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Exploration Of Key Approaches to Enhance Evacuated Tube Solar Collector Efficiency

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ABSTRACT

This research is carried out to investigate and examine the critical benefits and significant contributions of integrating nanoparticles into the ETSC system to enhance the thermal efficiency, thermal performance, temperature out, and energy storage of the ETSC. The Simcenter STAR-CCM+ 2022.1 software package implemented numerical analysis and thermal simulations. Further, a comparative analysis is conducted on two case studies to validate the critical role and contributions of employing the aluminum oxide nanomaterial in the solar collector system to enhance its thermal efficiency and improve its thermal performance and heat transfer, including (1) conventional ETSC and (2) ETSC with Al2O3. According to the numerical analysis and comparative study findings, the results of this research revealed that employing and adding the aluminum oxide nanomaterial into the ETSC system had contributed to several beneficial impacts and significant advantages. In addition, using Al2O3 achieved enhancements in the thermal efficiency, increases in the outlet collector's temperature, improvements in the rate of heat flux of the pipes, the tube inside the collector, heat transfer of the hot water storage tank, and a rise in the temperature gradient the hot water temperature increased from (between 44.3 and 74.8 ºC) to (between 49.6-80.3 ºC). Besides, the velocity of the water flow inside the solar collector in the second case in which the aluminum oxide nanoparticles are used was higher due to the absorption of further solar radiation and thermal energy, which resulted in a considerable increase in the kinetic energy of water molecules from 0.01 to 0.07 m/s. Also, it was found that the velocity directions and profile were slightly more turbulent in the second case than the conventional solar collector due to more thermal energy absorbed and stored in the ETSC from solar radiation.

1. Introduction

Over the last decades, significant global attention and worldwide awareness towards the use of solar energy systems have been remarkably growing due to the rapid growth in the international

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population, which put further demand on hot water requirements and the harmful consequences of climate change and global warming mirrored by large greenhouse gas (GHG) emissions [1-4].

In general, most Iraqi citizens depend mainly on diesel generators that rely on fossil fuel resources (except in) to provide the electrical power needed for their homes since 2003, after the US invasion took place. In Baghdad alone, approximately eighteen percent of over 13,000 homes use diesel generators operated via the local provincial council [5,6]. The heavy dependence on and use of these diesel generators contributes to different environmental issues, reflected in air pollution emissions of Greenhouse Gas (GHG) emissions, like carbon dioxide, that are responsible for global warming and climate change. In addition, those diesel generators may emit poisonous gases like carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter due to heavy oil and diesel [7,8].

A challenging problem that needs to be substantially addressed for Baghdad and other Iraqi provinces is the requirement for hot water for both industrial and domestic uses. However, depending on diesel generators and expensive electricity would limit the citizens' ability to provide sufficient hot water for their families.

Hot water provision via solar energy is immensely profitable in saving significant money and electricity bills when hot water is required in winter and other seasons. The thermal efficiency of ETSCs is higher than the flat plate collector, as solar irradiation beams are continuously vertical on the ETSC's tubes from morning until evening [9]. Evacuated Tube Solar Collectors (ETSCs) are primarily beneficial and functional in different climate conditions, including moderate and cold climate temperature values. Using ETSC offers considerable practicality, more workability, and significant thermal energy storage than a flat plate collector, as the vacuum is used in ETSC to mitigate the thermal energy losses and heat transfer between the collector and the ambient [10]. Nevertheless, using ETSC in freezing climates with highly low-temperature values would lower their performance due to the significant difference between the ambiance and the hot water stored. Also, the opportunity for heat transfer between boiling water and very cold ambiance can increase due to the significant difference between temperature values. In this context, scientists and scholars have been working via research and development (R&D) to develop innovative ETSCs capable of storing a large amount of thermal energy throughout the day, contributing to shallow thermal losses.

Consequently, nanoparticles have been developed and designed to integrate into the ETSCs to improve their thermal energy storage potential and thermal performance, especially in frigid regions characterized by highly low-temperature values day and night [11-16]. Nanoparticles can be integrated into the ETSC and act like molten salts, storing thermal energy for extended periods without thermal losses [17]. Nanoparticles can increase the performance and thermal efficiency of the overall solar collector by absorbing more thermal energy and reducing the heat transfer rate into the ambient [18]. Figure 1 represents the nanoparticles integrated into an ETSC of U-tubes.

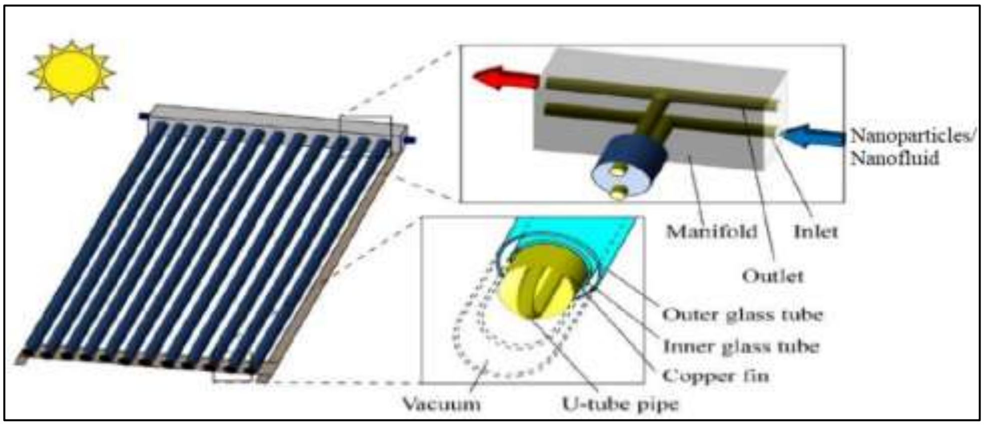


Fig. 1. Nanomaterials integrated into the evacuated U-tube solar collector [19]

An analysis is conducted to investigate the critical contributions and significant benefits of utilizing nanoparticles (nanofluids) in enhancing the ETSC's performance and thermal efficiency. The authors relied on a systematic literature review addressing recent nanoparticles and nanofluids. In addition, the literature identified the advantageous impacts of utilizing these materials in the ETSC to improve its thermal effectiveness and reliability. Their systematic literature analysis revealed that using nanoparticles and nanofluids in the ETSC is exceptionally beneficial and valuable as it can maximize the thermal energy stored in the ETSC. Furthermore, using these innovative materials is essential and practical to enhance the ETSC's thermal efficiency.

Additionally, they reported that using phase change materials (PCMs) is remarkably helpful in reducing thermal losses and promoting the ETSC thermal performance [20]. Research is carried out to analyze the critical benefits and significant relevance of employing nanoparticles in the ETSC regarding their performance and thermal efficiency. The authors depended on an experimental analysis by which a heat pipe ETSC was investigated using magnesium oxide/multi-walled carbon nanotubes (MgO/MWCNT) hybrid nanoparticles as the collector's working fluid. They used four several mixing ratios of MgO/MWCNT hybrid nanoparticles in the ETSC, including (50:50), (60:40), (70:30), and (80:20). Their experimental work revealed that using MgO/MWCNT hybrid nanoparticles in the ETSC provided significant enhancements to the overall system's thermal efficiency and sustainability. In addition, the results confirmed the remarkable boosting of ETSC's exergy efficiency and thermal energy by 77.14% and 55.83%, respectively, corresponding to a mix rate of (50:50) of MgO/MWCNT hybrid nanoparticles.

Furthermore, the experimental findings indicated that elevating the MgO/MWCNT hybrid nanoparticles' weight (between 20% and 30%) could significantly improve the ETSC's thermal performance compared to other nanoparticles [21]. A study investigates the critical benefits and relevance of exploiting nanoparticles in the ETSC on thermal efficiency and performance. The authors carried out the numerical analysis and modeling via computational fluid dynamics depending on the finite volume approach of an ETSC, which uses CuO nanoparticles. In addition, they analyzed the velocity and temperature distributions of hot water inside the ETSC and executed simulations to predict the distribution of these two parameters. The numerical analysis and simulations revealed that employing CuO nanoparticles in the ETSC contributed to considerable improvements in the thermal efficiency and performance of the ETSC [22]. This work is conducted to validate and verify the substantial role of employing nanoparticles in ETSC to enhance (A) its thermal energy storage, (B) thermal efficiency and performance, and (C) hot water storage for longer durations. Compared with conventional flat plate collectors, hot water generated from sunlight energy could be stored for only one to two days. However, using nanoparticles and special salts in the fluid circulated in the ETSC would increase its capability to store more thermal energy for longer times (more than one week).

Based on previous research, the employment of this new modeling and simulation software tool needs to be addressed and considered in global research [23,24]. Diverse peer-reviewed articles and research publications investigated and assessed the beneficial contributions of utilizing carbon nanotubes, nickel metal nanomaterials, graphene, and silicon oxide in different large-scale solar thermal energy applications [25,26]. Nonetheless, the integration of aluminum oxide into the ETSC has yet to be broadly discussed and is not available in global research [27].

Since 2003 (after the US invasion), approximately all Iraqi dwellers and citizens remarkably depend on diesel, heavy fuel, and other fossil fuel resources, which cause significant greenhouse gas emissions; intermittent and unreliable sources of electricity are provided by fossil fuels in several Iraqi provinces and regions [28,29]. Hot water and energy bills became remarkably expensive as most Iraqi citizens cannot provide hot water at lower prices or use free solar energy [30,31]. Even Iraqi people with sufficient electricity sources may face some issues in different seasons (especially in winter), some outages, and blackouts due to the degradation of the Iraqi electrical network infrastructure [32,33].

Conventional solar collectors face the thermal losses of hot water generated from solar energy, as hot water in the storage tank may radiate all its thermal energy to the surroundings [34,35]. Also, extensive industrial facilities (like pharmaceutical factories) and commercial buildings cannot rely only on conventional flat plat collectors or ETSC to provide continuous hot water (24 hr/7 days). Therefore, large-scale boilers burn a massive amount of fossil fuels to offer high hot water. Hence, renewable energy consideration is substantially vital and recommended to mitigate environmental pollution and reduce the considerable cost of fuel budget [36]. However, using simple systems depending on short-term hot water provisions, like flat plate collectors and ETSCs, may only be feasible if multiple systems are employed [37,38]. Thus, integrating aluminum oxide into these collectors, mainly ETSCs is feasible as Al2O3 oxides and nanoparticles provide long-term storage of thermal energy and significant enhancements in the thermal efficiency of ETSCs, helping store more hot water. In this context, this research is carried out trying to bridge all these research gaps and overcome all these problems by offering an effective and energy-efficient ETSC that employs Al2O3 material to provide more quantity of hot water for residential and large-scale uses, Achieve energy security for citizens and the whole country, Mitigate the dependence on expensive electrical power even in winter, Discard the use of diesel generators or electric geysers to provide hot water in winter, Provide longer-term storage of hot water with minimal thermal losses, Depend on a free, clean, and renewable source of energy (sun) to cover the permanent demand for hot water even in case of blackouts.

This work investigates and examines the critical benefits and significant contributions of integrating nanoparticles into the ETSC system to enhance thermal efficiency, thermal performance, temperature out, and energy storage of the ETSC. The Simcenter STAR-CCM+ 2022.1 software package implemented numerical analysis and thermal simulations. The inlet temperature, the outlet temperature, the temperature difference, the number of elements of the overall solar collector modeled and simulated, the heat flux across the tubes, the heat transfer across the outlet water pipe, the thermal energy flux across the hot water tank, and the thermal efficiency of the overall ETSC were analyzed. Furthermore, a comparative analysis is conducted on two case studies to validate the critical role and contributions of employing the aluminum oxide nanomaterial in the solar collector system to enhance its thermal efficiency and improve its thermal performance and heat transfer, including (1) conventional ETSC and (2) ETSC with Al2O3.

2. Materials And Methods

This research depends on numerical modeling and simulation of thermal characteristics and temperature properties associated with the ETSC. The numerical 2D and 3D modeling, thermal analysis, and simulations are carried out using the Simcenter STAR-CCM+ 2022.1 software package. In addition, in this work, a comparative analysis between two case studies is taken into account, including:

i. The First Case Study. This case comprises a conventional ETSC that has no additions or nanomaterials integrated into the solar collector.
ii. The Second Case Study contains nanoparticles (Aluminum Oxide [Al_2O_3]).

This study's location is Baghdad, Iraq, where people suffer from the extensive use of highly inefficient and expensive diesel generators. The boundary conditions identified in the newly globally issued simulation software contain some data that can be represented in Table 1. Figure 2 illustrates the monthly solar irradiation profile of Baghdad.

Table 1
Some boundary conditions considered in the case study are defined in the software

No.	Major boundary conditions considered in the new simulation software package	Values and units
1	Baghdad Latitude	33.3152° N
2	Baghdad Longitude	44.3661° E
3	Annual Maximum Average Temperature	44.4 ºC
4	Annual Minimum Average Temperature	27.7 ºC
5	Average Precipitation	15.72 millimeters
6	Annual Maximum Average Solar Energy	8.3 kWh
7	Annual Minimum Average Solar Energy	2.8 kWh

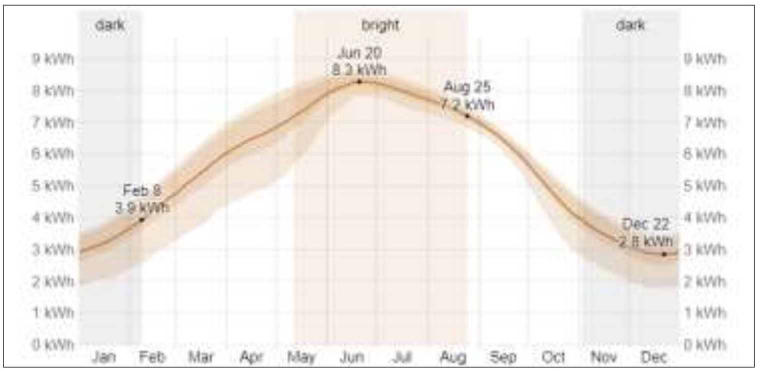


Fig. 2. The monthly solar irradiation profile of Baghdad

The aim of the analysis related to the two case studies is to explore and assess the critical contributions and significant benefits of integrating nanoparticles into the solar collector and their impact on improving thermal energy storage and enhancing the thermal performance and the outlet temperature value of the ETSC. Some parameters and indices will be considered to conduct the numerical analysis and thermal simulations using the Simcenter STAR-CCM+ 2022.1 software package. These critical factors and parameters include (1) the inlet temperature, (2) the outlet temperature, (3) the temperature difference, (4) the number of elements of the overall solar collector modeled in the software package, (5) the heat flux across the tubes, (6) the heat transfer across the outlet water pipe, (7) the thermal energy flux across the hot water tank, and (8) the thermal efficiency of the overall ETSC. These parameters can determine to what degree the integration and employment of nanoparticles in the solar collector will contribute to some enhancements and improvements in the thermal efficiency, the overall outlet temperature of the hot water, and heat transfer. Furthermore, the simulation work of this study will calculate the value of the water flow velocity inside the solar collectors and the tubes in which water receives considerable thermal energy from solar radiation.

3. Results

This section represents the simulation findings and numerical analysis outputs of the two case studies investigated in this work. The following sections illustrate more details on these results.

3.1. 2D Temperature Profile across the ETSC

Figure 3.(a) represents the temperature profile of the solar collector before the aluminum oxide nanomaterial was integrated into the solar collector. At the same time, Figure 3.(b) illustrates the

temperature profile of the ETSC after the aluminum oxide nanomaterial was integrated into the system. It can be inferred from Figsure 3.(a and b) that using nanoparticles in the ETSC contributed to a significant increase in the temperature values inside the pipes and hot water tank. The hot water temperature rose from (42-72 ºC) to (51-86 ºC). This increase, in turn, can result in considerable enhancements in the thermal performance of the ETSC to produce more hot water with higher temperatures when the aluminum oxide nanoparticles are utilized in the system. Furthermore, the thermal analysis and numerical simulation results provided the 2D temperature profile of the cross-section related to the ETSC hot water tank. Figure 3 describes the temperature profile of this cross-section before the aluminum oxide nanoparticles are used.

In addition, Figure 3.(d) illustrates the same cross-section associated with the second case study, representing an ETSC when the aluminum oxide nanoparticles are integrated into the system. It can be concluded from Figure 3 utilizing nanoparticles in the ETSC system contributed to a remarkable increase in temperature values, as shown in the cross-section of the hot water tank. It can be noted that the hot water temperature rose from the range of (50.8-76.5 ºC) to (59.3-87 ºC). This rise, in turn, has resulted in substantial enhancements in the thermal performance of the ETSC to produce hot water with higher temperature values to serve the residents in winter when nanomaterials are integrated into the solar collector [39,40].

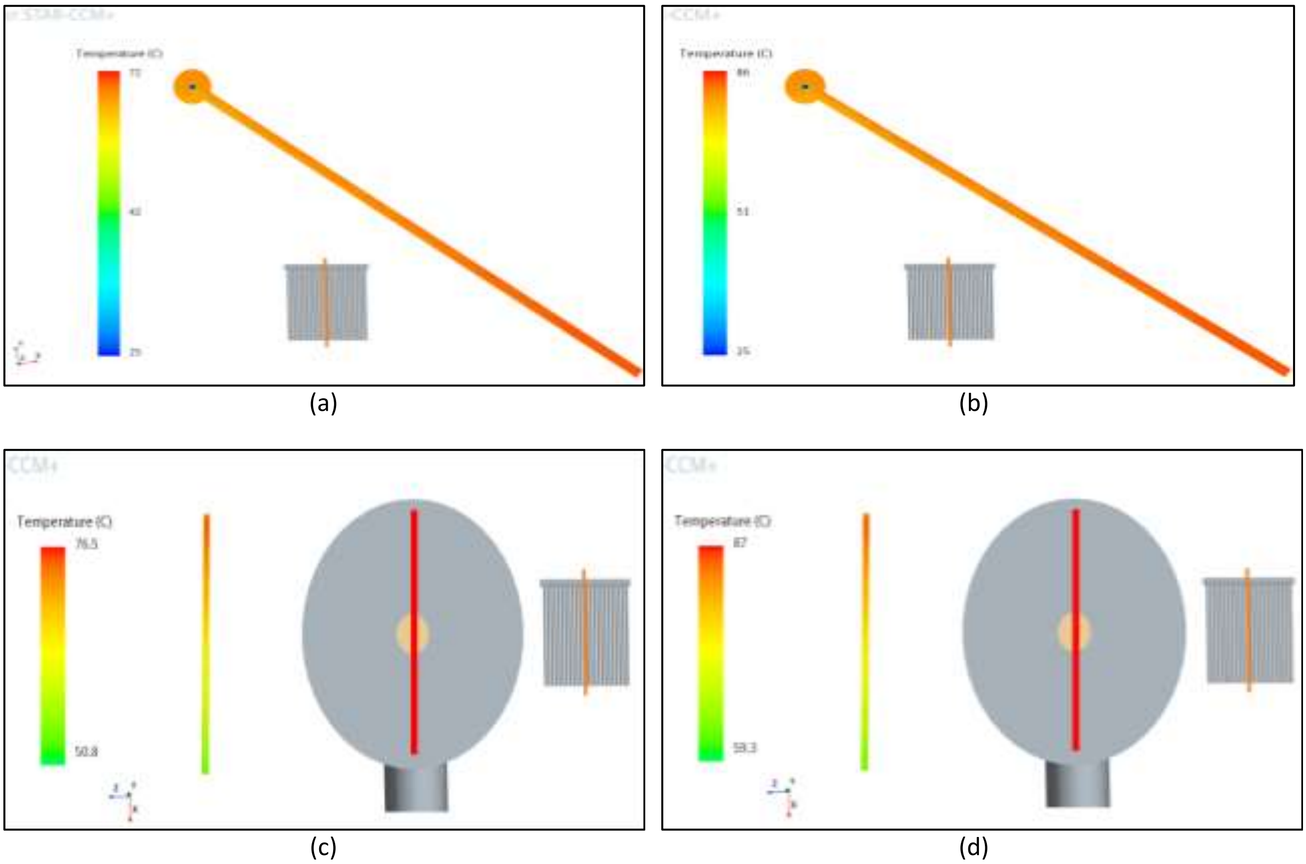
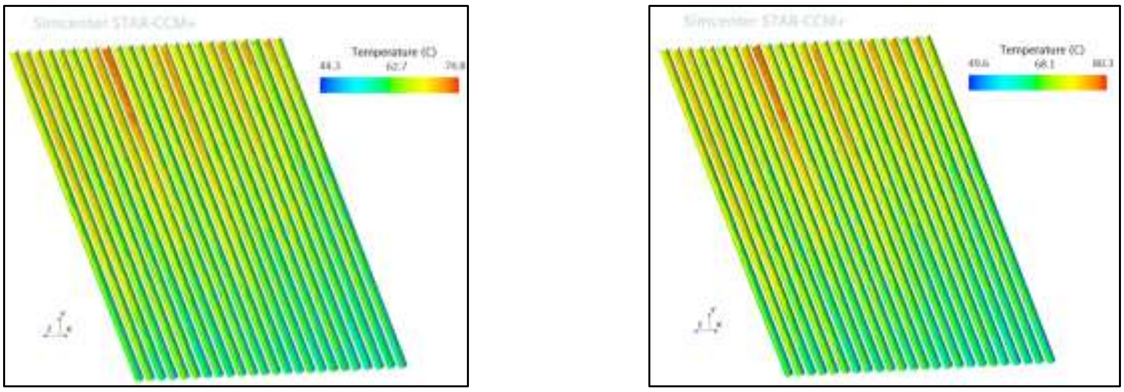


Fig. 3. (a) The temperature profile of the ETSC without employing aluminum oxide nanoparticles (b) after using aluminum oxide nanoparticles (c) before the aluminum oxide nanoparticles are use (d) after the aluminum oxide nanoparticles are used

3.2. 3D Temperature Profile across the ETSC

Figure 4.(a) represents the 3D temperature profile of the solar collector pipes before the aluminum oxide nanomaterial was integrated into the system. Also, Figure 4.(b) represents the 3D

model of the second case study in which nanomaterials of Al2O3 are integrated into the solar collector. It can be indicated from Figure 4 (a and b) that the cold water absorbs solar radiation, elevating its temperature and reducing its density. Thus, hot water can flow to the top of the solar collector as its weight and density decline over time through continuous heating.



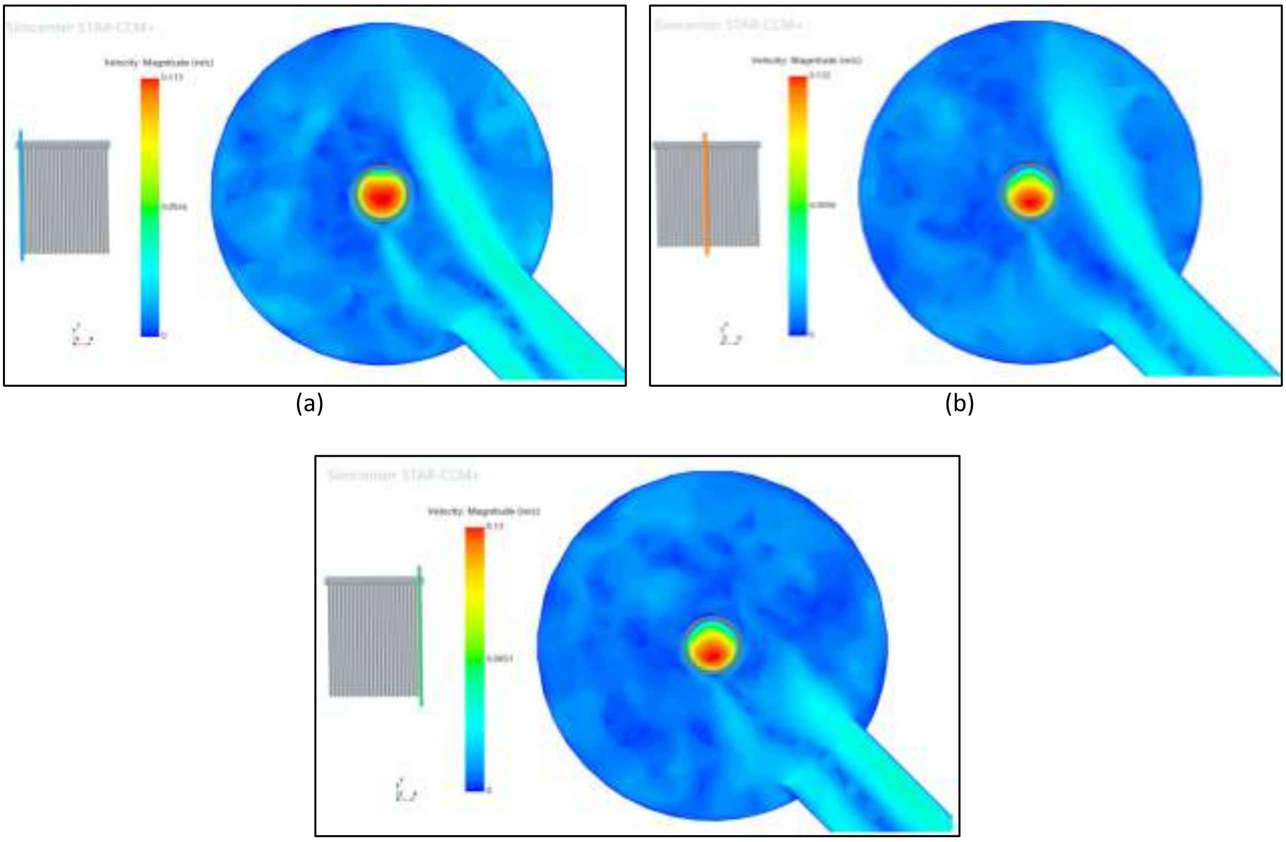
(a) (b)

Fig. 4. (a) 3D temperature configuration of the ETSC pipes before the aluminum oxide nanomaterial was integrated into the system (b) A 3D temperature configuration of the ETSC pipes after the aluminum oxide nanomaterial was integrated into the system

Also, it is concluded that employing nanomaterials in the ETSC system helped achieve a significant elevation in the temperature values of the solar collector, which is shown in the 3D profile of the solar collector pipes in both cases. From these two 3D configurations, it can be observed that the hot water temperature increased from (between 44.3 and 74.8 ºC) to (between 49.6-80.3 ºC). This increase, in turn, has contributed to substantial improvements in the thermal performance of the ETSC, which generates hot water with higher temperature values and serves the residents in winter when nanomaterials are employed in the solar collector.

3.3. 2D Velocity Profile across the ETSC

Figure 5.(a) represents the 2D velocity configuration of the solar collector pipes before the aluminum oxide nanomaterial was integrated into the system for a cross-section taken from the left of the solar collector. The same 2D velocity profile is depicted for a cross-section taken at the middle of the collector, as shown in Figure 5.(b). Another cross-section is taken at the right side of the solar collector to predict the 2D velocity profile, as shown in Figure 5.(c).

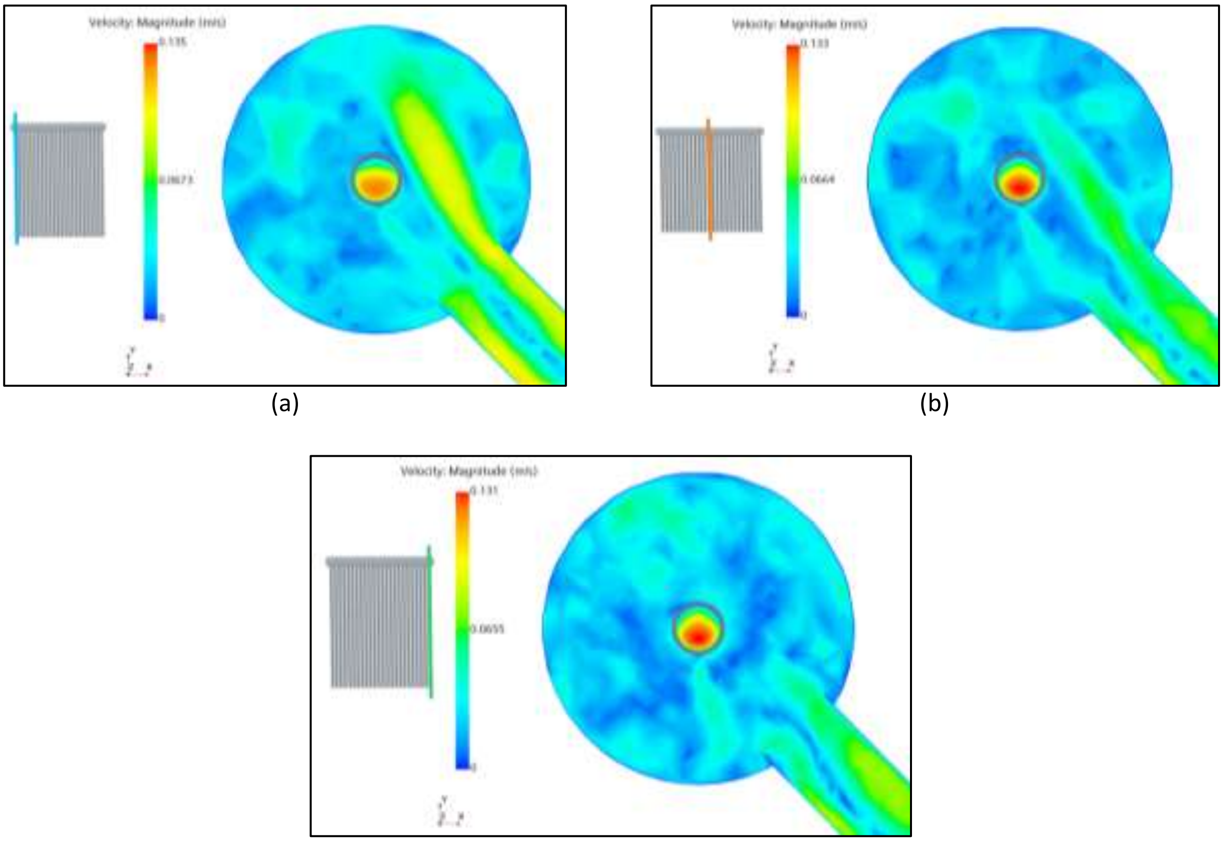


(a) (b) (c)

Fig. 5. (a) A 2D velocity profile of the ETSC pipes before the aluminum oxide nanomaterial was integrated into the system (left cross-section) (b) (middle cross-section) (c) (right cross-section)

It can be observed from Figure 6. (a, b, and c) that the velocity of the hot water inside the glass pipes in the three cross-sections ranges from around 0.01 to 0.07 m/s. At the same time, the velocity of the domestic water used by residents (in a separate pipe inside the central region of the hot water tank) is larger than the speed of the hot water inside the glass pipes. The higher velocity is due to the significant temperature difference between the inlet water (25 ºC) and the outlet temperature, which may reach around 73 ºC when no nanoparticles are used. On the other hand, the same velocity profile related to the ETSC is described in Figure 6. (a, b, and c) for the second case study in which the aluminum oxide nanomaterial was used in the solar collector.

Figure 6 (a, b, and c) show that the water flow speed increased after the aluminum oxide nanomaterial was added to the solar collector. This fact explains that integrating the aluminum oxide nanomaterial into the system contributed to a significant kinetic energy increase, which resulted from more thermal energy stored in hot water.

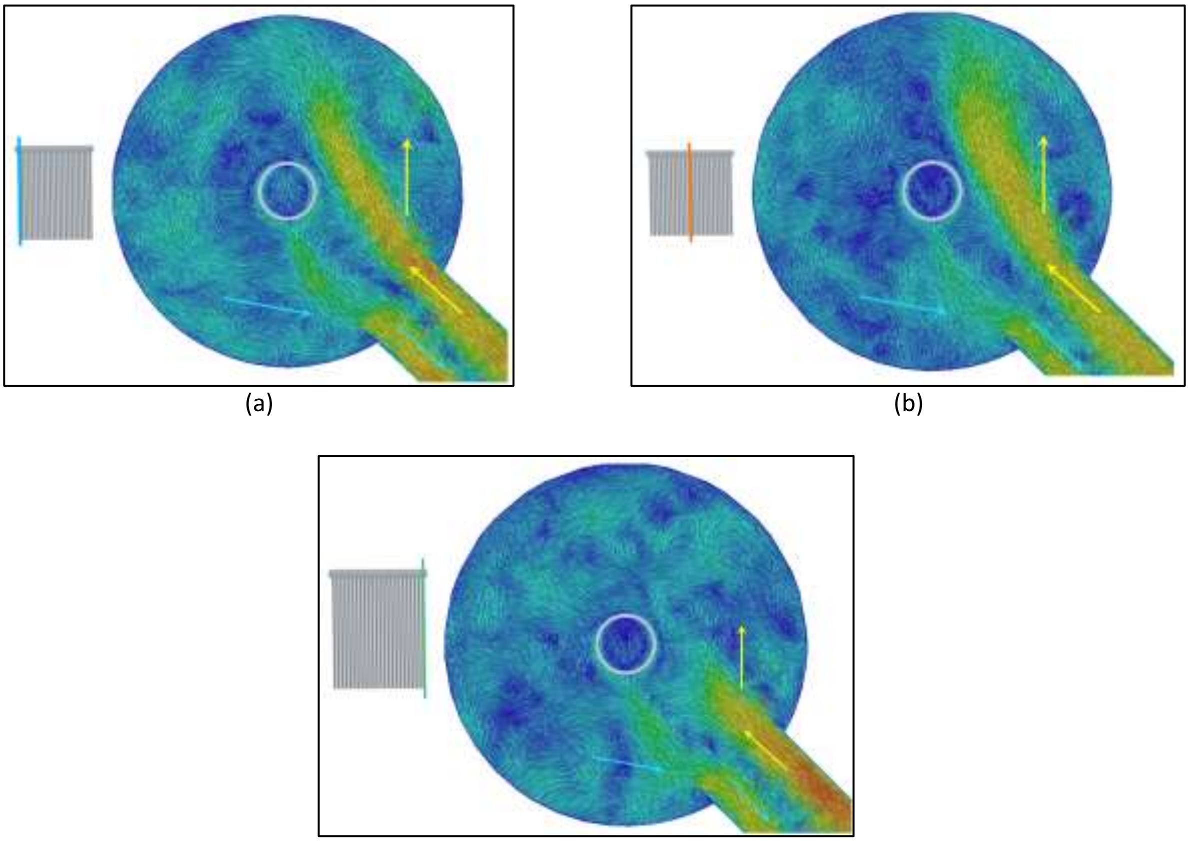


(a) (b)

(c)

Fig. 6. (a) A 2D velocity profile of the ETSC pipes after the aluminum oxide nanomaterial was integrated into the system (left cross-section) (b) (middle cross-section) (c) (right cross-section)

Also, the results indicated the velocity directions representing the orientation of hot water flow inside the ETSC. Figure 7.(a) illustrates the velocity directions of the hot water before adding the aluminum oxide nanomaterial into the system for a left cross-section. Figure 7.(b) describes the velocity directions of the hot water before adding the aluminum oxide nanomaterial into the system for a middle cross-section. Figure 7.(c) describes the velocity directions of the hot water before adding the aluminum oxide nanomaterial into the system for a right cross-section. Also, the results indicated the 2D velocity directions of the solar collector for the second case study in which aluminum oxide nanoparticles are used in the solar system.



(a) (b) (c)

Fig. 7. (a) A 2D configuration of the water flow's velocity direction inside the ETSC pipes before the aluminum oxide nanomaterial was added into the system (left cross-section). (b) (middle cross-section). (c) (right cross-section)

It can be inferred from Figure 7.(a, b, and c) that the velocity directions are more homogeneous, laminar, and sober in the first case study before adding the aluminum oxide nanomaterial into the ETSC. Nevertheless, after adding the nanoparticles of Al_2O_3 into the collector, it was observed that the velocity directions inside the ETSC became slightly more turbulent and variant. This fact is related to the increase in the kinetic energy of the water molecules due to more heat gain from solar energy, as the nanoparticles enabled the absorption and storage of more thermal energy than in the first case.

3.3. Comparison of Heat Flux and Thermal Efficiency

The comparative analysis of this work is conducted on the two case studies to validate the critical role and contributions of employing the aluminum oxide nanomaterial in the solar collector system to enhance its thermal efficiency and improve its thermal performance and heat transfer. Table 2 describes the results of the comparative analysis of this research.

Table 2
The results of the comparative analysis of the two solar collector case studies

Category/ Parameter	Symbol	Conventional	Al_2O_3 Nanomaterial
Inlet temperature	T_{in}	25.0 ºC	25.0 ºC
Outlet temperature	T_{out}	76.53 ºC	84.97 ºC
Temperature gradient	ΔT	51.53 ºC	59.97 ºC
Number of elements simulated	--	4,142,728	4,142,728
Heat flux of solar collector's pipes	$\dot{Q}_{Pipe}$	2,000 W/m^2	2,000 W/m^2
Heat transfer for the tube inside the hot water storage tank	$\dot{Q}_{Tube}$	5,438.5 W	6,346.2 W
Heat transfer in hot water storage tank	$\dot{Q}_{Tank}$	1,1811.9 W	13,677.9 W
Thermal efficiency of hot water generated	η_{Therm}	58.79%	60.99%

It can be indicated from Table 2 that there are significant increases in the values of (1) outlet temperature, (2) heat flux of the tube inside the hot water storage tank, (3) heat transfer inside the hot water storage tank, and (4) thermal efficiency. These results show that considerable benefits and contributions can be attained by employing the aluminum oxide nanomaterial in the solar collector system. Therefore, integrating the aluminum oxide nanomaterial into the solar collector can accomplish better thermal performance, higher temperature outlet value, and larger thermal energy stored in the hot water storage tank.

4. Discussion

This research indicated that using and adding the aluminum oxide nanomaterial into the ETSC system had contributed to several beneficial impacts and significant advantages. These advantages include enhancements in the thermal efficiency, increases in the outlet collector's temperature, improvements in the rate of heat flux of the pipes, the tube inside the collector, heat transfer of the hot water storage tank, and a rise in the temperature gradient. Also, the results of this work revealed that the velocity of the water flow inside the solar collector in the second case in which the aluminum oxide nanoparticles are used was higher due to the absorption of further solar radiation and thermal energy, which resulted in a considerable increase in the kinetic energy of water molecules. The results of this work are consistent with the results of [20]–[22], who carried out research investigating the effects and advantages of integrating nanoparticles into the solar collector system and found that using nanofluids in the ETSC can contribute to remarkable improvements and enhancements in the thermal efficiency and performance of the overall solar collector.

5. Conclusions

According to the numerical analysis and comparative study findings, the results of this research can be classified into the following points:

i. Employing and adding the aluminum oxide nanomaterial into the ETSC system contributed to several benefits and significant advantages.
ii. Using Al_2O_3 enhanced thermal efficiency, increased the temperature of the outlet collector, improved the rate of heat flux of the pipes, the tube inside the collector, heat transfer of the hot water storage tank, and raised the temperature gradient.
iii. The velocity of the water flow inside the solar collector in the second case in which the aluminum oxide nanoparticles are used was higher due to the absorption of further solar

radiation and thermal energy, which resulted in a considerable increase in the kinetic energy of water molecules.

iv. The velocity directions and profile were slightly more turbulent in the second case than the conventional solar collector due to more thermal energy absorbed and stored in the ETSC from solar radiation.

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