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Effects of nanofluids on the performance of solar collectors

Thesis Booklet

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Budapest
2019

Introducing the research area

The Sun is the source all of the energy that we utilize on our planet and there are different ways for direct utilization of solar energy like solar thermal systems. Unfortunately, a big part of solar energy is lost due to different reasons such as a low efficient solar collector. In addition, the higher initial cost of solar power systems stands like a wall in front of the expansion of its construction. On the other hand, fossil fuel systems, which can work day and night, have less expensive cost. Therefore, increasing the efficiency of the solar collector is the means by which this situation can be changed and the chance of using solar energy increased. Therefore, the present work was done to find new techniques for raising the efficiency of the solar collector by the application of nanofluids.

History and context of the research

Mixing nanoparticles with base fluids result in a kind of suspension, called nanofluid. The used particles have a diameter less than 100 nm. The thermal properties of the nanofluids mainly depend on the properties of the nanoparticles. Various research works prove that the thermal conductivity of nanofluids is higher than that of the base fluid. Therefore, using nanofluids in heat transfer applications becomes one of the newest methods for increasing efficiency. The solar collector as one of the heat transfer enforcements makes use of these nanofluids. Plenty of researchers and organizations are pushing forward making this research work as Raj et al [1] Pandey et al [2], Mahmud et al [3], Hussein et al [4]. However, many nanoparticles having massive thermal properties, have not been studied yet. Moreover, several types of base fluids were not tested. Although concentrating type solar collectors are mainly used in solar power plant no sufficient work was done about using nanofluids as working fluids in such systems as well.

The research goals

The present work is focusing on testing the effect of using nanofluids in the solar collector. In order to meet the goals, different types of metal and metal oxides of nanofluids were prepared such as Cu/water, WO_3/water and CeO_2/water. Table (1) summarizes all prepared and tested nanofluids. In addition, finding the way to make these nanofluids stable was the primary concern in the research. According to the literature overview, some of these nanoparticles weren't used before such as WO_3 and CeO_2. In addition, a detailed economic study was performed on using Cu/water as working fluid for the evacuated tube solar collector. The environmental analysis is also carried out, to find the role of nanoparticles in CO_2 emission reduction. The embodied energy, Carbon Payback Time, Annual Certified Emission Reduction, Energy payback time, Energy Yield Factor, and the payback period was calculated for solar system in case of applying nanofluids. Other challenges throughout the research work were to study the collector performance in real outdoor conditions and not to make a lab simulation. Finally, the research goals were successfully achieved by designing and establish a complete test station at the roof of building D of BME.

Methods

A) Preparation method and characterization of the nanofluid

Different types of nanofluids were prepared and each one has its own method of preparation. Table (1) shows the preparation methodology for nanofluids. The ultrasonic probe homogenizer (Bandelin, SONOPULS HD 2200) was used in processing the nanofluids. Figure (1) show the preparation steps.

Table (1): nanofluid preparation conditions

Nanoparticles/ base fluid	**Diameter (nm)**	**Ultrasonic time (min)**	**PH**	zeta potential (mV)
CeO_2/water	25	75	7	-36.91
WO_3/water	90	90	6.9	-37.22
Cu/water	50	180	6.8	-31.1

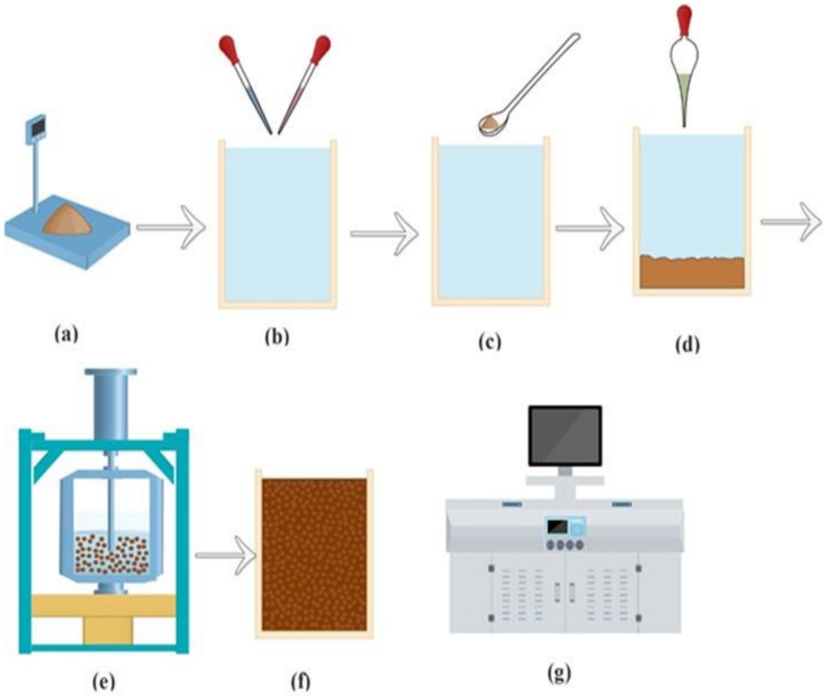

Figure (1): Layout of the synthesis and stability check of nanofluids
(a) weight the nanoparticles,(b) controlling the pH values,(c) adding the nanoparticles to base fluid, (d) adding surfactant, (e) Ultrasonic mixing, (f) the stabile nanofluid, (g) zeta potential measurements

B) Experimental method

The test station consisted of an electrical pump, which circulates the working fluid. A heat exchanger transfers heat energy from the solar collector to fan coil units. The measurements tools were a static fluid oscillatory flow sensor which measures the flow rate of the fluid and a series of Pt-100 resistance type thermocouples were fitted on the collector measuring the temperature of the working fluid in the collector at the inlet and outlet. A thermometer was used to measure the ambient temperature. The solar radiation was measured by an LP PYRA 03 solar meter. Figure (2) shows the arrangements of the experimental set-up.

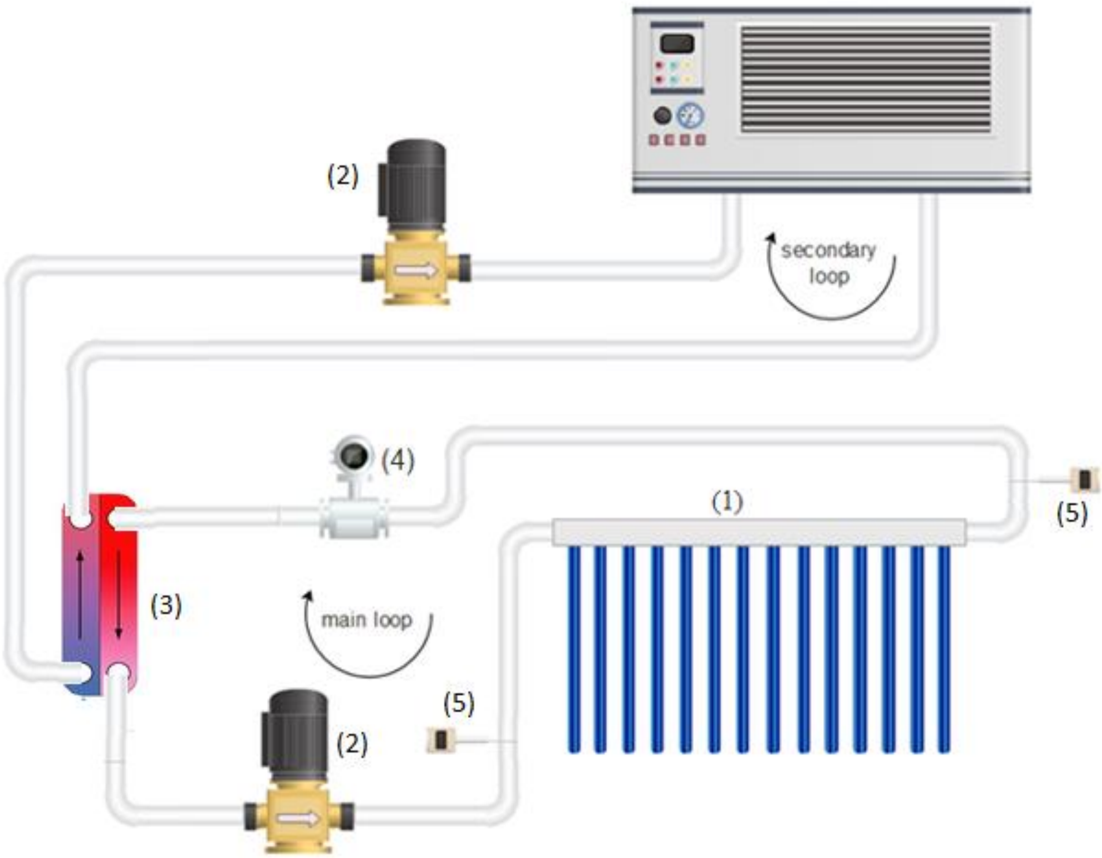

Figure (2). (a) System components layout
(1 solar collector, 2 pumps, 3 heat exchanger, 4 flow meter, 5 temperature sensor)

C) Test steps and calculation method

The instruction given in ASHRAE Standard 93-2003 used to evaluate the thermal performance of the solar collector. The experiments were performed on sunny days from 11 a.m. to 3 p.m. (local time). This period was divided into six-time intervals where each time interval (or test run) was 60 min. The duration of the test period was 15 min. All calculation was done based on the 1st law of thermodynamics. The instantaneous efficiency of the collector is calculated by Equation (1)

$$\eta_i = \frac{Q_u}{A_c\, G_T} = \frac{\rho\, V^{\cdot} C_p (T_o - T_i)}{A_c\, G_T} = F_R\,(\tau\alpha) - F_R U_L (\frac{T_i - T_a}{G_T}) \tag{1}$$

The density of the nanofluid is calculated by the following Equation (2)

$$\rho_{nf} = \rho_{np}(\varphi) + \rho_{bf}(1-\varphi) \tag{2}$$

The heat capacity of the nanofluid can be evaluated as follows (Equation3).

$$(\rho C_p\,)_{nf} = (\rho C_p)_{np}(\varphi) + (\rho C_{bf})_{bf}(1-\varphi) \tag{3}$$

Where:η_i is instantaneous efficiency,Q_u is useful heat energy rate, G_T is solar radiation normal to collector, C_p is Heat capacity, A_c is surface area of the solar collector, ρ density, $V^{\cdot}$ volume flow rate, τ transmissivity, α , absorptivity, φ is volume fraction of Nano-particles, F_R is the collector heat removal factor and U_L is overall coefficient of heat losses, T_i inlet temperature, T_a ambient temperature, nf for nanofluid, np for nanoparticles, bf for base fluid.

Results

The experiments and results showed that using CeO_2-water nanofluid raised the efficiency of the flat plate solar collector more efficiently than using only water. It was found that the maximum efficiency, when reduced temperature parameter, $[(T_i–T_a)/G_T]$, equals to zero, was 10.74%, volume fraction(φ) was 0.066% and mass flux rate was 0.019 $kg/s.m^2$. However, for a wide range of reduced temperature parameters, $[(T_i–T_a)/G_T]$, the best performance was given with the application of 0.0333% volume fraction for all mass fluxes. The values for absorbed energy parameter, $F_R\ (\tau\alpha)$ and the removed energy parameter, $F_R U_L$ for different volume fractions of CeO2-water nanofluid at different mass flux rates are shown in Table(2). The changes in absorbed energy parameter, $F_R\ (\tau\alpha)$ vary from 3.51% to 10.74%, and in removed energy parameter, $F_R U_L$ vary from 30.61% to 191.8%, compared to the water with the same mass flux. The efficiency of the collector was directly proportional to the mass flux, and it was observed that the optimal volume fraction was 0.0333% for the present study's ranges.

Table (2). Values of $F_R U_L$ and $F_R\ (\tau\alpha)$ for CeO_2/water nanofluid and pure water for flat plate collector

Mass flux ($kg/s.m^2$)	Volume fraction φ%	$F_R U_L$	$F_R\ (\tau\alpha)$	R^2
0.015	0.0167	-4.7354	0.6428	0.9684
	0.033	-7.4975	0.6782	0.9937
	0.066	-10.555	0.687	0.9884
	Pure water	-3.6257	0.621	0.9734
0.018	0.0167	-5.1247	0.6512	0.9558
	0.033	-7.9044	0.6837	0.9804
	0.066	-10.964	0.6919	0.9543
	Pure water	-3.7574	0.6301	0.9896
0.019	0.0167	-5.9593	0.6675	0.9795
	0.033	-7.8871	0.696	0.975
	0.066	-11.029	0.7013	0.9886
	Pure water	-3.8961	0.6333	0.968

The stability of WO_3-water nanofluid was found to be 7 days. Volume fractions of 0.0333%, and 0.0666% were tested at three mass flux rates, including 0.0156, 0.0183, and 0.0195 $kg/s.m^2$. The experiments and results indicated that using WO_3-water nanofluid raises the efficiency of the flat plate solar collector compared to the using water only. It was found that the maximum efficiency, when the reduced temperature parameter, $[(T_i–T_a)/G_T]$ equals to zero, was 71.87% for volume fraction (φ) 0.0666% and mass flux 0.0195 $kg/s.m^2$. The highest increase in the absorbed energy parameter, $F_R\ (\tau\alpha)$ was 13.48% in case of the volume fraction(φ) 0.0666% and mass flux rate 0.0195 $kg/s.m^2$. So this case has the maximum increase in efficiency compared with water. The maximum increase in $F_R U_L$ was for volume fraction (φ) 0.0666% and mass flux 0.0195 $kg/s.m^2$. Values for $F_R\ (\tau\alpha)$ $F_R U_L$ are shown in Table (3). The changes in absorbed energy parameter, $F_R\ (\tau\alpha)$, varies from 6.04% to 13.48% and in removed energy parameter, $F_R U_L$, changes from 42.46% to 101.8% compared with water. Hence, it was concluded that the efficiency of the collector is directly proportional to both the volume fraction of nanoparticles and mass flux rate.

Table (3): Values of $F_R U_L$ and $F_R\ (\tau\alpha)$for WO_3/water nanofluid and water for flat plate collector

Volume fraction φ%	Mass flux rates (kg/s.m^2)	$-F_R U_L$	$F_R\ (\tau\alpha)$	R^2
0.0167	0.0156	-3.8835	0.6387	0.9461
	0.0183	-5.1998	0.6539	0.9746
	0.0195	-5.4837	0.6602	0.9981
0.0333	0.0156	-5.1652	0.6585	0.9821
	0.0183	-6.1904	0.6835	0.9729
	0.0195	-6.5256	0.6966	0.9935
0.0666	0.0156	-5.5225	0. 6672	0.9943
	0.0183	-6.3325	0.6936	0.9782
	0.0195	-7.8624	0.7187	0.967
water	0.0156	-3.6257	0.621	0.9734
	0.0183	-3.7574	0.6301	0.9896
	0.0195	-3.8961	0.6333	0.968

For the evacuated tube collector, the CeO2-water nanofluid was used as the working fluid. The stability of CeO2-water nanofluid was studied and no sedimentation was found for a period of 7 days. Different values of CeO2 were used in the study presented. These volume fractions of CeO2 nanoparticles values were 0.015%, 0.025% and 0.035%. The experiments were performed at different mass flux rates of 0.013, 0.015 and 0.017 kg/s.m2. The performance of the evacuated solar collector was checked with different variables like temperature difference, the useful heat gain, and thermal efficiency. Findings showed that using nanoparticles raises the temperature difference comparing to water. Moreover, the higher volume fraction of CeO2 nanoparticles results in higher temperature difference. The investigation shows that the maximum increase in temperature difference is 37.3% in case of using the volume fraction of CeO2 nanofluids of 0.035% at the mass flux rate of 0.017 kg/s.m^2 compared with water at the same mass flux. On the other hand, the results indicated that useful heat gain increased by using nanofluids. Also, the more CeO2 nanoparticles inserted to water the more heat was absorbed. Based on that the maximum rise of heat gain was higher by 42.3% than the heat-gain in case of water for the volume fraction of 0.035% at 0.017 kg/s.m^2. The maximum rise in the heat removal factor was found 34.66% for the case of volume fraction flow rate of 0.035% at the mass flux of 0.017 kg/s.m^2 compared with water at the same mass flux. The thermo-optical characteristic of the collector of the evacuated tube solar corrector is increased up to 34% for all the range studied. It may be stated that most of the results clearly show that the increase of the volume fraction of CeO_2 enhances the outlet temperature of the solar collector, increases the heat transfer to the fluid and raises the thermo-optical characteristic of the collector but it also raises the thermal loss coefficient. Hence, the best performance of the evacuated tube solar collector was obtained with the using of 0.025% volume fraction for all values of the mass flux. Figures (3) and (4) show the Absorbed Energy Parameter against mass flux rate for water and nanofluids and Thermal loss coefficient against the mass flux for water and nanofluids, respectively.

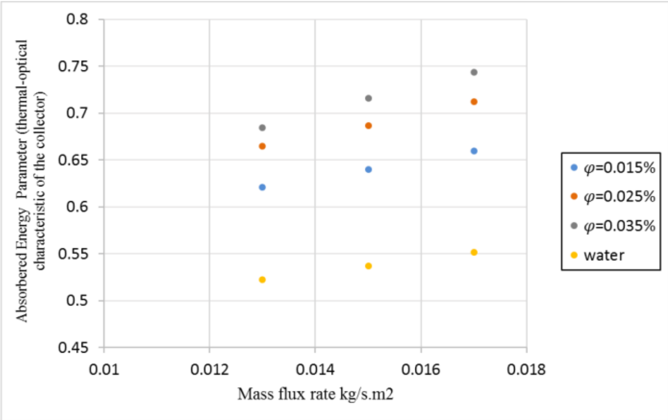

Figure (3): Absorbed Energy Parameter against mass flux rate for water and nanofluids for evacuated solar collector

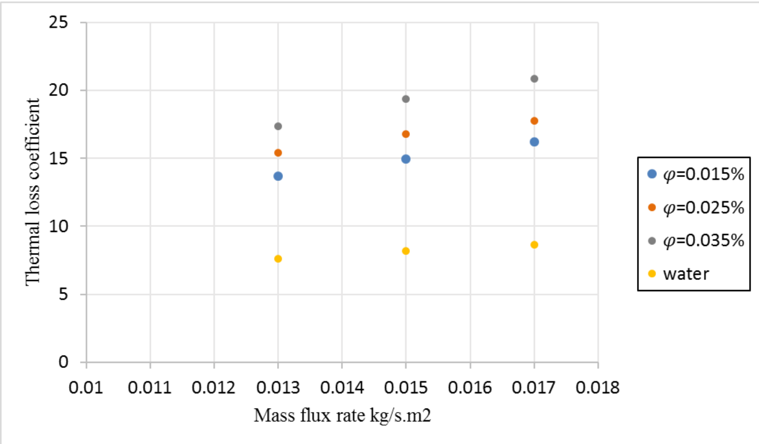

Figure (4): Thermal loss coefficient against the mass flux rate for water and nanofluids for evacuated solar collector

Copper/water nanofluids were prepared by using an ultrasonic machine. The stability of the nanofluid was studied using two approaches an eye inspection approach and the zeta potential approach. Three different concentrations (0.01%, 0.02%, and 0.03%) were checked at three-volume flow rates (0.6, 0.7 and 0.8 L/min). Results show that the minimum and the maximum increase in the temperature difference were 17% and 51.5%, respectively. The heat collected by the collector was directly proportional to the concentration of nanoparticles. On the other hand, the area of the evacuated tube solar collector was decreased by 34% when copper nanoparticles with a concentration of 0.03% were applied. The heat removal factor was clearly increased with the adding of copper nanoparticles. The absorbed energy parameter $F_R\,(\tau\alpha)$ was enhanced and it reached a maximum value of 0.83 for the concentration of the copper nanoparticles 0.03%. For the same case, the removal energy parameter $F_R U_L$ the absolute value was enhanced to 21.66. Moreover, the results indicated higher efficiency of the collector especially at lower values of the reduced energy parameter $[(T_i–T_a)/G_T]$. The present work shows that 312 kg of CO_2 may be saved when copper nanoparticles are used in the collector. In addition, the copper nanoparticles reduced the payback period up to 30.8%. Figure (5) shows the thermal efficiency of the evacuated tube solar collector with copper nanofluid at volume flow rates of 0.6, 0.7 and 0.8 L/min.

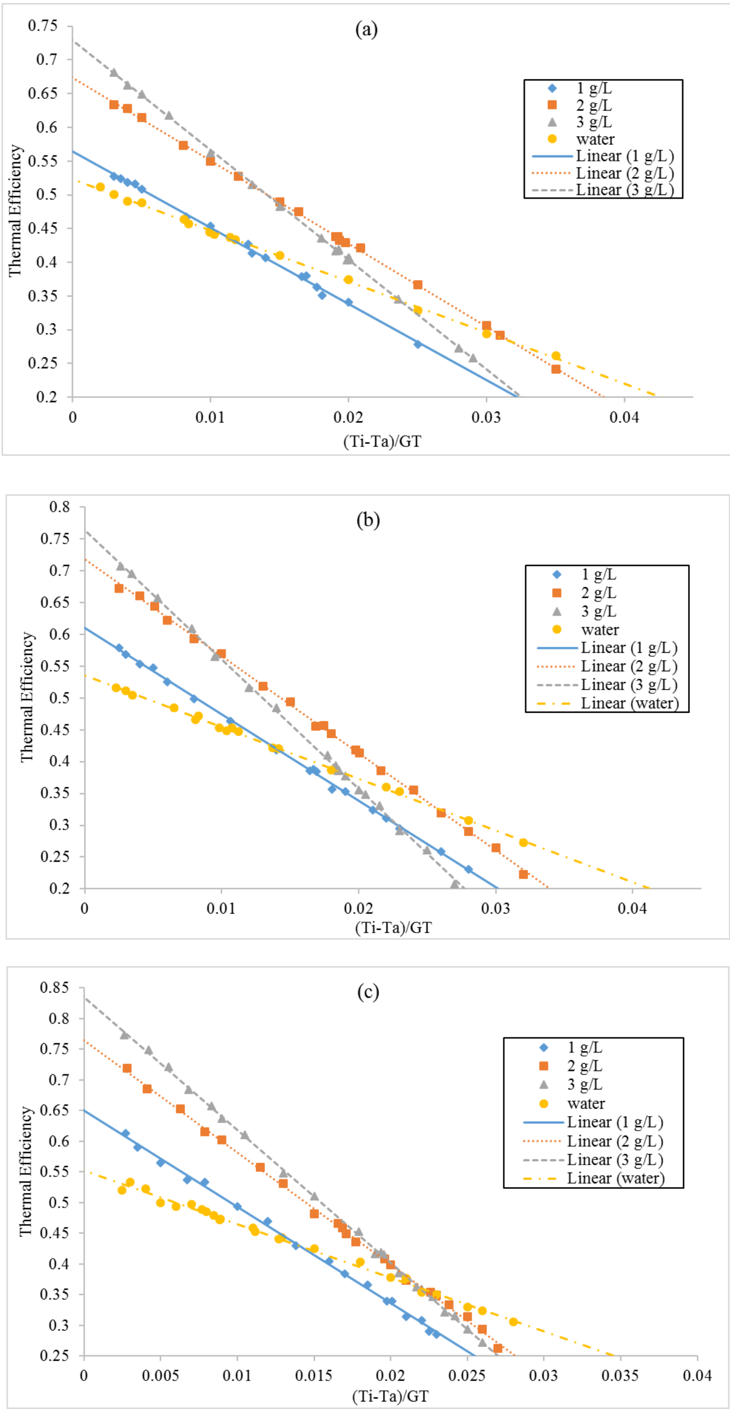

Figure (5): Thermal efficiency of the collector for copper/water nanofluid for evacuated solar collector at different volume flow rate (a) 0.6 L/min, (b) 0.7 L/min, (c) 0.8 L/min

Another experimental study is performed to find the effect of the WO_3 nanoparticles on the performance of the evacuated tube solar collector. Comparison between three different volume fraction concentrations of the WO_3 nanoparticles (0.014, 0.028 and 0.042%) was performed. The experiments were done for several mass flux values (0.013, 0.015, and 0.017 kg/s.m^2) to study the effect of mass flux on the efficiency of the solar collector. The results showed that using WO_3 helps to push up the outlet temperature of the fluid. Nanoparticles enhance the useful heat gain by the evacuated tube solar collector. The highest increase in the heat removal factor was 16%. Both thermal-optical efficiency and the removed energy parameter increased by adding WO_3 nanoparticles and by increasing the mass flux. The thermal-optical efficiency of the evacuated tube solar collectors was 72.83%, which means a plus rate of 19.3% compared with water. It worthy mention that there are critical points which are considered as a limit for using nanoparticles. It was found that using nanofluids doesn't necessarily mean improvement in solar collector efficiency. Based on the literature overview there is no previous work/report about using WO_3 nanofluid as the working fluid of the evacuated tube solar collector.

Table (4): Values of $F_R U_L$ and $F_R\ (\tau\alpha)$for WO_3/water nanofluid and water for evacuated tube solar collector

Mass flux rates(kg/s.m^2)	Volume fraction φ%	$F_R\ (\tau\alpha)$	$-F_R U_L$	R^2
0.013	Water	0.579	-9.99	0.997
	0.014	0.6131	-22.23	0.992
	0.028	0.626	-25.72	0.997
	0.042	0.6518	-29.14	0.998
0.015	Water	0.5991	-11.9	0.996
	0.014	0.638	-25	0.999
	0.028	0.6673	-30.12	0.998
	0.042	0.7091	-31.77	0.997
0.017	Water	0.6103	-12.94	0.993
	0.014	0.6633	-26.03	0.987
	0.028	0.6931	-33	0.999
	0.042	0.7283	-33.22	0.999

New scientific results

Thesis 1 (B[1], B[2], B[3], B[4], B[5], B[6], B[7], B[8], B[9], B[10])
It was found that for getting usable, stable WO_3/water nanofluid one needs to apply continuous 75 minutes' ultrasonic homogenisation, for CeO_2/water nanofluid continuous 90 minutes' ultrasonic homogenisation needed. To reach the same result with copper/water nanofluid a two-step method is needed: the first step of preparation is the mixing of nanoparticles with the water by a centrifugal mixer and after that 150 minutes' ultrasonic homogenisation needed with 50% amplitude settings. The stability of the nanofluids in point was proven by two methods: first is the repetitive naked eye observation, the second is the systematic application of the zeta potential investigation. The WO_3/water and CeO_2/water nanofluids do not show sedimentation in a 7 days' period while the copper/water nanofluid for 24 hours. The observed mean zeta potential for WO_3/water is -43.12mV and for CeO_2/water is -36,91 mV with a little decrease in 7 days. The mean zeta potential of copper/water nanofluid during its stability period was -31,1 mV.

Thesis 2 (B[1], B[2], B[3], B[4], B[5], B[6], B[7], B[8], B[9], B[10])
It was investigated how the concentration and the temperature influence the thermal conductivity of the nanofluids. It was found that the heat conductivity increases by increasing the concentration and the temperature as well in the investigated ranges as the table below shows it.

Table for Thesis 2.

Nanofluid	Concentration vol%	Temperature (K)	Enhancement ratio %
CeO_2-water	0.0166	324	5.76
		302	1.53
	0.0333	324.5	8.58
		305.5	3.52
	0.066	324	14.69
		303	4.15
WO_3-water	0.01667	325	4.3
		300	1.14
	0.0333	325	11.17
		300	4.03
Cu-water	0.01	327.5	10.06
		307	2.4
	0.02	324.25	12.89
		307.5	6.33

Thesis 3 (B[1], B[2], B[3], B[4], B[5], B[6], B[7], B[8], B[9], B[10])

By keeping the same inlet temperature, the outlet temperatures of the flat plate and the evacuated tube solar collector were investigated. It was found that using nanofluids increases the outlet fluid temperature and a maximum increase could be reached in the ranges investigated. Certain values will vary according to the collector type. In case of the used collector types it was found that:

- The maximum increase of the temperature for WO_3/water nanofluid was 21% comparing to water at the volume fraction of 0.042%, at the mass flux rates of 0.017 kg/s.m^2.
- The maximum increase in temperature for CeO2/water nanofluid was 37.3% at the volume fraction 0.035%, at the mass flux rate of 0.017 kg/s.m^2.
- For copper/water nanofluid maximum increase in temperature was observed at 0.03% concentration as the values for the flow rates of 0.6, 0.7 and 0.8 L/min: 39, 42 and 51.5%, respectively.

Thesis 4 (B [2], B [4], B [5])

It was found that the flat plate and evacuated tube solar collectors absorb more energy in case of operating with nanofluid comparing to the water operation. Certain heat gain values will vary according to the collector type. In the case of the collector types used it was found that:

- For copper/water nanofluid, the highest values of the heat gain were found at the greatest values of the flow rate 0.8 L/min. These values were 441 W for water, and 520, 612 and 699W for concentration of 0.01, 0.02 and 0.03%, respectively.
- For CeO_2-water nanofluid the minimum increase of heat gain was 19% for the volume fraction of 0.015% at 0.013 kg/s.m^2. The maximum increase of heat gain was 42.3% for the volume fraction of 0.035% at 0.017 kg/s.m^2.
- For WO_3-water nanofluid the maximum heat gain increased by 23%. The highest values of the heat gains are listed for 0.042% volume fraction of WO_3 nanoparticles and 0.017 kg/s.m^2.

Thesis 5 (B [1], B [2], B [3], B [4], B [5])

Heat removal factor (F_R) is a key factor for testing the solar collector. For evacuated tube solar collector the results were:

- For copper/water nanofluid, the maximum values of the heat removal factor were at the volume flow rate of 0.8 L/min as 0.64, 0.75, 0.89 and 0.97 at the concentrations of 0.01, 0.02 and 0.03%, respectively.
- For WO_3/water nanofluid, the ratio of the increase of the heat removal factor for nanofluids comparing to water at the same mass flux rate is between 1.05 and 1.16.
- For CeO_2/water nanofluid, the maximum increase in the heat removal factor is 34.66% for the volume fraction flow rate of 0.035% at the mass flux rate of 0.017 kg/s.m^2.

For a flat plate collector, the heat removal factor for nanofluid is greater than that of water. The heat removal factor rises with the increase of mass flux and nanofluid concentration. Therefore, it can be concluded that by using WO_3-water and CeO_2-water nanofluids the flat plate solar collector performance improves.

Thesis 6 (B [2])
To get the same energy from the solar radiation, the size of the component materials used in the collector such as glass, absorber and insulation can be reduced by using nanofluids. For copper/water nanofluid:

- The area of the collector is decreased by 28, 22 and 7% for concentrations of 0.03, 0.02 and 0.01%, respectively at the volume flow rate of 0.6 L/min.
- When the volume flow rate is boosted to 0.7 L/min the area of the collectors is decreased by 30, 25 and 12% for 0.03, 0.02 and 0.01%, respectively.
- The highest reduction of the area of the collector is registered at volume flow rate 0.8 L/min as 34, 28 and 15% for the copper nanoparticles concentration of 0.03, 0.02 and 0.01%, respectively.

Thesis 7 (B[1], B[2], B[3], B[4], B[5], B[6], B[7], B[8], B[9], B[10])
The thermal efficiency of collectors is determined based on the absorbed energy parameter F_R $(\tau\alpha)$ and the removal energy parameter F_RU_L as follows:

- In case of copper/water nanofluid used in evacuated tube solar collector, their maximum values of the absorbed energy parameter F_R $(\tau\alpha)$ and the removal energy parameter F_RU_L were found for a volume concentration of 0.03% and at the volume flow rate of 0.8 L/min to be 0.83 and 21.66, respectively.
- The absorbed energy parameter F_R $(\tau\alpha)$ of the evacuated tube solar collector reached 72.8% when volume fractions 0.042% of WO_3 nanoparticles used.
- The absorbed energy parameter F_R $(\tau\alpha)$ of the evacuated tube solar collector is raised up to 34% with a concentration of 0.035% of CeO_2 nanofluid.
- The experimental results of WO_3/water and CeO_2/water nanofluids reveal that the maximum enhancement in the efficiency of the of flat plate solar collector at zero value of $[(T_i\text{-}T_a)/G_T]$ was 13.48% and 10.74, respectively for the volume fraction of 0.0666% and mass flux of 0.019kg/s.m^2 compared to water.

Thesis 8 (B [2], B [4], B [5])
It was found that there is a limitation on the efficiency of the solar collector when using nanofluids. In addition, adding nanoparticles to enhance the performance of the evacuated tube solar collector one should consider the effect of the inlet fluid temperature and the atmospheric circumstances such as solar radiation and the ambient temperature. Based on a parameter called the reduced temperature parameter, $[(T_i–T_a)/G_T]$, one can determine which concentration is preferred to get higher efficiency. The optimal value of the concentration of nanoparticles mainly depends on finding a balance between positive and negative impact of nanoparticle on both sides of efficiency i.e. the absorbed energy parameter $F_R(\tau\alpha)$ and the removal energy parameter F_RU_L. These turning values of reduced temperature parameter, $[(T_i–$

T_a)/G_T] are found for copper, WO_3, and CeO_2 nanofluids.

Thesis 9 (B [2])
The economic effect – as a highly important issue – were investigated and according to the findings the use of nanofluid makes more economical the solar thermal energy utilization. The lowest energy payback time is found for the maximum concentration and maximum flow rate of copper-water nanofluids. The Energy Yield Factor changes from 19.8 for water to 20.664 for 0.03% concentration of copper nanofluids. The copper nanoparticles reduced the payback period up to 30.8% with a 0.03% concentration compared to water at the same flow rate. The present work indicates that it takes 1.28 years for the payback period which is by 50% less compared with water at the same circumstances.

Thesis 10 (B [2])
The results show that the Embodied energy of the collector is 2011.45 MJ while 252.55 kg of CO_2 is emitted in the manufacturing process of the collector. The Embodied energy to establish the system is 3808 MJ and 385 kg of CO_2 is released during the production of all components. The Carbon Payback Time decreases by adding copper nanoparticles. As the concentration of nanoparticles increases the Carbon Payback Time shortens. The lowest value of the Carbon Payback Time was 0.419 year for the volume flow rate of 0.8 L/min and a concentration of 0.3% of copper nanoparticles. The Annual Certified Emission Reduction is defined as the amount of money can be saved by avoiding the one-ton equivalent of CO_2 emission through solar energy systems. Because of the Annual CO_2 emission, mitigation has its higher value at the maximum concentration of copper nanoparticles with the highest mass flow rate. The maximum value of the ACER is 14.823$ for this case. The present work shows that 312 kg of CO_2 is saved when copper nanoparticles are used in the collector.

Thesis 11 (B [2], B [5])
Comparisons were performed between the present work and the previous work. In the case of thermal efficiency, the derived results indicated that copper/water nanofluids have the best values compared with others. In addition, CeO_2/water nanofluid has a great benefit comparing to other types of nanofluids and has a significant effect on the performance of the evacuated tube solar collector. In the case of environmental and economic impact, results showed that more CO_2 emissions were saved and lower payback time was achieved.

Publications related to the theses

[B1] M.A. Sharafeldin and Gyula Gróf "Experimental investigation of flat plate solar collector using CeO2-water nanofluid" Energy Conversion and Management 155 (2018) 32–41 [IF: 7.181(Q1)]

[B2] M.A. Sharafeldin and Gyula Grof "Evacuated tube solar collector performance using CeO2/water nanofluid" Journal of Cleaner Production 185 (2018) 347-356 [IF: 6.395(Q1)]

[B3] Mahmoud Ahmed Sharafeldin, Gyula Grof and Omid Mahian "Experimental study on the performance of a flat-plate collector using WO_3/Water nanofluids" Energy 141 (2017) 2436-2444 [IF: 5.537(Q1)]

[B4] M.A. Sharafeldin and Gyula Gróf "Efficiency of evacuated tube solar collector using WO_3/Water nanofluid" Renewable Energy134 (2019) 453–460 [IF: 5.439(Q1)]

[B5] M.A. Sharafeldin, Gyula Gróf, Eiyad Abu-Nada, and Omid Mahian "Evacuated tube solar collector performance using copper nanofluid: Energy and environmental analysis" Applied thermal engineering, Applied Thermal Engineering 162 (2019) 114205 [IF: 4.026(Q1)]

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