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Upgrading Solar Thermal Performance with Engine Oil in Evacuated-Tube Collectors for Sustainable Energy Solutions

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ABSTRACT

The high-demand for solar power systems has stimulated research efforts to find better heat transfer fluids for evacuated tube solar collectors (ETSCs). This research aims to appraise the thermal characteristics of an ETSC, which utilises engine oil as a heat transfer vehicle within a new efficient system beyond conventional flat-plate collectors. Temperature elevation under solar radiation becomes rapid because the evacuated tube contains engine oil with Grade 20-w50, which possesses a high-boiling point of >350 °C and heat transfer properties including 2.5 kJ/kg K heat capacity and 88 kg/m³ density. Experiments are conducted for different ranges of solar radiation intensity with different ranges of engine oil temperatures. According to the results, this system reacts swiftly to solar radiation changes and reaches a maximum temperature of 198 °C at a solar radiation of 800 w/m^2, which makes water evaporation and superheating possible. More importantly, in comparison to traditional flat-plate collectors, this collector demonstrates a high conversion efficiency and quick response to the influencing parameters. The introduced approach not only enhances energy efficiency but also brings into line with the United Nations Sustainable Development Goal (SDG 7) to deliver reasonable and clean energy solutions to conflict climate change and improve sustainable industrialization.

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1. Introduction

The hourly occurrence solar flux on the earth is more than the yearly global energy consumption, making solar radiation a gifted source of renewable energy [1]. Solar energy is a sustainable, consistent, and multipurpose renewable resource known for its wide-ranging reach and assorted applications. It is considered one of the most gifted renewable energy sources capable of conveying steady, high-intensity energy output [2]. The most effective methods of capturing and harvesting solar energy and associated implications are introduced in solar-powered water evaporation and steam generation. Undeniably, solar-powered evaporation, a central piece of the natural water cycle, has progressively arisen as an imperative technique for harnessing solar energy [3]. Ever since prehistoric times, humanity have employed solar-powered evaporation to obtain fresh water since it is a fundamental mass and heat transfer process with widespread uses. This might mitigate the fight between population growing and water scarcity as it becomes one of the most challenging problems of the 21st century. Apart from enhancing the efficacy of current freshwater resources, the combination of saltwater desalination, wastewater treatment, and electricity generation are also thought to be important strategies for addressing the present scarcity of both water and energy [4]. Also, it should be noted that there are other systems were also commercialized based on solar energy such as large-scale power generation, absorption chillers, and desalination technologies, as well as more compact applications of drinking water purification, sterilization, and hygiene systems [5], [6]. Solar energy can be obtained for free, but there are specific difficulties of its efficient collection and storage. Since solar radiation may only be obtained during the day, the energy subsequently needs to be kept after being efficiently gathered to utilise the majority of the daylight hours. Components that now exist to collect solar radiation, convert it to thermal energy, and then transport that energy to a working fluid are called solar thermal collectors [7], [8]. Therefore, solar collectors are the primary and utmost important parts of any solar unit. In this regard, commercial solar-driven evaporation system typically employs a solar absorber to collect solar energy, which is subsequently transformed into thermal energy, which is used to heat a mass of water to produce steam. However, the absorber reaches high temperatures and is vulnerable to radiation and convection heat losses [9].

Solar collectors can be broadly divided into two categories: tracking and stationary. A broad temperature range can be achieved with the use of several collector configurations. For example, an ETSC functions at a an operational temperature between 50 to 200 °C [10]. This is due to their larger insulation and vacuum-sealed tubes, making them more effectual for medium to high-temperature implications such as process heat and solar-assisted cooling. Specifically, the vacuum in the annular space between two concentric glass tubes would prevent sunlight from passing through its tubular design, which is the most effect of this design. The second type of solar collectors is the flat plate collector (FPC) typically operates within a lower range of operational temperature of 20–80 °C. This is ascribed to its greater heat losses and lower thermal efficiency at elevated temperatures IF compared to ETSC. Thus, the FPC can efficiently suit a specific type of applications such as space heating, domestic water heating, and low-temperature industrial technologies [11]. Traditional FPCs are primarily made for sunny, warm climates; however, the efficiecny declines on windy, cold, and cloudy days. This is because moisture and condensation source prompt deterioration of internal materials, that could lead to system letdown. On the other hand, ETSCs have exceptional thermal performance, are easy to transport, and install, with a less cost, making them suitable for unfavorable climates [4].

Al-Tabbakh and Mohammed [12] examined five ETSCs filled with regular engine oil and an evacuated-tube (all-glass) solar collector. The tubes were integrated with another stainless steel pipe to transport the working fluid (water). Five bends were made in the steel pipe (through-flow pipe) to create five U-shaped turns. One evacuated tube was submerged in each U-turn. Between the inner surface of the tube and the outer surface of the stainless steel pipe, oil serveed as a heat transfer medium. A range of water mass flow rate values and meteorological conditions (irradiance, ambient temperature) were tested in these experiments. In comparison to traditional flat-plate collectors, the results ascertained a higher efficacy of the tube solar collector and quick response to the influencing parameters (temperature changes of inlet water, clouding, and oil replacement). However, there were some variations in the exit water flow rate in the ETSC due to the small diameter of the stainless steel pipe and its large length of 14 meters. Indeed, the narrow diameter limited water flow inside the pipe, which increases resistance and therefore causes a reduced flow rate, particularly under variable thermal conditions. Also, the use of long length aided to introduce notable friction losses, which diminishs flow consistency. Thus, these reasons can attribute the retard of heat transfer, which then affect the overall system efficacy.

Zhang et al. [13] introduced a comprehensive review of the most recent advancements made to the direct solar steam generation (DSSG) system to produce clean water. The researchers focused on detailing the different categories of DSSG, the solar thermal conversion principle, the mechanism of water evaporation, the efficiency computation, and the possible the strategies to assure a high performance water evaporation. These strategies included regulating the amount of absorbed light by sunlight to maximise the light utilisation, optimising the DSSC system to reduce heat loss, adjusting the water transport system to ensure a sufficient supply of water, and so forth. Benefiting from the fundamental knowledge and practical methods of the DSSG system, the generated clean water's quality, the removal of pollutants from the remaining water body, and the different solar still designs for maximum clean water productivity were presented in more details.

Two different solar collectors were evaluated for their thermal performance by Alaskaree et al. [14]. A black absorbent solar collector coats the first collector, while chromium trioxide covered the second. With a chromium trioxide coating, the absorbed energy was increased from 908.28J to 1221.5J at the lowest solar irradiation period, and the thermal efficiency was also increased from 37.3% to 50.1%. In addition, the thermal efficiency was improved from 63.9% to 78.9% and the absorbed energy was enhanced from 1340.5 J to 1528.4 J at the highest solar irradiance period. Following three months of exposure to outside conditions, the collectors coated with chromium trioxide outperformed the collectors coated with dark black in terms of thermal performance. The results demonstrated that when the sun irradiation reaches its maximum value, the absorbed energy increases from 501.1J to 1440.7J and thermal efficiency from 20% to 62.2%.

A model for Heating, Ventilation, and Air Conditioning (HVAC) systems was suggested by Ismail et al. [15]. To mathematically detect the optimal thermal comfort of the suggested model according to occupant satisfaction as measured by ASHRAE Standard, the ANSYS Fluent tool was used. A room light, a personal computer, and the occupant were the three heat-generating characteristics that were considered. While there are advantages to the Overhead Air Distribution (OHAD) unit, the obtained Computational Fluid Dynamics (CFD) findings demonstrated that the Underfloor Air Distribution (UFAD) unit may outperform it. The OHAD system was determined to be inefficient in providing thermal comfort to the occupant and consumed more energy than the UFAD system due to the need to cool the entire room instead of just a portion of it. In contrast, the UFAD system offered the best thermal performance. The CFD findings validated that, in comparison to the OHAD system's 1.2 m height, the UFAD system kept the room temperature at 26 °C while being located below 2 m.

The engine oil based thermal energy storage developed by Mehla and Kumar [16] incorporated novel evacuated tube solar air collector (NETAC). The NETAC test was tested in winter seasons to produce hot air in presence of 13 h on different air flow rates and various air flow direction (counter air flow and parallel air flow). 159 kg/h of air flowrate at circular fin and counter flow arrangement with 28.8% of an efficacy of NETAC and 79.5 kg/h of air flowrate were obtained the maximal temperature difference of 24.8 °C of air. In this regard, maximum energy efficiency of 27.15% and exergy efficiency 24.8% of the oil thermal storage tank were attained at high air flowrate of 159 kg/h when it was in a circular fin and parallel flow set up.

According to Jamshed et al. (2021) [17], the flow of Casson nanofluid was applied in Parabolic Trough Solar Collector (PTSC) on an infinite and porous sheet. Specifically, the heat transfer rate was lowered with the assistance of induced magnetic factor and the parameter of skin resistance rose significantly. When applied as base fluid, Cu/Fe_3O_4-EO was vital on the rate of heat transfer. The lowest and extreme percentages of total enhancement in the thermal efficiency of Cu-EO on Fe_3O_4-EO were 2.7 and 18.5, respectively.

Dev et al. [18] assessed the availability of utilising waste car engine oil (WCEO) instead of Servotherm medium (STM) as medium of storage of energy to sustain the fixed amount of heat output. The researchers used three ETCs with a U-pipe heat exchanger in the centre of ETC. WCEO was placed in one of the ETCs in the available space within the tube in the form of ESM to contrast the presentation with the ETC filled with STM as energy storage medium and with the ETC that does not have any energy storage medium. All the three ETCs were fed with fixed 1.47 kg/h of supplied air.

In contrast to the aforementioned studies, the current research introduces a groundbreaking heat transfer methodology that uses engine oil with Grade 20-w50 for high-temperature applications, leveraging its robust thermal characteristics of a boiling point beyond 350 °C. This feature would enable both rapid heat elevation and efficient water boiling process. Undoubtedly, research into engine oil effectiveness in these systems remains essential due to a limited examination of solar thermal evacuated-tube collector in a comparison to traditional flat-plate collectors. Thus, this research would full a critical gap in the open literature and deliver appreciated visions into alternative thermal management sustainable solutions. Indeed, the outcomes of this research would pave the way towards the development of an effective thermal energy storage solar system based on evacuated-tube collector. Recent advancements in solar thermal energy research have placed significant emphasis on enhancing the performance of evacuated tube solar collectors (ETSCs) through both fluid-based and structural improvement strategies. Thanikodi et al. [29] (2025) demonstrated that utilizing nanofluids and advanced heat-transfer fluids can substantially increase the thermal efficiency of ETSC systems due to their superior thermophysical properties. Similarly, Rahman et al. [30] (2025) performed an energy and exergy evaluation using Al_2O_3/water nanofluid and reported remarkable improvements in heat-transfer behavior and overall system effectiveness. These studies highlight the recent global trend toward adopting enhanced working fluids to boost solar collector performance, providing a comparative context for the present work.

From a structural enhancement perspective, Agade et al. [31] (2025) investigated the use of perforated wavy tube inserts and demonstrated their potential to increase turbulence and improve absorber–fluid interaction within the collector, thereby enhancing thermal performance. More recent studies published in 2026 have further advanced the understanding of ETSC behavior. For example, ferric-based hybrid nanofluids were shown to significantly elevate heat-transfer capability in U-tube ETSC configurations [32], emphasizing the critical role of optimized internal flow patterns. A comprehensive review published in 2026 [33] also outlined emerging design trends, materials, and operational strategies for ETSC technologies. Engine oil has recently gained notable attention as an alternative heat-transfer fluid (HTF) for solar thermal applications, owing to its high boiling point, chemical stability, and favorable thermophysical behavior at elevated temperatures. Chinnasamy et al. [34] (2025) addressed the drawbacks of conventional HTFs used in high-temperature solar thermal technologies, that are indispensable for different industrial applications such as process heat, desalination, and energy production. The assigned limitations are low thermal stability, corrosion concerns, and high viscosity at high-temperatures. Bouarfa et al. [35] (2025) assessed sunflower, safflower, and rapeseed oils as alternative HTFs for medium-temperature parabolic trough collector (PTC). The researchers compared, their performance against synthetic fluids such as Therminol VP-1 and Delcoterm E15. The results showed that vegetable oils can attain somewhat greater thermal efficiency (64–65%) if compared to synthetic fluids (62–63.5%) due to greater thermal features. Furthermore, Barbosa et al. [36] (2025) conducted a experimental and computational investigation of a hybrid photovoltaic-thermal (PVT) system combined to a heat pump for engine heating in thermal power plants. Accordingly, the researchers assessed the thermal performance and efficiency of the PVT system under actual operating conditions. The results showed that the PVT system can attain high thermal efficacy, with an extreme outlet water temperature of 328.15 K in experimental tests and 315 K in simulations. The greatest thermal efficiency was 73% at noon.

Collectively, these recent contributions underscore the importance of both fluid innovation and structural enhancement in determining ETSC performance. The present study aligns with these modern developments by experimentally examining the thermal behavior of an evacuated tube solar collector using engine oil as a heat-transfer medium, thereby contributing new evidence to the rapidly evolving body of research on high-efficiency solar thermal technologies.

2. Materials and Methods

2.1 Experimental rig and test procedure

The high-production of steam using ETSCs requires an efficient heat transfer between the tube cavity and the through-flow pipe. One possible option to accomplish this target is by using engine oil to full the evacuated tube of a higher boiling point if compared to water. One evacuated glass made up the experimental rig. Figure 1 depicts a schematic diagram of the evacuated tube filled with an engine oil. The through-flow copper pipe is submerged in a single evacuated tube after being bent in a U-shape. Between the inner surface of the tube and the outer surface of the copper pipe, oil serves as a medium for heat transfer. The schematic diagram of Figure 1 illustrates how solar radiation penetrates the tube, heating the oil, which then transfers thermal energy to the copper pipe, enabling water evaporation. The vacuum layer minimises convective losses, enhancing efficiency. This design underscores the innovation of using engine oil as a high-temperature heat transfer medium, as validated by our experimental results. The characteristics of evacuated tube are provided in Table 1 [21]. The evacuated tube was filled with a roughly 2.5 liters of engine oil with Grade 20-w50. As solar radiation enters the evacuated tube through the two walls, the engine oil absorbs it and rapidly increasing its temperature. In other words, the double-glazed tube completely converts the entered solar radiation into a rise in engine oil temperature. During the first 15 minutes of the operation, it was noticed that the oil temperature rises quickly (ΔT = 40 °C) before the water in the cupper pipe begins to circulate by tank pressure. Given the small amount of oil (about 2.5 L per tube) and nearly nonexistent convection losses, the rapid rise in temperature is to be expected. More importantly, the tests were conducted for four to five hours at solar noon. The information was gathered every fifteen minutes. In this aspect, the experiments were focused on recording the engine oil temperature at each interval, and existed intensity of solar radiation. Specifically, the heat transfer medium filling the tube cavity is an engine oil with a boiling temperature greater than 350 °C (Table 2). The comparison of physical properties of engine oil and water are given in Table 2.

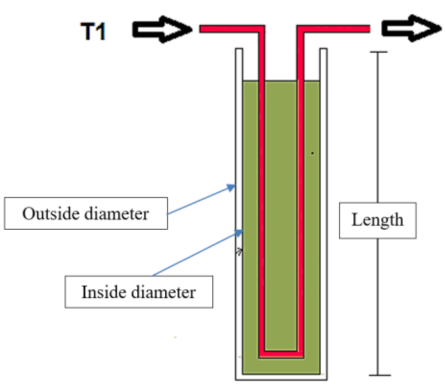

Figure 1. A schematic diagram of the evacuated tube filled with an engine oil

Table 1. Characteristics of the evacuated tube

Part	Dimension (m)
Inside diameter	4.5
Outside diameter	5.7
Total length	1.8

Table 2. Physical characteristics of engine oil compared to water working fluids [19]

Working fluid	Heat of capacity (Cp)	Density (ρ)	Boiling point (°C)
Engine oil	2.5 kJ/kg k	88 kg/m^3	>350
Water	4.2 kJ/kg k	1000 kg/m^3	100

2.2 Mathematical modelling

Thermal energy is stored in sensible heat storage (SHS), which involves elevating a liquid's or solid's temperature. The SHS system used the heat capacity of the material and temperature changes throughout the charging and discharging process. The specific heat of the medium, temperature variations, and the quantity of storage material all affect the amount of stored heat. The following demonstrates the associated equations [20];

$$m = \rho\ V \quad (1)$$

m, *V* are the mass and volume, respectively. The useful thermal energy (*Qu*) and the inlet thermal energy (*Qin*) are calculated using Eqs. 2 and 3, respectively [20],

$$Qu = m\ Cp\ \Delta T \quad (2)$$

$$Qin = I\ A \quad (3)$$

ΔT refers to the temperature difference between input and output temperatures. Also, *I* and *A* are the intensity of solar radiation (measured in w/m^2), and tube area, respectively. Based on the intensity of solar radiation and the dimensions of evacuated tube, the exit engine oil temperature can be calculated by equating Eqs. 2 and 3.

2.3 Assumptions and Model Considerations

In the present study, several assumptions were adopted to simplify the thermal analysis of the evacuated tube solar collector. The system was assumed to operate under steady-state conditions, following the approach commonly used in evacuated-tube modeling [20]. The working fluid was considered as a single-phase flow, and phase change or chemical reactions were neglected, similar to the assumptions reported in recent ETSC investigations [23]. The thermo-physical properties of the engine oil were treated as temperature-dependent, based on correlations reported in the literature [23]. Heat losses through the tube ends were considered negligible due to their small contribution compared to radial heat losses, consistent with previous ETSC evaluations [24], [26]. Solar irradiance was assumed uniform over the collector surface during each measurement interval, as recommended in experimental solar thermal studies [27]. The flow inside the U-tube was assumed fully developed and turbulent, and the Nusselt and Reynolds correlations were adopted according to standard practices in nanofluid and oil-based ETSC modeling [28].

The input data listed in Table 3 were selected based on standard dimensions and thermo-physical properties commonly used in evacuated-tube solar collector studies. The geometric dimensions of the tube are consistent with the standard 58×1800 mm all-glass evacuated tubes reported by Sabiha et al. [21]. The thermal properties of engine oil (density, specific heat, and thermal conductivity) were adopted from validated datasets and correlations reported in recent literature [25]. Solar irradiance and ambient temperature ranges were obtained from standard measurements and comparable ETSC experiments [26], [27]. These referenced input values ensure that the simulation and analysis are based on realistic and scientifically supported data.

Table 3. Input Data Used in the Thermal Model

Parameter	Value	Reference
Inside diameter of evacuated tube	4.5 cm	[21]
Outside diameter of evacuated tube	5.7 cm	[21]
Tube length	1.8 m	[21]
Thermal conductivity of engine oil	0.145 W/m K	[25]
Specific heat capacity of engine oil	2100 J/kg K	[25]
Density of engine oil	870 kg/m³	[25]
Solar irradiance (average)	800 W/m²	[27]
Ambient temperature	25–35 °C	[26]
Oil mass flow rate	0.026 kg/s	[20]
Optical efficiency factor	0.62	[23]
Heat loss coefficient	1.8 W/m² K	[24]

2.4 Case Study Description

The experimental work was conducted in Al-Jadiriyah district, Baghdad, Iraq (33.25°N, 44.38°E) during June 2023. This location was selected due to its high solar irradiance and long sunshine duration.

3. Results and Discussion

Several tests were performed at several days. Table 4 summarises the obtained results. To clearly demonstrate the behaviors of inlet engine oil temperatures against the operational time throughout four operational days, Figures 2 – 4 are established. Specifically, Figures 2 – 4 present the data analyses throw the operational hours of engine oil temperature and intensity of solar radiation for three operational days.

Table 4 Experimental results

No.	Date	Time	Inlet temperature of engine oil (*Ti*) °C	Intensity of solar radiation (I) (w/m^2)
1	11/6/2023	9:36 am	31	710
2		10:14 am	59	756
3		10:36 am	71	743
4		11:14 am	87	750
5		11:36 am	96	736
6		12:00 pm	105	700
7		12:35 pm	116	716
8		1:00 pm	124	738
9		1:30 pm	130	730
10		1:45 pm	133	710
1	12/6/2023	8:35 am	103	666
2		9:05 am	111	702
3		9:30 am	117	717
4		10:00 am	122	735
5		10:40 am	130	750
6		11:10 am	135	750
7		12:30 pm	139	745
8		1:00	140	740

		pm		
9		1:30 pm	143	730
10		1:45 pm	146	730
1	13/6/2023	8:30 am	107	703
2		9:50 am	128	740
3		1100 am	138	730
4		12:00 pm	140	750
5		12:30 pm	142	670
6		1:00 pm	144	780
7		1:30 pm	147	750
8	14/6/2023	1:30 am	198	650

Figure 2 presents the relationship between the measured oil temperature inside the evacuated tube and the corresponding solar radiation on 11 June 2023. A clear and direct correlation is observed, where the increase in solar radiation during the morning and midday hours leads to a proportional rise in oil temperature. This trend ascertains the expected thermal behavior of the collector, as higher irradiance enhances heat absorption and results in temperature elevation.

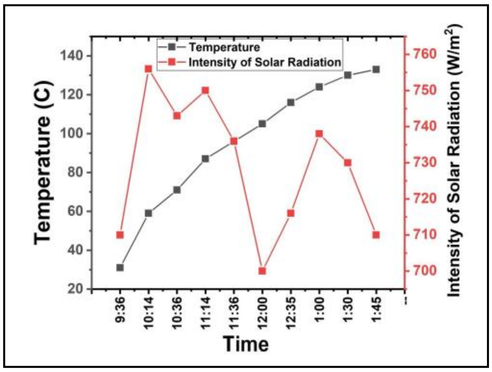

Figure 2. Engine oil temperature and intensity of solar radiation against operational hours of 11/6/2023

Figure 3 illustrates the same variables for 12 June 2023, with a similar pattern to that of Figure 2. The solar radiation gradually increases toward midday, and the oil temperature responds correspondingly. However, compared to the previous day, the temperature rise is more consistent due to relatively stable radiation levels. This demonstrates the collector's strong responsiveness to solar input under steadier atmospheric conditions.

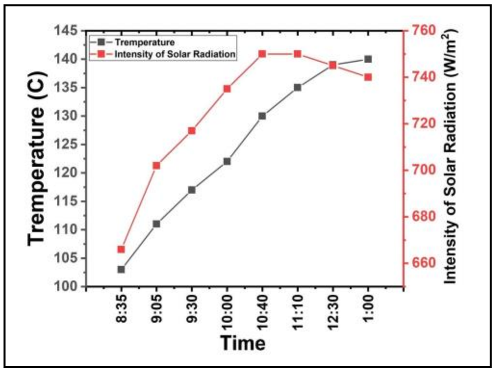

Figure 3. Engine oil temperature and intensity of solar radiation against operational hours of 12/6/2023

Figure 4 depicts the thermal behavior on 13 June 2023. In this case, solar radiation reaches its highest peak among the three days, exceeding 770 W/m². As a result, the oil temperature exhibits a more pronounced increase, achieving the highest measured values during the experiment. The sharp rise in temperature after 1:30 pm suggests improved energy absorption and reduced heat losses, which highlights the potential of the evacuated-tube system for high-temperature thermal applications.

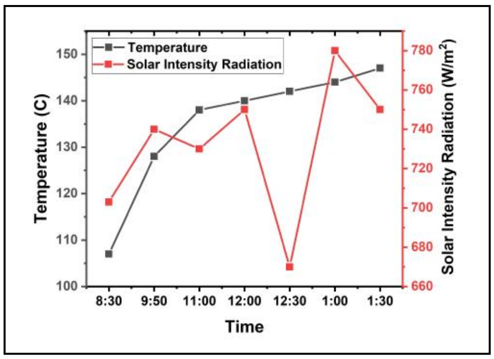

Figure 4. Engine oil temperature and intensity of solar radiation against operational hours of 13/6/2023

Figure 5 provides a clearer understanding of the system's thermal response over different operating days, Figure 5 compares the measured oil temperature for 11–13 June. All curves exhibit a steady rise in oil temperature during the morning hours as solar input increases. The highest temperature was recorded on 13 June, corresponding to the strongest solar radiation levels.

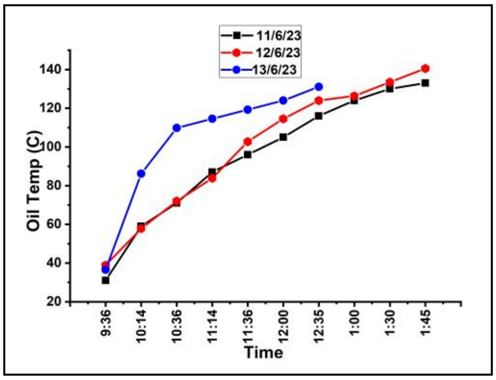

Figure 5. Comparison of Oil Temperature for 11–13 June 2023

To better interpret the temperature behavior shown in Figure 5, Figure 6 presents the corresponding solar radiation for the same days. The radiation follows an upward trend toward midday, with 13 June showing the highest irradiance, explaining the corresponding higher temperatures.

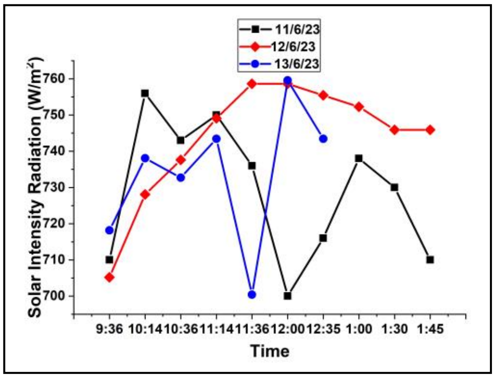

Figure 6. Comparison of Solar Radiation for 11–13 June 2023

Through theoretical calculations based the model developed in section 2.2, and experimental results of experiments conducted on the engine oil vacuum tube, it can be stated that the temperature of the engine oil has been increased to 198 °C (maximum temperature) in the fourth operational day. Indeed, this temperature is quite sufficient to heat and evaporate the water and turn it into a superheated temperature when it is passed through the copper tube inside the vacuum engine oil tube. However, the presence of thermal losses is the reason for the observed time difference to reach temperature (198 °C). Additionally, the practical rate of solar radiation varies between 300 to 700 w/m^2 during the experiments. Thus, it can be said that both thermal losses and time delays can affect the overall efficiency. On top of this, attaining the maximum engine oil temperature of 198 °C by the fourth operational day has been done in accordance to a clear fluctuation in solar radiation. It is believed that this fluctuation would contribute to thermal losses as some energy is dissolute rather than to be used for heating. Accordingly, the system was taken a considerable time to attain the peak temperature, signifying the request for enhanced system design with better insulation to mitigate the heat loss and enhance the overall performance.

Referring to the discussed results above, the associated increase of engine oil temperature with solar radiation intensity indicates an effective energy utilisation of the ETSC. Accordingly, this research has highlighted the significance of renewable energy sources like solar radiation in operating systems such as the evacuated tube solar collector. Indeed, an increase in the number of evacuated tubes can improve the overall system performance and make it suitable for higher loads. However, it should be expected that a considerable degradation issue in engine oil might be the consequence of repeated thermal cycling. Undoubtedly, the chemical features of oil would be changed throughout each heating and cooling cycle in addition to the oxidation and formation of sludge. Having high temperatures of 198 °C can quicken this degradation, which can lead to a diminished oil activity to preserve high-lubrication and protection levels. Furthermore, the evaporation of lighter fractions of the oil can be another consequence of thermal cycling, which would reduce the oil efficiency at increased wear on engine components. Accordingly, regular oil changes with careful oil selection are vital to lessen the impacts of thermal degradation and guarantee optimum engine performance.

4. Conclusions

This research focused on evaluating the competence of an ETSC that uses engine oil as a

heat transfer medium. The research analysed the collector's thermal performance and sensitivity to variable solar radiation intensity.
The obtained results of the conducted experiments introduce the following;

- The evacuated-tube solar collector elaborated a quick response to changes in solar radiation intensity, permitting for an effective and timely heating of the engine oil working fluid.
- A maximum engine oil temperature of up to 198 °C can be achieved at a solar radiation intensity of 800 W/m².
- The prominent engine oil temperature was sufficient to heat, evaporate, and superheat the water working fluid flowing via the U-shaped copper pipe. Thus, it was assured that the engine oil can be an efficient medium for heat transfer, enabling efficient thermal conduction between the evacuated tube and the copper pipe. This implicitly can enhance the overall thermal performance of the ETSC.

Finally, an increase in the number of vacuum tubes (the surface area exposed to solar radiation) can positively increase the amount of heated water to the point of evaporation as opposed to concentrating systems. Also, an optimisation of the ETSC would contribute to lessen the dependence on fossil fuels and reduce the green-house gas emissions.
Based on the above conclusions, further research is required to optimise the design of the ETSC to upgrade the overall efficacy and thermal performance. Also, the effect of various layouts of vacuum tubes should be explored. Finally, alternative heat transfer fluids can be investigated that could deliver enhanced thermal characteristics or environmental advantages.

Nomenclature

Symbol	Definition
A	Tube area
CFD	Computational Fluid Dynamics
Cp	Heat of capacity
DSSG	Direct solar steam generation
ETSC	Evacuated tube solar collector
FPC	Flat plate collector
HVAC	Heating, Ventilation, and Air Conditioning
I	Intensity of solar radiation
m	Mass
OHAD	Overhead Air Distribution
Qin	Inlet thermal energy
Qu	Useful thermal energy
SHS	Sensible heat storage
Ti	Inlet engine oil temperature
UFAD	Underfloor Air Distribution
V	Volume
ρ	Density
ΔT	Temperature difference

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