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Hybrid Nanofluids in Solar Thermal Collectors: Size and Cost Reduction Opportunities

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ABSTRACT

Solar thermal collector, an alternative way to harvest renewable solar energy, requires high heat transfer area. Hybrid nanofluid has potential to reduce the size of the collector due to its high thermal conductivity and low specific heat capacity. This study investigates the effects of Multi-Walled Carbon Nanotubes (MWCNT) combine with metal oxides, including Al_2O_3, CeO_2, TiO_2, ZnO at the volume ratio of 1:4 between MWCNT and metal oxides with a total of 1 vol.% in water. The investigation focuses on assessing this nanofluids with 1 kg/min mass flow rate for its effect in size and cost reduction. Following the validation of nanofluids properties predictor and the numerical model of flat plate solar collector with experimental data, the original size of collector is calculated to be 1.51 m^2. The effects in terms of size and cost reduction are evaluated. In best case scenario, the use of MWCNT-TiO_2 can reduce the size of flat plate solar thermal collector by up to 8.54% and cost by 5.15% compared to using water as the heat transfer fluid.

1. Introduction

Energy production produces dramatically CO_2 emission [1,2] while the sun generates immense solar energy output, estimated at 3.8×10^{20} MW, but only a fraction reaches the earth, about 1.7×10^{14} kW [3]. It has been stated that 30-min solar radiation energy is able to produce the annual world energy demand [4]. Solar thermal energy is widely employed in many industrial sectors, including electricity generation and hot water production for domestic use and absorption cooling system [5,6]. Using solar energy for water heating in residential areas is expected to lower electricity costs significantly. To harness the power of the sun effectively, the heat transfer needs to be increased—which eventually leads to a larger area of solar collectors [7]. However, the expansion of the solar collector comes with an increase in the cost of materials used to build the solar thermal collector and space requirements for installation. Among different types of solar thermal collector, flat plate solar

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collectors are widely used for solar energy absorption around the world due to their simplicity in construction, compactness, and cost effective [8].

Nanofluid, initially introduced by Choi *et al.,* [9] is produced by dispersing nanoparticles into liquid. Nanofluids have been widely used as the heat transfer medium because of higher effective thermal conductivity [10]. The exploration of dispersing multiple particles into the liquid has prompted the emergence of the term "hybrid nanofluid." However, the study of hybrid nanofluids has not been widely conducted due to the complexity arising from the combinations of different particles with the base fluid. Muneeshwaran *et al.*, [11] investigated the use of hybrid nanofluid as a heat transfer enhancement and found that carbon based–metal oxides hybrid nanofluids exhibited a high stability period, with some nanofluids had stability period more than two months without sedimentation. Their study also revealed that the combination of these nanoparticles between carbon-based and metal oxides improved thermal conductivity—which is suitable for solar collector application. Gholizadeh *et al.,* [12] studied the accuracy of viscosity models developed for nanofluid. The authors found most of the classical and empirical correlations did not exceed the R^2 of 0.661 when compared with 2,890 experimental results. Selecting correlations that accurately reflect experimental data requires careful consideration. Rubbi *et al.,* [13] conducted a review on solar collectors with a temperature output of less than 80°C considering water-based nanofluids. The diameter of nanoparticles used in these studies typically ranged from 1 to 100 nm. The concentration of nanofluid could be up to 5 vol.%. Verma *et al.,* [8] investigated the use of nanofluid with 0.25-2 vol.% and 0.025 kg/s mass flow rate for flat plate solar collector. They found that MWCNT/water nanofluid reduced the size of collector by 19.11%. Similarly, Gad *et al.,* [14] used 2 wt.% TiO_2/water and Al_2O_3/water nanofluids at flow rates between 2-6 L/min in flat plate solar collector. They increased the solar collector efficiency by ~30-32%, respectively. Recent study in 2024 by Kumar *et al.,* [15] found that 0.1 wt.% of MWCNT/water with biosurfactant in flow rate of 0.5 L/min could reach 61% thermal efficiency. These findings suggest that the use of nanofluid improves the performance of flat plate solar collectors by reducing its size and increasing its efficiency. Previous studies on nanofluids for solar collectors mainly focused on mono nanofluids. However, there is an unexplored understanding gap in whether hybrid nanofluids further enhance collector performance especially in the numerical analysis.

This study aims to investigate the effects of hybrid nanofluids on flat plate solar collectors. A numerical simulation is conducted to predict the performance of flat plate solar thermal. A particular focus is placed on the size and cost reduction of the proposed technology. The potential keys finding is to establish the accurate nanofluid properties predictors and investigate the size and cost reduction effects of solar collectors when using the hybrid nanofluid as transfer medium via numerical models. The novelty of this study is the using of numerical methods for predicting the potential of hybrid nanofluids in real-world applications, which has not been extensively studied before, providing new insights in thermal performance determination.

2. Methodology
2.1 Hybrid Nanofluid Properties Calculations Method

Verma *et al.,* and Gad *et al.,* [8,14], in their previous studies utilizing nanofluids for solar thermal collectors, selected particles based on their potential to enhance properties. On this basis, MWCNT and nanoparticles such as Al_2O_3, CeO_2, TiO_2, ZnO with a ratio of 1:4 totaling 1 vol.% in water have been selected for this study.

The 1:4 ratio was selected because it provided stability in the thermophysical properties. The stability of this ratio over extended periods has also been previously studied and confirmed by Kumar et al. [16] and Tiwari et al. [17].

The MWCNT is also a carbon-based nanoparticle while Al_2O_3, CeO_2, TiO_2, ZnO are metal oxides which these combinations of carbon-based and metal oxides particles were previously investigated to be able to greatly increase heat transfer compared to metal oxides hybrid nanofluids [11] and suitable for heat transfer equipment like solar collector. The reason may be due to MWCNT tube structure, in which cylindrical nanoparticles exhibit increasing thermal conductivity [18]. In terms of cost and availability, metal oxides are easy to find and have relatively low cost compared to carbon nanoparticles. By using the combination of these nanoparticles, it could provide more economical efficiency with thermal performance benefits from carbon-based particles [19].

The density of hybrid nanofluid is calculated using mixing rules by modifying the model for mono nanofluid [11], as follows:

$$\rho_{hnf} = \rho_{np1}\emptyset_{np1} + \rho_{np2}\emptyset_{np2} + (1 - \emptyset_{hnp})\rho_{bf} \tag{1}$$

$$\emptyset_{hnp} = \emptyset_{np1} + \emptyset_{np2} \tag{2}$$

where ρ_{np} is the density of nanoparticle, ρ_{hnf} is the density of hybrid nanofluid, ρ_{bf} is the density of base fluid, and $\emptyset$ is the volume fraction of nanoparticles in nanofluid. For specific heat capacity, Cp, the model on equation (3) first developed by Pak *et al.,* [20] for nanofluid then it was modified for hybrid nanofluid in equation (4). This model uses the density to calculate heat capacity and proven to show good agreement with experimental data for mono nanofluid [11].

$$Cp_{nf} = \frac{\rho_{np}\emptyset_{np}Cp_{np} + (1-\emptyset_{np})\rho_{bf}Cp_{bf}}{\rho_{nf}} \tag{3}$$

$$Cp_{hnf} = \frac{\rho_{np1}\emptyset_{np1}Cp_{np1} + \rho_{np2}\emptyset_{np2}Cp_{np2} + (1-\emptyset_{hnp})\rho_{bf}Cp_{bf}}{\rho_{hnf}} \tag{4}$$

Water is used as the base fluid in this research due to its availability across the planet. The properties including density, specific heat capacity and viscosity are taken from NIST database by Wagner *et al.,* [21]. The properties of nanoparticles are taken from various research on nanofluid [7, 21-24].

Furthermore, the properties of the nanofluid will be calculated using Eqs. (1)-(4) with the properties of liquid and nanoparticle from Table 1. In case if the correlation results don't represent the experimental data, the curve-fitting equations derived from the experimental data will be used instead as there are some evidence of correlations that cannot forecast the properties accurately [25].

Table 1
Properties of base fluid at 25°C and nanoparticles

Nanofluid type	Specific Heat Capacity (J/kg°C)	Density (kg/m^3)
Water [21]	4183	997
Al_2O_3 [7]	773	3960
CeO_2 [22]	460	7132
MWCNT [23]	733	2100
TiO_2 [7]	692	4230
ZnO [24]	494	5600

2.2 Numerical Calculations of Solar Thermal Collector

The numerical equation used in this study based on Duffie *et al.,* textbook [26]. The following assumptions are adopted in the numerical simulation:

i) Steady state condition.
ii) Atmospheric pressure.
iii) Loss through front and back are to ambient temperature.
iv) Single-phase and homogenous flow for fluid.
v) Constant solar irradiance.
vi) Zero wind velocity.
vii) One dimensional heat flow.
viii) Blackbody for long-wavelength radiation at an equivalent sky temperature.
ix) Negligible dust and dirt on the collector.
x) Negligible shading of the collector absorber plate.

Heat loss coefficient (U_L) is determined by summing the top loss coefficient (U_t), bottom loss coefficient (U_b) and edge loss coefficient (U_e). Top loss coefficient is calculated by Klein correlation [27]. The heat loss coefficient is in W/K.

$$U_L = U_t + U_b + U_e \tag{5}$$

$$U_t = \frac{\frac{1}{N}}{\frac{C}{T_p}\left[\frac{T_p - T_a}{N+f}\right]^{0.33} + \frac{1}{h_a}} + \frac{\sigma(T_p - T_a)({T_p}^2 - {T_a}^2)}{\varepsilon_p + 0.5N(1-\varepsilon_p) + \frac{2N+f-1}{\varepsilon_g} - N} \tag{6}$$

$$C = 365.9(1 - 0.00883\beta + 0.0001298\beta^2) \tag{7}$$

$$f = (1 + 0.04h_a - 0.0005{h_a}^2)(1 + 0.091N) \tag{8}$$

$$h_a = 5.7 + 3.8V \tag{9}$$

where C and f are the variable to shorten the form of U_t, β is angle of the collector in degree, h_a is heat transfer coefficient of air in W/m^{2}K, ε_p is the emissivity of plate, ε_g is the emissivity of glass, N is the number of covers, T_p is plate temperature, T_a is ambient temperature, and V is the wind velocity.

$$U_b = \frac{k_b}{x_b} \tag{10}$$

$$U_e = U_b \frac{A_e}{A_c} \tag{11}$$

where k_b represent the thermal conductivity of back insulation in W/mK, x_b is the thickness of back insulation in metres, A_e is the area of edge, and A_c is the area of collector in m^2.

The fin efficiency for rectangular profile is calculated as follows:

$$m = \sqrt{\frac{U_L}{k\delta}} \quad (12)$$

$$F = \frac{tanh\left[\frac{m(W-D}{2}\right]}{\left[\frac{m(W-D}{2}\right]} \quad (13)$$

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D+(W-D)]}+\frac{1}{C_b}+\frac{1}{\pi D\left(h_{fi}\right)}\right]} \quad (14)$$

$$F_R = \frac{\dot{m}Cp}{A_c}\left[1 - e^{\left(-\frac{U_L F' A_c}{\dot{m}Cp}\right)}\right] \quad (15)$$

where W is the width between the tube, D is the inside diameter of the tube, C_b is the bond conductance in W/mK, h_{fi} is the heat transfer coefficient inside the tube, and $\dot{m}$ is the mass flow rate of the collector. The specific heat capacity is the specific heat capacity at the average inlet and outlet temperature.

The heat transfer is then calculated from the efficiency, which is used to calculate the outlet temperature of the collector.

$$\dot{Q} = A_c F_R (G_T(\tau\alpha) - U_L(T_i - T_a)) \quad (16)$$

$$\dot{Q} = \dot{m}Cp(T_o - T_i) \quad (17)$$

where A_c is the size of collector, G_T is solar irradiance, $\tau\alpha$ is effective absorptivity transmittivity, T_i is inlet temperature of the collector, and T_o is outlet temperature of the collector.

The specifications of the flat plate collector were obtained from Verma *et al.,* [8] to serve as a standard collector for usage in the residential and industrial sector. Yousefi *et al.,* [28] performed experiment using the ASHRAE standard 86-93 [29] for testing the thermal performance of a solar collector at various time. These experimental results serve as validating data for the calculation method proposed in this study.

Upon the validation of the model, the effects of hybrid nanofluids on size and cost reduction are investigated using the same model and the same model parameters. The outlet temperature from the collector is over 50°C, while the inlet temperature is 35°C, the ambient temperature is 37°C and solar irradiance is 975 W/m^2. After adjusting the fluid properties to that of hybrid nanofluid, the size of the collector is calculated.

2.3 Economic Analysis of Flat Plate Solar Thermal Collector

The economic analysis is conducted using the equation by Rockenbaugh *et al.,* [30] by generalized effects of collector type, and location based on USA. The equation uses the collector area to calculate the cost of the collector:

$$C_i = C_a A_c + C_f \quad (18)$$

where C_i is the cost of flat plate solar collector, C_a is the area-dependent cost, and C_f is the fixed cost. A_c is calculated to be 1.51 m^2 from validation process. According to the study by Rockenbaugh *et al.,* [30], the fixed cost is 1000 USD including overall system which states "do not differ much between a small system and a large one." while the area-dependent cost varies from 300 to 1100 USD/m^2.

3. Results

The results from correlations is compared with the experiment data reported by *Kumar et al.,* [16] using commercial nanofluid at the temperature between 25-50°C to make sure that the properties of nanoparticles for hybrid nanofluid is accurate as shown in Figures 1 and 2, and Table 2. The percentage error is calculated using absolute error at the calculated/measured temperature.

$$\%error = \frac{|Experimental\ Data - Calculated\ Data|}{Experimental\ Data} \times 100 \quad (19)$$

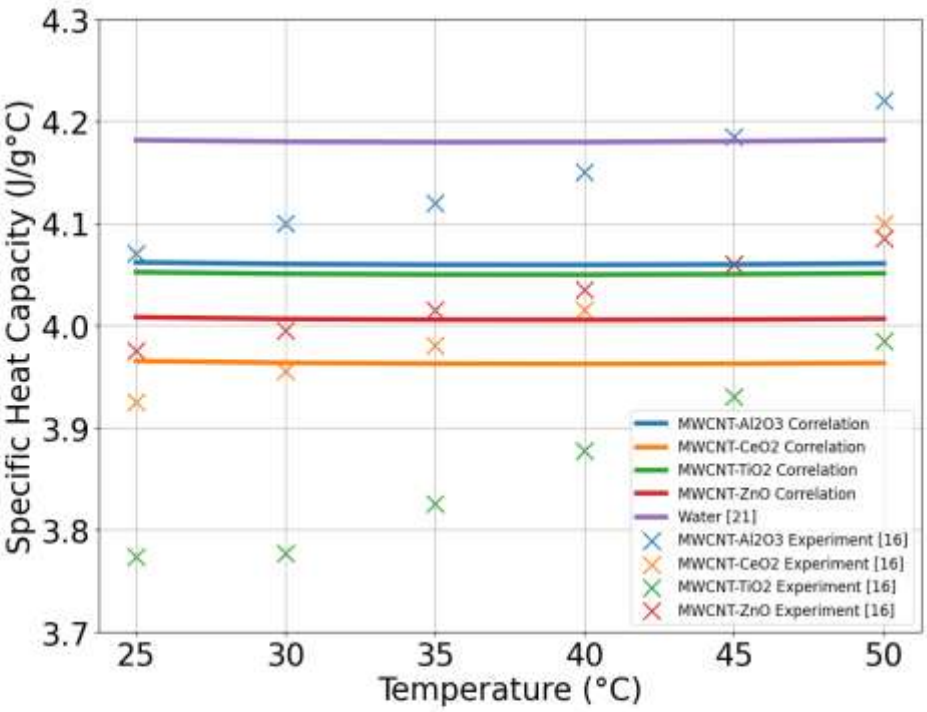

Fig. 1. Comparison of specific heat capacity of fluid

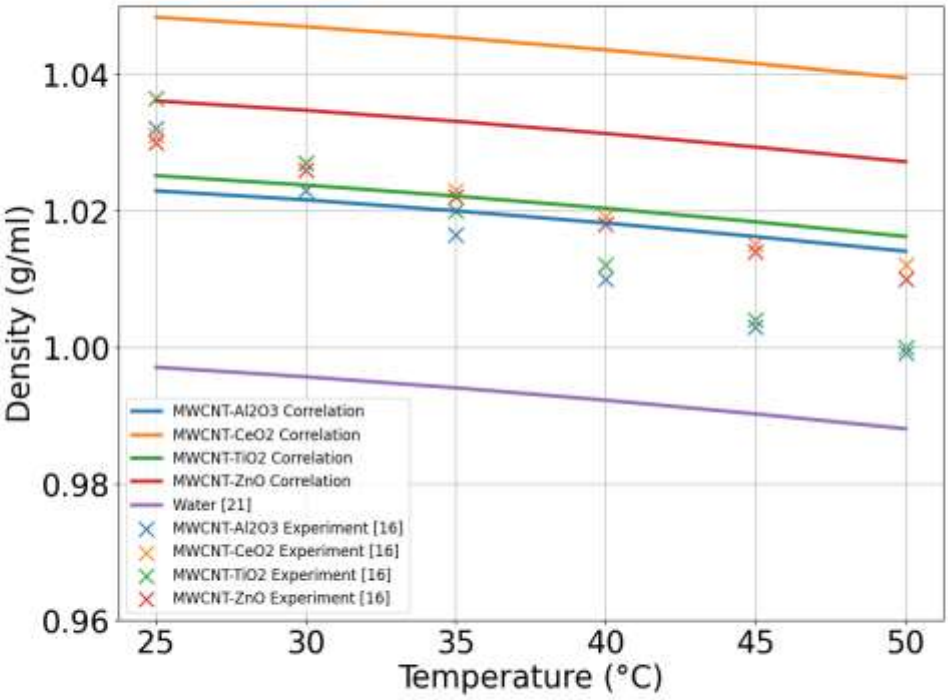

Fig. 2. Comparison of density of fluid

Table 2
Maximum error of correlations

Nanofluid type	Specific Heat Capacity	Density
MWCNT–Al_2O_3/Water	3.78%	1.49%
MWCNT–CeO_2/Water	3.34%	2.71%
MWCNT–TiO_2/Water	7.39%	1.62%
MWCNT–ZnO/Water	1.92%	1.70%

From the figures, it's evident that all the properties predicted from the correlations exhibit a maximum error of less than 10%. However, Figures 3 and 4 indicate that the correlations from equations (1) to (4) do not accurately represent the trends in the properties of the selected hybrid nanofluid. This shows similar results as the study by Gholizadeh *et al.,* [12], which found that the classical correlation is not generalized for the broad use of many types of nanofluid. The fit curve method is then used to derive empirical correlations from the experimental data.

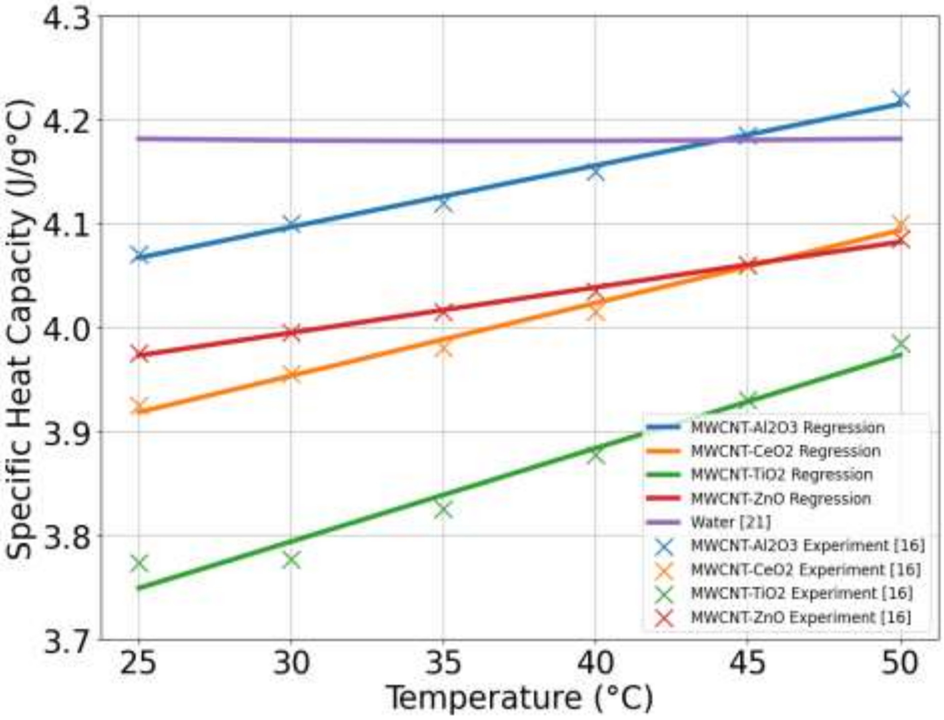

Fig. 3. Comparison of specific heat capacity of fluid

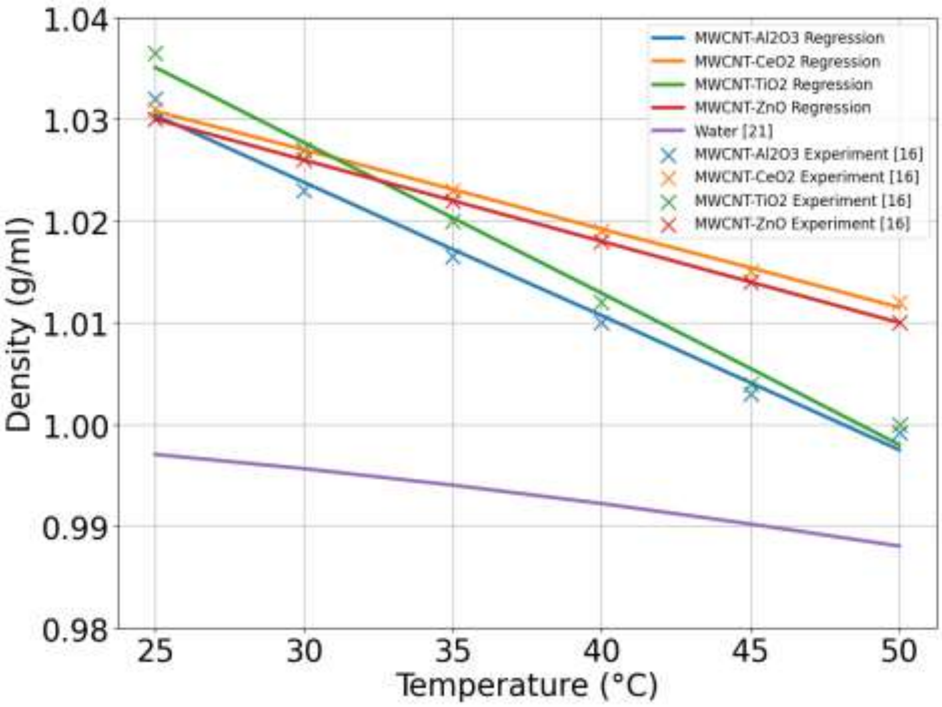

Fig. 4. Comparison of density of fluid

From Figures 3 and 4, a better representation of selected hybrid nanofluid properties is found. Table 3 shows the maximum percentage errors of each equation from the linear regression. These proposed equations are then used for calculating the selected hybrid nanofluids properties in numerical model of solar thermal collector.

Table 3
Maximum error of the regression equation

Nanofluid type	Specific Heat Capacity	Density
MWCNT–Al_2O_3/Water	0.15%	0.17%
MWCNT–CeO_2/Water	0.21%	0.05%
MWCNT–TiO_2/Water	0.64%	0.20%
MWCNT–ZnO/Water	0.08%	<0.01%

To ensure the accuracy of numerical method, the results are compared with experimental data reported by Yousefi *et al.,* [28] on water for flat plate solar collector. The outlet temperature of the solar collector was measured using a thermocouple during solar at noon, between 10:00 a.m. to 3:00 p.m. This outlet temperature served as the validation of the numerical model. The calculations provide a small relative error of 2.66%, 2.78%, 0.60% 4.15%, 7.48%, 7.92%, respectively. Figure 5 provides the picture of this error comparison. The highest errors may occur due to unpredictable phenomena. In the experiment, solar irradiance peaked the maximum value at around 2:20 – 2:30. The heat could be accumulated during that time in the absorber making the outlet temperature remain high while the numerical model under predicted since this study used steady state assumptions. Transient state simulations could be explored in the future to decrease the error in the numerical simulations. Notably, the maximum percentage error of 7.92% is found—which is considered reasonable for further calculations.

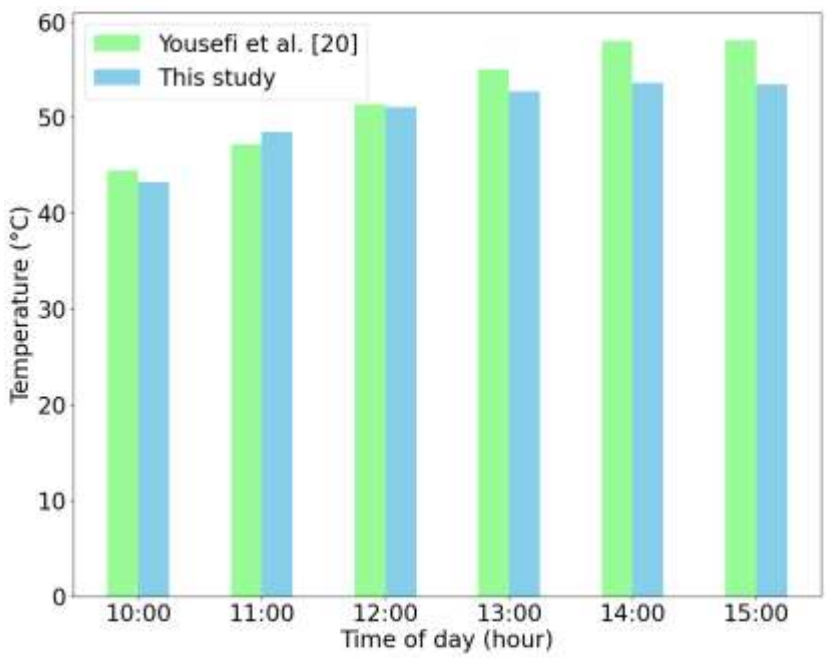

Fig. 5. Outlet temperature comparison between experiment data and numerical calculations

The selected hybrid nanofluids consisting of 4 combinations including MWCNT and Al_2O_3, CeO_2, TiO_2, ZnO with volume ratio of 1:4 by total of 1 vol.% in water is used in the numerical calculations.

Ranging from highest to lowest is MWCNT–TiO_2, MWCNT–CeO_2, MWCNT–ZnO, and MWCNT–Al_2O_3 with the results of 8.54%, 5.42%, 5.22%, 2.42% respectively. Figures 6 and 7 provide the graphical results of collector area and size reduction effects.

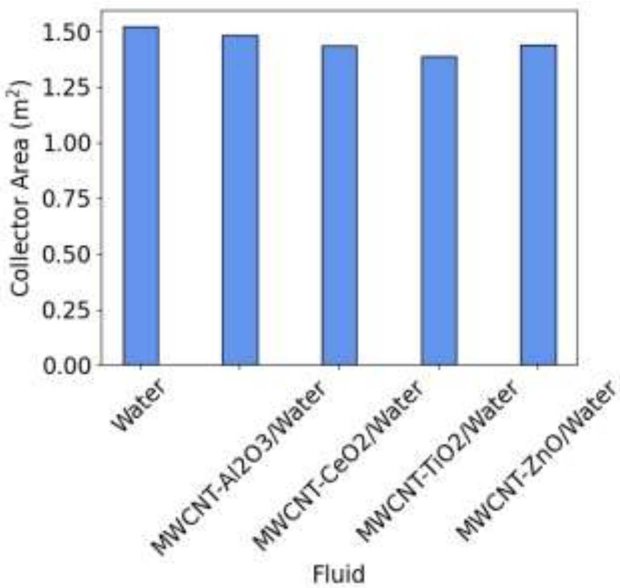

Fig. 6. Collector area with hybrid nanofluid

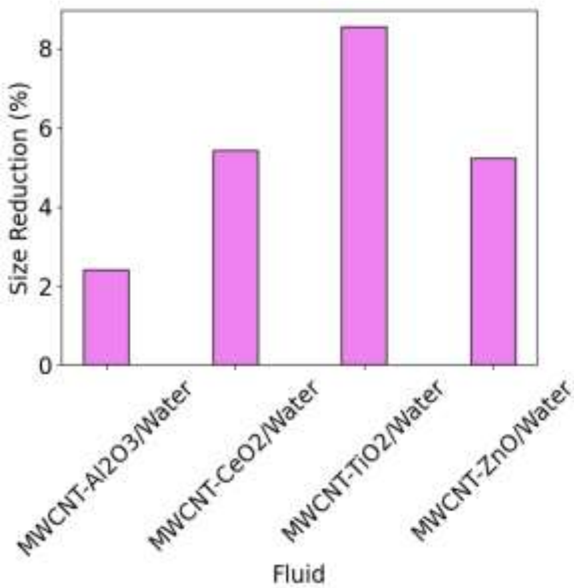

Fig. 7. Effects of hybrid nanofluid for solar thermal collector Size Reduction percentage

From the results, MWCNT-TiO_2/Water hybrid nanofluid is the most suitable hybrid nanofluid from selected hybrid nanofluids which have the most suitable size reduction effect. This effect could lead to cost and weight reductions due to fewer materials needed for the construction of the solar thermal collector [31].

The area required is smaller compared to the industrial sector, aggressive estimation is employed for the economic analysis. The value for area-dependent cost coefficients is assumed to be 1000 USD/m^2 from the range of 300 – 1100 USD/m^2. Figures 8 and 9 provide the graphical results of collector cost and cost reduction effects.

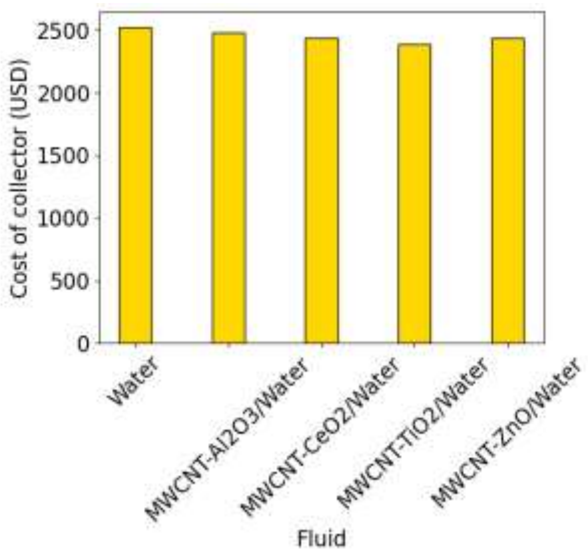

Fig. 8. Cost of solar thermal collector

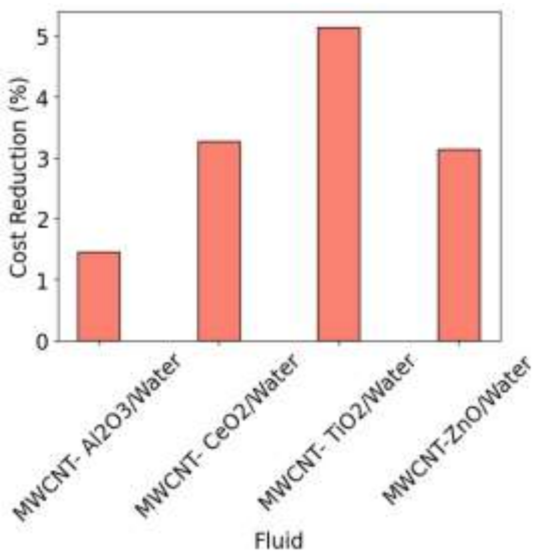

Fig. 9 Effects of hybrid nanofluid for solar thermal collector Cost Reduction percentage

The results of cost reduction effects are the same as size reduction effects compared to using water. Ranging from highest to lowest is MWCNT–TiO_2, MWCNT–CeO_2, MWCNT–ZnO, and MWCNT–Al_2O_3 with results of 5.15%, 3.27%, 3.15%, 1.46% respectively.

All hybrid nanofluids indicate cost reduction effects compared to water as fluid. Particularly, MWCNT–TiO_2/Water hybrid nanofluid exhibits the lowest cost and size among the considered cases. According to Yousefi *et al.,* [28], stochastic motion of nanoparticles is the underlying reasons for the better performance of nanofluids relative to water. This motion makes the nanoparticles in nanofluid have higher speed increment of molecules. Thus, more collisions occur in the fluid leading to high thermal conductivity and higher temperatures at the outlet than water. This random collision known as Brownian motions plays a significant role in improving the efficiency of nanofluid. Moreover, the temperature dependencies of properties are also a big factor in an increasing of the efficiency. From Figure 3, TiO_2 has the lowest specific heat capacity compared to other metal oxides; therefore, it needs less energy compared to water to heat up. In the study by Bunz *et al.,* [32] on metallic glass, temperature led to vibration modes, affecting the heat absorption leading to faster heating. These factors make MWCNT–TiO_2/Water require the least space to heat it up. The density of TiO_2 is also the highest of all the selected metal oxides which affect the collision of particles in the fluid. The higher density led to more Reynolds number which increase the convective heat transfer [33,34], making MWCNT–TiO_2/Water as the most suitable hybrid nanofluids in this study. These findings suggest that using hybrid nanofluids in solar collector system could make it reach the desired temperature while acquiring less space than using water, making larger size of collector cost lesser compared to using water.

Parametric study conducted by Zhou *et al.,* [35] found that small flow rate could lead to high heat loss while high flow rate could also lead to low thermal performance in trends similar to a parabola graph. This suggests that optimum flow rate needs to be engaged for the maximum thermal performance, leading to reduction in area and cost. Solar irradiance, wind speed and ambient temperature also play a big role in affecting area and cost. High irradiance leads to high performance while high wind speed cause high heat loss reducing the performance. In real world applications, all parameters may need to be studied to confirm the feasibility of flat plate solar collector. However, hybrid nanofluids suggest great opportunities in an incrassation of flat plate solar collector thermal performance even if the cloud and dust could vary the solar irradiance.

Further studies are necessary for the investigation of Nusselt number enhancement, and pressure drop needs to be done for this combination of hybrid nanofluid for flat plate solar thermal collector. Computational fluid dynamics could be used to study fluid behaviour in the pipe [36]. The economic and size reduction effects need to be analyzed in the future study for other specifications of solar thermal collectors and other conditions, for example, if large amounts of collector units are used instead or cloud and dusty condition.

4. Conclusions

The sun has produced free energy that can be harnessed by solar thermal collector, an alternative method for capturing renewable power. Among the various type of collectors, the flat plate solar collector is chosen for this study due to its simplicity, compactness, and cost-effectiveness. However, the size of solar thermal could be massive, leading to high cost and large space requirements for installation. To address this issue, the implementation of hybrid nanofluid is investigated in this study with the aim of reducing the size and cost of the collector by increasing it thermal properties compared to the base fluid. The study begins by validating conventional correlations with experimental data until the percentage errors are less than 10%. Subsequently, the numerical calculations are also validated with experimental data and show less than 10% of error. Following validation, the effects of 4 hybrid nanofluids with 1 vol.% has been study. From the analysis, the use of hybrid nanofluid could reduce the size of flat plate solar collector with a flow rate of 1 kg/min up by 8.54% using MWCNT–TiO_2. Additionally, by using MWCNT–TiO_2 could reduce the cost up to 5.15% compared to using water as fluid. These cost savings make hybrid nanofluids more economically viable for residential and industrial applications due to reduced financial barriers. Future investigation could be done for different combinations of hybrid nanofluids like metal carbide and solar collector type, for example parabolic trough and also developed transient state simulations to achieve more accuracy numerical simulations.

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