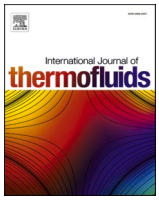
17 (2023) 100260

Contents lists available at ScienceDirect

International Journal of Thermofluids

journal homepage: www.sciencedirect.com/journal/international-journal-of-thermofluids



Thermal performance enhancement of evacuated tube solar collector using MWCNT, Al_2O_3, and hybrid MWCNT/ Al_2O_3nanofluids

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ARTICLE INFO

Keywords:
Solar water heater
Heat transfer fluid heat pipe
Evacuated tube
Thermal energy storage
Heat transfer enhancement
Nanofluids
Energy efficiency

ABSTRACT

Nanofluids have numerous applications in heat transference procedures due to their exceptional thermal characteristics. The most desirable parameter to enhance the solar collector's performance is the enhancement of the convective heat transfer coefficient between the working fluid tubes and the absorber. As a result, nanofluids have gained prominence as working fluids in solar thermal systems. The trendsetting review reveals that mostly the nanofluids in solar collectors are based on water employing nanoparticles of Al_2O_3, TiO_2, SiO_2, and CuO. Besides, nanoparticle concentration is a challenging factor in using nanofluids. In this research, under controlled conditions, the working fluids multi-wall carbon nanotube, Aluminum Oxide, and hybrid MWCNT/Al_2O_3 50:50% were experimentally examined for the thermal efficiency enhancement of the evacuated tube solar collector. For each type of nanofluid, four volume concentration percentages (0.5%, 0.025%, 0.01%, and 0.005%) were examined along with three distinct mass flow rates. According to the findings, using hybrid MWCNT/Al_2O_3 50:50% delivers an efficiency boost of about 20% overusing Al_2O_3, as was previously reported. Finally, it was found that the utilization of 0.5% MWCNT/water nanofluid at 3.5 L/m can enhance the ETSC's energy and exergy efficiency to reach 73.5% and 51% respectively while reaching approximately 60% and 44% for AL_2O_3, and 69% and 38% for hybrid MWCNT/Al_2O_3 (50:50%) under the same test conditions.

1. Introduction

We are facing the challenges of decreasing fossil fuel availability. Many alternative renewable sources of energy could actively bring down the utilization of conventional fuel supplies. Solar energy is a crucial option in many developing countries' commercial and industrial sectors to narrow the use of fossil fuels and their harmful environmental impact. Solar water heating (SWH) is a cost-effective method of generating hot water for domestic or commercial process heating utilizing solar thermal energy. The solar heat collector should be opted for based on the amount of energy it takes, the desired thermal spectrum, as well as the system's economy. In hospitals, domestic uses, and other operations in several businesses, huge quantities of energy go sunk and wasted specifically for water heating. Water heating utilizes a huge amount of fossil fuel, resulting in environmental damage and climate change owing to greenhouse gas emissions. In general, a solar collector is regarded as thermal equipment because it is designed to capture solar energy and convert it to heat energy. These systems usually get benefited from utilizing the working fluid that acts as an energy carrier by traveling through the solar collector pipes and absorbing the sun's energy. Although there are many different types of solar collectors, they can be mainly classified as stationery and sun-tracking concentration collectors. Stationary collectors consist of Evacuated Tube Solar Collectors, Flat Plate Solar Collectors, and Compound Parabolic [1].

Flat Plate Solar Collector (FPSC) and Evacuated Tube Solar Collector (ETSC) are the two most common types of solar water heaters. The ETSCs are characterized by vacuum insulation and careful exterior coating of the absorber component, resulting in high heat derivation functioning, heat loss can be decreased, and is suitable for foggy or severely cold circumstances. FPSC is a well-known solar collector for providing fluid temperatures in the 50–100 °C range, among other solar thermal collectors. Both forced; using a circulation pump, and thermosiphon water circulation; which uses the thermosiphon effect of water to operate, are used by SWH systems. Additionally, the working fluid is the component that absorbs the most heat from the collector, so replacing conventional fluids with nanofluids may be the most efficient technique to enhance heat transfer in the collectors under discussion [2]. Thermal energy is by far the most widely employed form of solar energy in water boiling and heater systems in both residential and commercial settings.

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https://doi.org/10.1016/j.ijft.2022.100260
Received 1 September 2022; Received in revised form 29 November 2022; Accepted 29 November 2022
Available online 1 December 2022

Nomenclature

ETSC	Evacuated Tube Solar Collector
FPSC	Flate Plate Solar Collector
MWCNT	Multi-wall carbon nanotubes
AL_2O_3	Aluminum oxide
T	Temperature
Tin	Inlet temperature
Tout	Outlet temperature
TEM	Transmission electron microscopy
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric analysis
F_R	Heat removal factor
G	Radiation intensity [W/m^2]
Ac	Collector area [m^2]
$\dot{m}$	Mass flow rate [kg/s]
Qu	Useful Energy Gain [W]
S_{gen}	Entropy generation
bf	Base fluid
nf	Nano Fluid
np	Nanoparticle

Greek Symbols

φ	Nanofluid volume Concentration
C_p	specific heat capacity [J/kgK]
k	thermal conductivity [W/mK]
ρ	Density[kg/m^3]
η	Efficiency
η_{ex}	Exergy
τ	Transmissivity
ε	Emissivity
α	Absorptivity

Due to its simple operating principle, solar water heating is the most common application of solar energy around the world [3].

According to Perea-Moreno et al., solar thermal systems might cut annual emissions by 90 α.14 tons of N_2O, 804.2 tons of CO_2, and 0.114 tons of CH_4. The energy-conversion efficiency of solar collectors is low, and research has been done to enhance it. To address this issue, numerous studies on the application of various working fluids have been carried out. It is a common method to change the working fluid to increase the solar collector's efficiency by adding high thermal conductivity nanoparticles. A nanofluid is a fluid that contains a relatively small quantity of uniformly distributed and suspended nano-sized particles with an average size of fewer than 100 nanometers in the base fluid. When a little percentage of nano-sized particles is added to a pure fluid, its thermal conductivity is increased, and the fluid is called nanofluid. Nanofluid has gained popularity in scientific research in the field of heat transfer in recent years, notably for renewable energy applications. Solar collector efficiency is improved by using nanofluids. As a result, more heat from the sun is received, and the demand for fossil fuels is reduced. If nanoparticles are uniformly disseminated and stably floating in base fluids, their partial contribution improves the thermal characteristics of the base fluid [4].

Nanofluid was first invented by Choi in 1995, with nano-sized particles varying from 1to100 nm in colloidal amalgam accompanying the working fluid and the nanoparticle fluid mixtures. Nanoparticles are made from a variety of materials, which includes both carbide and oxide ceramics, metals, nitrides, semiconductors, nanotubes made of carbon, and other composite materials including nanoparticle & core–polymer composites and alloyed nanoparticles depending on the application [5]. "Hybrid metals" are created when two or more materials are blended in such a way that the resulting blend would have an entirely new chemical bond. In fact, "hybrid nanofluid" was coined when more than one metal derived a homogenous phase with concurrent mixing. When compared to unitary nanofluids, such a modern class of nanofluids demonstrated potential improvements in heat transport characteristics as well as thermophysical and hydrodynamic characteristics [6]. Aside from the nonmetal components, the metal and other materials used for the nanoparticles, and different structures that have been used, are referred to as "doped" with molecules in the solid-liquid state. The result is the acquisition of exceptional thermal properties associated with the smallest practicable volume fraction (Λ =1%). As a result, Improved heat transfer requires floating nearly mono-dispersed nanoparticles or non-accumulated in mixtures [7]. When utilizing a 1% nanoparticle concentration, the heat enhancement of a nanofluid flow over water flow is around 5%, and it rises to 12% when using a 2% nanoparticle concentration [8].

The main four primary benefits of utilizing nanofluids in solar thermal systems can be stated as follows. First, nanofluids have high conductivity, and heat transmission coefficient, also the reduced specific heat of such particles, increases the efficiency of thermo-devices. Second, nanoparticles possess a very reduced size and a big surface area, which results in an exponential rise in the heat valence of nanofluid and solar energy absorption. Third, better optical properties; better optical properties include greater absorption and extinction coefficients. Fourth, nanofluids take out the needed heat transmission area and lower the important transmission surface in these systems. Fifth, the advantages of nanofluids over micro-suspension; nanofluids have higher stability in terms of clogging and sedimentation of pumps and pipes due to their extremely small size when compared to micro or suspended millisized particles, and that is an important aspect to be considered in several solar applications [9].

Table 1
Thermal conductivity (k) of different metal oxides values at 300 K. [11].

Material	*k*
SiO_2, polycrystalline	1.38
TiO_2, polycrystalline	8.4
Al_2O_3, polycrystalline	36
Al_2O_3, Sapphere	46

One of the most difficult aspects of employing nanofluids is the increase in pressure drop and pumping power caused by high viscosity and nanoparticle concentration. MWCNT and Al_2O_3 have been the most common nanofluids, with a few additional nanofluids such as CuO, ZnO, SWCNT, Ag, SiO_2, Fe_2O_3, and TiO_2 [10]. Table 1 gives the readings of different metal oxides that are generally employed as heat transfer materials at 300 K temperatures.

The ETSCs have been investigated using nanofluids in many experimental and numerical studies. High-concentrated SWCNT nanofluids have better thermal conductivity, allowing more heat to be absorbed by the fluid. The Brownian flow had a significant impact on the evacuated collector system due to the circulation of nanofluid in the tube at a particular flow rate rather than being stopped. The thermal performance was compared to the state with water, it was discovered that employing SWCNT nanofluids as heat transfer fluid increased collector efficiency. More specifically, the comparable maximum efficiency in this circumstance was 0.2 vol%. At a mass flow rate of 0.025 kg/s, the efficiency of SWCNT nanofluids was discovered to be 93.43% and 48.57% for 0.05 vol% nanoparticle concentration. By increasing the volume percentage of SWCNT nanoparticles and increasing the mass flow rate, the collector efficiency improved [12]. Another experimental study by Mahbubul

et al., revealed that the ETSC's efficiency can be enhanced by 10% by applying 0.2 vol.% of SWCNT compared to water under the same experimental conditions [13].

In an experimental investigation of the use of MWCNTs as a working fluid in a solar plate collector, Natarajan and Kiatsiriroat discovered that MWCNTs significantly outperform most other nanoparticles, especially for high temperatures applications [14]. According to Faizal et al., lowering the collector size by 37% can be employed by using MWCNT/water as the working fluid while keeping the same efficiency [15]. Tong et al., studied the effect of using MWCNT/water as a base fluid for ETSCs. The results show that by using MWCNT/water with a concentration of 1% as a working fluid, the ETSC's efficiency increased by 8% compared to water [16]. A theoretical study done by Kim et al. shows that applying MWCNT/water with 0.2 vol.% in U-tube ETSC can improve its efficiency to reach 62.8% [17].

Dehaj et al. used MgO nanofluid to perform an experimental analysis based on an ETSC. Water/magnesium oxide nanofluids with concentrations of 0.014 percent and 0.032 percent were combined and tested in a heat pipe ETSC at flow rates of 5, 8, 11, and 14 L/min. It was discovered that the heat pipes ETSC using the considered nanofluid have substantially greater efficiency of 69% and 77% for the two studied flow rates respectively compared to 60% for using base water. Furthermore, the ETSC's thermal performance is influenced by the flow rate and working fluid [18].

Because of their high thermos-physical properties, TiO_2 nanofluids outperformed water in terms of yield. ETSC thermal performance was enhanced by 42.5% by employing TiO_2/water with a concentration of 2% as proved by Mahendran et al. [19]. Farajollahi et al. tested various nanofluids in a heat exchanger to find the most effective nanofluid in a turbulent flow. In comparison to their contemporaries, the experimental results show that TiO_2 is more effective. Al_2O_3 outperformed TiO_2 in higher concentrations of nanofluid [20]. Mirzaei et al. found that at the ideal flow rate of 2 L/m, the use of Al_2O_3 nanocomposites with a volumetric concentration of 0.1 percent boosted the collectible efficiency by 23.6 percent [21]. Rajput et al. found that raising the Al_2O_3 nanofluid concentration from 0.1 percent to 0.3% boosted effectiveness by 21.32% [22]. Ghaderian and Sidik's experimental investigation of using Al_2O_3/water nanofluid with 0.06% concentration shows that the system's efficiency can increase by 36% and reach a maximum value of 58.65% [23].

Hybrid nanofluid and thermal technologies are critical for energy exchange and solar sensor performance improvements. The temperature conductance of hybrid nanofluids may be affected by the concentrations or solid volume proportion of nanoparticles, which is directly linked to the nanoparticle dimension as well as the volume circulation channel of fluid [24].

To validate the manufactured nanocomposites, the hybridized fluids created by the dissemination of different materials in working fluids need to be characterized, where the greater the fluid nanoparticles content, the greater the viscosity, and the lower the mass flow rate will be. An experimental investigation was performed for rheological properties prediction of MWCNTs–ZnO/water– Ethylene glycol (80:20 vol. %) hybrid non-Newtonian nanofluid with volume fractions of 0.075%, 0.15%, 0.3%, 0.6%, 0.9%, and 1.2% in the temperature range of 25–50 °C. The results show that by increasing the nanoparticle's volume fractions, its effect is better, and the non-Newtonian property is more likely to appear. On the other hand, the fluid's viscosity is reduced by 21%, 17%, and 8% percent, respectively, at 50 °C, 40 °C, and 30 °C for the maximum volume fraction [25].

Heat transfer and mixing quality of a hybrid nanofluid containing silver Ag and iron oxide Fe_3O_4 nanoparticles on distilled water inserted in a microchannel equipped with a dual mixer in different volume fractions were assessed. It was concluded that both the volume fraction and the Reynolds number have positively influenced heat transfer. However, the volume fraction has a bigger impact on boosting heat transfer than velocity. In addition, the mixing quality may improve or deteriorate with time for high Reynolds numbers and a steady frequency. While the mixing quality rapidly improves over time at low Reynolds numbers, it takes at least 0.015 s to reach stable heat transmission [26].

The effect of temperature and volume fraction on the viscosity of a hybrid nanofluid ZnO/Ag 50:50%/Water was experimentally evaluated. Results indicate that the dynamic viscosity increases with increasing nanoparticle volume percentage and decreases with increasing temperature. While a rise in relative viscosity is connected to a rise in volume fraction at all temperatures [27].

According to Harandi & Karimipour, whenever a hybrid nanofluid is made employing Al_2O_3/Fe, Al_2O_3/water, with a concentration of 0.05 and 0.2%wt., the volume percentage increases the effectiveness of heat exchange by 6.9% [28]. Eidan et al., employed Al_2O_3/CuO acetone nanofluids in their study, with each studied condition efficiency being compared to acetone-based fluid. Experiments were performed with two volume concentration values (0.025% and 0.05%) and the enhancement percentage reached maximum of about 34%, 74%, 32%, and 73%, respectively [29].

Using MgO/MWCNT (50:50) hybrid nanofluid produced the highest thermal performance compared to MgO/MWCNT 90%:10%, MgO/MWCNT 80%:20%, MgO/MWCNT 70%:30%, and MgO/MWCNT 60%:40%, hybrid nanofluids at all studied flow rates, but it was marginally lower than MWCNT/water nanofluid based on Shady et al. research [30].

As observed from the literature review that the working fluid in a solar collector act as a heat transfer medium and a thermal energy absorber, when nanofluids are used as the working fluid, the

Fig. 1. ETSC complete system.

Table 2
ETSC specifications.

Parameter	Value
ETSC Gross Area	2.35 m^2
ETSC Active Area	1.407 m^2
Number of Tubes	15
Tube Length	180 cm
Glass Transmissivity	$\tau \geq 92\%$
Absorber Emissivity	$\varepsilon \leq 8\%$
Absorber Coating Emissivity	$\varepsilon \leq 5\%$
Absorber Absorptivity	$\alpha \geq 92\%$
Absorber Plate Material	Aluminum
Cycle's Working Fluid volume	3.46 L
Collector's Working Fluid space capacity	1.256 L
Heat Pipe Material	High purity copper

performance of the solar collector can change, potentially leading to higher efficiencies. The most noticeable effect of employing nanofluids in solar collectors is an increase in thermal absorption and heat transfer rate depending on the nanoparticle type added.

Investigations into the impact of hybrid nanofluids on solar collectors have been ongoing for a while. The family of carbon-based nanotubes, which is the highest conducting nanoparticle used in solar collector applications, was depicted in the literature. On the other hand, the aluminum oxide was observed to have a great enhancement in solar collectors' efficiency while having lower cost and environmental impacts. However, it was shown that carbon nanotubes, aluminum oxide, and hybrid combinations need a more extensive experimental study to explore the response of ETSC in terms of energy, exergy, total heat gained, the enhancement in the collector's area to provide the same thermal energy, and the efficiency improvement toward using MWCNT, Al_2O_3 and hybrid MWCNT/Al_2O_3 at the same working conditions for higher concentrations and mass flux rates which will be explored in this study.

The main goal of this study is to engage the MWCNT – Al_2O_3/water nanofluids in the ETSCs to show the improved natural convection performance and to compete and access the performance of ETSCs including the MWCNTs, Al_2O_3, and hybrid MWCNT/ Al_2O_3 50%:50% at various flow rates in thermal energy, system efficiency, and exergy. The study also indicates the reduction percentage in the collector's area when using different nanofluids compared to water.

2. Experimental method

2.1. Experimental study

The purpose of the research's initial phase is to examine the energy use and associated efficiency of a heat pipe ETSC utilizing varied composition partakes of MWCNT/Water nanofluid at various rates of flux varying from 1.5 L/m to 3.5 L/m. Second, utilizing varying compositions of Al_2O_3/Water nanofluid at various rates of flux rates fluctuating from 1.5 to 3.5 L/min, and finally, employing varied compositions of hybrid MWCNT- Al_2O_3/Water nanofluid again at different rates of flow of 1.5, 2.5 and 3.5 L/min. As represented in Fig. 1, this experiment work is performed on an educational system, the ETSC with a 1.407 m^2 aperture area and 15 evacuation tubules. The evacuation tubes are 1.8 m long and have an inner diameter of 47 mm and an outside diameter of 58 mm; every tube has a heating pipe within the middle of the assembly, which is surrounded by an aluminum fin to maximize the absorption area. The heat pipes are filled with thermally conductive liquid and attached to the manifold. In comparison to an air-filled compartment, a vacuum fills the gap between the employed tubes and the exterior cover, minimizing conductional heat losses. With a 210 L tank capacity, a heat exchanger provides a closed loop for the fluid. Solar collector specifications are shown in Table 2.

The system comprises four thermocouple sensors of type PT1000, with a range of -40 to 150 °Celsius, and a screen to show the readout. Thermocouples are utilized to monitor the temperature of the collector as well as the inlet and outlet of the tank. The YF–S201 flow meter is used to observe the fluid's flow.

In the experiment, an artificial sunlight system was employed to reproduce sun radiation inside the laboratory. To manage the system's radiation output level, a radiation sensor, type 21 R7s 500-Watt, was linked to the lights. A PYR 1307 sun power meter sensor and a solar pump station were used to detect solar intensity (UniMaxx-Plus-SC-500-AC-V3). A monitoring and control system is included in the system with a 210 Liter tank where the used fluid is circulated in a closed loop connected to a heat exchanger connected to the collector. The ETSC is illustrated in Fig. 2.

In this research, the distilled water results served as the comparison's reference values. the experiment then employed four different concentrations of nanofluids in the tests: 0.005%, 0.01%, 0.025%, and 0.05%

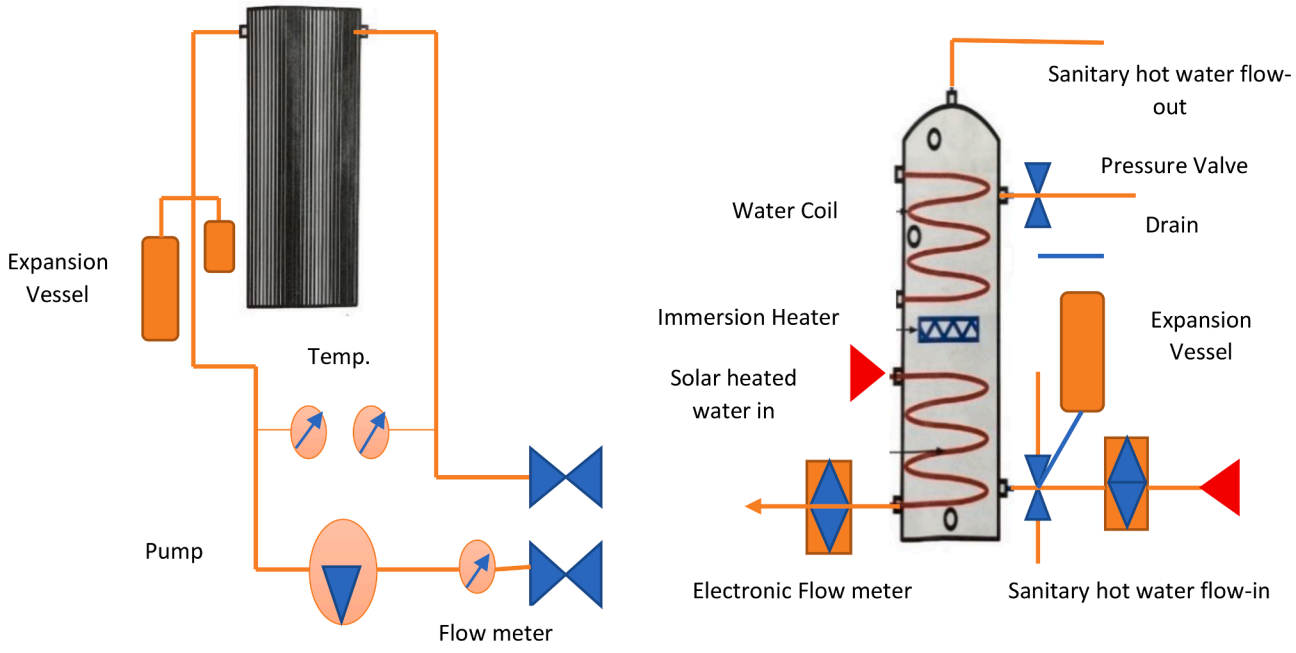

Fig. 2. Complete system diagram.

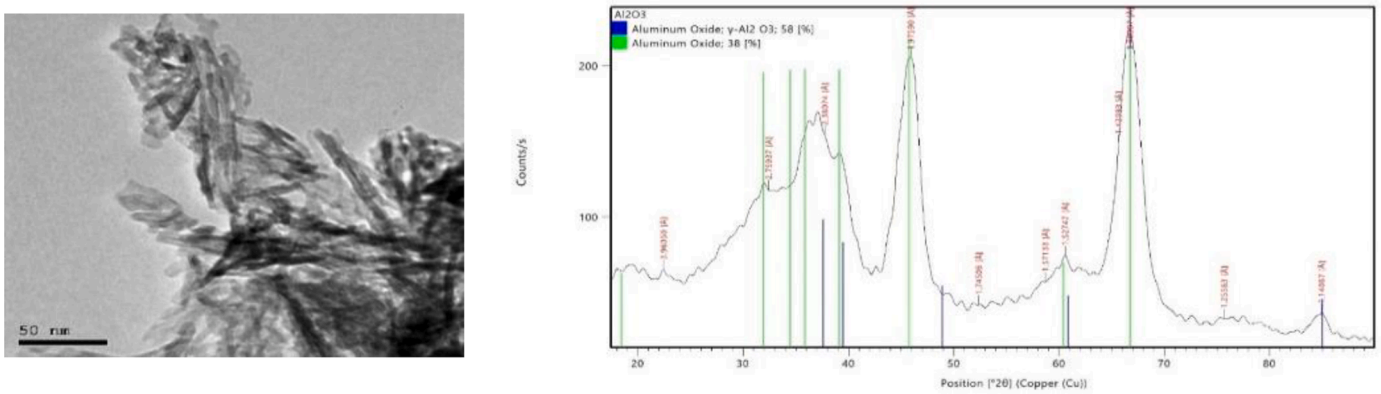

Fig. 3. TEM images and XRD pattern of Alumina nanoparticles.

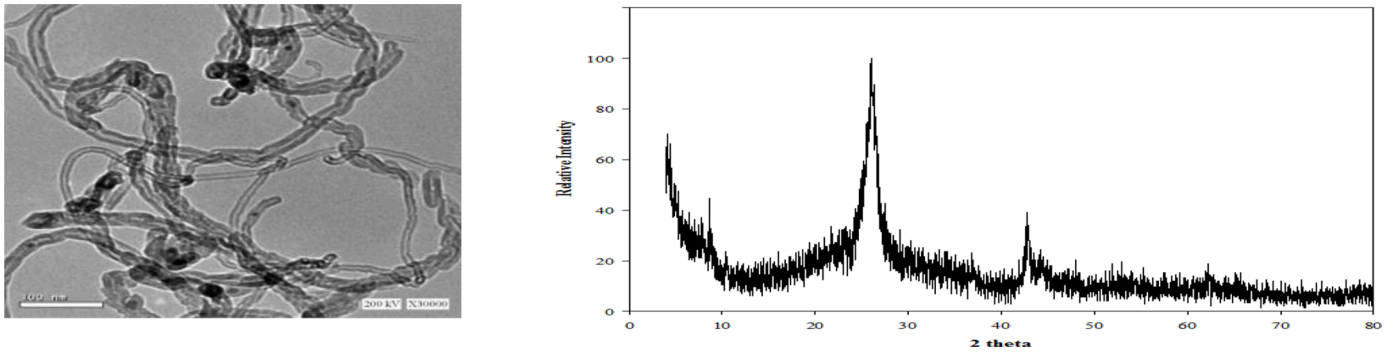

Fig. 4. TEM images and XRD pattern of MWCNT nanoparticles.

Table 3
TEM properties of Al_2O_3 nanoparticle.

Color	White.
Form	powder.
Average Size	< 30 nm
Shape	Spherical

Table 4
TEM properties of MWCNT nanoparticle.

Parameter	Value	Test Method
Diameter	10–40 nm	TEM
Length	Up to 5 μm	SEM
Purity	>90%	TGA

by weight fraction for three flow rate values; 1.5, 2.5, and 3.5 L/m.

2.2. Nanofluid preparation

The creation of nanofluids is a crucial step in using nanoparticles to improve fluid thermal conductivity. The single-step technique and the two-step technique are the two most prevalent methods for producing nanofluids. To provide excellent thermal characteristics for nanofluids, it is critical to producing stable and robust nanofluids [31]. For this experiment, the two-step approach was applied due to its greater stability and durability. Distilled water was utilized to be the base fluid. The working fluids were Al_2O_3 nanofluids with four concentrations of 0.005%, 0.01%, 0.025%, and 0.05% by weight fraction. Sol-gel, controlled boehmite precipitations, and hydrothermal processing are all used in the synthesis of Al_2O_3 nanoparticles. Alkoxides, metallic powder, and aluminum salts are typically used to make boehmite. A sol-gel approach using an aluminum nitrate precursor and an ammonium carbonate pathway with spherical nano-sized particles was used to

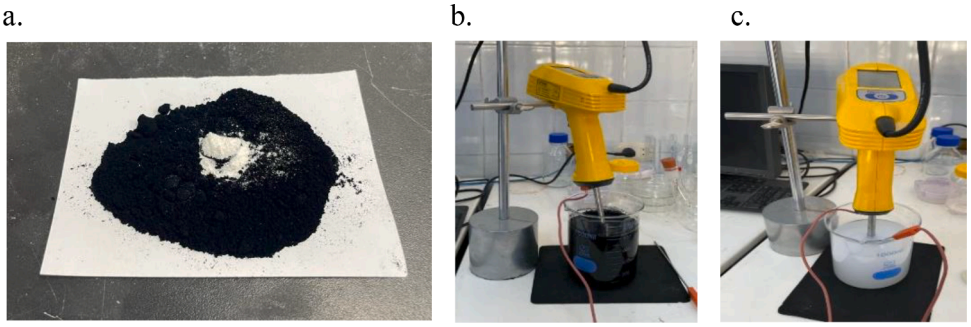

Fig. 5. a) Hybrid MWCNT/Al_2O_3 nanoparticles b) MWCNT/water c) Al_2O_3/water nanofluids preparation

Table 5
The features of water and solid particles.

property	Symbol	Unit	Water	Al_2O_3	MWCNT
Density	P	$(kg.m^{-3})$	998.2	3970	2100
Specific Heat	C_p	$(J.kg^{-1}.k^{-1})$	4182	765	519
Thermal Conductivity	K	$(W.m^{-1}.k^{-1})$	0.6	40	3000
Viscocity	μ	$(kg.m^{-1}.s^{-1})$	0.001	—	—

create gamma alumina nanoparticles. TEM was carried out on a JEOL JEM-2100 high-resolution TEM at a 200 kV accelerating voltage. The TEM and XRD images for Al_2O_3 and MWCNT nanoparticles are shown in Figs. 3 and 4, and the MWCNT and Al_2O_3 particles' properties are shown in Tables 3 and 4.

Using an ultrasonic homogenizer (Sonicator), the nanoparticles were mixed with the distilled water bf to create the nanofluids, the Hielscher UP200HT. The homogenizer was utilized for 3 h at f of 50 Hz with a 100 percent amplitude and t of 20 s ON and 10 s OFF pulses until perfect dispersion was obtained. Fig. 5a. depicts hybrid Al_2O_3- MWCNT nanoparticles, whereas Figs. 5b. and c. depict the nanofluids' preparation. The MWCNT, Al_2O_3, and H_2O features are shown in Table 5.

2.3. Mathematical calculations

Solar energy is a form of energy for harnessing solar energy to generate thermal energy for use in different with a weak effect on the environment.

The thermal energy-balanced equation for steady-state conditions [32] can be expressed as:

$$\dot{Q}_u = \dot{Q}_{Abs} - \dot{Q}_{loss} \tag{1}$$

Where, $\dot{Q}_u$ is the useful gained energy from $\dot{Q}_{Abs}$,

$\dot{Q}_{Abs}$ is the total amount of solar energy collected, excluding losses due to convection, conductivity, and irradiation between both the environment and the collector, and $\dot{Q}_{loss}$ is the total lost energy between the collectors and the surrounding atmosphere and can be calculated by:

$$\dot{Q}_{loss} = U_L A_c (T_M - T_a) \tag{2}$$

Where U_L is the overall heat transfer coefficient, A_c is the area of the collector, and T_M and T_a are the mean plate temperature and the ambient temperature respectively.

$$\dot{Q}_u = \dot{m} C_p (T_o - T_i) \tag{3}$$

T_o and T_i are the working fluid's output temperature and inlet temperature, respectively, while C_p is the heat capacity of the working fluid, which may be water or a nanofluid. The gained usable energy can be computed as:

$$\dot{Q}_u = A_c F_R [I_T(\tau\alpha) - U_L(T_i - T_o)] \tag{4}$$

Where, (F_R) is the heat removal factor which refers to the ratio between the usable heat acquired and the energy obtained if the collector's interface temperature is the same as the inlet temperature, and I_T is the solar radiation. F_R can be calculated by the following equation [20,21]:

$$F_R = \frac{\dot{m}\, Cp(To - Ti)}{Ac[I_T(\tau\alpha) - UL(Ti - Ta)]} \tag{5}$$

The Total Irradiation Received by the collector is calculated as:

$$q_{IT} = I_T A_C \tag{6}$$

Solar thermal efficiency refers to the ratio between the rates of useful heat (Q_u) transferred by solar radiation on the solar heater. The formula provided below can be used to calculate thermal efficiency [33].

Table 6
Uncertainty percentages of experimental measuring instruments.

Parameter	Uncertainty
H	5%
$\dot{m}$	±1.5%
T	±1.5%
I_T	±2%

$$\eta = \frac{\dot{Q}u}{I_T I A_c} = F_R\left[(\tau\alpha) - UL\,\frac{(Ti - Ta)}{I_T}\right] \tag{7}$$

The following equation can be used to compute the exergy efficiency [33], which is defined as the highest output a system can produce concerning the ambient temperature.

$$\eta_{ex} = 1 - T_a\, S_{gen} / [1 - (T_a / T_s)]\, q_{abs} \tag{8}$$

The base fluid and nanoparticles' thermal conductivities are combined to form the nanofluid thermal conductivity. The following adapted equations are used for the nanofluid properties calculation [34]

$$K_{nf} = (1 - \varphi)\, k_{bf} + \varphi\, k_{np}\beta \tag{9}$$

where K_{nf}, K_{bf}, and K_s are the thermal conductivity for nanofluid, base fluid, and nanoparticles, respectively. The formula given by (φ) gives the nanofluid volume concentration.:

$$\varphi = \frac{\frac{W_{nf}}{\rho_{nf}}}{\frac{W_{nf}}{\rho_{nf}} + \frac{W_{bf}}{\rho_{bf}}} \tag{10}$$

The specific heat and density of nanofluids can be represented by:

$$Cp_{NF} = \frac{(1 - \varphi)\rho_{bf} Cp_{bf} + \varphi\rho_s Cp_s}{\rho_{nf}} \tag{11}$$

$$\rho_{nf} = \rho_{np}(\varphi) + \rho_{bf}(1 - \varphi) \tag{12}$$

2.4. Uncertainty analysis

A flawless measurement cannot be made, and the experimental measurements revealed some errors. The mistakes were caused by systemic flaws in calibration and data recording, as well as data variations caused by inappropriate instrumentation (random errors). To determine the divergence between the actual readings and the experimental data, the uncertainty of measurement outcomes was estimated. The experi-

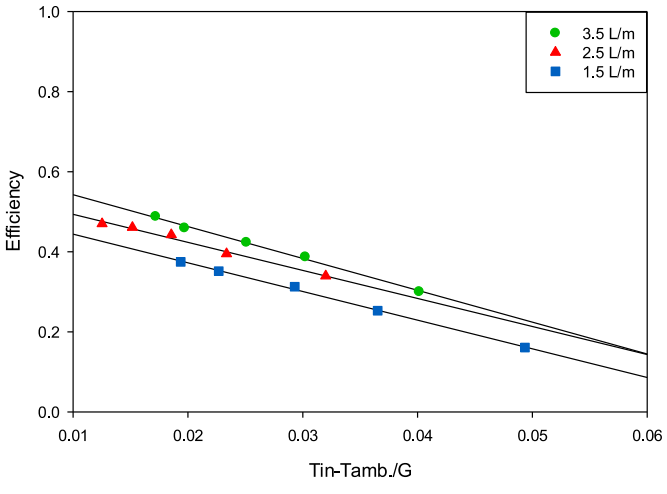

Fig. 6. ETSC recorded efficiency at 1.5, 2.5, and 3.5 L/m of H_2O.

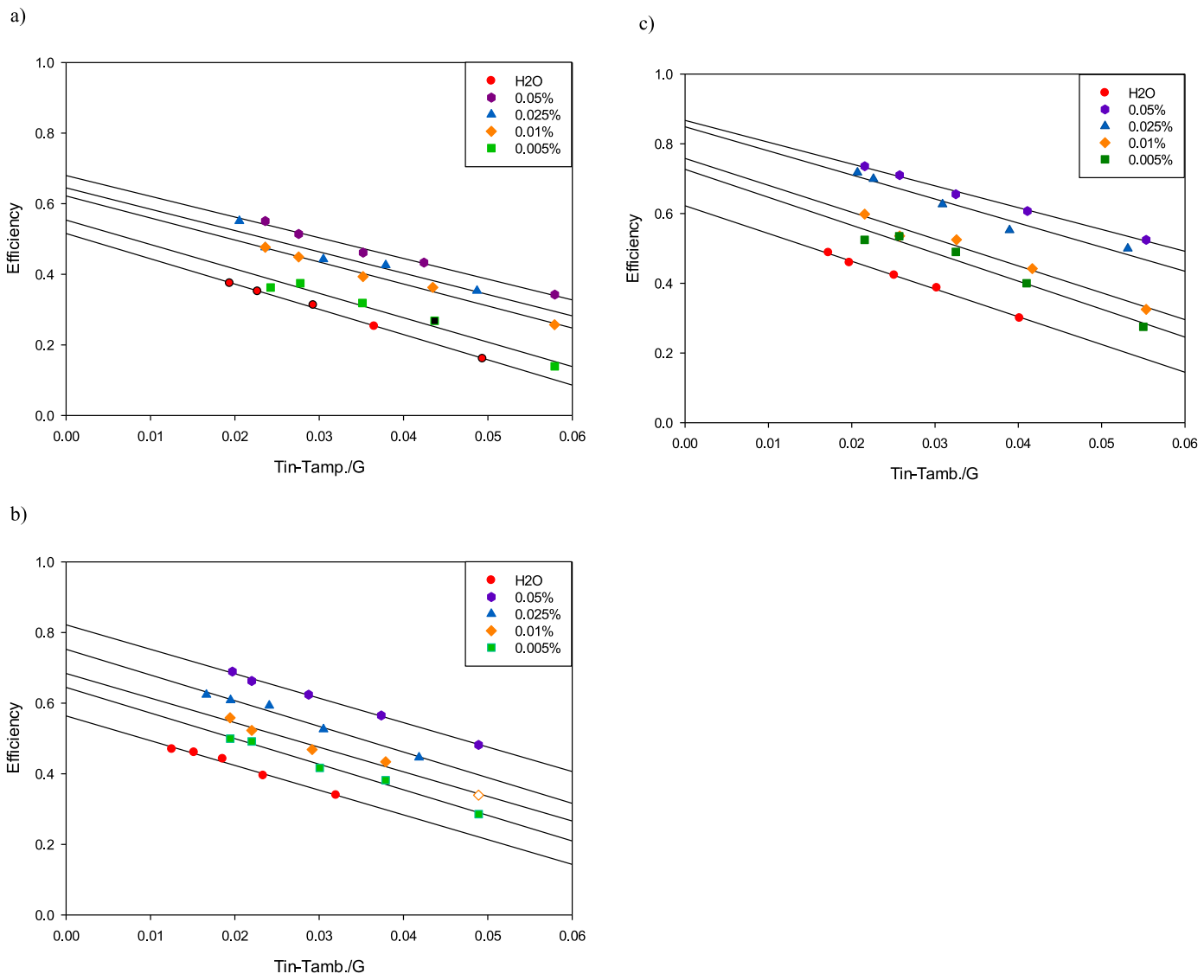

Fig. 7. ETSC efficiency for H_2O, 0.05%, 0,025%, 0.01%, and 0.005% MWCNT at a) 1.5, b)2.5, and c) 3.5 L/m.

ment's error assessment is a requirement for trust in the observed results. Analyses of uncertainty focus on test measurements, which are always associated with a range of uncertainty. The analytical equation for uncertainty has the general form shown below [35]:

$$U_y^2 = \sum_{x=i}^{n} U_{xi}^2 \tag{13}$$

The used standard equation for observing the uncertainty analysis of the applied system while ignoring C_p and A_c is as follows.:

$$U_y = \eta \times \sqrt{\left(\frac{\Delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta(To - Ti)}{(To - Ti)}\right)^2 + \left(\frac{\Delta G}{G}\right)^2} \tag{14}$$

Table 6 describes the features and accuracy of the sensors and monitoring equipment used in the current experimental setting.

3. Results and discussion

3.1. Distilled water results

With [(Ti-Ta)/G] retained on the graph's X-axis and the efficiency (η) on the Y-axis at three distinct flow rates 1.5, 2.5, and 3.5 L/min with a 5-minutes interval time, the experimental results are recorded and shown based on the collector's efficiency against the falling temperature variables for the ETSC as shown in Fig. 6. Tests had been carried out on the solar collector temperature outputs and the varying efficiency of the collector is mainly based on the base fluid flow rate according to the type of collector. The efficiency of the collectors was found to rise with higher fluid flow rates.

For the 1.5 L/m flow rate, the changes in the efficiency regarding (Ti-Ta)/G increased from 0.16 to 0.37 within the parameters of our investigation. Similar to this, the efficiency varied between 0.30 and 0.47 for the 2.5 L/m flow rate and from 0.34 to 0.48 for the 3.5 L/m flow rate. The $F_R U_L$ recorded values were 3.27, 3.38, and 3.52, respectively, at each concentration, matching the slope of all linear methods. The efficiency decreased as the (Ti-Ta)/G increased, as was to be expected. For the flow rates of 1.5 L/m, 2.5 L/m, and 3.5 L/m, respectively, the average variances were 43.0 percent, 70 percent, and 72 percent. Also, increases in the decreased temperature parameter $[(T_i\text{-}T_a)/G]$ result in greater inlet fluid temperatures, which raise the fluid's bulk temperature and increase convection losses over the studied range. Changes in $(T_i - T_a)/G$ have a significant impact on the heat transmission and circulation between the solar collector and the glazed covering, which has an important effect on the precision of the total heat transfer coefficient and the solar collectors' thermal efficiency.

It was observed and shown how the mass flux rate of distilled water

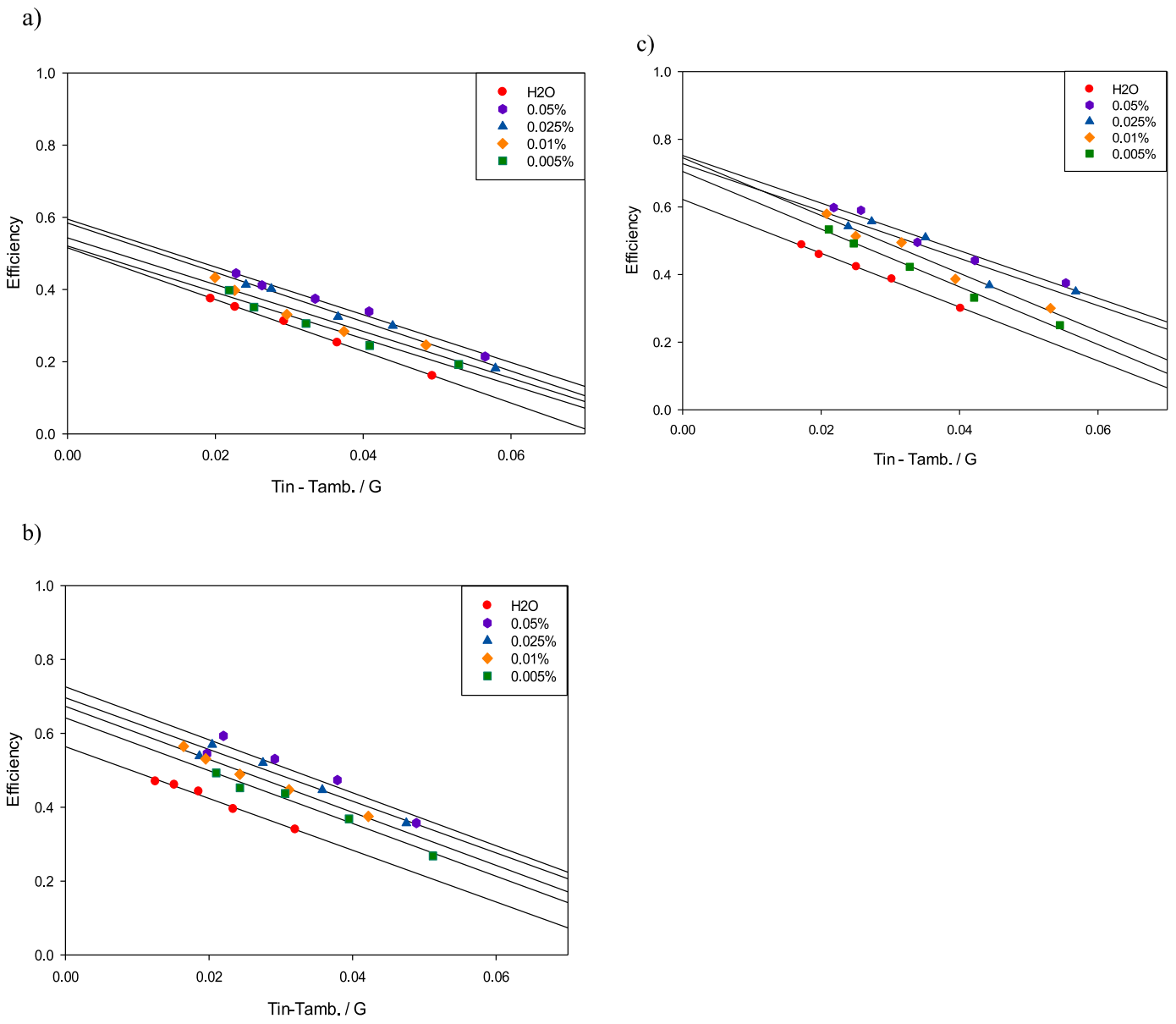

Fig. 8. ETSC efficiency for H_2O, 0.05%, 0,025%, 0.01%, and 0.005% Al_2O_3 at a) 1.5, b)2.5, and c) 3.5 L/m.

affected the ETSC's efficiency. The comparison between the different water flow rates shown in Fig. 6 indicates that the higher flow rates have greater efficiency than lower flow rates for the same conditions, as a result of increasing the temperature difference between the receiver's exit and inlet, where turbulent flow is dominant.

3.2. MWCNT/ water results

Fig. 7 shows the results of testing four different MWCNT concentrations at three distinct mass flux rates for ETSC. The collector's efficiency can be improved by changing the nanofluid type, concentration, and mass flux rate. The Reynolds number rises as the mass flux rate rises, increasing the motion rate, and turbulence for the Brownian motion particles. The heat transfer rate is considerably affected by nanoparticle movement, which leads to an improvement in collector efficiency. In addition, the working fluid's thermal conductivity has a significant impact on the energy efficiency of solar collectors. As shown in Fig. 7, escalating the weighted fragment of MWCNT in the base fluid enhances the thermal conductivity of the fluid, which enhances the fluid's gains in heat. When employing nanofluids, combining both elements has a twofold effect. For the four MWCNT concentrations, it can be seen that raising the mass flux rate enhances efficiency. At all mass flux rates, 0.05% wt. percent MWCNT/water achieves the maximum absorbed energy increase, as shown in the figure, the favorable effect of raising the mass flux rate, on the other hand, diminishes as the concentration rises.

The MWCNT concentrations 0.05%, 0.025%, 0.01%, and 0.005% by weight in the distilled water were used in this experiment. Initially, the system's effectiveness was determined by using a control fluid. On the X-axis of the graph, the temperature parameter (T_{in} –$T_{amb.}$ /I_T) was retained, while the efficiency (η) was recorded on the Y-axis. Fig. 7 shows the efficiency of the ETSC at varied flow rates for the four given concentrations of MWCNT/water nanofluid. The average collector efficiencies for the varied concentrations of the MWCNT/water nanofluids were 57%, 54%, 44%, and 39%, respectively. The utilization of MWCNT/water nanofluid as the operating fluid enhanced the collector's efficiency, as seen in Fig. 7. The working fluid's thermal conductivity and absorption coefficient, as well as the heat transfer between the receiver and the coolant, were all improved by the nanostructures. adding a small concentration percentage of MWCNTs, the network efficiency increased significantly. The MWCNT nanofluid heat extraction

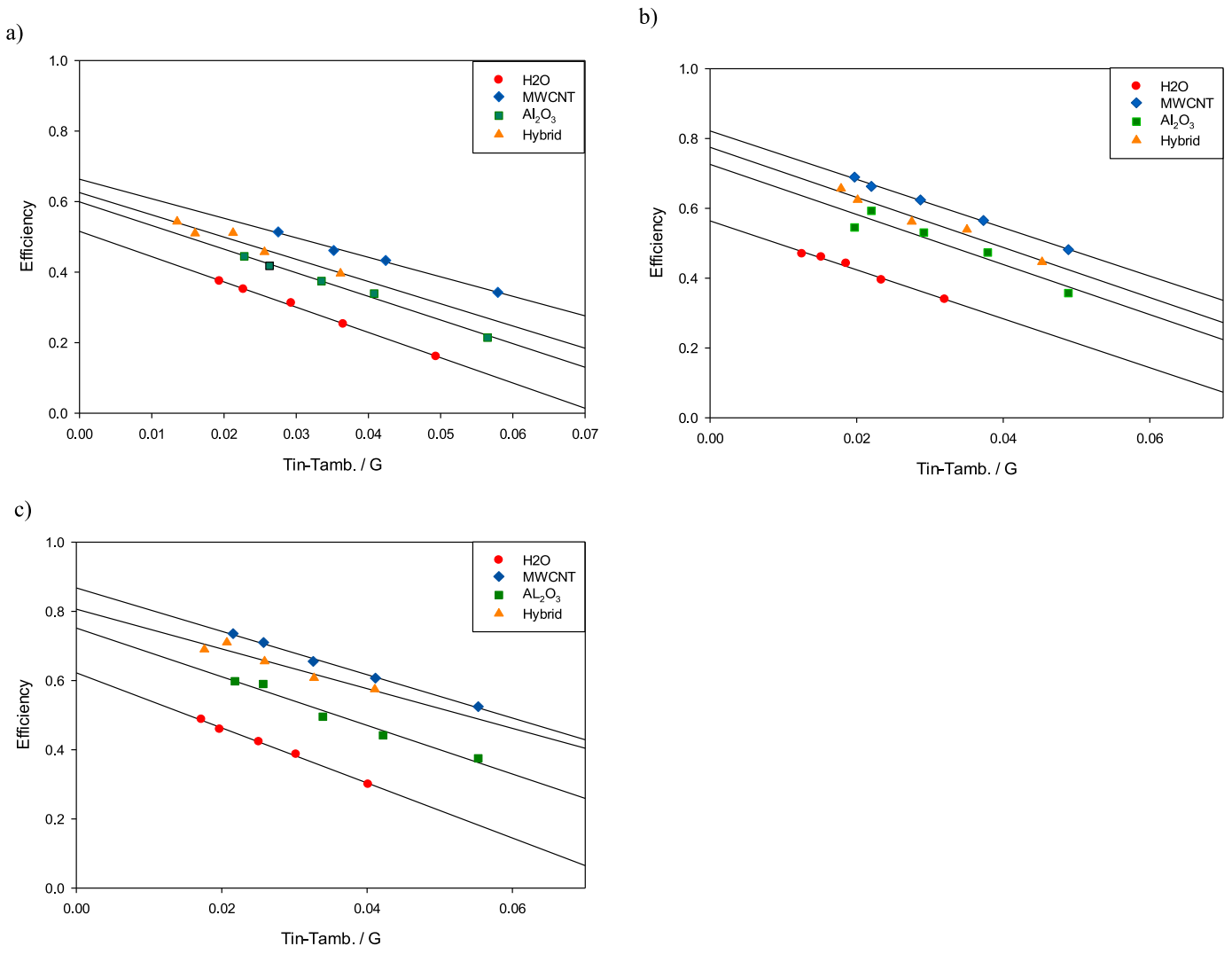

Fig. 9. ETSC efficiency at a)1.5, b)2.5, and c)3.5 L/m for 0.05% MWCNT, 0.05%Al_2O_3, and hybrid MWCNT/Al_2O_3 50:50%.

parameter of the absorber F_R was calculated for each weight percentage. The nanofluid's heat removal factor is higher than that of pure water, and it also increases when the weight percentage of MWCNTs increases and the received energy factor rises. When utilizing an MWCNT nanofluid, boosting these parameters enhances the effectiveness of the collector. Adding MWCNTs raised the absorbed energy parameter (F_R (τα)) of pure water by 23.6%, 31.2%, 40.5%, and 51.1% for nanoparticle concentrations of 0.005%, 0.01%, 0.025%, and 0.05% respectively.

3.3. Al_2O_3/ water results

As previously mentioned in the MWCNT/water investigation, similar concentrations of Al_2O_3 were utilized to observe the enhancement in the solar collector's efficiency. Fig. 8 demonstrates the enhancement in the ETSC's efficiency with different concentrations and mass flow rates of Al_2O_3/water nanofluid. For the studied concentrations, the average collector effectiveness was 60%, 54%, 53%, and 50%, successively at 3.5 L/m. The figure illustrates how the efficiency trend has significantly improved on the plotted graph with the temperature parameter (T_{in} –$T_{amb.}$ /G) retained on X-axis, while the Y-axis represents the efficiency (η) for ETSC, especially for higher flow rates.

It was determined that as flow rates are decreased, the amount of heat energy available decreases, the effectiveness of the nanoparticles decreases, and the influence of the nanoparticles on the temperature of the output fluid is less.

According to the findings, adding Al_2O_3 nanoparticles to pure water improved the absorbent medium's ability to transfer heat. The graphs show that Al_2O_3/water with the four studied concentrations can enhance efficiency by 12%, 6%, 5%, and 2% respectively, compared to water at 3.5 L/m. Furthermore, the addition of Al_2O_3 nanoparticles led to the decreased specific heat capacity of the fluid compared to plain base fluid; it requires lesser energy to reach higher temperatures which is the main target in the case of solar collectors. Finally, efficiency enhancement is lower in the case of Al_2O_3 than in MWCNT because of its lower thermal conductivity.

3.4. Hybrid MWCNT/Al_2O_3/water 50:50%

Fig. 9 shows a graphical comparison of the prior findings utilizing nanofluid compositions of 0.025 wt percent MWCNTs and 0.025 wt percent Al_2O_3, with the hybrid form including 50:50 of each of the two materials. The hybrid MWCNT/ Al_2O_3 (50:50%) is shown to give the average efficiency data staying between the two individual types. The hybrid material shows the average functionality of the hybrid nanofluid in the current study.

Results show that the use of hybrid nanofluid composed of 0.025 wt.% MWCNTs and 0.025 wt.% Al_2O_3 resulted in approximately 20% enhancement in thermal efficiency at a flow rate of 3.5 L/min compared to distilled water. Graphs show that the enhancement in energy efficiency resulting from MWCNT/water is more than that of hybrid

Table 7
Absorbed heat energy by ETSC for water and nanofluids at different concentrations.

Evacuated Tube Solar Collector					
Flow rate		**Gained heat energy (W)**		**Gained heat energy (W)**	**Hybrid Fluid-Gained heat energy (W)**
1.5	H_2O	281.7247	H_2O	281.7247	426.69
	MWCNT_0.05%	432.63	Al_2O_3_0.05%	341.3302	
	MWCNT_0.025%	421.2783	Al_2O_3_0.025%	313.7535	
	MWCNT_0.01%	368.732	Al_2O_3_0.01%	323.3908	
	MWCNT_0.005%	284.475	Al_2O_3_0.005%	288.6716	
2.5	H2O	390.5217	H2O	390.5217	527.162
	MWCNT_0.05%	562.0272	Al_2O_3_0.05%	467.4178	
	MWCNT_0.025%	518.3996	Al_2O_3_0.025%	455.0074	
	MWCNT_0.01%	437.6996	Al_2O_3_0.01%	449.9571	
	MWCNT_0.005%	393.7943	Al_2O_3_0.005%	383.2251	
3.5	H2O	386.7477	H2O	386.7477	593.05
	MWCNT_0.05%	600.1463	Al_2O_3_0.05%	472.4684	
	MWCNT_0.025%	578.3186	Al_2O_3_0.025%	440.3795	
	MWCNT_0.01%	457.8765	Al_2O_3_0.01%	435.6709	
	MWCNT_0.005%	440.6966	Al_2O_3_0.005%	393.8884	

Table 8
Thermal efficiency comparison.

Author, Year	**Investigation type, Conditions**	**Efficiency**
Sabiha et al., 2015 [12]	Experimental, ETSC SWCNT/water 0.05% - 0.2%	48.57% - 93.43%
Mahbubul et al.,2018 [13]	Experimental, ETSC SWCNT/water 0.2 vol%	10% increase compared with water
Tong et al., 2015 [16]	Experimental, ETSC MWCNT/water 1%	The efficiency improved by 8% compared with that for water.
Kim et al., 2016[17]	Theoretical, U-tube ETSC MWCNT/water 0.2 vol%	62.8%
Dehaj et al., 2019 [18]	Experimental, heat pipe ETSC MgO/water 0.014% - 0.032%	69% and 77% compared with 60% for water
Mahendran et al., 2012 [19]	Experimental, ETSC TiO_2 /water 2%	42.5% increase compared to water
Ghaderian and Sidik, 2017[23]	Experimental, ETSC Al_2O_3/water 0.06%	36% enhancement, highest 58,65%
Eidan et al.,2018[29]	Experimental, ETSC Al_2O_3 and CuO/acetone 0.025% - 0.05%	34%, 74%, 32% and 73%, respectively
Shady M. Henein and Abdel-Rehim, 2022 [30]	Experimental, ETSC MWCNT/MgO/water 50:50% at 3 L/m	62%
	Experimental, ETSC MWCNT/water 0.05%, 0.025%,0.01%, and 0.005% at 1.5, 2.5, and 3.5 L/m	55%, 53%, 47%, and 39% respectively at 1.5 L/m 69%, 62%, 55%, and 48% respectively at 2.5 L/m 73.5%, 71%, 59% and 52% respectively at 3.5 L/m
	Experimental, ETSC Al_2O_3/water 0.05%, 0.025%,0.01%, and 0.005% at 1.5, 2.5, and 3.5 L/m	44%, 41%, 40%, and 38% respectively at 1.5 L/m 54%, 52%, 51%, and 46% respectively at 2.5 L/m 60%, 54%, 53% and 50% respectively at 3.5 L/m
	Experimental, ETSC MWCNT/ Al_2O_3/water 0.025% MWCNT/0.025% Al_2O_3/water at 1.5, 2.5, and 3.5 L/m	52% at 1.5 L/m 65% at 2.5 L/m 69%at 3.5 L/m

nanofluid by 3.5% while the hybrid nanofluid exceeds the Al_2O_3/water efficiency by 10% which reveals a great improvement in the system's total efficiency.

One of the main goals of this study is to compare the results of the utilized materials with other materials used as a nanofluid or hybrid nanofluid in ETSCs. Table 7 compares the energy efficiency outcomes of the experimental study with the outcomes of the earlier research described in the introduction section.

One of the most improved factors as a result of using nanofluids in ETSCs is the amount of gained heat energy. The given heat energy values for pure water compared with MWCNT/ Al_2O_3 50:50% in the ETSC are presented in Table 8. It shows an increase from a value of 281 W for the case of water to higher values of 432 W, 421 W, 368 W, and 284 W for the concentrations of 0.005, 0.01%, 0.025%, and 0.05%, respectively at a flow rate of 1.5 L/min. When the flow rate is increased to 2.5 L/min the gained energy is also enhanced to 562 W, 518 W, 437 W, and 393 W for 0.005, 0.01%, 0.025%, and 0.05%, respectively concerning 390 W for water. At the highest flow rates of 3.5 L/min, the supplied energy is discovered at its highest values, as their values are 600 W, 578 W, 457 W, and 440 W at 0.01%, 0.02%, and 0.03%, respectively, compared to 386 W for water.

Fig. 10 represents the useful heat gained for pure water compared with MWCNT and Al_2O_3 in the ETSC. The useful heat gain can be expressed as the increasing percentage of the outlet temperature for the same mass flow rate. Using nanoparticles boosts the heat energy supplied by both systems, which is the main goal of this work. The thermal conductivity, heat capacity, and density of the solar collector's working fluids vary when nanoparticles are added. By intensifying heat transmission, increasing the thermal conductivity of the working fluid helps to increase the heat gain of the solar collector.

The heat removal factor (F_R) is the proportion of the collector's actual usable heat energy transferred to the maximum available heat energy and is influenced by the fluid's thermos-physical properties; hence the addition of nanoparticles can enhance it. When the inlet fluid temperature is identical to the ambient temperature, the maximum amount of heat energy may be transported; no heat is lost to the surroundings. Also, because it appears at two parameters in the same equation, the heat removal factor F_R has a double side effect on the collector's efficiency: absorbed energy parameter F_R ($\tau\alpha$) and removal energy parameter F_RU_L. If the F_R value rises, it signifies that more heat energy was absorbed, and the temperature of the outflow fluid increased. Also, as the temperature of the output fluid rises, the temperature of the collector's absorber plate rises, increasing heat loss with the ambient temperature.

To determine the maximum available energy that may be converted to usable heat, it is also necessary to study the exergetic efficiency of the ETSC. The exergy efficiency of solar systems refers to the exergy flow of the generated usable heat to the incident solar irradiation flow. Exergy analysis is a thermodynamic tool used to assess each energy source based on its properties, most commonly on its temperature levels. The exergy analysis is also used as an indicator to characterize and examine the investment opportunities of sustainable and green technology as well as renewable energy sources. Exergy helps in improving inefficiencies and reducing thermodynamic drops, which are in line with more environmentally friendly energy systems. Furthermore, it can aid in understanding the environmental and financial advantages of energy systems more precisely than energy analysis. By reducing energy losses, improving energy efficiency can lessen its negative effects on the environment.

Prepared nanofluids were tested at mass flow rates of 1.5, 2.5, and 3.5 L/m, with an exergy efficiency of 0.05 wt.% MWCNT, 0.05 wt.% Al_2O_3, and the hybrid MWCNT/ Al_2O_3 (50:50%) nanofluids were determined.The addition of nanoparticles and an increase in mass flow rate improved the exergy efficiency. as shown in Fig. 11. For the same flow rate used in ETSC, the highest enhancement of the exergy efficiency is 51%, 44%, and 38% for MWCNT/water nanofluid, hybrid MWCNT/

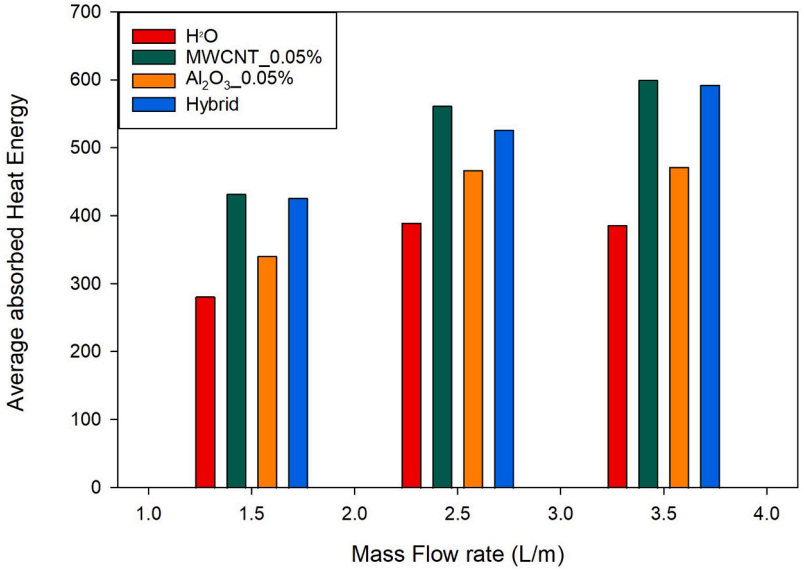

Fig. 10. Variation of the ETSC average absorbed heat energy at 1.5 L/m, 2.5 L/m, 3.5 L/m for water, 0.05%MWCNT, 0.05%Al_2O_3, hybrid MWCNT/ Al_2O_3 50:50%.

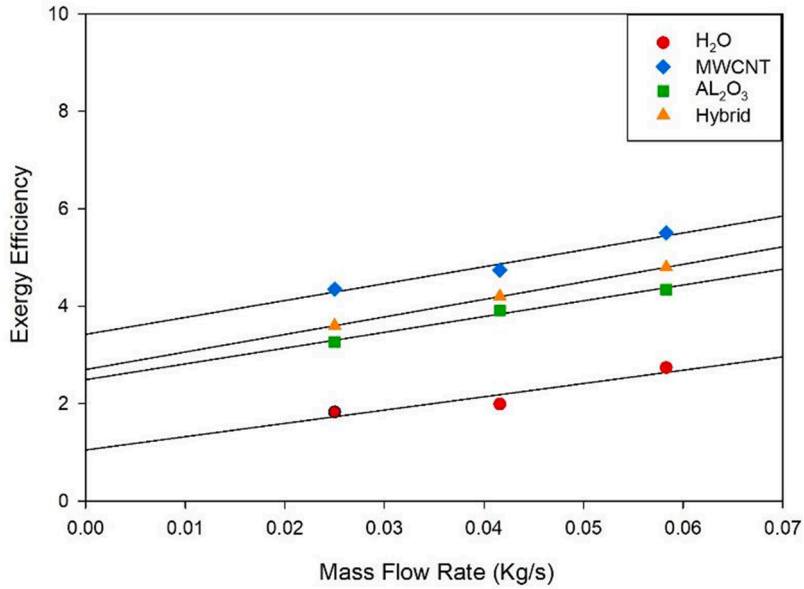

Fig. 11. ETSC exergy efficiency at different mass flow rates.

Al_2O_3 (50:50), and Al_2O_3 /water nanofluid compared to water, respectively. It can be concluded that hybrid nanofluid has improved the exergy efficiency higher than the Al_2O_3 /water nanofluid but, still less than the MWCNT/water nanofluid.

The study employed different types of nanofluids for enhancing the thermal performance of solar collectors. The employed fluids included MWCNT, Al_2O_3, and the hybrid MWCNT/ Al_2O_3 50:50%. The general trend in the experiment was increasing efficiencies with increasing concentrations of the nanofluids. Also, the efficiency was directly affected by the flow rate of the fluids. Given in Fig. 12, the 3D surfaces illustrate the general trend of efficiencies with the two studied parameters; concentration and flow rate, which indicates the effect of high flow rate and concentration on the total efficiency for MWCNT and Al_2O_3. The MWCNT samples generated better efficiency results for all three composite fluids used in the experiments.

4. Collector size reduction

Utilizing solar collectors primarily aims to increase the effective output of these collectors while lowering the cost of production. Fig. 13 shows a comparison between the reduced percentage in ETSC for the three studied nanomaterials.

The use of nanofluids as a working fluid can improve energy production and reduce the amount of used glass and copper used in the manufacturing process of solar collectors in addition to lowering emissions into the environment. It is concluded from Figs. 12 and 13 that the collector's efficiency and size reduction percentage are highly influenced by main three factors which are the used material, the flow rate, and the concentration of the used nanoparticles in the working fluid.

The highest size reduction percentage was 27% reported for MWCNT/water at 3.5 L/m compared to 25% for hybrid nanofluid, and 22% for Al_2O_3. These results reveal that using MWCNT/AL_2O_3/water 50:50% is highly recommended in ETSCs for the system's efficiency

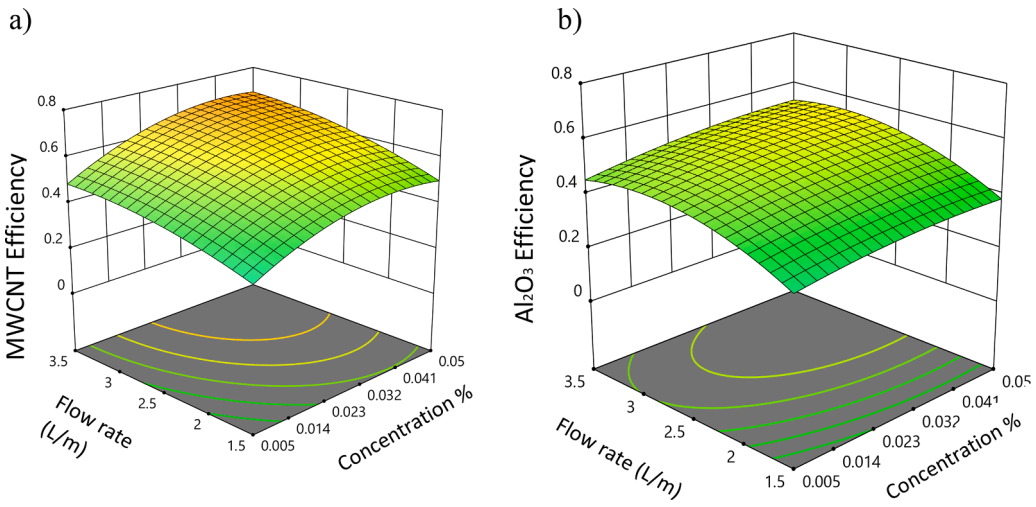

Fig. 12. 3D Illustration for flow rate and radiation effect of a) MWCNT and b) Al_2O_3 on the ETSC efficiency.

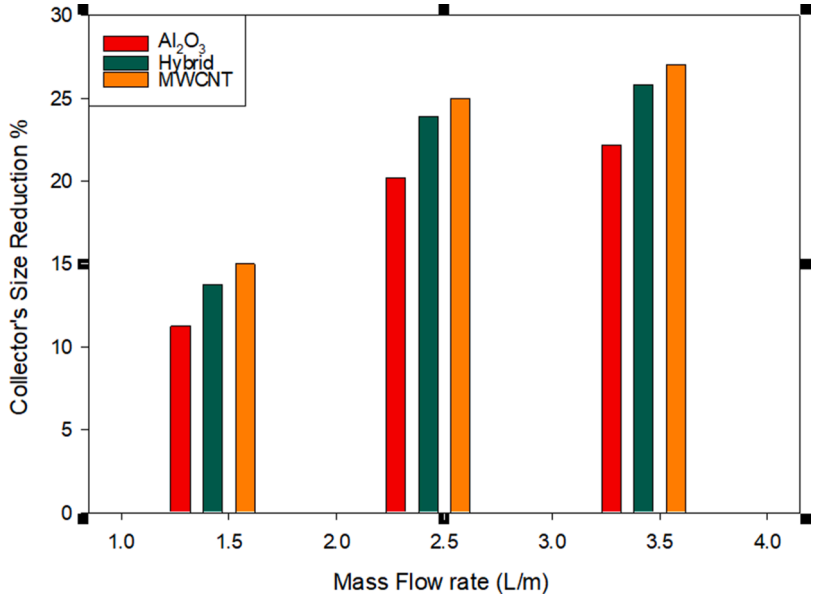

Fig. 13. ETSC size reduction percentage for 0.05% MWCNT, 0.05%Al_2O_3, and hybrid MWCNT/Al_2O_3 50:50%.

enhancement and cost reduction improvement.

5. Conclusion and future work

An experimental study was performed on a variety of nanofluids to improve the thermal performance of Evacuated Tube Solar Collectors. MWCNT, Al_2O_3, and a hybrid MWCNT/ Al_2O_3 (50:50 percent) were examined. The basic finding is that

- The concentration of nanoparticles and the fluid flow velocity have a direct impact on ETSC efficiency.
- For all three composite fluids utilized in the trials, the MWCNT has the highest efficiency.
- The average efficiency of MWCNT was approximately 8% greater than Al_2O_3 under the same experimental conditions.
- This research indicates that replacing half of the Al_2O_3 with MWCNTs (50:50) increases efficiency by an average of 20% compared to that reported for Al_2O_3, and this percentage is affected significantly by increasing the fluid's mass flow rate, recommending that 50% of the MWCNTs can be replaced with the more cost-effective and eco-friendlier Al_2O_3.
- It is recommended to study the impact of different volume fractions of MWCNT/ Al_2O_3 and study the rheological behavior of nanofluids. In addition, there is a need to emphasize the stability of different nanofluids.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Engy Elshazly reports equipment, drugs, or supplies was provided by The British University in Egypt. Engy Elshazly reports a relationship with The British University in Egypt that includes: employment.

Data availability

Data will be made available on request.

Acknowledgements

The authors are extremely grateful to the Centre of Renewable Energy (CRE) at the British University in Egypt for providing the experimental apparatus and equipment to carry out the research.

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