

Research Article

Long-Term Performances and Technoeconomic and Environmental Assessment of Al_2O_3 /Water and MWCNT/Oil Nanofluids in Three Solar Collector Technologies

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Bringing together nanofluids and solar collectors has been widely discussed without any major advance or long-term study being carried out. In this context, this paper provides a useful feasibility study to help future decisions in using nanofluids in Solar Water Heating Systems (SWHSs) in different locations. The performances of SWHSs using the nanofluid-based flat plate solar collector (FPSC), evacuated tube collector (ETC), and compound parabolic collector (CPC) under the Mediterranean, arctic, and desert climate conditions are presented and discussed. The analysis is carried out using a transient-based numerical approach, solving energy balance equations for different systems. Various performance factors such as energy saving, solar fractions, and environmental impacts of auxiliary energy supplies are evaluated to feasibly assess the use of nanofluids in such devices. Simulation results demonstrate that the use of nanofluids increases the solar heater performance which reduces considerably the payback period (P_p) of the investment in solar heating systems up to 3.34 years in Tunisian climate. Under Quebec's climate region, the annualized solar return of the ETC system increases from 4874.65 US\$ to 9785.93 US\$ by adding 0.06 v% Al_2O_3 in water. Also, the use of nanofluids in solar collectors with electric auxiliary heaters reduces harmful CO_2 emissions up to 0.49 tons/year.

1. Introduction

We always talk about renewable energies and energy transition to solve environmental problems, according to the latest report of the International Energy Agency [1]. In the world, their consumption reaches 25% of the total. One-quarter of this consumption is for solar energy. Solar collectors which transform solar energy into thermal energy are the most common technologies in this context. It is a device designed to collect solar energy transmitted by radiation and transfer it to a heat transfer fluid (gas or liquid) in the form of thermal energy. This thermal energy can then be used for heating buildings for the production of domestic hot water or in various industrial processes. In Tunisia, the use of solar water heaters has increased significantly during the last years thanks to the financial assistance granted by the state by the

program to promote the use of solar water heaters (35% of the purchase price is refunded). This project is one of the projects handled by the Clean Development Mechanism (CDM). This mechanism is one of the flexibility mechanisms for Article 12 of the Kyoto Protocol on the Convention on Climate Change signed by Tunisia [2]. Several works have been interested in improving the thermal performances of solar collectors, especially in terms of efficiencies and loss coefficients. In order to improve the maximum thermal efficiencies of solar collectors, several authors have improved the heat transfer in these thermal systems by adding nanoparticles into the base fluid which can be water, ethylene glycol, or thermal oils. In fact, despite the encouraging and sometimes surprising results, other researchers have found that introducing nanofluids does not give favorable results in terms of energy and exergy performances [3]. In the

literature, some research works are interested in studying the effect of adding nanoparticles on the energy and exergy performances of flat plate solar collectors (FPSCs) and they found that using nanofluids increased the performances of FPSCs. Yousefi et al. [4] studied experimentally the efficiency of a FPSC under the effect of adding Al_2O_3 in water with the weight fraction of the nanoparticles ranging from 0.2% to 0.4%. They used a particle size equal to 15 nm and a nanofluid mass flow rate varying from 1 to 3 L/min. Their results showed that the efficiency increases using nanofluids as the working fluid compared to using water as the absorption medium. They also found that the efficiency reached 28.3% for 0.2 wt% compared to the case when using water as the absorption medium. Raj and Subudhi [5] reviewed research works interested in FPSC which is the least efficient compared to other solar systems. They studied the effect of optimal functioning status and of various parameters on solar thermal devices. They identified the usage of nanofluids in solar systems as opportunities for research work in this field in the future. Ziyadanogullari et al. [6] added Al_2O_3 , CuO, and TiO_2 nanoparticles at 0.2, 0.4, and 0.8 flight % in distilled water at a flow rate equal to 250 L/h. They have shown that the use of the three different nanofluids improves the efficiency of the flat plate solar collector compared to the use of distilled water. Said et al. [7] used a 0.1% TiO_2 particle concentration/water nanofluid stream in a flat plate manifold with a flow rate of 1.5 kg/min. They proved that the thermal efficiency increases by 76.6%. Choudhary et al. [8] studied a flat plate solar collector using 50% water-50% ethylene glycol/ZnO nanofluids with a flow rate of 60 L/h and a particle dispersion concentration equal to 1%. They found that the efficiency reached 69.24%. Farajzadeh et al. [9] studied the thermal efficiency of the manifold in a flat plate manifold with particle weight loads of 0.1% and a fluid flow rate of 2.5 L/min. They found that the efficiency reached 19%, 21%, and 26% for the flow of nanofluids Al_2O_3 /water, TiO_2 /water, and Al_2O_3 - TiO_2 /water, respectively. They found that the thermal efficiency increases by 19%, 21%, and 26% (relative to water as a fluid) using Al_2O_3 (0.1% by weight), TiO_2 (0.1% by weight), and the mixture of these two nanofluids, respectively. Rajput et al. [10] studied a flat plate collector with Al_2O_3 /water nanofluids at a flow rate of 1.3 L/min and a particle concentration equal to 0.3%. They proved that the efficiency of the collector undergoes an improvement of around 21.23%. Kiliç et al. [11] studied a flat plate solar collector using TiO_2 /water nanofluids with a particle load of 0.2% and a fluid flow rate of 0.033 kg/s. They found that the thermal efficiency reached 48.67%. Jouybari et al. [12] analyzed research work that uses SiO_2 /water nanofluids in flat plate solar collectors. They deduced that all these works found that the efficiency increases by increasing the volume concentrations of particles. They also cited the most relevant works that use nanofluids. Meibodi et al. [13] studied a flat plate solar collector using SiO_2 /ethylene glycol- (EG-) water nanofluid with volume fractions of up to 1% and mass flow rates ranging from 0.018 to 0.045 kg/s. They found that SiO_2 nanoparticles are able to improve the efficiency of solar collectors despite the low value of thermal conductivity compared to other usual nanoparticles. Gad and Said [14] added Al_2O_3 and TiO_2 , prepared at a concentration of 2% by

weight, to the water in order to study their effects on the thermal efficiency of the flat plate solar collector. They found that at a flow rate of 2 L/m, the thermal efficiency of the collector is around 30 and 32% under the effect of Al_2O_3 and TiO_2 , respectively. They also proved that the thermal efficiency of the sensor increases by around 22% and 30% compared to water, using Al_2O_3 and TiO_2 , respectively. Arikan et al. [15] studied the effect of Al_2O_3 /water and ZnO/water, with and without ethylene glycol (EG), on the performance of the flat plate solar collector. They have proven that efficiency increases by using ethylene glycol and increasing mass flow. They also found that at a flow rate of 0.09 kg/s, the highest efficiency increase was recorded using Al_2O_3 /water/EG. They demonstrated that this increase is equal to 15.13% compared to the base fluid. Gangadevi et al. [16] studied the effect of Al_2O_3 /water on the efficiency of the flat plate solar collector. They found that the efficiency increases by 30% compared to water. Another technology widely used in the solar industry is evacuated solar collectors (ESCs). In such technologies, the heat transfer fluid circulates inside a single or double vacuum tube. The vacuum improves insulation against convection losses compared to the FPSC. Two principles are met here: the first principle is the same as for FPSC; the heat transfer fluid travels through the tube back and forth to collect the heat; the second is more technologically advanced; it uses a heat pipe, using a second heat transfer fluid remaining in the tube. Using nanofluids in these technologies has also attracted the intention of many researchers. Ghaderian and CheSidik [17] experimentally studied the thermal efficiency of the all-glass passive circulation vacuum tube solar collector with an internal spherical coil inside the horizontal tank under the effect of Al_2O_3 /distilled water nanofluid as working fluid. They carried out this study with a flow rate inside the coil which varies between 20 and 60 L/h. They found that for a mass flow rate equal to 60 L/h and a volume fraction of nanoparticles of 0.06%, the thermal efficiency is maximum and reached 57.63%. Eltaweel et al. [18] analyzed experimentally the energy and exergy efficiency of the ETC using multiwalled carbon nanotubes and water nanofluid as the working fluid in this collector. They performed the study with flow rates of 1 to 3.5 L/min and weight fractions of 0.005%, 0.01%, and 0.05%. They showed that by using 0.05% as weight of MWCNT/water nanofluid, the average of energy and exergy efficiencies are maximum and reached 55% and 10%, respectively. Mahbulul et al. [19] studied the effect of adding single-walled carbon nanotubes (SWCNTs) on the performances of the ETC and compared the solar collector working with pure water and nanofluid. They proved that the efficiency attained 56.7% and 66% with water and nanofluid, respectively. Therefore, they deduced that nanofluids improve the efficiency of ETCs. Sabiha et al. [20] used 0.2% SWCNT/water nanofluid in an evacuated tube manifold at a flow rate of 0.025 kg/s. They demonstrated that the thermal efficiency was increased by 26.25%. Sharafeldin and Grof [21] used a flow of CeO_2 /water nanofluids in ETC with a particle dilution concentration of 0.066% and a flow rate of 0.017 kg/s. They proved that the thermal efficiency undergoes an increase of 10.74%. Hussain et al. [22] studied the performance of a vacuum solar collector using silver (Ag (30 nm)) and titanium oxide (ZrO_2 (50 nm)). They found that the

efficiency of the solar collector for nanofluid (Ag (30 nm)+distilled water) is higher than that for ZrO₂ (50 nm)+distilled water due to the high thermal conductivity of silver and also thanks to the small size of the particles of silver compared to zirconium oxide. They deduced that the improvement in the performance of the ETC depends on the type of nanofluids. Ismail et al. [23] experimentally studied the performance of the ETC using water and titanium oxide nanofluids (30–50 nm), prepared at a volume concentration of 1.0%, 2.0%, and 3.0% at various flow rates ranging from 2.0 to 3.0 liter/min. They demonstrated that at a flow rate equal to 2 L/min and a concentration of 2.0% with respect to water, the efficiency of the vacuum sensor increases reaching 42.5%. The experience of the last thirty years shows that four main technologies make it possible in practice to achieve the concentration of solar radiation under viable technical and economic conditions by using compound parabolic collectors (CPCs). In order to test the effect of nanofluids on the performance of CPCs, Kasaeian et al. [24] built a trough manifold pilot with a reflector of steel mirror height and width at 2 and 0.7 m, respectively. They tested nanotubes/nanofluids having volumes equal to 0.2% and 0.3% in the pilot with the vacuum copper absorber tube coated with black chromium oil-based carbon. They confirmed the previous results by finding that the overall thermal efficiency of the evacuated tube is higher than that of the bare tube, which on average equals 11%. Bozorg et al. [25] studied the performance of a new parabolic solar trough collector with oiled synthetic nanofluid Al₂O₃ as heat transfer fluid using a finite volume method. They improved heat transfer using a porous ring, the structure installed inside the absorber tube. They proved that for Reynolds numbers higher than 3×10^4 , the use of nanoparticles with a Darcy number equal to 0.3 increases the thermal energy efficiency up to 8% and 15%, the overall efficiency to 5% and 14%, and the exergy efficiency to 7% and 15% for inlet temperature of 500 and 600 K, respectively. Gopalsamy and Karunakaran [26] studied the performance of Al₂O₃ and Al₂O₃-deionized water (DI) nanofluid on a parabolic hollow solar collector associated with a hot water production tank. They carried out experiments with different concentrations of aluminum oxide nanoparticles varying from 0.5 to 2.5%. Their results showed that the efficiency of alumina nanofluid increases by 3.90% compared to that of the base fluid. Bellos et al. [27] used oil-based nanofluids with 6% CuO in a parabolic trough collector. They compared this technique with the use of internal rectangular fins in the absorber. They also looked at the combination of these two techniques. They showed that thermal efficiency is improved by 0.76%, 1.10%, and 1.54% by using nanofluids, internal fins, and the two technologies together, respectively. Olia et al. [28] analyzed the latest research work studying the effect of nanofluids in parabolic trough collectors (PTCs). They have shown that in most of the published works, nanofluids improve the thermal efficiency of PTC.

In fact, there is some potential inconsistency of study findings in this subject. There are some authors who have found that the use of nanofluids decreases the efficiency of solar collectors. Mondragon et al. [3] evaluated the effect of

the solid fraction of Al₂O₃ nanoparticles dispersed in water on the thermal performances of a FPSC. They found that the efficiency decreased from 47% to 41.5% when using 0.25 and 5 v% nanoparticle concentrations. They explained the increase by the appearance of a deposition layer of nanoparticles which gave additional thermal resistance. Yousefi et al. [29] showed that the difference between the pH of the nanofluid and that of the isoelectric point has a direct effect on the performance enhancement.

The economic effect of adding nanoparticles into solar collectors has not yet been evaluated which explains the non-industrialization of solar systems, in particular, on a large scale for domestic uses operating with nanofluids. For that reason, there are few studies dealing with the long-term and economic evaluation of nanofluid-based solar collectors.

Nanodiamond (ND)/water nanofluid-based FPSC has been experimentally studied by Sundar et al. [30]. The role of adding nanodiamond nanoparticles in heat transfer, energy, and exergy efficiency enhancement has been also evaluated. Their investigations indicated that increasing by 1.0% the volume concentration of ND/water increased the thermal efficiency of the collector by 21% against the water data. They also gave regression correlation models to obtain both the Nusselt number and friction factor. Sundar et al. [31] also performed collector cost, energy, and environmental assessments of the nanodiamond (ND)/water-based FPSC system. In particular, they found that the embodied energy decreased from 1451.4 MJ to 1039.51 MJ when using water and 1% of nanodiamonds in water, respectively. They also found that when using 1.0 vol% of nanofluid in FPSC, the CO₂ emissions are equal to 249.98 kg.

Abadeh et al. [32] showed that the size reduction of the photovoltaic thermal (PVT) systems reached 12% by using ZnO/water nanofluid compared to that of the water-based PVT system. Alashkar and Gadalla [33] studied the effect of metallic and nonmetallic nanoparticles in conventional heating fluids on the performance and cost of an Integrated Solar Regenerative Rankine Cycle (ISRRC) composed of a parabolic hollow solar collector (PTSC). They reported that the overall energy produced by the ISRRC for the three operating modes increased and the net savings of the ISRRC are increased by using nanofluids. They also showed that by adding Cu nanoparticles to Syltherm 800, the maximum increase in the annual energy production is about 3.1%. Otanicar and Golden [34] compared the economic and environmental impacts of solar collectors operating with nanofluids and conventional systems. Their results showed that the water-based solar collector has a slightly longer payback period, but in the end, it has the same economic aspect as a conventional collector. Tiwari et al. [35] have examined the works which use nanofluids and hybrid nanofluids in the parabolic trough collectors (PTCs). They reported that hybrid nanofluids gave more collector efficiency enhancements in thermal properties against monofluids. They also concluded that the use of hybrid metal oxide nanofluids improves the thermal conductivity of nanofluids better than oxides. They also deduced that optimizing the weathering parameters helps in choosing specific techniques to improve the overall efficiency of PTC. Nanofluid-based parabolic trough solar

collectors have also caught the attention of Bellos et al. [36]. They systematically examined the use of (Syltherm 800/Cu) nanofluid in a parabolic collector. Their study focused on the evacuated tube receiver, the nonevacuated tube receiver, and the uncovered bare tube. They found that the maximum enhancement in heat transfer performances is envisaged in the cases that imply higher thermal losses. They proved the improvement in thermal performance throughout the bare tube by using the prescribed nanofluid. They also found that the enhancement values for the 25 L/min flow rate and for a nonselective absorber are 17.11%, 12.30%, and 12.24% for the bare tube, for the nonevacuated receiver, and for the evacuated receiver, respectively. Existing numerical investigations focusing on high-temperature solar thermal collector systems have been reviewed by Hachicha et al. [37]. In addition to new designs, the authors discussed the assessment of the use of nanofluids on high-temperature collectors. They showed that reported results suggested that the rheological and thermophysical properties of the nanofluids depend strongly on the volume fraction, pH, and duration of sonication time. They also concluded that both monofluids and hybrid nanofluids are efficient and would improve PTC technologies.

With the advancement of nanotechnology and its ability to increase the performance of energy storage systems, it is important to carry out a long-term study as well as an economic assessment of solar collector technologies using nanofluids. The majority of published works have studied the effect of nanofluids on the efficiency of solar collectors, but they have not tested their effect on the long-term performances, namely, the solar fraction and the produced thermal energies. For that purpose, the aim of this work is to give a more precise assessment of using nanofluids in the three prescribed technologies of solar heaters, namely, the FPSC, the ETC, and the CPC. The commercial TRNSYS software is used in order to analyze the solar fraction, the energy collected, and the auxiliary energy under the effect of Al_2O_3 and MWCNT nanoparticles. The effect of using nanofluids in solar water heaters is also evaluated with different weather conditions, and their environmental and economic influence is studied in terms of energy efficiency and CO_2 emission reduction.

2. Problem Setup and TRNSYS Models

In this section, the global and annual thermal behavior of three FPC, ETC, and CPC solar collector technologies using nanofluids as heat transfer fluid (absorbent medium of solar radiation) is studied. Numerical simulation of the prescribed three solar systems—a flat plate solar collector (FPSC) using water, water+0.2% Al_2O_3 , and water+0.4% Al_2O_3 with a mass flow equal to 0.033 kg/s m^2 , an evacuated tube collector (ETC) using water, water+0.03% Al_2O_3 , and water+0.06% Al_2O_3 with different mass flow rates (20, 40, and 60 L/h) (see Figure 1), and a compound parabolic collector (CPC) using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil—was established by the simulation program under the climatic conditions of Tunis (Tunisia). The schematic view of the problem is shown in Figures 2-4. All these

collectors have an area equal to 2 m^2 , and they are linked mainly to a storage tank with a volume of 200 liters and to a pump. We use a water profile which covers the needs of a family of 4 members. A general equation for solar thermal collector efficiency can be obtained from the Hottel-Whillier equation [38, 39] as

$$\eta = \frac{Q_c}{I \cdot A_c} = \alpha_0 - \alpha_1 \frac{T_c - T_a}{I} - \alpha_2 \frac{(T_c - T_a)^2}{I}, \quad (1)$$

which is the general solar collector thermal efficiency equation used in type 1. The thermal efficiency is defined by 3 parameters α_0 , α_1 , and α_2 determined from the η plot by using the least square method. The useful energy supplied by the FPSC is given by

$$Q_u = \dot{m}_n C_{pn} (T_0 - T_i). \quad (2)$$

The yearly useful energy is obtained from

$$Q_{u,a} = \sum_{d=1}^{365} \sum_{h=1}^{24} Q_u. \quad (3)$$

The required auxiliary energy to cover the shortage of solar irradiation Q_{aux} is calculated by

$$Q_{aux} = Q_{load} - [Q_{u,a} - Q_{loss}], \quad (4)$$

where Q_{load} is the energy required by the load and Q_{loss} is the energy lost from the storage tank and pipes. The better indicator of the system performance compared to the other parameters such as the collector efficiency or heat removal factor is the solar fraction, S_F , since it manifests the overall performance of the entire system [40, 41]. S_F is given as

$$S_F = \frac{Q_L - Q_{aux}}{Q_L} = 1 - \frac{Q_{aux}}{Q_L}, \quad (5)$$

where Q_L is the total energy supplied from the collector to support the water heating requirements and Q_{aux} is the total auxiliary energy added to the system to hold up the fraction of the total load that cannot be provided exclusively by solar irradiation. The heat loss coefficient, U_C , of the storage tank is generally determined in an independent test method by measuring the hot water cylinder temperature decrease while the hot water cylinder is left to cool down for about 24 h [39].

3. Long-Term Average Performances

3.1. Al_2O_3 /Water Nanofluid in the Flat Plate Solar Collector (FPSC). In TRNSYS investigations, it is necessary to estimate the monthly and/or the annual average heating loads which depend on many factors, e.g., hot water consumption rate, cold water inlet, and desired hot water set temperatures and system characteristics. The flow sheet already presented in [42] is mainly composed of a series of unit types: parameters, climatic data, solar collectors (here FPSC or ETC or CPC), a pump, a backup, and a load and storage tank.

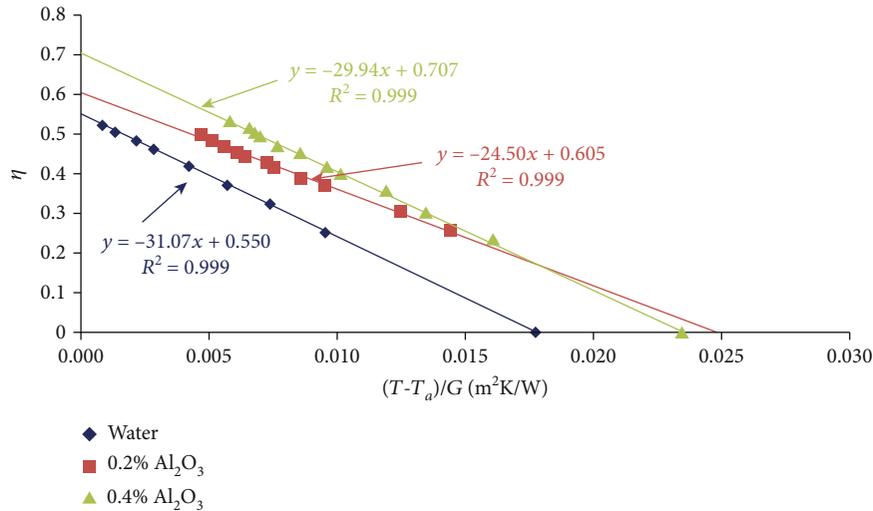


FIGURE 1: Efficiencies of the flat plate solar collector for water and for Al_2O_3 nanofluid (Yousefi et al. [4]).

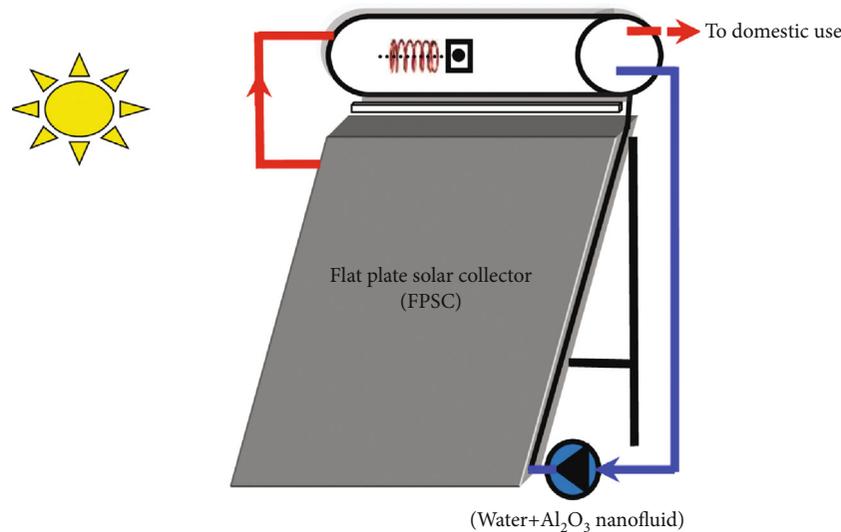


FIGURE 2: Flat plate solar collector using water, water+0.2% Al_2O_3 , and water+0.4% Al_2O_3 .

Figure 1 shows the plot of the thermal efficiency η as a function of the reduced temperature $(T - T_a)/G$ of the FPSC system using water, 0.2% Al_2O_3 , and 0.4% Al_2O_3 as found by Yousefi et al. [4]. It is clear from Figure 1 that the efficiency of the collector with Al_2O_3 nanofluid is higher than the efficiency of the reference case with water. Figure 5 reports the plot of the collected energy Q_{coll} by the FPSC system using the three prescribed fluids. As shown in Figure 1, Q_{coll} ranged between 412.6 in January and 599.73 MJ in September, between 429.6 in January and 622.26 MJ in September, and between 503.7 in January and 729.22 MJ in September when using water, 0.2% Al_2O_3 , and 0.4% Al_2O_3 , respectively. It was also seen that using 0.2% Al_2O_3 , Q_{coll} increased by about 3.76% compared to the case using water. It is then established that using Al_2O_3 at 0.4 v%, the collected energy increases by about 21.59% compared to using water. The monthly variation of the auxiliary energies Q_{aux} of the FPSC system using

water, Al_2O_3 at 0.2 v%, and Al_2O_3 at 0.4 v% is shown in Figure 6. Q_{aux} varies from 264.31 in August to 419.4 MJ in January, from 246.73 in August to 404.32 MJ in January, and from 159.6 in August to 341.44 MJ in January by using water, 0.2% Al_2O_3 , and 0.4% Al_2O_3 , respectively. The computations also gave that using 0.2% Al_2O_3 , the auxiliary energy decreases by about 6.65% points compared to using water. As it can be seen, using Al_2O_3 at 0.4 v%, Q_{aux} decreases by about 39.62% points compared to the reference case using water. The monthly variation of the solar fraction S_F using water, water+ Al_2O_3 at 0.2 v%, and water+ Al_2O_3 at 0.4 v% is shown in Figure 7. It is shown that S_F ranges between 44.39 in January and 64.93% in August, between 46.4 in January and 67.27% in August, and between 54.71 in January and 78.82% in August using water, 0.2% Al_2O_3 , and 0.4% Al_2O_3 , respectively. As shown, the use of 0.2% Al_2O_3 increases the solar fraction by 3.6% points compared to using

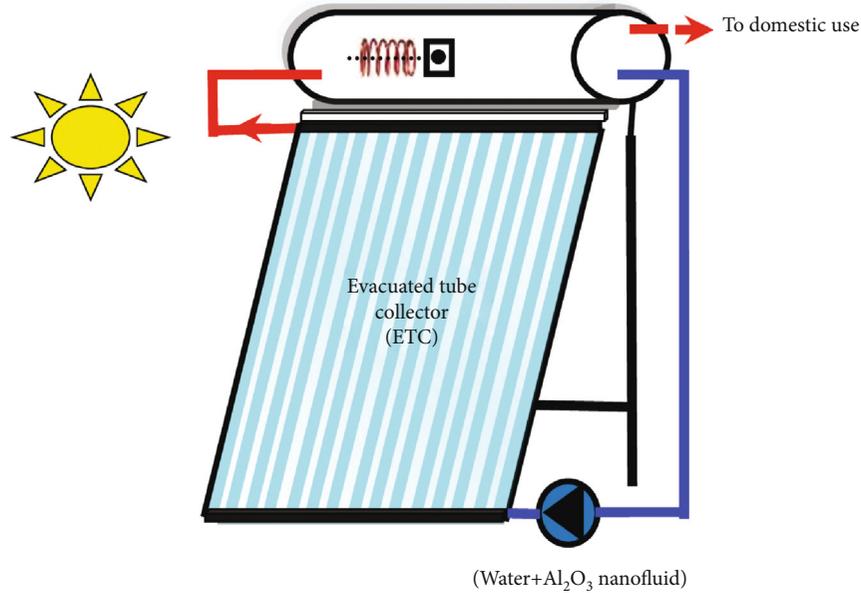


FIGURE 3: ETC using water, water+0.03% Al_2O_3 , and water+0.06% Al_2O_3 .

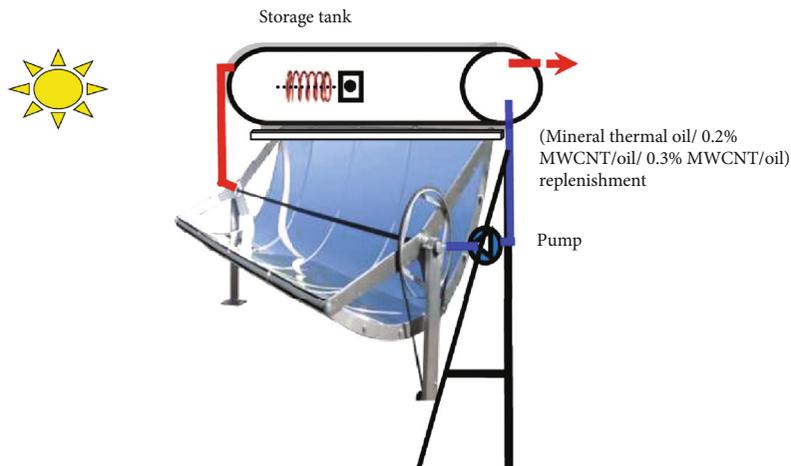


FIGURE 4: CPC using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil.

water. It was also established that using 0.4% Al_2O_3 , S_F increased by about 21.39% points compared to using water.

In Figure 8, the monthly variation of the solar fraction by the solar system using water, Al_2O_3 at 0.2 v%, and Al_2O_3 at 0.4 v% in Quebec (Canada) and Kuwait (Kuwait), which are characterized by extremes of cold climate and hot climate, respectively, is plotted. The solar fraction ranged between 18.24 in November and 53.92% in June, between 19.31 in November and 56.2% in June, and between 23.15 in November and 65.9% in June using water, 0.2% Al_2O_3 , and 0.4% Al_2O_3 , respectively. It was seen that compared to using water, S_F increased by about 4.23% points and by about 22.22% points using 0.2% Al_2O_3 and 0.4% Al_2O_3 , respectively. As shown from Figure 8, in a desert climate like Kuwait (Kuwait), S_F is around 45% in December and reaches 69.05% in March, is around 46.9% in December and reaches 71.74% in March, and is around 55.4% in December and

reaches 83.6% in March using water, 0.2% Al_2O_3 , and 0.4% Al_2O_3 , respectively. It was obvious that using 0.2% Al_2O_3 , S_F increased by about 3.9% points compared to using water. It was also seen that using 0.4% Al_2O_3 , the solar fraction increased by about 21.07% points compared to using water.

3.2. Al_2O_3 /Water Nanofluid in the Evacuated Tube Collector (ETC). Figure 9 reports the plot of the efficiency η as a function against the reduced temperature parameters $(T - T_a)/G$ of the ETC system using water, 0.03% Al_2O_3 , and 0.06% Al_2O_3 at different flow rates, namely, 20 L/h, 40 L/h, and 60 L/h [17]. As found by the authors, the important enhancement in thermal performances of the ETC system was discovered for 0.06% Al_2O_3 nanoparticles. Figure 10 reports the plot of the collected energy Q_{coll} by the system using water, 0.03% Al_2O_3 , and 0.06% Al_2O_3 at a 20 L/h flow rate. Q_{coll} ranged between 124.12 in January and 220.53 MJ in

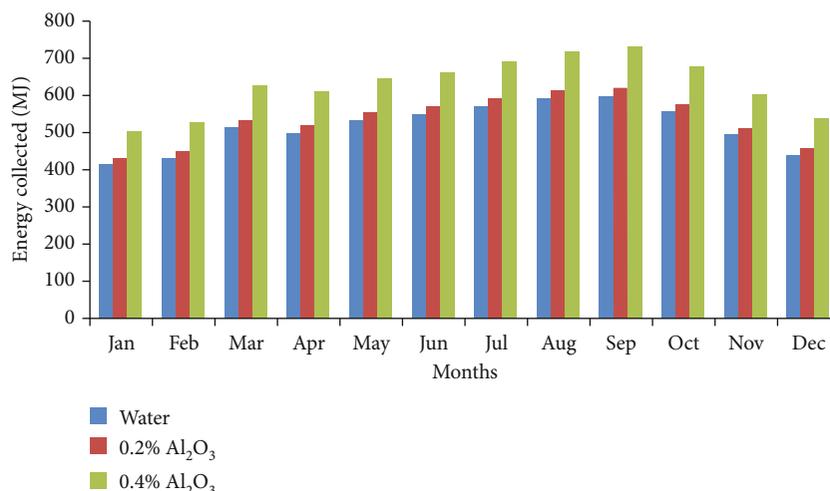


FIGURE 5: Simulated monthly energy collected flow changes of the FPC system.

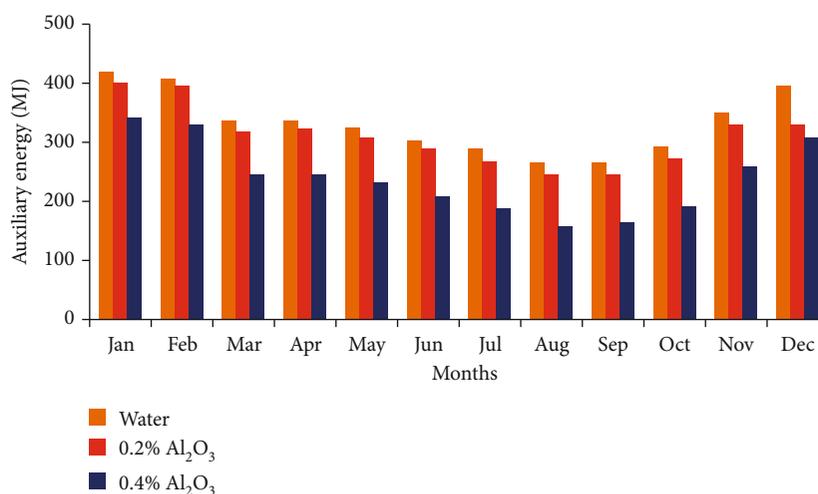


FIGURE 6: Simulated monthly auxiliary energy flow changes of the FPC system.

September, between 298.9 in January and 464.93 MJ in August, and between 370 in January and 567.8 MJ in August using water, 0.03% Al₂O₃, and 0.06% Al₂O₃, respectively. It was found that using 0.03% Al₂O₃, Q_{coll} increased by 110.82% points compared to using water. We can then take from Figure 10 that the use of Al₂O₃ at 0.06 v% increases the energy collected by about 157.47% points compared to using water. The monthly variation of the auxiliary energy of the system using water, 0.03% Al₂O₃, and 0.06% Al₂O₃ at 20 L/h is represented in Figure 11. The auxiliary energy varies from 492.4 in August to 743.35 MJ in February, from 285.64 in August to 597 MJ in February, and from 200.71 in August to 532 MJ in February using water, 0.03% Al₂O₃, and 0.06% Al₂O₃, respectively. It was established that using 0.03% Al₂O₃, Q_{aux} decreased by about 42% points compared to using water. It was also seen that using Al₂O₃ at 0.06 v%, the auxiliary energy decreased by about 59.24% compared to using water. The monthly variation of the solar fraction of the ETC system using the three prescribed fluids at 20 L/h is shown in Figure 12. The solar fraction S_F ranges

between 13.65 in February and 24% in August, between 30.7 in February and 55.9% in August, and between 37.91 in January and 69% in August using water, 0.03% Al₂O₃, and 0.06% Al₂O₃, respectively. It can therefore be stated that the use of 0.03% Al₂O₃ increases S_F by 132.92% points compared to using water. On the other hand, using 0.06% Al₂O₃, the solar fraction increased by about 187.5% points compared to using water. Figure 13 shows the predicted monthly energy collected Q_{coll} by the ETC system using water, 0.03% Al₂O₃, and 0.06% Al₂O₃ at 60 L/h. Q_{coll} is around 254.42 MJ in January and reaches 403.04 MJ in July, is around 377.6 in January and reaches 578.02 MJ in July, and is around 510.8 in January and reaches 774.16 MJ in August using water, 0.03% Al₂O₃, and 0.06% Al₂O₃, respectively. It is obvious that compared to using water, the energy collected increased by 43.42% and by 92.08% points using Al₂O₃ at 0.03 v% and 0.06% Al₂O₃, respectively. In Figure 14, the predicted monthly auxiliary energy Q_{aux} needed by the system when using water, 0.03% Al₂O₃, and 0.06% Al₂O₃ at 60 L/h is plotted. Q_{aux} varies from 339.6 in August to 640.8 MJ in February,

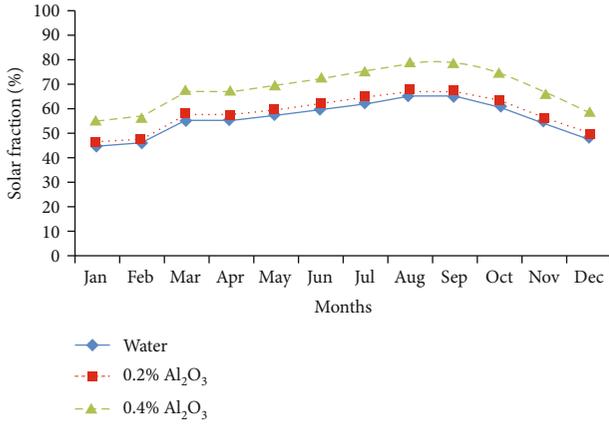


FIGURE 7: Monthly solar fraction changes of the FPC system.

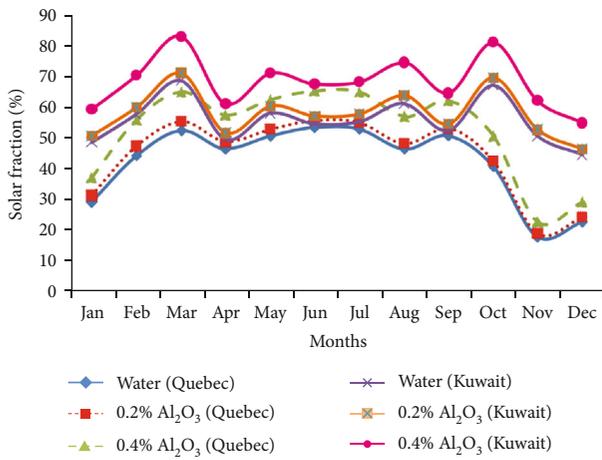


FIGURE 8: Simulated monthly solar fraction changes of the FPC system in Quebec and Kuwait.

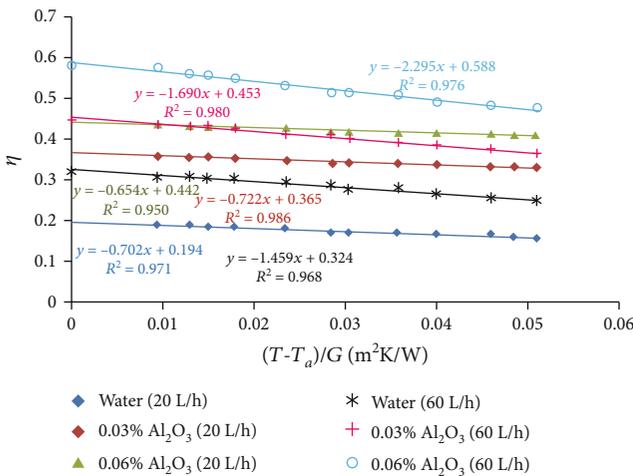


FIGURE 9: Efficiencies of the evacuated solar collector for water and for Al₂O₃ nanofluid at different mass flow rates (20, 40, and 60 L/h) (Ghaderian and CheSidik [17]).

from 196.8 in August to 531.2 MJ in February, and from 39.93 in August to 413.61 MJ in February using water, 0.03% Al₂O₃, and 0.06% Al₂O₃, respectively. Based on Figure 14, we can affirm that when using 0.03% Al₂O₃/water nanofluid, Q_{aux} is reduced by 42.05% compared to the reference case that uses water. It is also well established that the use of 0.06 v% Al₂O₃/water nanofluid decreases the auxiliary energy needed by the system by 88.24%. Figure 15 reports the plot of the monthly variation of the solar fraction S_F of the ETC using water, 0.03% Al₂O₃, and 0.06% Al₂O₃ at 60 L/h. As shown, S_F ranged between 25.6 in February and 47.5% in August, between 38.32 in February and 69.6% in August, and between 51.8 in January and 93.82% in August using water, 0.03% Al₂O₃, and 0.06% Al₂O₃, respectively. The solar fraction increased by about 46.53% when using 0.03% Al₂O₃/water compared to the same system when using water. It is also shown that using 0.06% Al₂O₃, S_F increased by about 97.52% points compared to using water. To better understand the effect of weather conditions, we plot the predicted monthly variation of the solar fraction of the ETC in Figure 16 using the three prescribed fluids in Quebec and Kuwait at a flow rate equal to 60 L/h. In Quebec, the solar fraction ranges between 9.5 in November and 36.4% in July, between 15.74 in November and 56.7% in July, and between 22.4 in November and 76.93% in July using water, Al₂O₃ at 0.03 v%, and Al₂O₃ at 0.06 v%, respectively. It was also established that in Kuwait, S_F varies from 26.81 in December to 45.74% in August, from 39.9 in December to 67.6% in October, and from 53.5 in December to 90.14% in August using water, 0.03% Al₂O₃/water, and 0.06% Al₂O₃/water, respectively. It was also seen that solar fraction, using 0.03% Al₂O₃, increased by about 55.77% points and about 47.79% points compared to using water in Quebec and Kuwait, respectively. It was also established that using Al₂O₃ at 0.06 v%, S_F increased by about 111.35% and about 97.07% points compared to the case using water in Quebec and Kuwait, respectively.

3.3. MWCNT/Oil Nanofluid in the Compound Parabolic Collector (CPC). Our goal was first and foremost to evaluate the economic contribution as well as the impact of the reduction in the number of kilowatt-hours necessary to overcome the need for water heating on the number of tons of CO₂ emitted into the atmosphere for different nanofluids (with different base fluids). To do this, it is essential to start with an experimental result of the solar water heater performance testing. Although there are quite several bibliographic references that use MWCNT nanoparticles in water circulating fluid in the PTC [37, 43], there are few works that have focused on the overall performance testing of the parabolic trough collector before and after adding MWCNT according to ASHRAE standards. With regard to the FPS and the ET collectors, we have found experimental investigations and testing results by Yousefi et al. [4] and Ghaderian and CheSidik [17] using Al₂O₃ nanoparticles suspended in water. For the parabolic trough collector, our study is based on experimental testing of MWCNT+mineral oil nanofluid. Thus, studies dealing with PTC-based MWCNT+water nanofluid did not give thermal performance testing results

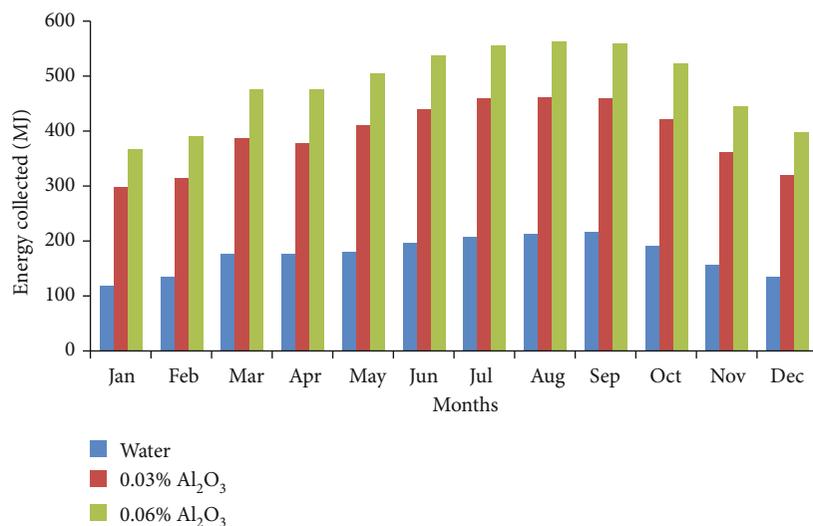


FIGURE 10: Simulated monthly energy collected flow changes of the ETC system at 20 L/h.

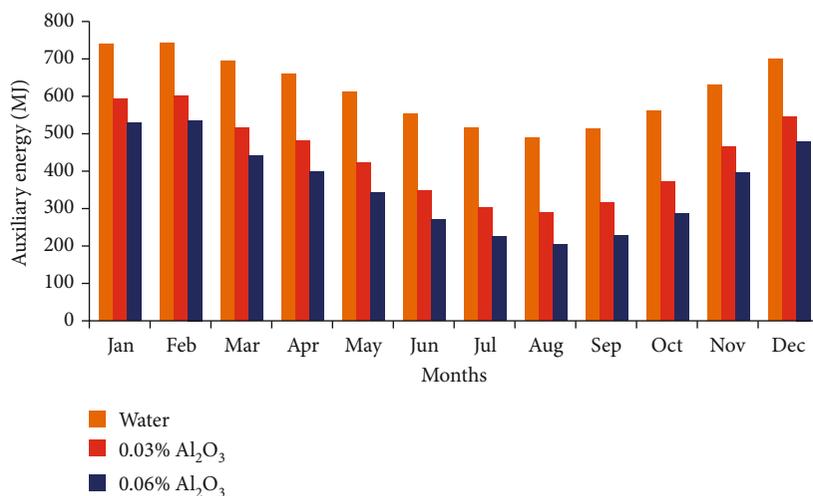


FIGURE 11: Simulated monthly auxiliary energy flow changes of the ETC system at 20 L/h.

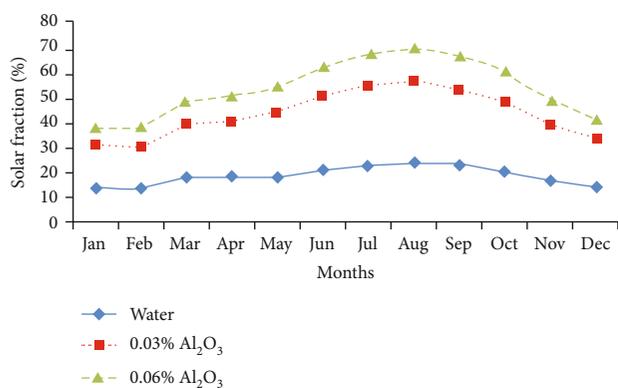


FIGURE 12: Simulated monthly solar fraction changes of the ETC system at 20 L/h.

which will subsequently be essential for the implementation of the thermal model in TRNSYS. Nevertheless, the use of oil+MWCNT nanofluid for the PTC can affect neither the economic nor the environmental assessment of the use of MWCNT nanoparticles in the parabolic trough solar collector. It is true that Al₂O₃ may be used as base fluid in PTC technologies as mentioned, and we did not conduct assessment studies of these types of nanofluids in the PTC since we focused on the combination (nanofluid+solar water heater technology) that has been experimentally tested, and its thermal performances can be implemented in the TRNSYS software. However, this does not preclude quoting these points, and we added pertinent references in this context in the revised manuscript.

Figure 17 shows the plot of η as a function of $(T - T_a)/G$ by the CPC system using the mineral thermal oil and the same fluid with 0.2% MWCNT and 0.3% MWCNT nanoparticles [24]. The increase of the wt% of MWCNT in the

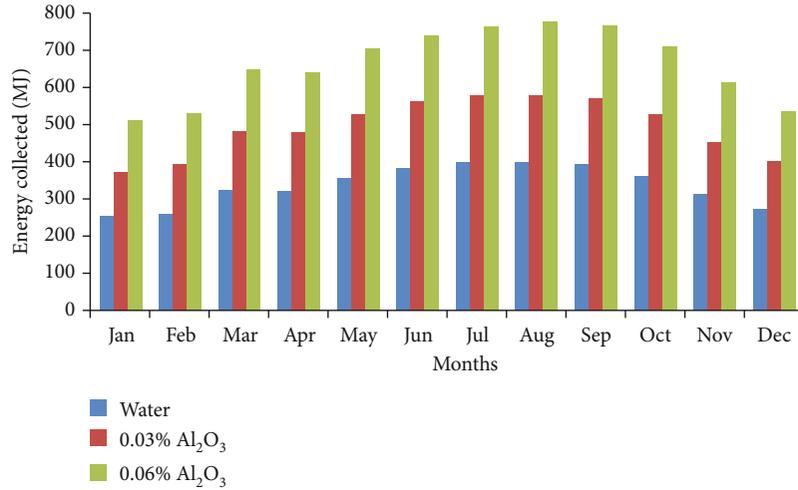


FIGURE 13: Simulated monthly energy collected flow changes of the ETC system at 60 L/h.

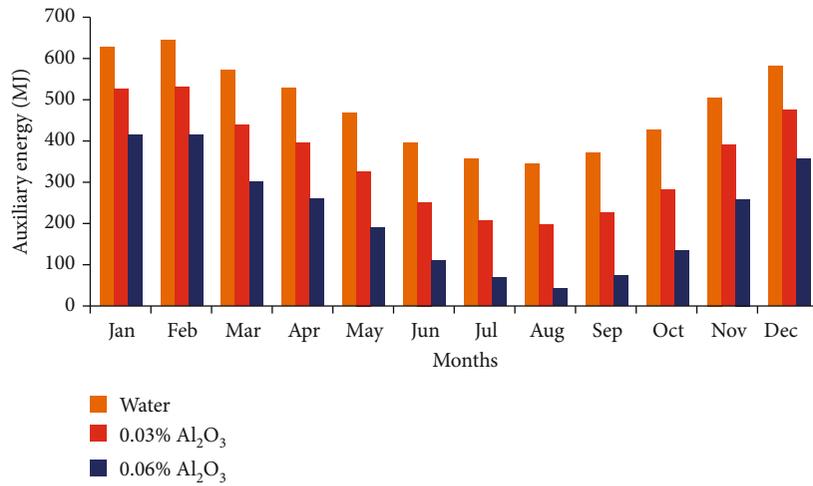


FIGURE 14: Simulated monthly auxiliary energy changes of the ETC system at 60 L/h.

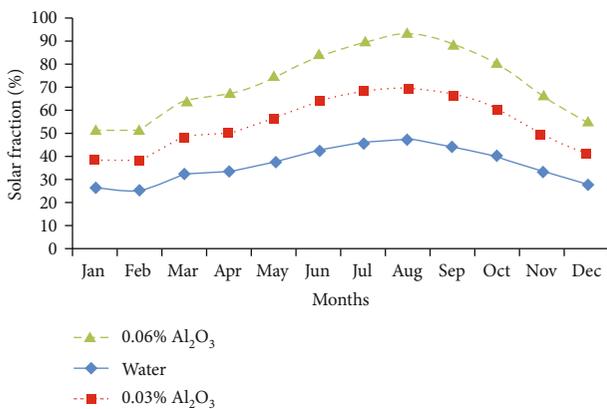


FIGURE 15: Simulated monthly solar fraction changes of the ETC system at 60 L/h.

nanofluid leads to add thermal resistance to heat transfer because of the nanoparticle deposition layer. The nanoparticles tend to be attached to collector surfaces, and they form substrates. This allows the nanofluid to undergo the formation of large bubbles. The major part of MWCNT nanoparticles will aggregate and sediment. In this situation, one should avoid wall deposition by using pH-controlled surfactants in order to reduce the agglomeration of nanoparticles. Thus, there exists an optimum ratio of the concentration of the surfactants and the nanoparticles which coincides with better stability of the nanofluids and hence the best enhancement in the heat transfer rate [29]. As this solution has a harmful effect on the environment and human health, there exist other nonchemical solutions such as the use of surfactin [44] which are biosurfactants obtained by the fermentation process.

The monthly energy collected by the CPC system using the three fluids is represented in Figure 18. It was found that Q_{coll} ranges between 346.44 in January and 539.1 MJ in July, between 443.73 in January and 666.53 MJ in August, and

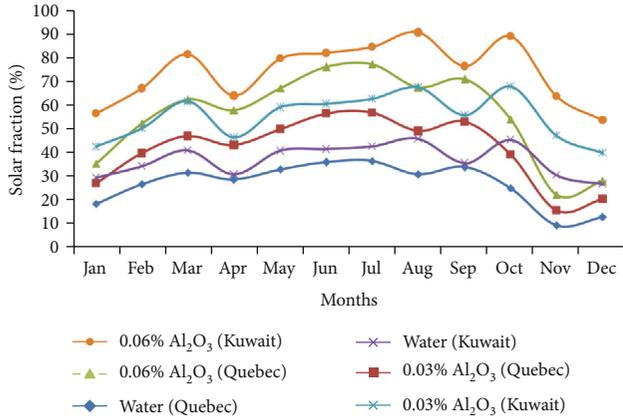


FIGURE 16: Simulated monthly solar fraction changes of the evacuated SDWH system in Quebec and Kuwait at 60 L/h.

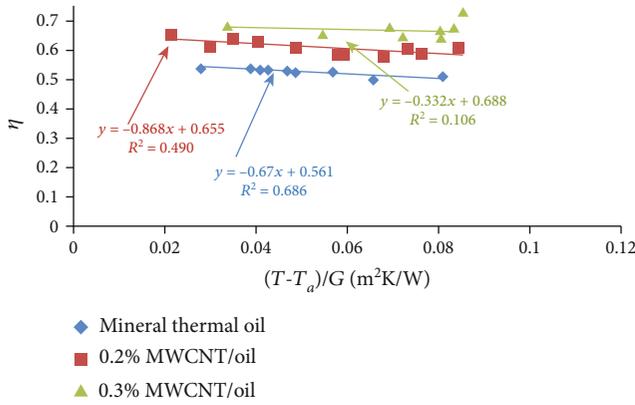


FIGURE 17: Efficiencies of the compound parabolic collector (CPC) for mineral thermal oil and for MWCNT nanofluid (Kasaeian et al. [24]).

between 471 in January and 711.4 MJ in August using mineral thermal oil and mineral oil with 0.2% MWCNT and with 0.3% MWCNT nanoparticles, respectively. Using 0.2% MWCNT/oil, the energy collected increased by 23.64% compared to the reference case using mineral thermal oil. It is also shown that by using 0.3% MWCNT/oil, Q_{coll} increased by about 31.96%. By computing the auxiliary energy Q_{aux} needed by the system using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil, we found that the auxiliary energy varies from 227.4 in August to 554.34 MJ in February, from 118.12 in August to 474.41 MJ in February, and from 86.54 in August to 448.6 MJ in February using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil, respectively. It is seen that using 0.2% MWCNT/oil, Q_{aux} reduced by about 48.06% points compared to using the reference case. Using 0.3% MWCNT/oil, the auxiliary energy reduced by about 61.94% points compared to using mineral thermal oil. S_F is recorded at a value of 35.62% in February and reaches 64.9% in August, is recorded at a value of 44.92% in February and reaches 81.9% in August, and is recorded at a value of 47.74% in January and reaches 86.61% in August using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil, respectively. From

Figure 19, it can also be deduced that when using 0.2% MWCNT/oil, the solar fraction increased by about 26.19% points compared to using mineral thermal oil. It is also seen that by 0.3% MWCNT/oil, S_F increased by about 33.45% compared to the reference case. The monthly variation of the solar fraction of the parabolic collector system using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil in Quebec and in Kuwait is presented in Figure 20. The solar fraction varies from 14.4 in November to 52.2% in June, from 18.9 in November to 66.8% in July, and from 20.51 in November to 71.1% in July using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil, respectively. It is found that using 0.2% MWCNT/oil, the solar fraction increased by about 27.97% points compared to using mineral thermal oil. It is also shown that by 0.3% MWCNT/oil, S_F increased by about 36.21% compared to the system using mineral oil. Figure 19 also reports that S_F is around 36.93% in December and reaches 62.91% in October, is around 46.44% in December and reaches 78.9% in August, and is around 49.4% in December and reaches 83.53% in August using mineral thermal oil, 0.2% MWCNT/oil, and 0.3% MWCNT/oil, respectively. It is established that using 0.2% MWCNT/oil, the solar fraction increased by about 25.42% compared to the situation using mineral thermal oil. It is also obvious that by 0.3% MWCNT/oil, S_F increased by about 32.78% points compared to the reference case.

4. Economic Evaluation and Carbon Dioxide Emission Reduction

In this section, we perform an economic evaluation of the use of the mentioned nanofluids in the three solar collector technologies. On the other hand, since the reduction in carbon emission is strongly attributable to renewable energy, the aim of this section is also to estimate the total CO_2 reduction due to the use of nanofluids in the prescribed technologies. The economic study was made by evaluating the cost of solar project investment (C_{SPI}), the total electric boiler cost (C_{EB}), the price of the energy collected (P_{EC}), and the payback period (P_p) as evaluated in the literature [45–47].

$$C_{\text{EB}} = P_{\text{SB}} + C_{\text{MSB}}, \quad (6)$$

where C_{EB} , P_{SB} , and C_{MSB} are the total electric boiler cost (US\$), the price of the substituted boiler (US\$), and the cost of the maintenance of the substituted boiler (US\$), respectively.

$$C_{\text{SPI}} = C_I + C_{\text{MS}} + C_{\text{YAD}}, \quad (7)$$

where C_{SPI} is the cost of solar project investment (US\$), C_I is the installation cost (US\$), C_{MS} is the maintenance system cost (US\$), and C_{YAD} is the yearly auxiliary demand cost (US\$).

$$P_p = \frac{(C_{\text{SPI}} - C_{\text{EB}})}{P_{\text{YEC}}}, \quad (8)$$

where P_p is the payback period (year) and P_{YEC} is the yearly energy collected price (US\$).

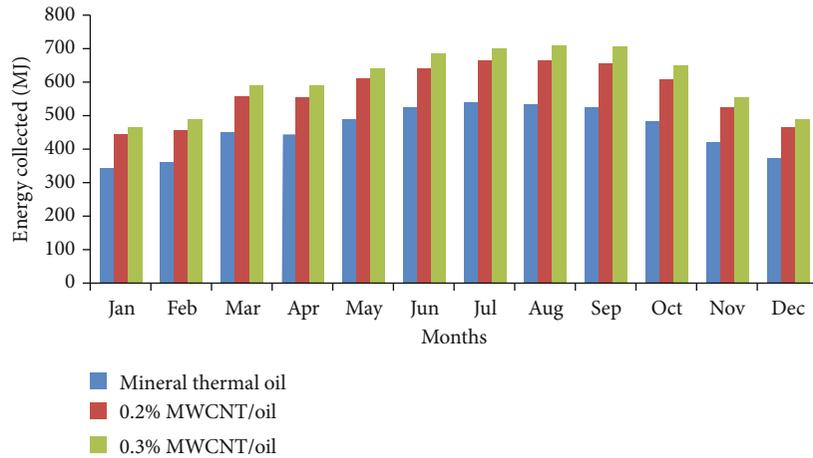


FIGURE 18: Simulated monthly energy collected flow changes of the CPC system.

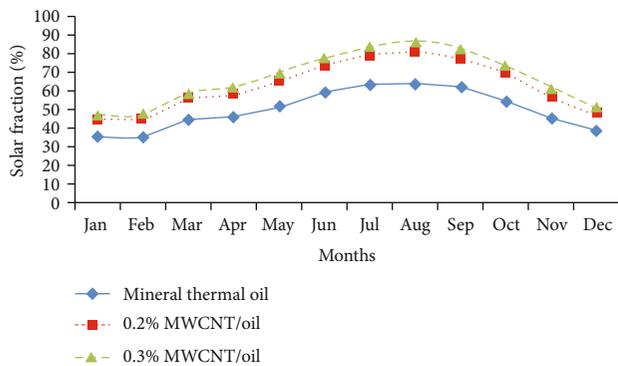


FIGURE 19: Simulated monthly solar fraction changes of the CPC system.

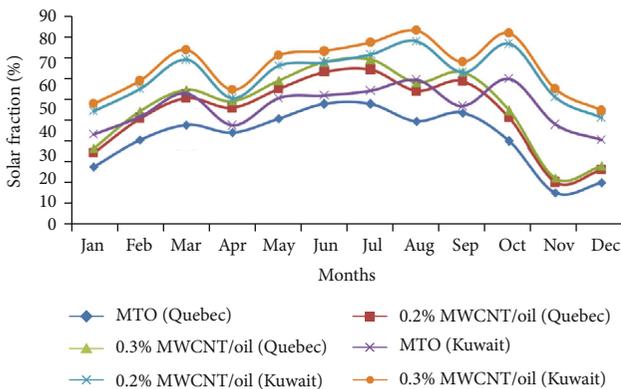


FIGURE 20: Simulated monthly solar fraction changes of the CPC system in Quebec and Kuwait.

Table 1 shows the effects of using different nanofluids on the annual total quantity of electricity (kWh) in different regions by using the prescribed solar collector technologies. In Tunisian weather conditions, by using the FPSC, the annual quantity of the auxiliary energy added is 1111.2kWh by using water. This same quantity reaches

801.3 kWh when using water+0.03% Al_2O_3 with a decrease in electric demand of 27.9%. In a relatively cold climate like Quebec and hot climate like Kuwait, the consumed quantities of energy decrease by 17.9% and 28.52% by using the same nanofluid, respectively. The table also shows that by using a 60 L/h flow rate in the ETC, the quantity of energy added to overcome the annual demand decreases from 1610.7 to 726.7 kWh by adding 0.06% Al_2O_3 nanoparticles to water and using Tunisian weather conditions. When using Quebecois and Kuwaiti meteorological data, the decrease in auxiliary energy consumption reached 38.42% and 57.26% by using the same percentage of nanoparticles in water, respectively. The use of 0.3% MWCNT/oil as working fluid in CPC has a direct impact on the annual backup quantity of energy which decreases by about 32%, 21%, and 34% when dealing with Tunisian, Quebecois, and Kuwaiti climates, respectively.

The reduction in the annual quantity of auxiliary energy can be translated into the annual gain of different solar water heaters as shown in Table 2. The table reveals that the FPSC based on the electric boiler (EB) gives an annual free energy cost of 499.2, 518.7, and 607.7 US\$ by using water and water with alumina at 0.2 v% and 0.4 v%, respectively. The FPSC provides worth of 22.1 and 216.11 US\$/year by using the same (water+0.4 v% Al_2O_3) nanofluids when electricity is substituted by Natural Gas (NG) and Liquefied Petroleum Gas (LPG), respectively. The annual gain of the FPSC system reached 9498.54 and 63.4 US\$ in Quebec and Kuwait, respectively. In fact, the remarkable difference between solar gains is mainly due to the huge difference in the price of fossil fuels in the two regions. Even though nanofluids in countries where fossil fuels are cheaper like Kuwait reduce auxiliary energy consumption (Table 1), countries where energy is more expensive like Quebec are still able to extract more free solar energy by using nanofluids (Table 2). Thus, the annual gain of using ETC by EB changed from 4874.65 using water to 9785.93 US\$ using water+0.06 v% Al_2O_3 in Quebec. This increase is smaller using the CPC with the mineral oil+0.2% MWCNT/oil nanofluids which changed from 6774.3 to 9086.22 US\$/year.

Based on the electric boiler, the payback periods referring to the times required to recover the costs of the solar water

TABLE 1: Effects of using nanofluids on the annual production of solar water heaters in different locations.

Technology	Fluid	Annual total quantity of electricity (kWh)		
		Tunis (Tunisia)	Quebec (Canada)	Kuwait (Kuwait)
FPSC	Water	1111.2	1438.03	1100.2
	Water+0.2% Al ₂ O ₃	1054.2	1384	1042.43
	Reduction (%)	(-5.13%)	(-3.8%)	(-5.25%)
	Water+0.4% Al ₂ O ₃	801.3	1180.73	786.4
	Reduction (%)	(-27.9%)	(-17.9%)	(-28.52%)
ETC	Water	1610.7	1845.5	1591.93
	Water+0.03% Al ₂ O ₃	1174.13	1489.2	1147
	Reduction (%)	(-27.1%)	(-19.3%)	(-27.95%)
	Water+0.06% Al ₂ O ₃	726.7	1136.44	680.44
	Reduction (%)	(-54.9%)	(-38.42%)	(-57.26%)
CPC	Mineral oil	1271.42	1568.1	1246.01
	0.2% MWCNT/oil	956	1314.02	920.8
	Reduction (%)	(-24.8%)	(-16.2%)	(-26.1%)
	0.3% MWCNT/oil	860.34	1235.92	819.1
	Reduction (%)	(-32.33%)	(-21.2%)	(-34.26%)

TABLE 2: Effects of using nanofluids on the annual gain (US\$) of solar water heaters in different locations.

Technology	Fluid	Annual gain				
		EB	Tunis (Tunisia) GTB	GPLB	Quebec (Canada) EB	Kuwait (Kuwait) EB
FPSC	Water	499.2 US\$	499.2 US\$	177.51 US\$	7730.2 US\$	52.05 US\$
	Water+0.2% Al ₂ O ₃	518.7 US\$	18.83 US\$	184.85 US\$	8096.41 US\$	54.1 US\$
	Water+0.4% Al ₂ O ₃	607.7 US\$	22.1 US\$	216.11 US\$	9498.54 US\$	63.4 US\$
ETC	Water	326.8 US\$	11.9 US\$	216.21 US\$	4874.65 US\$	34.5 US\$
	Water+0.03% Al ₂ O ₃	34.5 US\$	17.31 US\$	169.6 US\$	7456.6 US\$	50.25 US\$
	Water+0.06% Al ₂ O ₃	637.53 US\$	23.14 US\$	226.7 US\$	9785.93 US\$	67.6 US\$
CPC	Mineral thermal oil	443.45 US\$	16.1 US\$	157.7 US\$	6774.3 US\$	46.8 US\$
	0.2% MWCNT/oil	553.94 US\$	20.11 US\$	197 US\$	8538.04 US\$	58.4 US\$
	0.3% MWCNT/oil	588.74 US\$	21.4 US\$	209.4 US\$	9086.22 US\$	62.2 US\$

heater investments in Tunisia are summarized in Table 3. Take into account that the stability impact leads to an increase in the maintenance cost and the payback period of systems using nanofluids. For this reason, we increased the maintenance cost of the solar water heaters by 50 US\$/year as an estimated cost due to the stability mechanisms in Tables 3 and 4.

It is well established that using water+0.4% Al₂O₃ as working fluid in FPSC reduces the payback period by around 0.6 years, i.e., 7.2 months. Theoretically, the same nanofluid at 0.06 v% of nanoparticles in ETC reduces P_p by 3.34 years, i.e., 3 years and 4.08 months. On the other hand, the time required to recover the costs of the CPC decreases by 0.44 years, i.e., 5.28 months, when using 0.2% MWCNT/oil as circulating fluid. More importantly, the minimum reimbursement period for the investment cost is that recorded for the CPC using 0.3% MWCNT/oil nanofluid which reached 1.42 years.

The payback period of FPSC, ETC, and CPC systems with and without nanofluids in Quebec and Kuwait is shown in Table 4. As expected from the high cost of fossil fuels, the minimal computed P_p are found to be close for the three technologies in Quebec. The table reveals that the reimbursement period was found to be around one year. In Kuwait, the difference in the reimbursement periods using the three nanofluids only appears if we use ETC. The payback periods of the ETC system are about 6.89, 5.46, and 3.85 years using water, water+0.03% Al₂O₃, and water+0.06% Al₂O₃ as working fluids, respectively.

In fact, while the payback period is of great importance, it does not give a rigorous evaluation of a project. The environmental impact is also an indicator to evaluate the use of nanofluids in solar water heaters. The use of solar water heaters with nanofluids is economically profitable and acts on the payback of the project as shown above. As it was previously mentioned and largely shown in the literature [48],

TABLE 3: The economic comparison results between FPSC, ETC, and CPC systems with and without nanofluids (including the maintenance cost due to the stability mechanism).

Technology	Fluid	C_{SPI} (US\$)	C_{RI} (US\$)	E_{AR} (US\$)	Payback period (year)
FPSC	Water	1851.5	362.3	499.17	2.98
	Water+0.2% Al_2O_3	1884.96	362.3	518.7	2.94
	Water+0.4% Al_2O_3	1811.62	362.3	607.71	2.38
ETC	Water	2385.01	362.3	326.79	6.19
	Water+0.03% Al_2O_3	2308.42	362.3	476.88	4.1
	Water+0.06% Al_2O_3	2178.7	362.3	637.53	2.85
CPC	Mineral thermal oil	1265.71	362.3	443.45	2.04
	0.2% MWCNT/oil	1224.24	362.3	553.94	1.6
	0.3% MWCNT/oil	1196.5	362.3	588.74	1.42

TABLE 4: The payback period of FPSC, ETC, and CPC systems with and without nanofluids in Quebec and Kuwait (including the maintenance cost).

		Quebec (Canada)	Kuwait (Kuwait)
FPSC	Water	1.06	1.79
	Water+0.2% Al_2O_3	0.98	2.61
	Water+0.4% Al_2O_3	0.71	2.1
ETC	Water	2.29	6.89
	Water+0.03% Al_2O_3	1.22	5.46
	Water+0.06% Al_2O_3	0.72	3.85
CPC	Mineral oil	1.35	3.36
	0.2% MWCNT/oil	0.9	3.38
	0.3% MWCNT/oil	0.8	3.13

the use of nanofluids not only is economically profitable but also has a significant environmental impact in terms of reducing harmful emissions. It is important to note here that renewable energies also result in the release of CO_2 during energy production. When wind power releases 11 g of CO_2 per kWh produced, solar energy releases 48 g and hydraulic power plants release 24 g [49]. Nevertheless, the fact remains that solar energies are still a good alternative for electricity production which improve environmental sustainability because they emit much less CO_2 than the combustion of fossil fuels. Just like other nanomaterials that can be transferred to ecosystems by various pathways [50], MWCNTs are considered toxic and are cancer-causing and lung tumor agents [51]. For this reason, the volume fraction of MWCNTs did not exceed 0.3% in our study. While the nanomaterial lifespan can reach 50 years, the guaranteed lifespan of the solar collectors is low and around 10 to 15 years. It is considered that this type of technology can function optimally for about twenty years. It remains to be mentioned that this danger can be mitigated in the preparation process of nanoparticles by using short fiber length. During the life cycle of the MWCNTs, the composites are resistant to degradation and the release will occur slowly. The significant potential for CNT release will occur in their end-of-life phase [52]. As suggested by Caballero-Guzman et al. [53], the fate of the largest proportion of MWCNT nanomaterials will flow off as waste that can then be properly treated in incineration

plants or landfills. Certainly, the recycling process should focus on toxicity and occupational exposure. Material flow analysis of CNT and other nanomaterials during the incineration process by Mueller et al. [54] shows that, in most cases, nanomaterials flow to the landfill through the residual ash, with the exception of CNT, which is mainly burned. This is because CNTs ignite in the presence of oxygen at the critical temperature of 1100 K [55]. Therefore, recycling this waste does not lead to the significant dissipation of other new products.

The collected energy gain by using nanofluids calculated previously can be converted into an environmental impact by assuming that the average emission of 1 kWh is 0.449 kg of CO_2 [56]. Table 5 summarizes the results of the annual quantity of CO_2 emitted in tons using the three prescribed solar thermal collectors with and without nanofluids in Tunisia, Quebec, and Kuwait. The table shows that the use of FPSC in Tunisian climate allows avoiding the production of 0.772, 0.803, and 0.940 tons of CO_2 when using water, water+0.2% Al_2O_3 , and water+0.4% Al_2O_3 , respectively. Using the same technology in Quebec avoids the production of 0.6, 0.628, and 0.737 tons of CO_2 per year by using water, water+0.2% Al_2O_3 , and water+0.4% Al_2O_3 , respectively. On the other hand, when using FPSC in Kuwait, the reduction of the annual production of CO_2 is about 0.779, 0.809, and 0.948 tons by using water, water+0.2% Al_2O_3 , and water+0.4% Al_2O_3 , respectively. The table also reveals that

TABLE 5: Effects of using nanofluids on the annual production of carbon dioxide (CO₂) of electrical heaters in the solar water heaters in different locations.

Technology	Fluid	Annual quantity of CO ₂ (tons/year)		
		Tunis (Tunisia)	Quebec (Canada)	Kuwait (Kuwait)
FPSC	Water	0.772	0.6	0.779
	Water+0.2% Al ₂ O ₃	0.803	0.628	0.809
	Water+0.4% Al ₂ O ₃	0.940	0.737	0.948
ETC	Water	0.506	0.379	0.516
	Water+0.03% Al ₂ O ₃	0.738	0.579	0.752
	Water+0.06% Al ₂ O ₃	0.987	0.760	1.01
CPC	Mineral oil	0.687	0.526	0.700
	0.2% MWCNT/oil	0.858	0.663	0.874
	0.3% MWCNT/oil	0.911	0.706	0.931

using water+0.06% Al₂O₃ nanofluid in ETC, the annual production of CO₂ reaches 0.987, 0.760, and 1.01 in Tunisia, Quebec, and Kuwait, respectively. It was also established that using 0.3% MWCNT/oil in CPC, the reduced annual quantity of carbon dioxide reaches 0.911, 0.706, and 0.931 in Tunisia, Quebec, and Kuwait, respectively. This trend of the results shows that using the prescribed nanofluids in the three solar heater technologies, the greatest reduction in the predicted annual quantity of CO₂ emitted will be recorded in Kuwait. This is in addition to the relatively low cost of the solar projects under these typical climatic conditions. This will also reduce environmental pollutants because smaller heating units use less power, and the heat transfer unit has less liquid and material waste to discard at the end of its life cycle. In all, the use of nanofluids in solar collectors could reduce the sun-exposed surface and the mass flow rates circulating in the pipes. The reduction in the circulating fluid flow rate directly reduces the pumping power which has a considerable economic cost. The same amount of thermal energy can be provided using a smaller gross area, and therefore, the system becomes less expensive. This certainly reduces the initial cost of the equipment, excluding the cost of the nanofluids. This will directly reduce environmental pollutants because the use of nanofluids avoids the production of more kilowatt-hours by thermal power plants which pump out a lot of greenhouse gases and ash, the source of a large part of the polluting emissions. In another way, using nanofluids in solar water heaters leads to provide fewer wastes to throw away at the end of the thermal system's life cycle. On the other hand, nanofluids have an initial cost [57] and another cost related to the maintenance if we take into account the impact of stability on the cost of maintenance. This reason may hinder the application of nanofluids in the solar water heater industry which has a rapid growth and could lower the initial and maintenance costs.

5. Conclusion

The use of nanofluids in solar collectors remains limited, and there is in some way a long engagement without wedding solar water heaters and nanofluids. This is mainly due to the problems of their rheological behavior and chemical

risks, especially when dealing with the use of surfactants. On the other hand, the comprehension of the thermal contribution of nanofluids and their economic and environmental evaluations in such devices should be studied. In such context, this paper provides a useful feasibility study to help future decisions for the use of nanofluids in solar heaters. For this purpose, a long-term study of using Al₂O₃ and MWCNT/oil in the most used solar water heater technologies, namely, the flat plate solar collector (FPSC), the evacuated tube collector (ETC), and the compound parabolic collector (CPC), has been executed. The effect of meteorological conditions has also been carried out. The main results gave the following conclusions:

- (i) Nanofluids have a remarkable effect on the solar fraction and also energetic, economic, and environmental effects for the three technologies. But their effects are greater in the ETC technologies
- (ii) Using 0.06% Al₂O₃ with water in ETC at 60 L/h, the solar fraction S_F reached 93.82% in August, 76.93% in July, and 90.14% in August in Tunisia, Quebec, and Kuwait, respectively
- (iii) By the electric boiler (EB), the biggest gain has been recorded in Quebec by using ETC and is about 4911 US\$/year by using 0.06% Al₂O₃+water
- (iv) In Mediterranean climates like Tunisia, the payback period P_p was considerably reduced by 0.62 years when using 0.3% MWCNT/oil in CPC. In Quebec, by using the three prescribed nanofluids, the P_p may be reduced by 3.04 years and 0.23 years when using ETC and CPC technologies, respectively
- (v) The use of nanofluids has a considerable ecological benefit as it reduces greenhouse gas emissions. Particularly, the use of water+0.06% Al₂O₃ nanofluid can avoid harmful CO₂ emissions up to 0.48, 0.38, and 0.49 tons/year in Tunisian, Quebecois, and Kuwaiti climates, respectively
- (vi) Finally, it seems to be important to note that the next-generation developed nanofluids should

present solutions to the issues of cost, sedimentation of nanoparticles, corrosion, and toxicity [58] in order to compete with conventional heat transfer fluids like water

Nomenclature

A :	Collector area, m^2
A_c :	Total collector area, m^2
C_{YAD} :	Yearly auxiliary demand cost, US\$
A_i :	Surface area of the i th tank segment, m^2
C_{pn} :	Nanofluid specific heat, $kJ/kg\ K$
C_{EB} :	Total electric boiler cost, US\$
C_{SPI} :	Cost of solar project investment, US\$
P_{YEC} :	The yearly energy collected price, US\$
F_{aux} :	Auxiliary energy of the energy collected, %
F_{load} :	Portion of the energy required by the load of the energy collected, %
I :	Total solar irradiance at the collector's aperture, W/m^2
C_I :	Installation cost, US\$
C_{MS} :	The system maintenance cost, US\$
\dot{m}_n :	Nanofluid mass flow rate in the solar collector, kg/s
\dot{m}_{nh} :	Nanofluid mass flow rate to the tank from the heat source, kg/h
M_{ni} :	Mass of nanofluid in the i th section, kg/h
\dot{m}_{nL} :	Nanofluid mass flow rate to the load and/or of the makeup fluid, kg/h
N :	Number of fully mixed (uniform temperature) tank segments
C_{MSB} :	Cost of the maintenance of the substituted boiler, US\$
P_p :	Payback period, year
P_{SB} :	Price of the substituted boiler, US\$
Q_{aux} :	Auxiliary energy, J
Q_{coll} :	Energy collected, J
Q_i :	Rate of energy input by the heating element to the i th segment, J
Q_L :	Total energy extracted from the system to support the water heating requirements, J
Q_{load} :	Energy rate to load, J
Q_{loss} :	Energy lost from the storage tank and pipes, J
Q_u :	Useful energy extracted from the collector, J
$Q_{u,a}$:	Total useful energy for the whole year, J
S_f :	Solar fraction, %
T_a :	Ambient (air) temperature, K
T_c :	Inlet temperature of the fluid to the collector, K
T_{env} :	Temperature of the environment surrounding the tank, K
T_h :	Temperature of the fluid entering the storage tank from the heat source, K
T_i :	Temperature of the i th tank segment, K
T_{i-1} :	Temperature of the $(i-1)$ th tank segment, K
T_L :	Temperature of the fluid replacing that extracted to supply the load, K
T_o :	Outlet temperature of the fluid from the collector, K
U :	Loss coefficient between the i th tank node and its environment, $kJ/h\ m^2K$
U_C :	Heat loss coefficient, $W/(m^2K)$

U_L : Overall thermal loss coefficient of the collector per unit area, W/m^2K .

Acronyms

MWCNTs:	Multiwalled carbon nanotubes
CPC:	Compound parabolic collector
ETC:	Evacuated tube collector
FPSC:	Flat plate solar collector
SDWH:	Solar domestic water heaters
SDWH FPC:	Flat plate solar domestic water heaters.

Greek Symbols

α_i :	Control function defined by $\alpha_i = 1$ if $i = S_h$, 0 otherwise
β_i :	Control function defined by $\beta_i = 1$ if $i = S_L$, 0 otherwise
γ_i :	Control function defined by $\gamma_i = \dot{m}_h \sum_{j=1}^{j=i-1} \alpha_j - \dot{m}_L \sum_{j=i+1}^{j=N} \beta_j$
h :	Hour
d :	Day.

Data Availability

All data generated or analyzed during this study are included in this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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