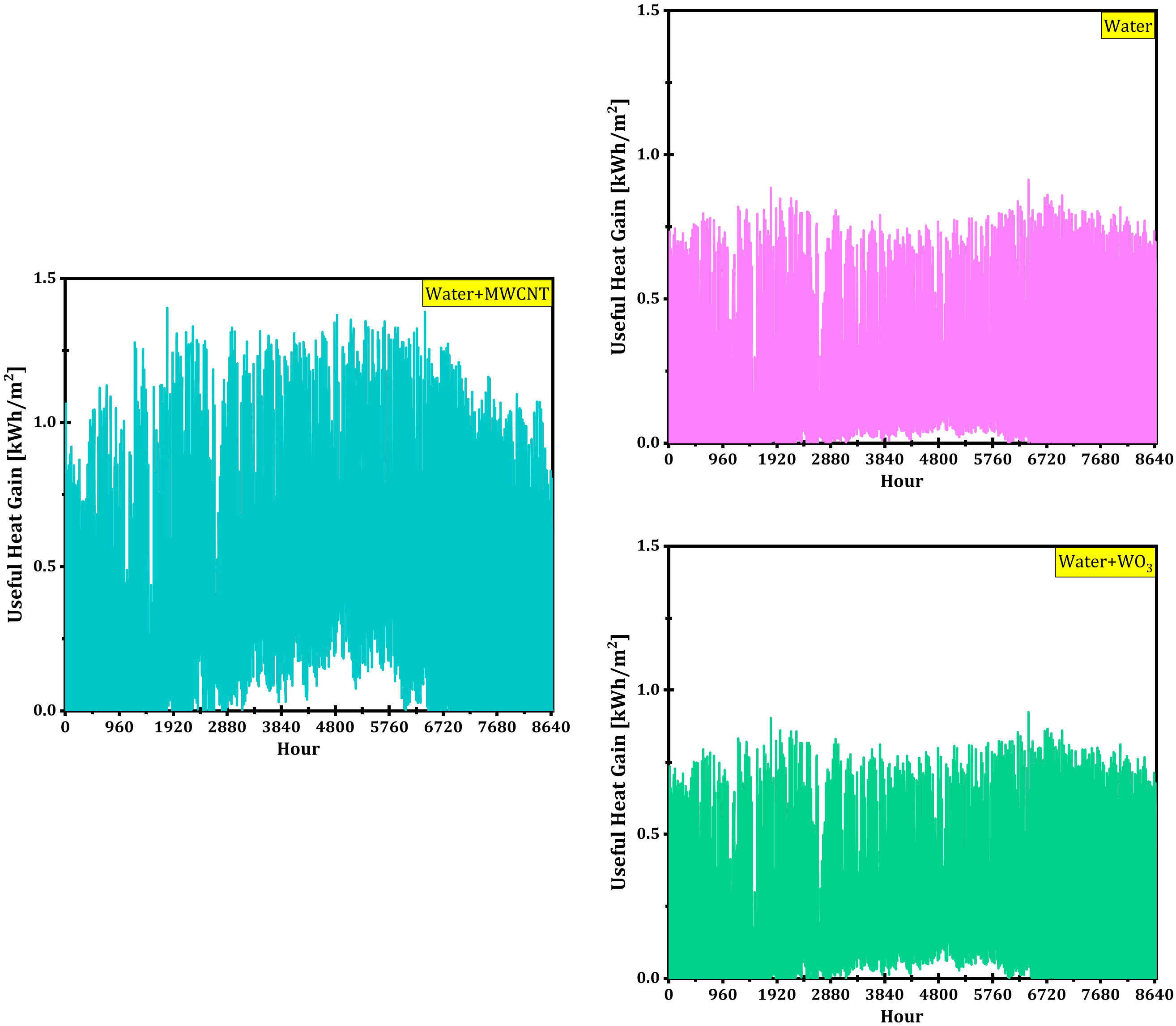


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Fig. 8. Heat gain variations for various nanofluid and comparison with base fluid.

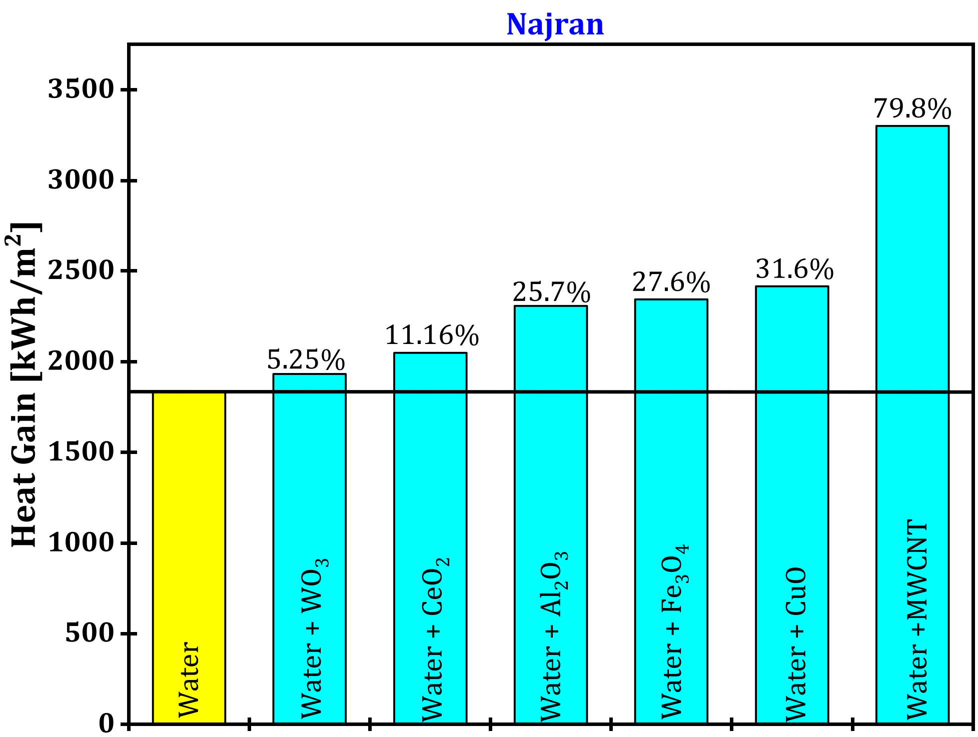

Fig. 9. Annual heat gain for collectors filled with various nanofluid.

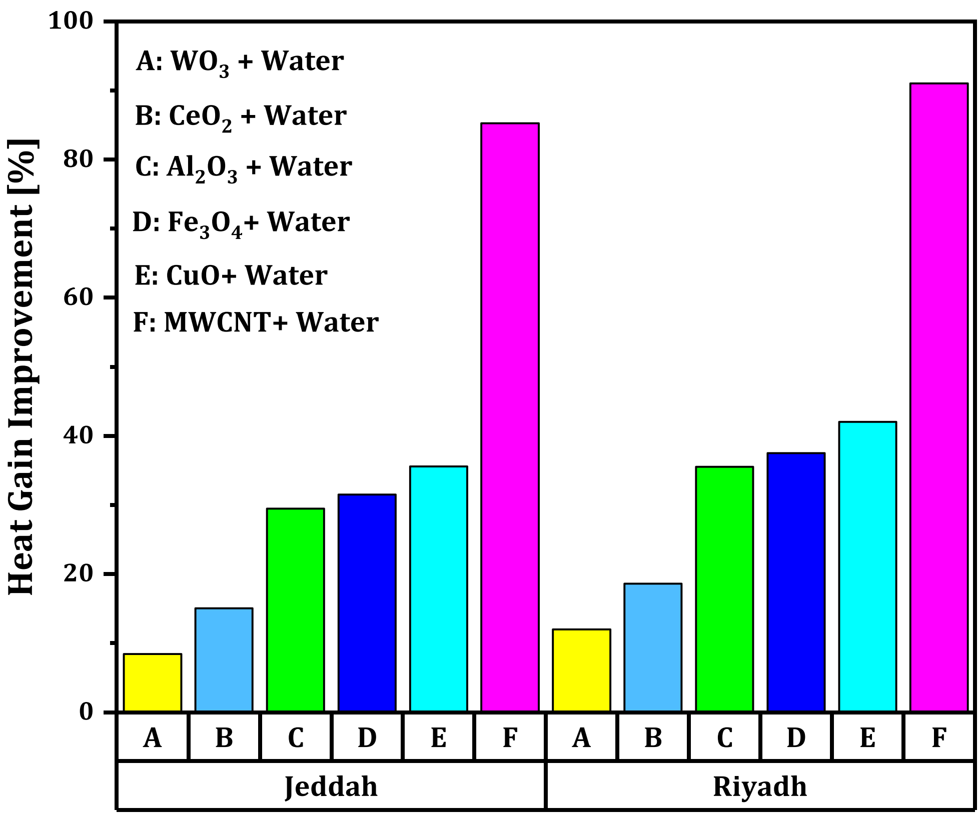

Fig. 10. Heat gain improvement in Jeddah and Riyadh.

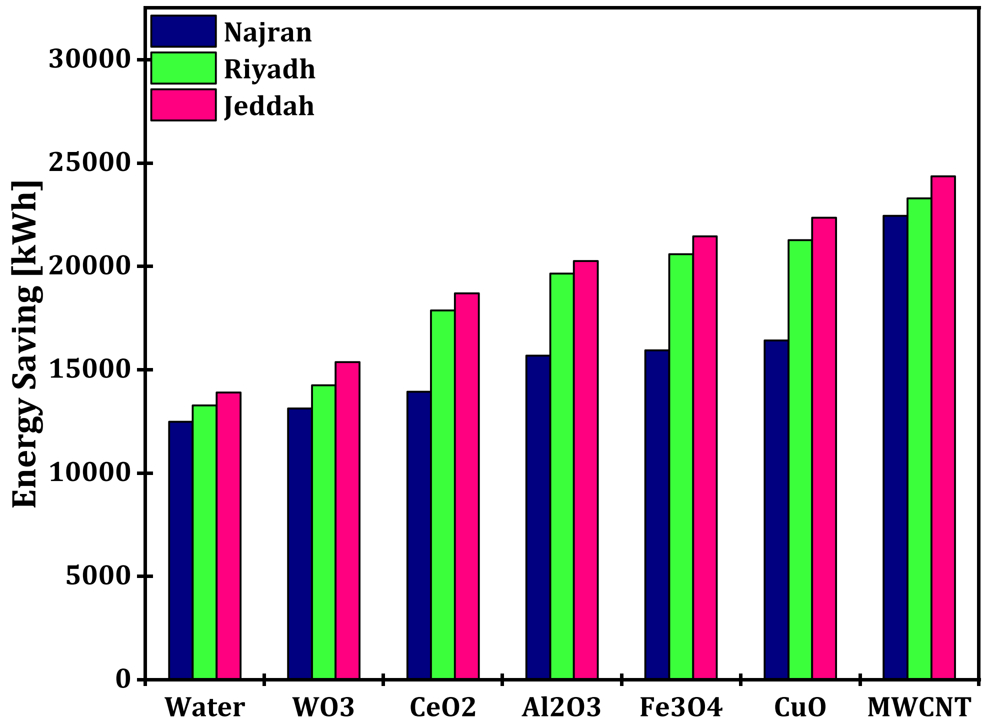

Fig. 11. Energy-saving for various nanofluid.

better.

Finally, the energy-saving value for each nanoparticle is shown in Fig. 11. As can be seen, even without the use of nanoparticles, the solar system has been able to reduce energy consumption. In Najran, Riyadh and Jeddah, the amount of energy is 12478, 13,289 and 13,896 kWh respectively. The best results were related to MWCNT nanoparticles, which produced up to 79% (for Najran), 75% (for Riyadh/Jeddah) and more energy-saving than water.

Conclusions

In this study, the thermal behavior of a solar system using several different nanoparticles was transiently investigated. By adding nanoparticles, they can boost the potential of energy absorption by the solar system and are therefore attractive. Two different techniques can be used to compare the effect of nanoparticles. In the first technique, using finite element methods, the heat transfer coefficients must be obtained and then the amount of energy absorption is determined according to the thermal resistances. In the second method, according to the method recommended by the ASHRAE standard, the effect of nanoparticles on the efficiency is determined. In this study, the second technique was used and it was found that nanoparticles increase the maximum efficiency (positive effect) and thermal losses (negative effect) simultaneously. Under the weather conditions of Saudi Arabia (Najran, Jeddah and Riyadh) to evaluate the final effect of nanoparticles, the variations of heat gain parameter (the most important parameter) were evaluated by comparing it for water/nanofluid filled solar system systems. It was revealed that loading nanoparticles improve the energy-saving content. For collectors filled with water, owing to using the solar system, the saving energy was 12478, 13,289 and 13,896 kWh for Najran, Riyadh and Jeddah. If MWCNT was loaded to the solar collector, these values increased by 79% (for Najran), 75% (for Riyadh/Jeddah). The worst results corresponded to WO_3 nanoparticles. This nanoparticle improved the effectiveness up to 10%.

CRediT authorship contribution statement

Jawed Mustafa: Methodology, Supervision, Writing – original draft. **Saeed Alqaed:** Software, Validation. **Mohsen Sharifpur:** Writing – review & editing, Conceptualization.

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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