



Comprehensive Numerical Investigation on the Thermal and Energy Performance of Flat Plate Solar Collectors Utilizing Different Types of Nanofluids Combined with Advanced Nanocoating Technology

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ABSTRACT

A new fluid called nanofluid has the potential to greatly enhance the efficiency of traditional fluids in heat transport. Using (CuO/water, MWCNT/water, and CuO+MWCNT/water (80:20%)) nanofluids. This numerical study used six volume fractions of different nanoparticles (0, 0.01, 0.02, 0.03, 0.04, and 0.05%) and six different volumetric flow rates (0.25, 0.5, 0.75, 1, 2 and 3 L/min) for each of these concentrations. Using (MWCNT/water) as a nanofluid yielded the maximum efficiency (76.8%, 78.3%, and 83.1%) for volume fraction of (0.03, 0.04 and 0.05) respectively, at a volumetric flowrate of (3 L/min). At the same volumetric flow, however, the base fluid (water) had a lower efficiency of (55.5%). At volumetric flowrate (3 L/min), (CuO/water) attained median efficiency (61.1%, 62.6%, and 64.2%) for volume fractions (0.03, 0.04, and 0.05), respectively. At a volumetric flowrate of (3 L/min), the hybrid nanofluid (CuO+MWCNT/water) (80:20%) had efficiencies of (77.7%, 79.1%, and 79.5%) for volume fractions of (0.03, 0.04 and 0.05%), respectively. The use of hybrid nanocoating technology improves the system efficiency in three nanofluids (CuO/water, MWCNT/water and CuO+MWCNT/water), the highest efficiency was recorded at a concentration of (0.05%) and a volumetric flow rate of (3 L/min) where were (70.4%, 88.4% and 86.1%), respectively.

1. Introduction

Energy has become increasingly important due to the rapid growth of the global economy and the

continuous increase in population, as the demand for energy resources is directly linked to human industrial and living needs. Physically, energy is the primary driver of all vital and technical activities,

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transforming into various forms such as thermal, mechanical, and radiant energy to meet the demands of industrial and technological development. Therefore, the sustainability of energy resources has become one of the most important challenges facing the scientific and engineering community in the modern era [1]. On the other hand, reliance on fossil fuels leads to numerous environmental problems, most notably the emission of carbon dioxide (CO_2), one of the most significant greenhouse gases, causing global warming. The combustion of this type of fuel leads to the emission of several gases, most notably nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), in addition to fine particulate matter, which contribute to air pollution, acid rain, and ecosystem degradation. Continued reliance on fossil fuels not only threatens environmental balance but also exacerbates global climate change, making the transition to renewable and clean energy sources an urgent necessity to ensure energy sustainability and protect the environment [2]. Accordingly, experts recommend the use of renewable energy sources such as solar, geothermal, and wind energy as effective solutions to mitigate these environmental problems [3]. One type of solar energy device that has been developed using a variety of materials and designs is the flat plate solar collector (FPSC). The design of this collector is a major factor influencing its thermal performance, determining heat distribution, solar radiation absorption efficiency, and thermal energy loss. Additionally, the choice of materials used for the plate and tubes, as well as their geometric arrangement, play a significant role in improving the thermal efficiency of the collector, making it a popular choice for residential and small- to medium-sized industrial heating applications [4], [5].

Many researchers have applied a variety of modifications and designs to improve the performance of solar power systems, including flat plate solar collectors (FPSC) [6]. The use of nanofluids is an effective method for enhancing heat transfer in flat plate solar collectors (FPSC). Nanoparticles dispersed in the fluid increase thermal conductivity and reduce flow resistance, improving the efficiency of heat transfer from the absorber plate to the working fluid. This approach contributes to enhancing the thermal performance of the collector and increasing the amount of energy extracted from solar radiation, making it a promising option for heating, water desalination, and concentrated solar power applications [7], [8]. For example, some researchers studied the effect of (SWCNT) nanofluids on (FPSC) and found that the heat transfer coefficient increased by (15.33%) compared to pure water [9].

Solar water heaters with flat plates (FPSWH) were numerically analysed. The findings suggest that (FPSWH) may achieve a maximum thermal efficiency of (83.9%) at a mass flow rate of (0.06 kg/s). A volume fraction (0.03%) raised the exit temperature by (7.2%) at a lower mass flow rate [10]. It was shown that the collector's efficiency rose by (23.6%) at the ideal flow rate of 2 L/min) When (Al_2O_3 /water) nanofluid with a volume fraction of (0.1%) was used at mass flow rates of (1, 2, and 4 L/min). In comparison to water, it was discovered that employing (0.1 vol.%) of (Al_2O_3 /water) nanofluid as a heat transfer fluid (HTF) enhanced efficiency by (21.9%) [11]. Additionally, energy efficiency increased by (56.9% and 49.6%) when using (0.1 vol.%) (Al_2O_3 /water) and (0.5 vol.%) (CuO /water) nanofluids, respectively [12]. Investigated the energy, financial, and environmental advantages of using (CeO_2 /water) nanofluid at flow rates of (1-3 L/min) and volume fractions of (0.01-0.1%). The efficiency increased by (20.07%), and the collector area decreased by (24.52%) at (0.05%) volume fraction and (2 L/min) volume flow rate, which led to (175 kg) less (CO_2) and a longer pack return time [13]. Studies have shown that using distilled water with multiwalled carbon nanotubes (MWCNTs) is more effective in natural cycle solar collectors (FSWH) than forced-cycle ones. The (FPSWHs) achieved the highest energy efficiency increases, reaching (34.13% and 23.35%), when using volume fraction (0.1% and 0.05%) for (MWCNT/water) at a flow rate of (3.5 L/min) [14]. By employing volume fraction (0.2%) of single-walled carbon nanotube (SWCNT/water) nanofluid, the solar collector's efficiency was raised by (10%) [15]. Determined that the (MWCNT/water) nanofluid offered the greatest energy efficiency gain when compared to (Al_2O_3 /water, TiO_2 /water, Gr/water, CuO /water, and SiO_2 /water) nanofluids [16]. Examined how different turbulence-inducing elements affect solar collectors. discovered that, in comparison to the simple condition, the thermal efficiency of different shapes could increase by as much as (27.6%) [17]. Some researchers have investigated passive methods for improving heat transfer, and the results have shown that using twisted square wires can significantly increase heat transfer, although it also increases friction loss compared to smooth-walled tubes [18]. Investigated tubes with cone loop turbulators and twisted tape swirl generators and found that using this technique can raise the thermal efficiency by (4-8%) and the Nusselt number by (4-10%), respectively [19]. Discovered that replacing the base fluid with (Fe_3O_4 /water-ethylene glycol) (50:50) nanofluid can

boost the thermal efficiency of (FPSC) by (15.27%) [20].

There are applications for nanofluids outside solar systems. By employing these techniques, numerous researchers have enhanced the performance of numerous energy systems, such as heat exchangers, tubes, cavities, etc. These investigations illustrate the significance of turbulators and nanofluids in thermal systems [21], [22], [23], [24]. Some researchers have numerically studied the thermodynamic behaviour of (CuO/water) nanofluids inside a tube equipped with a turbulator. The results showed that using different types and shapes of turbulators can adequately improve the performance of flat plate solar collectors (FPSC), depending on the nanofluid flow rate [25]. Conical diffusers and nanofluids were used to evaluate heat transfer enhancement in solar collectors. Numerical analyses were performed on the thermal and hydrodynamic performance of the tube equipped with conical diffusers. The results showed significant improvements in thermal performance when using conical diffusers, silicone oil instead of pure oil, and carbon nanotubes, with thermal efficiency increasing by (11.5%) and power efficiency by (18.2%) over the evaluation range of (0.9 to 1.82) [26]. Flat plate solar collectors (FPSC) with scattering were studied, and their hydrodynamic and thermal performances were evaluated using numerical analysis [27]. Turbulator devices' benefits and drawbacks were acknowledged. A novel (FPSC) was demonstrated, and a quantitative evaluation of its hydrothermal performance was conducted. Additionally, the friction factor and the resulting variations in heat transmission. The findings demonstrated that the (HTC) could be raised to (78.25%) by altering the flow direction in wavy tubes using (CuO/water) nanofluid (4%) [28].

One of the notable methods for improving the thermal performance of a solar collector is the use of hybrid nanofluids. These fluids combine the advantages of several different nanoparticles, resulting in significantly increased heat transfer efficiency. Hybrid nanofluids also offered higher stability compared to mono nanofluids and reduced particle settling, preserving the fluid's properties for a longer period. Furthermore, combining different types of nanoparticles reduces the number of expensive materials required, thus lowering manufacturing and maintenance costs, making them a practical and promising option for solar energy applications [29], [30], [31]. According to [32] the energy and energy efficiency of the (CuO/water, MgO/water, CuO-MWCNT/water, and MgO-MWCNT/water) as mono and hybrid nanofluids were

(69.11%, 70.55%, 70.63% and 71.54%), respectively. The (MgO-MWCNT/water) hybrid nanofluids performed (25.1%) better than conventional nanofluids in terms of maximum vitality and energy efficiency. At a volume fraction of (0.02%) and a flow rate of (2 L/min). These results highlight the effectiveness of the hybrid nanofluids in improving heat transfer and overall collector performance [33]. A study was conducted on the energy and exergonic performance of (Al_2O_3 /water) mono nanofluid and (Al_2O_3 -Fe/water) hybrid nanofluid in flat plate solar collectors at volume fractions of (0.05%, 0.1%, and 0.2%). The results showed that the (Al_2O_3 -Fe/water) hybrid fluid achieved higher thermal efficiencies compared to (Al_2O_3 /water), with differences of (1.79% and 2.16%) at volume fraction (0.1%). The study also revealed that the energy efficiencies of the hybrid fluids were (5.7% and 6.9%), respectively, highlighting the potential of hybrid nanofluids to enhance solar collector performance [34]. Researchers investigated the effect of (SiO_2 /water) nanofluids on the thermal and electrical performance of a domestic photovoltaic-thermal (DPVT) system. The results showed that increasing the nanoparticle concentration improved thermal and electrical efficiency, while increasing the particle diameter decreased the overall efficiency. The study also found that using a (3 wt.%) nanofluid with particle diameters of (11–14 nm) increased the overall system efficiency by (7.76%) compared to the base fluid, demonstrating the potential of nanofluids to enhance the efficiency of (PVT) systems [35]. The study focused on the design and manufacture of a solar still for producing fresh water, tailored to the climatic conditions of Ahvaz, to address the city's growing water scarcity problem. The study adopted a two-slope solar still after comparing several different designs. A thermal model was developed, incorporating various heat transfer mechanisms such as radiation, conduction, evaporation, and condensation, to predict the system's performance and analyse its thermal behaviour under diverse operating conditions. The governing equations were simulated using MATLAB software to determine the optimal device dimensions before manufacturing. The experimental results showed that the solar still achieved a yield of (0.98 L/m²) of fresh water during a winter test on January 4th, confirming the feasibility of using this type of solar still to provide fresh water in water-scarce regions [36]. One study investigated the design and evaluation of a novel, helical, stationary solar collector aimed at improving solar energy conversion to thermal energy. The study was conducted experimentally according to ASHRAE

standards, using water as the working fluid under the climatic conditions of Ahvaz, southern Iran. The results showed that the helical solar collector achieved an average thermal efficiency of approximately (53%), indicating its potential as a highly efficient solar water heater. The study also demonstrated that increasing the water mass flow rate further enhanced the collector's thermal efficiency [37].

This work aims to conduct a comprehensive numerical study to improve the thermal performance of (FPSC) by using (CuO/water) and (MWCNT/water) nanofluids, as well as (CuO+MWCNT/water) hybrid nanofluid. The study focuses on evaluating the effect of these fluids on heat transfer, analysing the energy and economic efficiency of the collector, and considering the environmental aspects associated with the use of nanofluids. Through this research, the goal is to provide a better understanding of how to improve the performance of solar collectors using advanced technologies, contributing to increased solar energy utilization efficiency and reducing the environmental impact associated with conventional thermal systems.

2. Methodology

This section describes and investigates the mathematical modelling and numerical simulation of the (FPSC). For mono and hybrid nanofluid, heat transfer and fluid dynamics' governing equations considering the three fundamentals of physics (mass, momentum of fluid, and energy) were presented. The provided numerical solution was developed using COMSOL Multiphysics (version 6.1). The model used in the simulation is introduced, and details about it, such as its geometry, parameters, and FPSC) materials, are provided.

This study relies on a three-dimensional numerical simulation of the geometry of a flat plate solar collector (FPSC) to accurately analyses its thermal performance. Figure 1 illustrates the geometry of the studied solar system, including the absorber plate and the tubes passing through the working fluid. (CuO/water) and (MWCNT/water) nanofluids, as well as (CuO+MWCNT/water) hybrid fluid, were used as heat transfer media within the collector. The study aims to compare the thermal performance results of the base fluid (pure water) with those of the mono nanofluids and hybrid fluids, to determine the effect of adding nanoparticles on the heat transfer and energy efficiency of the collector, and to understand the potential benefits of using nanofluids to improve the efficiency of conventional

solar energy systems. A two-model consisting of (CuO, MWCNT, and water) were used to represent the behavior of the hybrid nanofluid within the solar collector. To ensure the accuracy of the numerical calculations, an integrated mesh was created to cover the entire study scope, taking into account the quality of the elements to reduce numerical errors. A pressure-based method was used to simulate the continuous flow of the (CuO+MWCNT/water hybrid fluid, taking into account the mixing and phase effects. The effect of the fluid flow rate, ranging from (0.25 to 3 L/min), on the thermal performance of the collector was analyzed. The effect of the volume fraction(ϕ), ranging from (0.01% to 0.05%) were also studied to evaluate the changes in heat transfer and energy efficiency of the collector under different operating conditions.

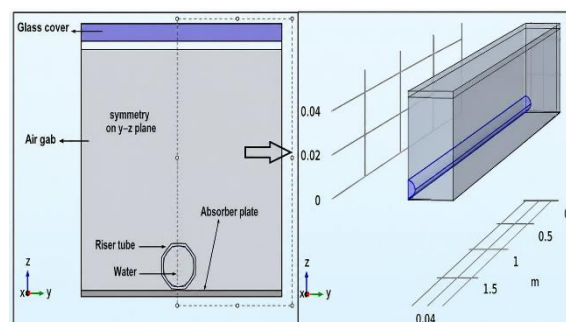


Figure1. Schematic for the CFD model FPSC

2.1 Problem Description

This study deals with the analysis and design of a three-dimensional (3D) flat plate solar collector (FPSC), set at a tilt angle of (30 degrees), which is the optimal angle in most of the studied climatic conditions to improve solar radiation capture during winter. Figure 1 illustrates the conceptual diagram of (FPSC), including the location of the absorber plate, the glass cover, the insulation structure, and the thermal fluid flow channels. The figure also shows the way in which the plate is oriented relative to the sun's rays to obtain the maximum possible amount of direct and indirect solar radiation. All dimensions and engineering specifications of the solar collector are specified in Table 1 and Table 2, which include the plate length and width, plate and insulation thickness, diameter and types of fluid-carrying pipes, as well as the type of materials used in each part of the collector, including the thermal conductivity coefficient of each material. This information is essential to clarify the design characteristics adopted during the simulation and thermal analysis process. Figure 2 shows the domain of evaluation used in the three-dimensional

numerical modelling and simulation process. This includes the geometric boundaries to which initial and boundary conditions were applied, in addition to the fluid inlet and outlet areas, areas exposed to solar radiation, and thermally insulated surfaces. These explanations are important for understanding the hypothetical working environment adopted in studying the thermal and hydraulic performance of the solar collector under the specified conditions.

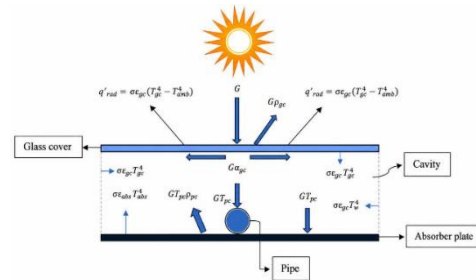


Figure 2. Domain of investigation

Table 1. The specifications of the (FPSC)

Specification	Details
Dimension of collector	(2000x1000x80) mm
Glass cover thickness	3.2 mm
Transmittance of glass	95%
Aluminum Absorber plate thickness	0.4 mm
Absorber plate absorptivity	95%
Absorber emissivity	5%
Copper header tube diameter	22 mm / 2 headers
Copper riser tube diameter	8 mm / 7 risers
Space between riser tube	110 mm
Fiber glass insulation thickness	30 mm
Fiber glass density	60 kg/m ³
Air gap spacing between glass and absorber	25 mm

Table 2. The proposed FPSC's dimensions and material characteristics [4]

Part	Material	ρ	k	C_p
Cover	Glass	60	0.78	840
Cavity	Air	1.25	0.0242	1006.43
Absorber plate	Aluminium	2719	202.4	871
Pipe	Copper	8978	387.6	381

2.2 Glass Cover

The effect of the solar collector's glass cover depends on the external airflow around it, with both heat transfer and radiative convection being considered when studying its thermal performance. The thermal coefficient in Equation 1 contains the heat transfer coefficient that reflects the efficiency of the cover in transferring heat between the cover and the working fluid, taking into account the effect of the external wind speed, which varies with time. This temporal variation in wind speed directly affects the heat loss through the glass cover and thus plays an important role in determining the thermal efficiency of the collector. Therefore, including these factors is essential to obtain an accurate assessment of the collector's thermal performance under various realistic operating conditions [38].

$$h_{\text{ext}} = 5.7 + 3.8V_{\text{wind}} \quad (1)$$

2.3 Air Cavity

The effects of buoyancy and convection within the collector airspace were studied using the Boussinesq approximation. This approximation simplifies the equations of thermal motion while preserving the effect of density differences on airflow due to thermal gradients. Using this approach, it is possible to analyse how natural convection currents form within the airspace and their effect on heat transfer from the absorber plate to the working fluid, contributing to a better understanding of the thermal performance of the collector under realistic operating conditions. The air properties shown in Table 3 were used to simplify the governing equations and facilitate numerical representation. This approximation is suitable for relatively small temperature differences, as it allows the fluid density to be considered constant in all equations except the buoyancy-induced impulse equation, achieving acceptable accuracy while reducing the cost of numerical calculations. To reduce heat losses and

ensure a more accurate representation of boundary conditions, the side surfaces were assumed to be adiabatic, meaning no heat transfer occurs across them. These surfaces were also assumed to have grey and diffuse radiative properties, a common assumption used in thermal models to simplify calculations of radiation heat transfer within cavities, as it reflects the realistic behaviour of many engineering materials at intermediate temperatures.

Table (3). Property of air [39].

ρ	β	C_p	k	μ
1.25	0.0033	1006.43	0.0242	1.478×10^{-5}

2.4 Working Fluid

The absorber plate was connected to the copper tube using a copper solder joint to ensure efficient heat transfer via thermal conduction from the plate to the tube. A Newtonian fluid was used in the study, along with a (3D) model and unsteady-state conditions, to realistically simulate the heat transfer and distribution mechanism. The tube was studied at a steady inlet flow and laminar flow regime, which is suitable for low velocities and small concentrations of nanoparticles. The selected working fluids included pure water as the base fluid, in addition to nanofluids (CuO/water and MWCNT/water), as well as a hybrid nanofluid composed of (CuO + MWCNT/water) (80:20%) using water as the base medium. A constant inlet temperature was set at (293 K), with different nanoparticle concentrations ranging from (0.01% to 0.05%) by volume. It was assumed that the low temperature gradient and the changing flow direction within the tube promote homogeneous dispersion of the nanoparticles, improving convective heat transfer properties and increasing the overall heat transfer coefficient. The use of metallic nanoparticles (MWCNT) enhances thermal conductivity due to the high thermal conductivity of copper, while multiwalled carbon nanotubes (CuO) add high stability to the nanosuspension and lower aggregation resistance. The hybrid mixture (CuO+MWCNT) provides a combination of improved thermal conductivity and thermodynamic stability. Details of the thermal radiation conditions and the thermal properties of the exposed surfaces are shown in Table 4, which includes the parameters required to define the boundary conditions in the numerical model.

Table 4. Conditions of the irradiated surfaces' boundaries [40]

Surface	ε	A	τ
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Cavity layer	0.05	-	-
Glass cover	0.88	0.05	0.93
Absorber plate	0.05	0.95	-

3. Mathematical Modelling

Flat plate solar collectors are an effective solution for converting solar energy into thermal energy, enhancing the use of renewable energy sources. The efficiency of these systems depends largely on the behaviour of fluid flow within the collector, with the direction and speed of fluid flow playing a vital role in optimizing heat transfer processes.

To analyse fluid flow in a solar collector, the three governing equations are used, which include the continuity, momentum, and energy equations. These equations reflect the basic principles of aerodynamics and help understand how various factors, such as temperature and pressure, affect system performance. By applying these equations, fluid behaviour can be predicted, and critical points affecting the efficiency of the solar collector can be identified.

In this context, we will discuss the use of the three governing equations to describe fluid flow within a solar collector, allowing us to better understand thermodynamic processes and enhance the potential for optimizing solar collector designs to achieve higher performance [32], [41].

Continuity:

$$\frac{\partial \rho_{hnf}}{\partial t} + \frac{\partial}{\partial x_j} (\rho_{hnf} u_j) = 0 \tag{2}$$

Momentum:

$$\rho_{hnf} \left(\frac{\partial u_i}{\partial t} \right) + \rho_{hnf} \left(\frac{\partial u_i u_j}{\partial x_j} \right) = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} (\mu_{hnf} \frac{\partial u_i}{\partial x_j}) \tag{3}$$

Energy:

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j} (u_j T) = \frac{k_{hnf}}{\rho_{hnf} C p_{hnf}} \left(\frac{\partial^2 T}{\partial x_j^2} \right) \tag{4}$$

Equations (5-12) [31], [38], [42], [43] were used to calculate the thermophysical properties of the working fluids used. The temperature-dependent properties of these properties were taken into account, as this is important for accurately representing buoyancy effects, especially in cases of natural and mixed convection within cavities or pipes. Including the thermal variation of properties such as density (ρ),

specific heat capacity (C_p), viscosity (μ), and thermal conductivity (k) provides a more realistic representation of the physical phenomena, as these variables directly control the Laplace number, Reynolds number, and Prandtl number, which influence the heat transfer mechanism and flow behaviour. In addition, the reference values and basic parameters of the thermophysical properties of different working fluids (water, nanofluids, and hybrid fluid) are documented in Table 5, which represents the basis for numerical modelling and validation of computational results.

Density:

$$\rho(T) = 9.9018 \times 10^6 T^3 - 0.012 T^2 + 4.9694 T + 424.4761 \quad (5)$$

$$\rho_{hnf} = \rho_1 \phi_1 + \rho_2 \phi_2 + \rho_f (1 - \phi_1 - \phi_2) \quad (6)$$

Specific heat capacity:

$$C_p(T) = 1.2677 \times 10^{-6} T^4 - 0.0018 T^3 + 0.9363 T^2 - 220.4437 T + 23648.34 \quad (7)$$

$$(C_p)_{hnf} = C_{p1} \phi_1 + C_{p2} \phi_2 + (C_p)_f (1 - \phi_1 - \phi_2) \quad (8)$$

Viscosity:

$$\mu(T) = 1.511 \times 10^{-11} T^4 - 2.2057 \times 10^{-8} T^3 + 1.2075 \times 10^{-5} T^2 - 0.0029 T + 0.2699 \quad (9)$$

$$\mu_{hnf} = \frac{\mu_f}{(1 - \phi_{np1} - \phi_{np2})^{2.5}} \quad (10)$$

Thermal conductivity:

$$k(T) = 1.7804 \times 10^{-8} T^3 - 2.8801 \times 10^{-5} T^2 + 0.0142 T - 1.5495 \quad (11)$$

$$k_{hnf} = \frac{(k_1 + k_2) + 2k_f - 2\phi_1(k_f - k_1) - 2\phi_2(k_f - k_2)}{(k_1 + k_2) + 2k_f + \phi_1(k_f - k_1) + \phi_2(k_f - k_2)} \quad (12)$$

Table 5. Working fluids thermophysical properties [44], [45], [46]

Material	ρ	k	C_p
Water	998	0.613	4180
Al_2O_3	3970	40	765
MWCNT	2600	3000	730

Equations (13) to (15) are used to get the collector efficiency (η), friction factor (f), and Reynolds number (Re), respectively [38], [45].

$$\eta = \frac{Q_{out}}{GA_c} \quad (13)$$

$$f = \frac{64}{Re} \quad (14)$$

$$Re = \frac{\rho U_{in} D_h}{\mu} \quad (15)$$

3.1 Boundary Conditions

The glass cover of the solar collector is the first element to interact with the incident solar radiation. A portion of the solar energy is reflected into the surrounding medium due to the difference in reflection and refraction coefficients between the air and the glass. In contrast, the spectral transmittance of the glass allows another portion of the solar radiation to pass into the collector, particularly at short-wavelength radiation. Additional energy is then lost through convection and thermal radiation between the surface of the glass cover and the surrounding medium, reducing the net amount of energy entering the cavity. The absorber plate plays the primary role in converting solar energy into thermal energy. Thanks to its high absorptivity, it absorbs a large portion of the radiation. This thermal energy is partially transferred to the tubes passing behind the plate via thermal conduction, heating the working fluid. Another portion is dissipated within the cavity in the form of long-wave radiation and natural convection from the upper surface of the plate. Some of the radiation penetrating the cavity is reflected multiple times between the interior surfaces before being absorbed or dissipated. Based on these thermal and physical considerations, appropriate boundary conditions include: assuming a semi-transparent and partially reflective glass surface, a highly absorptive and low-reflective absorbing surface, and considering convective and radiative heat transfer at the upper and side surfaces of the cavity [47], [48], [49].

A portion of the intake pipe:

$$u = v = 0, w = U_{in}, T = T_{in} \quad (16)$$

The absorber's bottom:

$$u = v = w = 0, \frac{\partial T}{\partial y} \quad (17)$$

Lateral surfaces:

$$u = v = w = 0, \frac{\partial T}{\partial x} \quad (18)$$

Upon the glass cover:

$$u = v = w = 0, q_w = G \quad (19)$$

3.2 Grid Independence Test

To ensure that the numerical results are independent of mesh density and to eliminate any

potential influence of grid resolution on the solution accuracy, a comprehensive grid independence study was conducted. Four different mesh configurations, namely Normal, Fine, Finer, and Extra Fine, were generated and tested under identical operating conditions. The outlet fluid temperature was selected as the monitoring parameter because it directly reflects the thermal performance of the flat-plate solar collector.

The mesh quality and the number of tetrahedral elements were systematically increased to evaluate the sensitivity of the numerical solution to mesh refinement. As presented in Table 7, the outlet temperature exhibited only minor variations as the mesh density increased. The maximum relative difference between successive mesh refinements was found to be less than (0.1%), while identical outlet temperature values were obtained for both the Finer and Extra Fine meshes. This behaviour indicates that the numerical solution had reached mesh-independent convergence.

Considering the negligible variation in the monitored parameter and the substantial increase in computational cost associated with further mesh refinement, the Finer mesh containing (917,812) tetrahedral elements was selected for all subsequent simulations, providing an optimal balance between computational efficiency and numerical accuracy.

Table 6. Grid independence test results for the numerical model

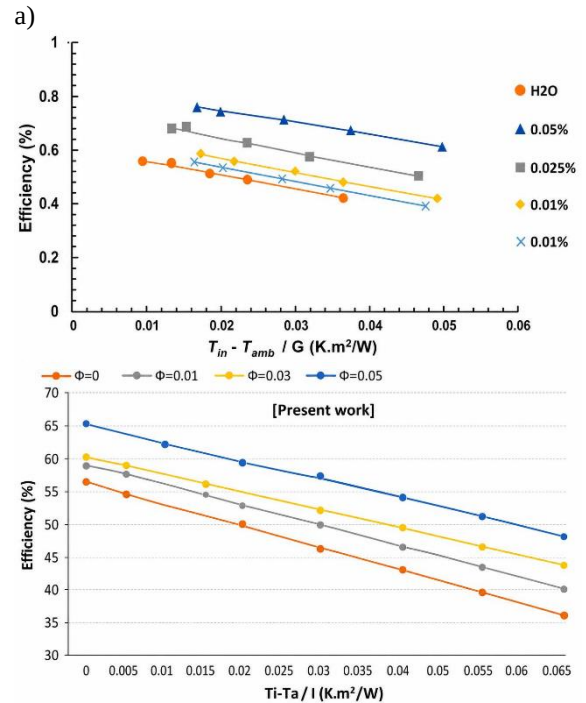
Mesh level	Elements	Mini. Elm. Qual.	Avrg. Ele. Qual.	T _{out} (K)	Rel. Diff. (%)
Normal	279338	0.02281	0.5476	297.44	-
Fine	465573	0.00668	0.5857	297.59	0.050
Finer	917812	0.02346	0.62	297.81	0.074
Extra Fine	2475223	0.02016	0.6619	297.81	0.00

4. Model Validation and Verification

Investigations were conducted into the thermal efficiency of a flat plate solar collector with straight pipes. The findings of the current investigation are confirmed with them at the identical water situation at the boundary.

In order to validate the results of the present work, a comparison between the present results and other previously published works was made, as shown in Figures 3 and 4. Two comparisons were selected to validate the computed present results. The first comparison (Figure 3) was done with [50] to explain the variation of the efficiency of (FPSC) filled

with (CuO/water) nanofluid against $((T_i - T_a)/I)$ for various (ϕ) and $(V=2.5 \text{ L/min})$. While the second one was made with experimental and numerical results (Figure 4) [6], [51] related to (T_{out}) variation against (V) for (FPSC) filled with (MWCNT/water) nanofluid at $(\phi=0.05\%)$. Both comparisons indicate a good match between the present and previously published results. This gives a good indicator of the accuracy of the solution procedure and experimental steps utilized in the present work.



b) Figure 3. Variation of the efficiency of (FPSC) filled with (CuO/water) nanofluid against $\left(\frac{T_i - T_a}{I}\right)$ for various (ϕ) and $(V=2.5 \text{ L/min})$, a) [48] and b) present work

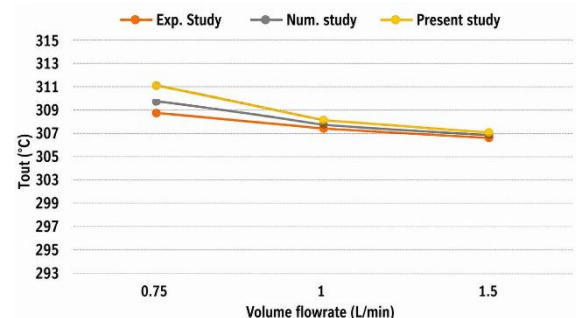


Figure 4. Variation of (T_{out}) of (FPSC) filled with (MWCNT/water) nanofluid for against (V) and $(\phi=0.05\%)$ with both experimental [6] and numerical [49]

5. Results and Discussion

The software program COMSOL Multiphysics (version 6.1) was used to perform numerical results. In order to offer experimental data that examine the impact of varying flow rate, working fluid type, and weather conditions on the performance of a flat plate collector (FPSC), simulation studies are required to confirm the results with those of prior research. This section presents the solution of the mixed convection flow in the pipes as well as the natural convection flow of confined air in the area between the absorber and the glass cover. To validate the numerical solution and the data reduction methodology for each phenomenon, two simplified models have been developed: the Natural Convection Validation model (NCV) for the natural convection process and the Mixed Convection Validation model (MCV) for the mixed convection process.

This study has investigated (3D) (FPSC) functioning under conjugated laminar mixed convection. The tilt angle was (30°) set for the collector. Equations (5-12) introduce water and nanofluid characteristics. Inlet temperatures of (293 K) are used to analyses the issue. Various volumetric flow rates and six different volume concentrations.

Figure 5 shows the temporal variation of both solar radiation intensity and ambient temperature during the test period in Najaf on 15th of January. The peak solar radiation value reached approximately (967 W/m²) at (12:00 P.M.), while the ambient temperature was low in the early morning hours at (9.8°C) and then gradually increased until it reached the peak value (17.5 °C) at (12:00 P.M.). (FPSC) was experimentally tested under wind speeds during the same period, ranging from (1.8 to 3.6 m/s) as shown in Figure 6. (FPSC) was numerically tested under varying climatic conditions, including changes in solar radiation, ambient temperature, and wind speed. The temperature of the water entering the collector was not constant, as the working fluid moves in a closed loop. The water exits the collector at a high temperature, then loses some of its thermal energy during its use for heating, before returning to the collector at a lower temperature. By repeating this process, the inlet temperature of the collector changes continuously over time. The system was operated at a variable volume flow. Physically, the thermal performance of (FPSC) depends primarily on the amount of solar radiation absorbed by the absorbing surface. Increased solar radiation increases the temperature of the fluid exiting the collector, thereby increasing system efficiency. Conversely, higher wind speeds surrounding the collector increase the

rate of heat loss by external convection, reducing overall efficiency. Therefore, the daily variations in solar radiation, air temperature, and wind speed play a pivotal role in determining the actual thermal performance of the collector under the climatic conditions of Najaf.

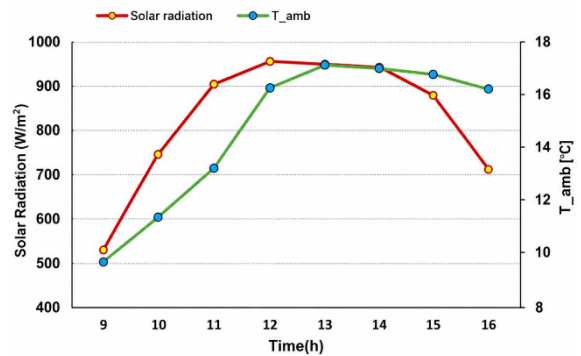


Figure 5. Variation Solar radiation and Ambient temperature with Time in 15th of January

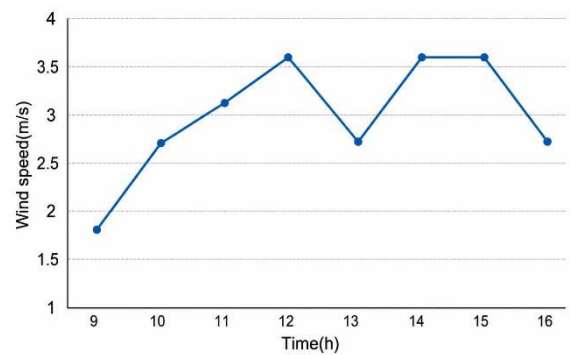


Figure 6. Variation Wind speed with Time in 15th of January

The solid volume fraction, volumetric flow rate, and type of nanoparticles have a significant impact on thermal performance when looking at the performance of (FPSC) employing mono nanofluid made of (CuO/water) and (MWCNT/water), as well as a hybrid nanofluid made of (CuO+MWCNT/water).

5.1 The Effect of Solid Volume Fraction

Increasing the volumetric concentration of (CuO and MWCNT) nanoparticles in the fluid improves the thermal conductivity of the fluid, which facilitates heat transmission inside the solar collector [33], [52]. Excessive concentration, however, might have negative consequences, such as the deposition of nanoparticles inside the collector, which increases

heat resistance and lowers collector performance, for example, [22], [53]. Using (Al_2O_3 , CuO , TiO_2 , ZnO /water) as the working fluid, the nanofluid exhibited higher heat transfer coefficients and energy efficiency. Also, [23], [54] using (TiO_2 , MgO , MWCNT /water) as working nanofluid, the nanofluids enhance the collector's performance, reducing auxiliary energy consumption.

5.2 The effect of volumetric flow rate

An increase in the volumetric flow rate inside the pipe leads to an increase in the temperature difference between the fluid and the absorber plate. This improves heat removal from the solar collector and lowers the temperature of the liquid leaving the system, increasing thermal efficiency as a result. Excessive flow, however, might shorten the liquid's duration inside the collector, which would decrease heat absorption. (Cu + MWCNT s/water) was used as the working fluid in a study with three different flow rates (0.5, 1, 1.5 L/min). The solar collector achieved an efficiency of (68.7%) at a volumetric flow rate of (1.5 L/min) when using the hybrid nanofluid [6], [55]. The usage of (Al_2O_3 /water (0.1wt%), TiO_2 /water (0.1wt%)), and the combination of these two nanofluids will result in an approximate (19%, 21%, and 26%) increase in thermal efficiency, respectively. The volume flow rates were (1.5, 2, and 2.5 L/min).

5.3 The effect of type of Nanoparticles

The type of nanoparticles has a major impact on the solar collector's thermal efficiency, which is based on how much the properties of the particles affect those of the nanofluid [46], [56]. Due to their extremely high thermal characteristics, certain (MWCNT) particles clearly increase thermal efficiency [6]. The usage of (MWCNT) particles, however, has drawbacks since it tends to silt, which impacts fluid flow and necessitates a high pumping capacity. In addition, sedimentation might have an impact on the collection equipment. Additionally, its expenses are extremely high [46]. Although using particles like (CuO) doesn't greatly increase efficiency, it has fewer drawbacks than (MWCNT) and is less expensive [57], [58], [59]. This led researchers to use hybrid nanofluids such as (CuO + MWCNT /water) hybrid nanofluid at different volume fractions to achieve a balance between increasing efficiency, maintaining fluid stability, and reducing the cost of nanomaterials [56].

Nanoparticles increase the liquid's thermal conductivity. This promotes heat transfer from the absorbent surface to the liquid, increasing the

efficiency of the solar collector. The type of particle used has a significant impact on how much performance is enhanced and how much efficiency is raised. When selecting nanoparticles, stability within the base fluid and efficiency enhancement must be taken into account [31].

The effectiveness of the solar collector is decreased when the concentration of nanoparticles increases because the liquid becomes more viscous, increasing flow resistance and possibly requiring more energy to pump [60]. High concentrations may cause nanoparticles to be deposited on the surfaces of the solar collector, increasing thermal resistance and decreasing heat transfer, both of which lower the thermal performance of the solar collector [61].

5.3.1 Effect CuO /water Nanofluid

Using (CuO /water) as a nanofluid significantly improves the efficiency of (FPSC) when compared to the base fluid (distilled water) due to the thermal properties of (CuO), which improve the properties of the nanofluid. The results showed a significant improvement when compared to distilled water as the working fluid. Figure 7 illustrates the use of (CuO /water) as a nanofluid with different volume fractions and volumetric flow rate. The best system efficiency was (64.2%) achieved at a solid volume fraction of (0.05%) and a volumetric flow rate of (3 L/min). This is because increasing the concentration of nanoparticles will increase the density and viscosity of the nanofluid, thus improving thermal conductivity to a greater extent, which in turn will increase the system efficiency. We note that efficiency decreases as the particle concentration decreases, with the lowest efficiency being achieved at a volume fraction of (0.01%). Also, the volumetric flow (3 L/min) provided the best efficiency compared to other volumetric flows because it allows for faster heat exchange and a greater improvement in the convection heat transfer coefficient, which results in extracting a greater amount of energy and prevents the absorber plate from overheating, thus avoiding heat loss to the ambient. (CuO /water) nanofluid demonstrated higher efficiency than the base fluid under the same conditions. This is due to optical absorptivity, where (CuO) particles absorb solar radiation more efficiently than water, increasing heat transfer through the fluid. In addition, it can enhance convection. Using (CuO /water) yields slightly higher thermal efficiency than water at the same flow rate and solar radiation. The differences are not significant due to physical and thermal constraints in the system.

5.3.2 Effect MWCNT /water Nanofluid

Figure 8 shows the effect of using (MWCNT/water) as a nanofluid inside a flat plate solar collector. The efficiency increases dramatically with increasing concentration of particles of (MWCNT), with each increase in nanoparticle concentration, the efficiency increases significantly, reaching a peak efficiency of over (83.1%) at ($\phi=0.05\%$) and a flow rate of (3 L/min). This is because (MWCNT) has a very high thermal conductivity (up to $\sim 3000 \text{ W/m}\cdot\text{K}$), which is much higher than that of (CuO). They also have a very high surface area ratio, which allows for rapid and efficient absorption, storage, and transfer of heat. These particles absorb solar radiation and redistribute it much more efficiently within the fluid, improving both convection and conduction. Efficiency increases with increasing flow rate, and we observe the same pattern as before: efficiency increases with increasing volumetric flow, with the highest efficiency at (3 L/min) for each concentration. This is because the higher flow improves heat transfer by forced convection. It also prevents the sedimentation or aggregation of nanotubes within the fluid and ensures a homogeneous distribution of particles. At low flow rates, the efficiency is low despite the presence of (MWCNT), due to fluid stagnation and increased static thermal resistance. At volume fraction ($\phi=0$) (water only), efficiency is poor at all flow rates because the water alone has limited thermal conductivity, and the flow rate does not compensate for the poor thermal properties. With volume fraction (0.01% - 0.02%), a significant jump in efficiency, especially at (2 and 3 L/min), even small concentrations of (MWCNT) make a significant difference due to their high thermal conductivity. With volume fraction (0.03% - 0.05%), continuous improvement, showing the highest possible efficiency. The particles conduct heat very rapidly, provided there is sufficient flow to prevent sedimentation or agglomeration. The efficiency is greatly increased when using (MWCNT/water) nanofluid, and the reason for this is the superior thermal properties of (MWCNT), specifically the thermal conductivity ($3000 \text{ W/m}\cdot\text{K}$), the solar absorptivity is very high, the surface to volume ratio is very large, and the ability to improve convection is excellent. It was observed that the difference between (MWCNT/water) and (CuO/water) is very large. This is due to several reasons, including super thermal conductivity; the conductivity of (MWCNT) is more than (100 times) that of (CuO). And the enhanced thermal convection, as (MWCNT), not only enhances thermal conductivity but also helps in exciting micro-convection currents, which greatly increases the heat

transfer rate. Also, due to their optical properties, (MWCNT) absorb solar radiation with near-perfect efficiency, acting as microscopic heat stores that quickly transfer it to the fluid. Finally, heat distribution within the fluid is more uniform due to the nanoscale, lattice-like properties of (MWCNT), which allow for uniform heat transfer throughout the fluid. The results showed that (MWCNT/water) nanofluid is clearly the most thermally efficient nanofluid of all types, offering a significant difference in performance even at low concentrations under high volume flow rates. Its superiority is due to its unique thermal and optical properties, which cannot be easily compared to metal oxides such as (CuO) or base fluids.

5.3.3 Effect CuO+MWCNT/water Hybrid Nanofluid

Figure 9 shows the performance of a solar collector using a (CuO+MWCNT/water) hybrid nanofluid. This is one of the most powerful hybrid fluids used in thermal applications. We observe that the efficiency increases clearly with increasing volume fraction of (CuO+MWCNT). At each volume fraction, the efficiency rises gradually, reaching its peak at ($\phi=0.05$), especially with a flow of (3 L/min) where the efficiency reaches about (79.1%). This is because the (CuO+MWCNT) hybrid particles combine the very high thermal conductivity of (MWCNT) and the good stability and high absorptivity of (CuO). This combination results in very high heat transfer due to conduction within the fluid (MWCNT), absorption and conversion of radiation to heat (CuO), and improved flow behaviour and micro-mixing within the fluid. It was found that the efficiency increases with increasing the flow rate, as we saw in the previous cases. As the flow rate increases from (0.25 to 3 L/min), the efficiency increases. The reason for this is that at high flows, the particles are prevented from settling or agglomerating, remain evenly distributed, and the temperature difference between the fluid and the tube surface is reduced, increasing the efficiency of convective heat transfer. Active particles such as (MWCNT) require high flows to achieve their full efficiency without stagnation or local thermal isolation. (CuO+MWCNT/water) hybrid nanofluid gives higher efficiency than water and (CuO), due to the high thermal conductivity of the composite. (CuO+MWCNT/water) hybrid fluid with higher conductivity than either water or (CuO/water). Also, it has a very effective solar absorption capacity. (CuO) has a good thermal absorption capacity for

solar radiation, and when combined with (MWCNT), the fluid becomes almost perfect for converting light into heat. In addition to improving heat distribution and reducing internal resistance, (MWCNT) rapidly disperses heat within the fluid, and (CuO) helps stabilize the flow, resulting in uniform heat transfer. The results showed that the efficiency of the (CuO+MWCNT/water) working fluid was higher than that of all other working fluids except (MWCNT/water) nanofluid. This was due to the lower concentration of (MWCNT) when combined with (CuO), which reduces the proportion of (MWCNT) in the hybrid nanofluid, weakening some of its superior conductive and absorbent properties. The addition of (CuO) also results in a slightly higher viscosity, resulting in higher flow resistance, which may slightly impede heat transfer compared to (MWCNT) alone. The overall absorbance is also lower than that of pure (MWCNT). Although (CuO) is a good absorber, it is not as super as (MWCNT), which acts almost as a black body. The difference in efficiency between (CuO+MWCNT/water) and water or (CuO/water) is very large because (MWCNT) adds a huge heat capacity (due to its conductivity and surface area), which increases the efficiency by up to (15–18%) more than (CuO) alone. In summary, (CuO+MWCNT/water) is one of the best hybrid nanofluids, achieving a thermal efficiency of up to (79.1%). This clearly outperforms water and (CuO/water), but it is still inferior to pure (MWCNT/water). This hybrid nanofluid represents an excellent balance between performance and practicality, and can be an ideal choice for industrial applications that require stability and efficiency.

In conclusion, the different types of working fluids exhibit varying performance as shown in Figure 10. The (MWCNT/water) nanofluid demonstrated the highest efficiency, but it requires greater pumping power and can cause system problems. The (CuO+MWCNT/water) hybrid nanofluid showed high efficiency and better stability than the first type. The (CuO/water) nanofluid exhibited moderate efficiency but very high stability compared to the two types mentioned above.

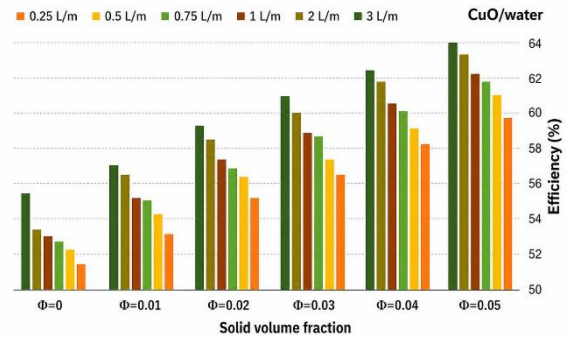


Figure 7. Variation Thermal efficiency with Volume fraction for (CuO/water) mono nanofluid in different volumetric flow rates (0.25-3) L/min

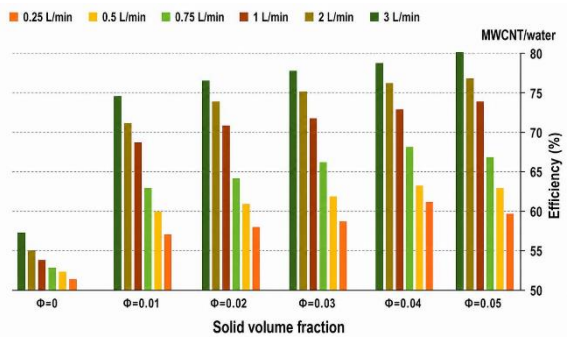


Figure 8. Variation Thermal efficiency with Volume fraction for (MWCNT/water) mono nanofluid in different volumetric flow rates (0.25-3) L/min

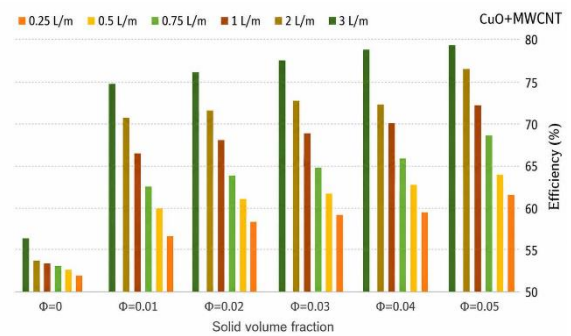


Figure 9. Variation Thermal efficiency with Volume fraction for (CuO+MWCNT/water) hybrid nanofluid in different volumetric flow rates (0.25-3) L/min

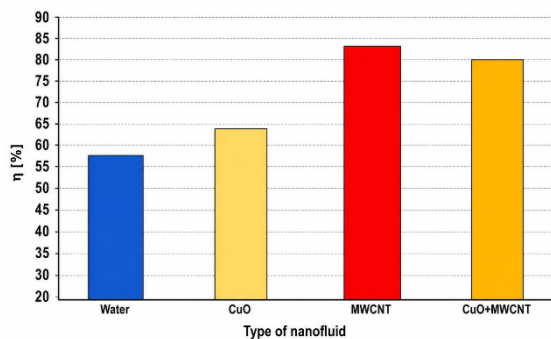


Figure 10. Comparison of efficiency for various working fluids at ($\phi=0.05\%$) and ($V=3$ L/min)

5.4 The Effect of Nanocoating

The nanocoating used in this study is a (0.5 mm) thin layer of (CuO+MWCNT/EG) hybrid nanomaterial. It is coated inside the tubes of a flat-plate solar collector through which the working fluid passes. The hybrid nanocoating acts as a thermally modified surface with high absorbance and high thermal conductivity. Nanocoating absorbs more solar radiation due to the unique optical properties of nanomaterials, such as broad-spectrum absorption, especially (MWCNT), which has an absorptivity close to (0.99) for the entire solar spectrum. This increases the amount of heat transferred to the fluid. Nanocoating improves convective heat transfer from the wall to the fluid. Nanomaterials such as (MWCNT) and (CuO), which have good thermal conductivity, increase the amount of heat transferred from the wall to the fluid more quickly and uniformly. The temperature difference between the tube wall and the fluid surface is reduced, which improves the rate of convective heat transfer. In addition, the nanocoating reduces heat loss within the tube, acting as a thermal barrier against radiation, particularly in copper tubes. It also prevents some of the heat loss that would otherwise escape outside the tube. The nanocoating layer modifies the temperature distribution inside the tube, reducing the longitudinal temperature variation along the tube. The effect of adding nanocoating on thermal efficiency with different types of working fluids was (5-8%) as shown in Figures 11 to 13. At low volume fraction (0.01%), the coating effect is good but limited because there are few nanoparticles in the fluid. At medium concentrations (0.03%), there is a better balance between thermal conductivity and viscosity. At high concentrations (0.05%), conductivity increases significantly, but with increased viscosity, which affects flow velocity and, consequently, increases efficiency. The coating compensates for the

losses of increased viscosity at high concentrations, so efficiency remains higher. The effect of flow rate with nanocoating. At (1 L/min) flow, there is a high thermal difference but lower heat transfer. The coating helps reduce thermal resistance. At a volumetric flow rate (2 L/min), the balance is better, and the coating promotes convective heat transfer even more. At higher speeds of (3 L/min), there is greater potential for coating utilization, but the internal time is shorter. The effect is still positive, but less so than at (2 L/min). In conclusion, the use of nano coatings increases heat absorption inside the tube, accelerates heat transfer to the fluid, reduces heat loss, and improves heat distribution inside the tube. When using nanocoating, the greatest benefit is observed when the nanofluid is (MWCNT/water) at a solid volume fraction of (0.03%) and volume flow rate of (2 L/min).

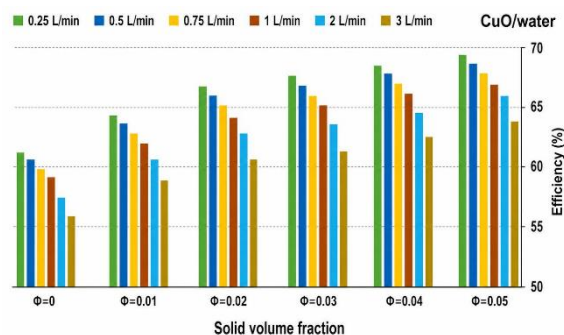


Figure 11. Effect adding of the nanocoating variation Thermal efficiency with Volume fraction for (CuO/water) mono nanofluid in different volumetric flow rates (0.25 to 3) L/min

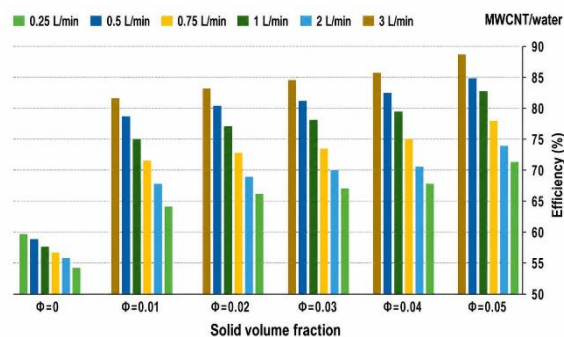


Figure 12. Effect adding of the nanocoating variation Thermal efficiency with Volume fraction for (MWCNT/water) mono nanofluid in different volumetric flow rates (0.25 to 3) L/min

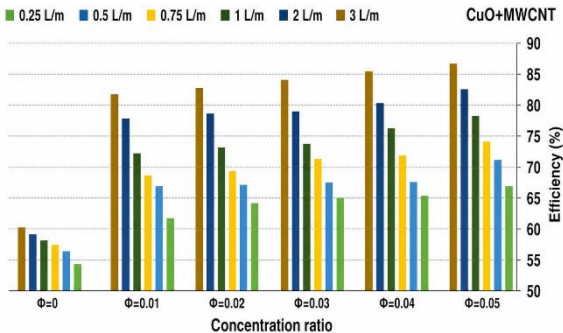


Figure 13. Effect adding of the nanocoating variation Thermal efficiency with Volume fraction for (CuO+MWCNT/water) hybrid nanofluid in different volumetric flow rates (0.25 to 3) L/min

5.5 Effect of Pumping Power on System

Performance

In the present numerical investigation, the primary focus is placed on evaluating the thermal and energy performance of the flat plate solar collector under different nanofluid configurations. Since the study is theoretical in nature, the hydraulic pumping system is not explicitly modelled in detail within the computational domain. However, for practical relevance, the influence of pumping power is briefly considered in the overall system interpretation.

In a realistic implementation, the circulation pump required to drive the nanofluid operates under low electrical consumption conditions. The expected operating range is approximately (0.4 A), (220 V), and (50 Hz), which corresponds to a relatively small auxiliary energy input compared to the solar thermal energy absorbed by the collector. Therefore, the pumping power contribution is considered negligible in comparison with the solar energy input and does not significantly affect the observed trends in thermal performance among different nanofluid cases. However, it is important to note that pumping power becomes relevant in the evaluation of net system efficiency, particularly in long-term or economic assessments where all auxiliary energy inputs are included. Accordingly, the presented results focus on thermal performance indicators, while acknowledging that a complete system efficiency assessment should account for pumping power as an additional energy cost

5.6 Cost Analysis

Cost analysis is a crucial aspect of evaluating the efficiency and feasibility of using nanofluids and thermal storage systems in (FPSC). In this study,

distilled water was used as the base fluid, with the addition of (CuO) and (MWCNTs) nanoparticles.

Generally, base materials like distilled water are characterized by their low cost and local availability, making them suitable for practical applications. In contrast, nanoparticles, especially (MWCNT) are relatively expensive compared to other materials, posing a significant challenge to the widespread use of nanofluids. However, the use of these particles leads to a clear improvement in thermal properties, such as increased thermal conductivity and heat transfer coefficient, which positively impacts the efficiency of the solar collector.

Table 7. Approximate cost estimation of materials used in the study

Material	Type	Relative cost	notes
Water	Base fluid	Very low	Available and easy to prepare
CuO	Nanoparticles	Medium	Relatively stable
MWCNT	Nanoparticles	High	Highest efficiency and cost

5.7 Analysis of the results of the Reynolds number and the convection heat transfer coefficient

In this section, we will discuss the effect of the Reynolds number and convection heat transfer coefficient behavior at different volumetric flows with different concentrations. This behavior will be discussed for different working fluids: water, single nanofluids, and hybrid nanofluids.

5.7.1 Analysis of CuO/Water Nanofluid results at different concentrations

As the volume fraction of (CuO/water) increases from (0 to 5%), the Re_s gradually decreases, while the convective heat transfer coefficient increases almost linearly as shown in Figure14. The addition of (CuO) particles increases the viscosity of the fluid compared to water, decreasing the flow rate and lowering the (Re) at the same flow rate. Conversely, the effective thermal conductivity of the fluid increases due to (CuO) particles being more

conductive than water, and the Nusselt number value is enhanced via micro transmission mechanisms (Brownian oscillation and micro-convection) at small to medium solid volume fraction, resulting in an increase in the flow rate despite the lower (Re). This general picture is experimentally confirmed in (CuO/water) nanofluid reviews and studies that show significant improvement with a small to moderate increase in pumping cost due to viscosity [59], [62]. At solid volume fraction ($\phi=0\%$), the (Re) highest (more fluid flow), which is the reference value, while at solid volume fraction ($\phi=0.01\%$), there is a clear initial drop in (Re) significant increase in viscosity, which is then followed by a significant increase in viscosity; this is due to the jump and the beginning of effective micro-transportation around the particles. At a solid volume fraction ($\phi=0.02\%$), the (Re) decrease continues at a slower rate, and the convective heat transfer coefficient continues to rise but with a lesser slope than the initial jump (a balance between the increased thermal conductivity and increased viscosity, which results in the Prandtl increase that thickens the boundary layer). At a solid volume fraction ($\phi=0.03\%$), the (Re) decreases further; the convective heat transfer coefficient increases significantly. Some studies show that this solid volume fraction (0.01–0.03%) is often the thermal optimum where good heat gain is achieved, and pumping costs are still acceptable. At a solid volume fraction (0.04–0.05%), the (Re) continues to decline, and the convective heat transfer coefficient improves, but it may gradually saturate. In this range, greater sensitivity to settling and agglomeration may occur, so the preparation of the suspension (dispersion/surfactant) becomes critical.

In conclusion, the (CuO/water) nanofluid provides a steady improvement at the expense of a gradual Reynolds value drop; that is, it balances heat gain with additional pumping capacity.

5.7.2 Analysis of MWCNT/Water Nanofluid results at different concentrations

The (Re) drop is much more severe, even at low concentrations, with a greater increase compared to water and (CuO/water) nanofluids, as shown in Figure 15. (MWCNT) have a high length-to-diameter ratio and tend to intertwine and form fine networks within the fluid, which rapidly increases the viscosity, resulting in a significant Reynolds drop. In contrast, (MWCNT) possess superior solid-state thermal conductivity and create thermal conductivity pathways within the fluid that exceed the efficiency of spherical particles. They can also enhance the Nusselt number through subtle mechanisms,

exhibiting a significant jump in the (Re). Numerous experiments with (MWCNT/water) nanofluid have reported significant increases in viscosity, with significant variations in severity depending on the size/length of the tube and stability. At a solid volume fraction ($\phi=0.01\%$), there is a high drop in the (Re), indicating a viscosity jump due to tube entanglement. In contrast, the convective heat transfer coefficient records a large jump, attributed to the fibre conduction pathways, and a rise that exceeds that of (CuO/water) nanofluid at the same solid volume fraction. At ($\phi=0.02\%$), the (Re) continues to fall, the convective heat transfer coefficient continues to rise, but at a gentler slope than the initial jump, with the potential for agglomeration if dispersion is not controlled. At ($\phi=0.03\%$), the (Re) drops further; while the convective heat transfer coefficient rises significantly, the effect of convective pathways still dominates over the effect of increased viscosity, especially if the suspension is stable. At a solid volume fraction (0.04–0.05%), there is a further (Re) drop; the convective heat transfer coefficient reaches high levels in the diagram, but hydraulic cost may become critical, and performance becomes increasingly dependent on stability and non-Newtonian rheology.

In conclusion, compared to (CuO/water), we notice that (MWCNT/water) shows greater thermal enhancement at the same concentration, but pays a higher hydraulic price. It is an excellent choice when thermal performance is a top priority and effective dispersion and stabilization policies are available.

5.7.3 Analysis of CuO+MWCNT/water Nanofluid results at different concentrations

Typically, the (Re) decreases with increasing solid volume fraction, but with an intensity intermediate between that of (CuO/water) and (MWCNT/water) nanofluids. The convective heat transfer coefficient increases significantly, often higher than that of (CuO/water) and closer to that of (MWCNT/water), with solid volume fraction increases as shown in Figure 16. The blending achieves a synergistic effect, the (CuO) particles provide the fluid with a significant increase in viscosity with a relatively moderate increase in viscosity, while the (MWCNT) particles add strong fibrous conduction pathways that raise the Nusselt number. The result is a blend that maintains significant thermal gains with fewer viscosity problems than (MWCNT) alone, thus exhibiting an intermediate behaviour, greater improvement than

(CuO), and milder (Re) drop than (MWCNT). The literature on hybrids (CNT with oxides) documents this synergistic increase in heat transfer enhancement and confirms the sensitivity of performance to the solid volume fraction and dispersion quality. At ($\phi=0.01\%$), there is an initial (Re) drop greater than for (CuO/water) nanofluid and lighter than for (MWCNT/water) nanofluid, indicating a viscosity effect of the composite; (h) rises more than (CuO/water) at the same solid volume fraction. At ($\phi=0.02\%$), the (Re) drop continues at a moderate rate, (h) increases significantly with improved thermal conductivity and micro transport efficiency, and this range is often considered practical from the perspective of balancing heat gain and hydraulic cost. At ($\phi=0.03\%$), the intermediate behaviour is constant. At a solid volume fraction (0.04–0.05%), there is further Reynolds drop, but typically lighter than for (MWCNT/water) nanofluid, and (h) continues to rise. Here, stability management (preventing agglomeration and rheological changes) becomes essential to maintain performance.

In conclusion, the (CuO+MWCNT/water) hybrid nanofluid provides a balanced solution between high gain, close to (MWCNT/water), and lower viscosity and good drop in (Re), which must be balanced with dispersion feasibility and pumping power.

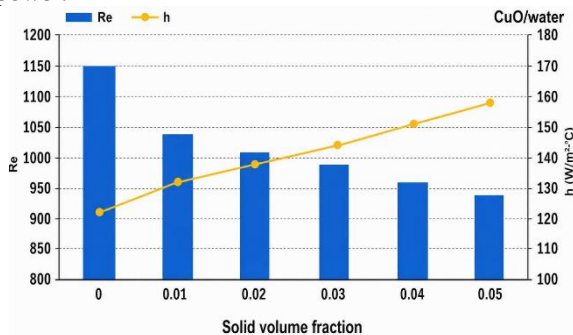


Figure 14. Shown the relationship between (Re) and (h) at (ϕ) of (0-0.05%) using (CuO/water) mono nanofluid with ($\dot{V}=3$ L/min)

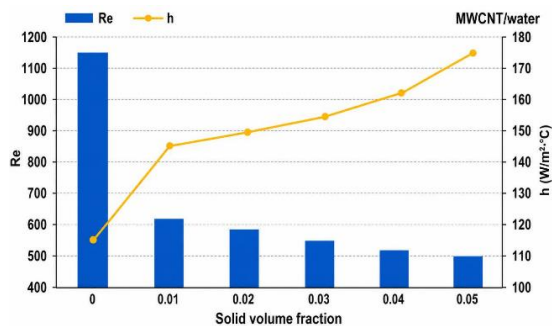


Figure 15. Shown the relationship between (Re) and (h) at (ϕ) of (0-0.05%) using (MWCNT/water) mono nanofluid with ($\dot{V}=3$ L/min)

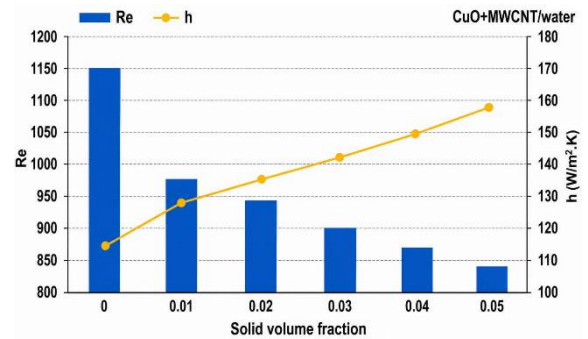


Figure 16. Shown the relationship between (Re) and (h) at (ϕ) of (0-0.05%) using (CuO+MWCNT/water) as hybrid nanofluid with a volume flow of (3 L/min)

5.8 Distribution of Temperature and Velocity

In this section, we will examine the temperature and velocity distribution within the pipe. The temperature distribution will be observed at the working fluid exit point, while the velocity distribution will be found at various points within the pipe.

5.8.1 Distribution of Temperature

Figures 17 to 19 show the temperature distribution as the working fluid exits the pipe in (CuO/water) and (MWCNT/water) mono nanofluids and (CuO+MWCNT/water) hybrid nanofluid. The highest working fluid temperature is in the layer adjacent to the tube, and it begins to decrease towards the centre. The working fluid recorded its highest temperature in the layer adjacent to the tube wall, while the lowest temperature was recorded in the centre of the tube. The (MWCNT/water) nanofluid recorded the highest temperatures, followed by (CuO+MWCNT/water) hybrid nanofluid, then (CuO/water) nanofluid, while water recorded the lowest temperatures.

5.8.2 Distribution of Velocity

Figure 20 shows the water velocity distribution across (FPSC) at ($\dot{V}=3$ L/min) and for different test times. This distribution reflects the hydrodynamic behaviour of the flow within the collector. The figure shows the water velocity at various areas of the pipe. The velocity pattern varies from one section to another depending on its location within the collector. The figure shows that the flow velocity is low at the

collector inlet and then gradually increases to its highest value at the end of the first tube. This can be explained by the fact that the passage of water through the heating tube causes it to heat up, which reduces its density and increases its velocity according to the continuity-energy relationship. It is also noted that the velocity is higher at the centre of the outlet section than at its edges, consistent with the condition of non-slip walls in the internal flow.

The results showed that replacing water with nanofluids (Figure 21 and 22) at the optimal solid volume fraction ($\phi = 0.05\%$) led to slight changes in the velocity distribution within the (FPSC), with a limited increase in local velocity values compared to water. This is attributed to changes in the fluid's physical properties, particularly density and viscosity, resulting from the addition of nanoparticles. However, the effect of this addition on the hydrodynamic field was less pronounced than its effect on thermal performance and heat transfer, indicating that the primary role of nanofluids is to enhance thermal properties rather than improve flow characteristics.

In general, it can be said that the addition of nanoparticles leads to a slight change in the flow velocity inside the (FPSC), but this effect was less pronounced compared to their effect on the thermal distribution, indicating that the role of nanoparticles in improving hydrodynamic performance is limited compared to their effect in enhancing heat transfer.

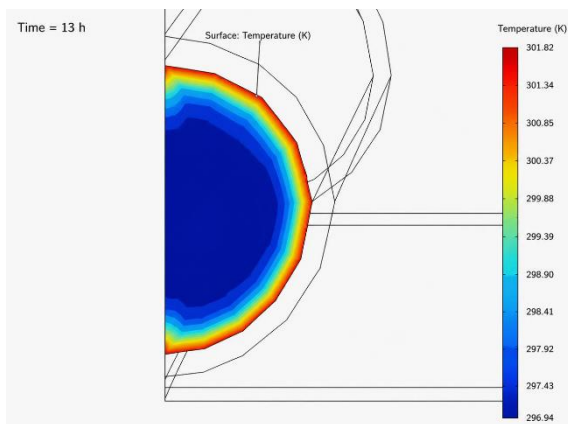


Figure 17. Temperature distribution of water across the riser of (FPSC) at ($V=3$ L/min)

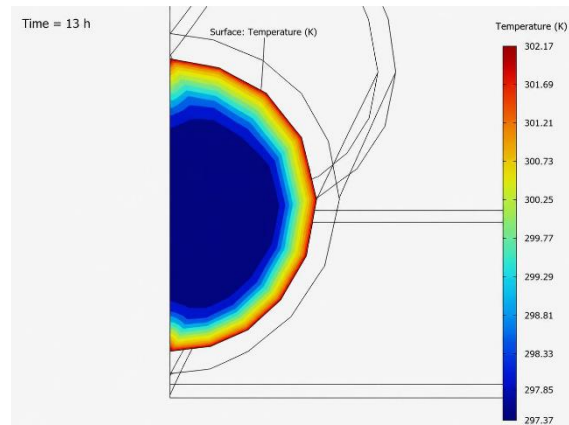


Figure 18. Temperature distribution of (CuO/water) nanofluid across the riser of (FPSC) at ($V=3$ L/min) and ($\phi=0.05\%$)

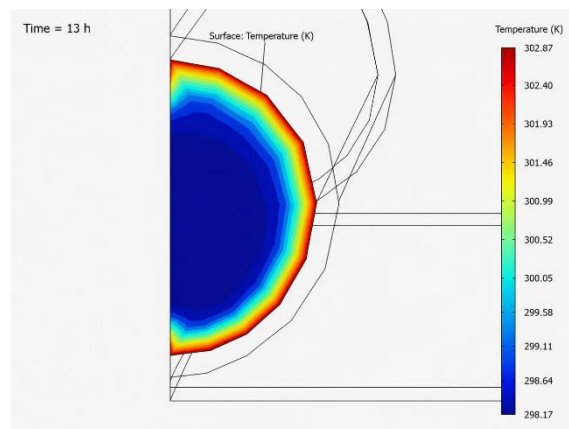


Figure 19. Temperature distribution of (MWCNT/water) nanofluid across the riser of (FPSC) at ($V=3$ L/min) and ($\phi=0.05\%$)

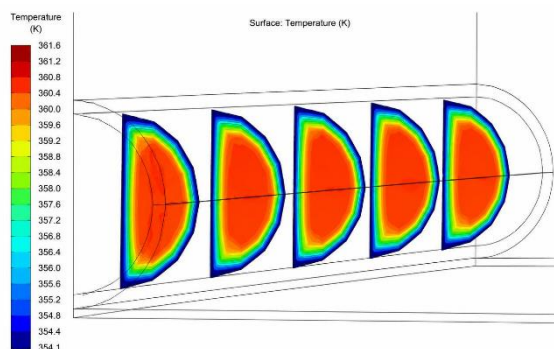


Figure 20. Velocity contours of water across the riser of (FPSC) at ($V=3$ L/min)

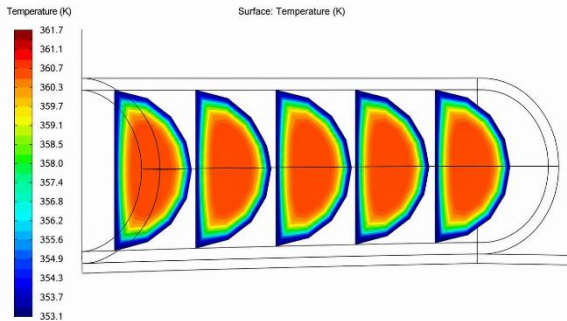


Figure 21. Velocity contours of (CuO/water) nanofluid across the riser of (FPSC) at ($V=3$ L/min) and ($\phi=0.05\%$)

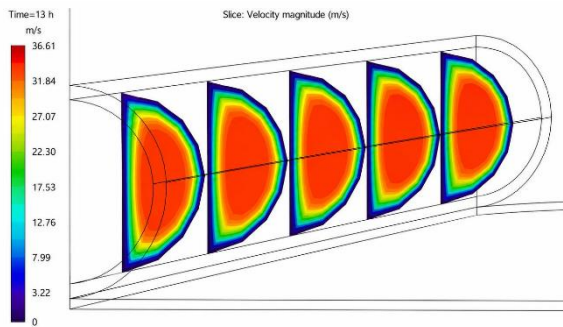


Figure 22. Velocity contours of (MWCNT/water) nanofluid across the riser of (FPSC) at ($V=3$ L/min) and ($\phi=0.05\%$)

6. Conclusions

To enhance the thermal performance of (FPSC), the study used a variety of nanofluid types, including (CuO/water), (MWCN/water) mono nanofluid, and the (CuO+MWCNT/water) (80:20%) hybrid nanofluid.

1. The (FPSC) efficiency was found to be directly influenced by the concentration of nanoparticles, the fluid flow rate, and the type of nanoparticles.
2. The three composite fluids utilized in the numerical study (MWCNT) produced the most efficient results.
3. According to the results, the (MWCNT) achieves the highest efficiency (80.4%) without nanocoating technology for solid volume fraction ($\phi=0.05\%$) at the volumetric flow rate of (3 L/min), which was around (24.8%) greater than water under the same mass flow rate.
4. The efficiency of (MWCNT/water) is higher than that of (CuO/water), considering the volumetric flow rate of (0.25-3 L/min).
5. According to this study, employing (CuO+MWCNT/water) (80:20%) hybrid nanofluid

increases the efficiency by (19.8%, 22.1%, and 23.9%) at volumetric flow rate (3 L/min) for solid volume fraction (0.01%, 0.03%, 0.05%), respectively.

6. The use of hybrid nanocoating technology improves the system efficiency in three nanofluids (CuO/water), (MWCNT/water), and (CuO+MWCNT/water), with the highest efficiency recorded at a ($\phi=0.05\%$) and volumetric flow rate of (3 L/min), which were (70.4%, 88.4%, and 86.1%), respectively.

7. This suggests that (80%) of the (MWCNT) be swapped out for the less expensive and less dangerous (CuO).

In conclusion, the findings showed that the use of (CuO/water) and (MWCNT/water) nanofluids increases the efficiency of (FPSC) relative to the base fluid. The use of (MWCNT/ water) mono nanofluid gives the highest efficiency relative to all types, but the cost of these nanoparticles is very high. In addition to their negative effects on the system, they are unstable and tend to agglomerate faster, which requires a higher pumping capacity because they may lead to damage to the system in case of agglomeration. Using (CuO+MWCNT/water) hybrid nanofluid is the best working fluid. The choice of solid volume fraction (80:20) (CuO: MWCNT) gives a more stable hybrid nanofluid and is less damaging to the system because the (CuO) nanoparticles have higher stability compared to (MWCNT).

Nomenclature

Symbol	Quantity
Ag	Silver
Al	Aluminium
Al ₂ O ₃	Alumina
CeO ₂	Cerium oxide
CNT	Carbon Nanotube
CO ₂	Carbon dioxide
C _p	Specific heat
Cu	Copper
CuO	Copper oxide
D _h	Hydraulic Diameter
EG	Ethylene Glycol
Fe	Iron
Fe ₃ O ₄	Iron III oxide

<i>FPSC</i>	Flat Plate Solar Collector
<i>FPSWH</i>	Flat Plate Solar Water Heating
<i>h</i>	Heat transfer coefficient
<i>k</i>	Thermal Conductivity
<i>m</i>	Mass flow rate
<i>MCV</i>	Mixed Convection Validation Model
<i>MgO</i>	Magnesium oxide
<i>MWCNT</i>	Multi Wall Carbon Nanotube
<i>NCV</i>	Natural Convection Validation Model
<i>ND</i>	Nanodiamond
<i>Q</i>	Useful Heat
<i>SiC</i>	Silicon carbide
<i>SWCNT</i>	Single Wall Carbon Nanotube
<i>T</i>	Temperature
<i>TiO₂</i>	Titanium dioxide
<i>u</i>	Fluid velocity
<i>V_{wind}</i>	Wind Speed
<i>WO₃</i>	Tungsten trioxide
<i>ZnO</i>	Zinc oxide
Symbols of Greek	
ρ	Density
μ	Dynamics Viscosity
Φ	Volumetric-Concentration Ratio
η	Thermal-Efficiency
θ	Collector Tilt Angle
β	Thermal-Expansion Coefficient
Optical parameters	
α	Absorptivity
ε	Emissivity
ρ	Reflectivity
σ	Stefan–Boltzmann Constant
τ	Transmissivity
Subscripts	
<i>abs</i>	Absorber
<i>avr</i>	Average
<i>ext</i>	External
<i>f</i>	Fluid
<i>gc</i>	Glass Cover
<i>hnf</i>	Hybrid Nanofluid
<i>in</i>	Inlet
<i>nf</i>	Nanofluid
<i>np</i>	Nanoparticle

<i>out</i>	Outlet
Dimensionless numbers	
<i>Nu</i>	Nusselt Number
<i>Pr</i>	Prandtl Number
<i>Re</i>	Reynolds Number

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