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Thermal Performance of Thermosyphon Evacuated Tube Solar Collector using TiO_2/Water Nanofluid

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Abstract – *In this paper, the performance of thermosyphon evacuated tube solar collector using TiO_2/water has been numerically investigated using commercial software ANSYS. TiO_2 nanoparticles were dispersed into the based fluid for volume fractions ranged $\varphi=0.05$-1%. The simulations were performed at three inclination angles of 30°, 45° and 60°. Numerical results indicated that the thermal performance of the evacuated tube was improved with nanofluids compared its base fluid. In addition, the thermal performance of the tube at inclination angle of 30° and 0.5vol.% was found to give the maximum enhancement which shows the highest thermosyphon and gravity effects on the evacuated tube.*

Keywords: TiO_2/Water Nanofluid, Nusselt Number, Thermosyphon, Evacuated Tube Solar Collector

1.0 INTRODUCTION

An alternative energy source is a topic of research for engineers and scientists. Solar energy is an alternative energy source, renewable energy that is environmentally pleasant and less hazardous. Fossil fuels are non-renewable energy sources and not environmentally friendly when compared to solar energy. Fossil fuels usually results in high climate change due to combustion of fuel-oxidizer that results in emissions of greenhouse gases and formation of sulphuric oxide, Nitrogen oxide, carbon oxide and other organic compounds which are harmful to the environment.

The solar energy is classified as dirt-free renewable energy that has less impact environmentally. It is estimated that one hour of solar energy received by the earth is equal to the total amount of energy consumed by humans in one year [1]. Similar to plants, they use chlorophyll to photosynthesize the sun's irradiation in order to provide energy for their growth. Only 14.4 percent of sunshine survives filtering from the earth's atmosphere and falls on the land where it can be harvested. This is however 2,800 times more than our energy needs [1].

A lot of research works have been reported in the literature on the harvesting energy from solar. In addition, many countries have made immense researches on solar energy utilization [2-14]. Generally, there are two ways of harvesting solar energy depends on the needs; (i) solar-electric conversion (converting solar energy into electrical energy using photovoltaic solar cell or concentrated solar power) and (ii) solar-thermal conversion (converting solar energy into thermal energy using solar collector) [15].

Research on solar-thermal systems has attracted many investigators from all around the globe. Soteris [16] provided an extensive review on the historical development and current progress of the solar collectors. Mills [17] in his review article, discussed the current technologies that are being applied in the development of single and two-axis tracking solar collectors, several kinds of low temperature technologies such as evacuated tube collector, organic Rankine cycle turbine and solar updraft power plants.

2.0 TYPES OF SOLAR COLLECTOR

Solar energy collectors are mediums generally design to collect and absorb the solar radiation. The absorbed solar radiation is converted into heat by the collector devices which are eventually transferred into the working fluid of the system usually water or air as the common working fluid. Basically, there are two types of solar collectors: stationary and sun tracking [16]. One axis and two axes tracking are categorised as sun tracking solar collector as shown in Fig. 1.

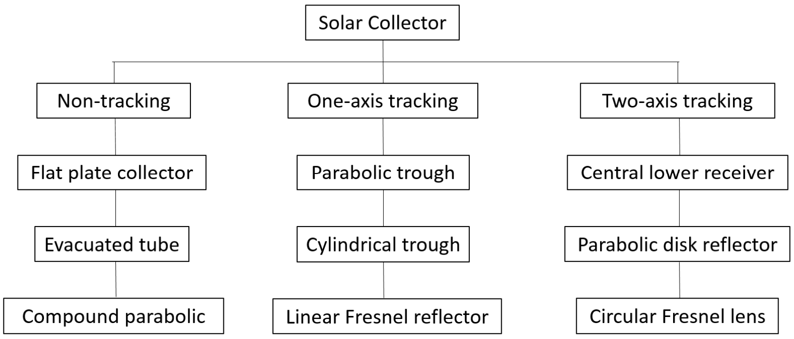

Figure 1: Types and classifications of solar Collectors [18]

The stationary type of solar collectors is characterized by having same area for intercepting and for absorbing solar radiation. However, they are installed at a particular tilt and orientation angle to maximize the harnessing of solar radiation, as shown in Figure 2. Depending on the applications, the optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10 – 15^0. Evacuated tube collector is the most common and widely use stationary solar collectors.

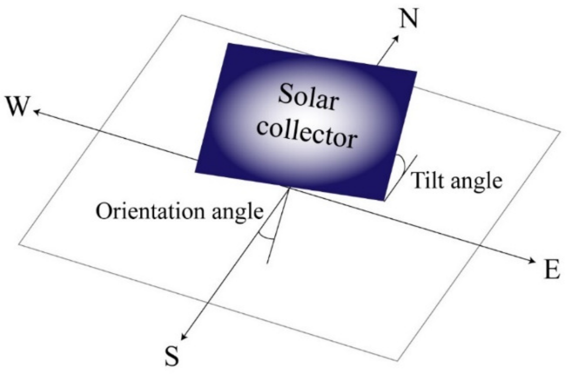

Figure 2: Orientation angle for harnessing solar energy

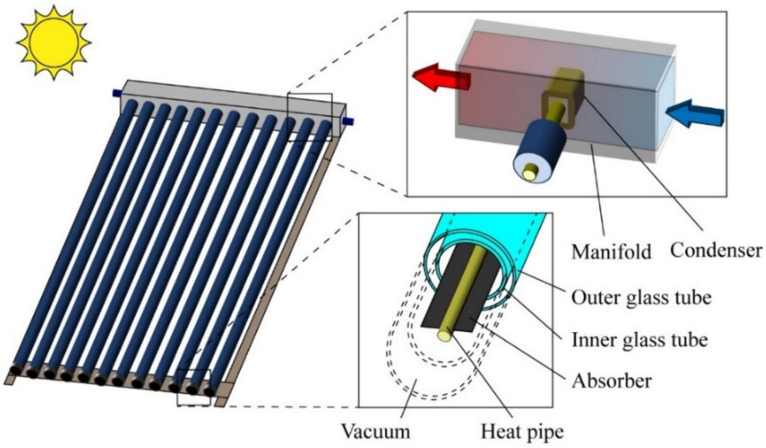

Figure 3: Evacuated tube solar collector

Solar collectors with evacuated tubes have many advantages compared to flat-plate collectors. Zambolin and Del Col [19] and Ayompe et al [20] experimentally examined the thermal performance of both flat-plate and evacuated tube collector under similar condition. The results demonstrated a higher efficiency for evacuated collector.

The main component in the evacuated solar collector is the parallel evacuated glass tube as shown in Fig. 3. The outer tube is transparent while the inner tube is coated with selective material coating to maximally absorb the incoming sun light. A vacuum is created between outer and inner tube to only allow solar radiation but not the heat. A highly efficient thermal conductor of heat pipe (usually cooper pipe) welded with absorber plate is then placed inside the inner tube.

Morrison et al. [21] reported numerical study of water-in-glass evacuated tube solar water heater using CFD numerical package. They found the possibility of the presence of a stagnant region in the bottom of the tube that would influence the operation of the very long tubes. In an earlier research, Gaa et al. [22] studied the effect of two modes of heating (uniform and differential) on the velocity profile of flow in an inclined cylindrical open thermosyphons. Their results confirmed the previous findings [23] that differential heating is more effective than uniform heating in that it promotes freer flow between the opposing streams even with lower heat input.

In a different study, Kim and Seo [18] experimentally and numerically investigated the thermal performances of four different shaped absorbers for U-pipe evacuated solar collector. The effect of fin on the absorber indicated that the U-pipe welded inside with circular fin was the best shape for the absorber tube of the evacuated solar collector. Their results also revealed that the used of copper plate material welded with pipe gave better performance when the beam insolation, shade and diffuse irradiation were taken into consideration. The design of U-tube evacuated solar collector is almost similar to that of water-in-glass evacuated tube. The major difference is that evacuated U-tube uses fins to store more heat and the U-tube are made of a copper element. The common working principal of most evacuated solar collectors is based on natural convection which involved repetition of cycle known as ‘thermosyphon’ principle.

Gao et al. [24] analysed the thermal performance of a U-pipe evacuated solar tube collector (UpEST collector) using the newly proposed model. They found that the thermal efficiency of the collector did not increase with increasing length. It is not recommended to produce a longer tube to enhance the thermal efficiency of the tube. In addition, they suggested that the optimal design of mass flow rate for higher thermal efficiency is necessary for the UpEST collector.

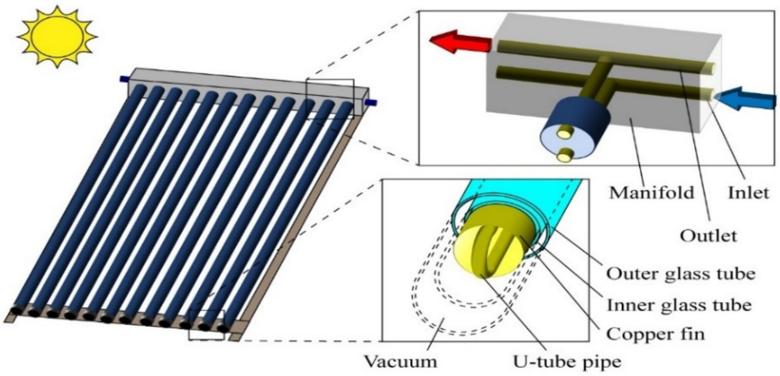

Figure 4: Evacuated U-tube solar collector

Ayompe et al. [25] investigated the thermal performance of evacuated solar collector with heat pipe for a period of one year. The collector was installed on a flat rooftop in the Focas Institute, Dublin, Ireland (latitude $53^0$20'N and longitude $6^0$15'). The result shows that the maximum fluid temperature was 70.3^0C while the temperature at the bottom of hot water is 59.5^0C. The annual average daily collector efficiency was 63% while the system efficiency was 52%. Morrison et al. [26] reported numerical results of flow rates in a single evacuated tube collector. The tank was represented as a rectangular shape of 325mm×175mm×140mm dimensions and tube length and diameter of 1420mm and 34mm respectively. Simulation works were compared with a similar experimental work and the computed velocity plume was analysed both qualitatively and quantitatively. Fig 5 demonstrates good agreement between the two results.

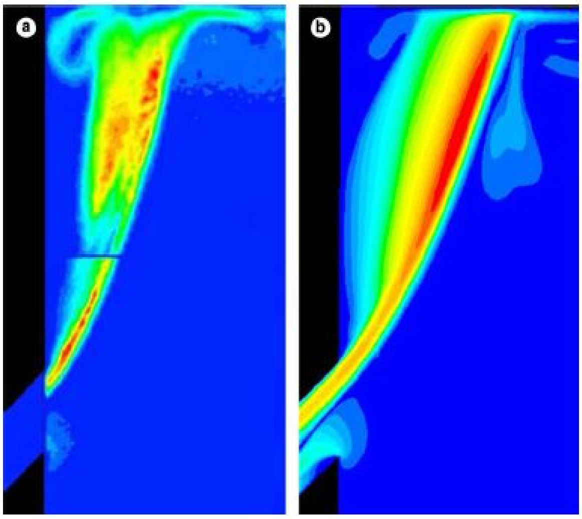

Figure 5: Velocity contour for heating on the top half of the tube, PIV experiment (left) CFD simulation (right) [26]

Few researchers have compared the thermal performance of different solar collectors. Dilip et al. [27] claimed that the evacuated U-tube collector is more efficient around 10-15% than water-in-glass evacuated collector. Hayek et al. [28] experimentally studied the performance of heat pipe design and water-in-glass evacuated tubes. The experiment was performed for a period of two months with experimental set-up made of 20 rows of evacuated tubes and a tank. A circulation pump was used to circulate the working fluid between the collector and the storage tank. The collector was tilted to 30^o and readings were taken manually every 15 minutes. The results demonstrated that the overall efficiency of heat pipe collectors was almost 15 to 20% higher than that of water in glass collectors.

Differently, Kumar et al.[29] experimentally studied a one ended evacuated tube solar collector using air as working fluid for the generation of hot air. The evacuated tube was designed with fifteen glass tubes which consist of two concentric glass tubes made of strong borosilicate glass. The manifold head channel was insulated to prevent the heat losses to the atmosphere. Four different analyses were conducted with and without reflector. The maximum efficiencies were recorded to be 0.58 and 0.50 with and without reflector respectively, at flow rate of 13.28 kg/hr. Thus, they concluded that the used of reflector will certainly increase the evacuated tube collector performance.

Recently, Lamnatou et al. [30] highlighted the needs of evacuated tube solar air collector in agricultural sector for drying of agricultural products. Evacuated air collectors were considered to obtain hot air for drying of apples, apricots and carrots. They also found that the air collector has the capacity of drying large quantities of the products which make the collector highly recommended for large industrial scale.

Li et al. [31] focused on the thermal performance of glass evacuated solar air collector based on the energy analysis approach. The result indicated a good agreement between the new dynamic model and the first order model. However, the new dynamic test model has shown the potential of performing at different climate conditions. Thus, it is suitable for use in places where the weather conditions is harsh.

Evacuated tube solar collector has also been used in many applications such as solar water heating [32-35], air conditioning [36-37], swimming pool [38], solar cooker [39-40], heat engines [41], solar drying [42-44], and steam generation [45]. For domestic application the collector operates from medium to high temperature ranges depending on the use. Conversely, in the case of industrial application, evacuated tube solar collector operates at a higher temperature of about 200°C; as such it can be utilized for industrial application for high temperature operations.

3.0 EVACUATED TUBE SOLAR COLLECTOR WITH NANOFLUID

The application of nanofluid research in heat pipes was firstly published by Chien et al. [46]. However, Lu et al [47] possible the first who considered nanofluid in tubular evacuated high temperature solar collector. In their study, water based CuO nanofluid was used as working fluid. Their experimental results show that the optimal filling ratio to the evaporator was 60% and the thermal performance of the thermosiphon increase with the increase of the operating temperature. By using CuO/water nanofluid, the thermal performance was enhanced by about 30% compared to those of deionized water and the optimal enhancement was found at CuO nanoparticles mass concentration of 1.2%. Within the same year, Li and his co-workers [48] investigated the heat transfer performance of different nanofluids in tubular solar collector. Nanofluids containing Al_2O_3, ZnO and MgO nanoparticles were prepared with distilled water as base fluid by violent stirring and ultrasonic dispersing. Based on their results of low viscosity and excellent heat transfer performance, 0.2% volume concentration of ZnO nanofluid was proposed as an attractive option to be applied in solar energy utilization.

In a different study, Mahendran et al. [49] prepared water-based titanium oxide nanofluid with particle size of 30-50 nm. In this experimental study, the effect of collector efficiency using nanofluid under clear sky and cloudy conditions within Universiti Malaysia Pahang, Pekan campus, were analyzed. It was observed that the solar insolation was parabolic during clear sky with maximum at 2:00 pm. They claimed that the efficiency of the collector was increased by 16.75% maximum compared to the system working with water. In their study, the flow rate was fixed at 2.7 liters per minutes. Mahendran et al [50] duplicated the previous study [49] but varied the nanofluid volume concentration from 1% to 3% and volume flow rate from 2 to 3 liters per minutes. Surprisingly, the results demonstrated the efficiency of evacuated solar collector have increased up to 42.5% by using 2% concentration nanofluids compared to water at 2.0 liters per minute of flow rate.

In another innovative research by Zhen et al [51], an evacuated tubular solar air collector was integrated with simplified compound parabolic concentrator to provide air with high and moderate temperature. A special thermosiphon using water based CuO nanofluid was used as working fluid. Their experimental results indicated that the air outlet temperature could reach 170^0C even during winter season.

The performance of metal oxide nanofluids as an absorbing fluid in evacuated tube solar collector was comprehensively studied by Saad and Abbas [52]. Among the measured parameters were the Al_2O_3/water nanofluid concentration and tube tilt angle for Baghdad climate condition from April 2011 till end of March 2012. Their research found that the best tilted angle of evacuated tube is 41^o annually. The collector efficiency was also found increased when using Al_2O_3/water nanofluid of 1, 0.6. 0.3% volume fraction as 28.4, 6.8 and 0.6% respectively. Hasim et al [53] extended the study by comparing the thermal efficiency of evacuated tube solar collector by using metal oxide nanofluid (ZrO_2/water) and metal nanofluid (Ag/water). They claimed that the use of nanofluid (both oxide metal and metal nanoparticles) as a working fluid could improve thermal performance of the collector compared with it base fluid, especially at high inlet temperature. However, the collector efficiency with Ag with 30nm size was greater than ZrO_2 with 50nm size due to high thermal conductivity for Ag.

To enhance the energy performance of an evacuated tube solar collector, Sabiha et al [54] proposed the used of water based single walled carbon nanotubes nanofluid as an absorbing medium. The effect of nanoparticles volume fraction ranges from 0.05vol% to 0.2vol.% and mass flow rates of 0.008, 0.017 and 0.025kg/s on the energy efficiencies has been investigated. Due to higher thermal properties of SWCNTs nanofluids, the collector efficiency increases up to 93.43% for 0.2vol.% SWCNTs nanolfuid which is 71.84% higher compared to water. At this concentration, the efficiency of the collector with nanofluid on cloudy days is better compared to water on sunny days.

Evacuated U-tube solar collector is a novel model for solar thermal system which was earlier proposed by several researchers [55-56]. Kim and Seo [18] numerically investigated different shapes of U-tubes to find the best shape of the absorber tube for the solar collector. Tong and his co-workers [57] possibly the first who considered multiwalled carbon nanotube (MWCNT) nanofluid as working fluid in enhancing the thermal performance of enclosed type evacuated U-tube solar collector. Based on this novel method, their calculations revealed that the annual CO_2 and SO_2 emission could be reduced by 1600kg and 5.3kg respectively, when 50 of this type of solar collector are employed.

Recently, Kim et al [58], theoretically calculated the solar collector efficiency and energy saving of a U-tube solar collector with nanoparticles in 20% propylene glycol-water nanofluid. Using thermal energy balance, the effect of concentration of MWCNT, Al_2O_3, CuO, SiO_2 and TiO_2 nanofluids on the efficiency of the collector has been analysed. Their results indicated that the greatest efficiency was obtained at 62.8% when 0.2vol% MWCNT was used. By dispersing nanoparticles in the working fluid, they arrived at the conclusion that the coal usage could be reduced up to 131.3kg per year when 50 solar collectors are used. This is equivalent in reducing up to 345.3 kg of CO_2 and maximum reduction of SO_2 1.1kg per year.

The objective of this research is to simulate the thermal performance on TiO_2-water nanofluid as an absorbing medium in a single evacuated tube solar collector. Other than to observe the effect of nanoparticles volume fraction, inclination angle of the tube will be varied from 30^o to 60^o to see the effect on the flow structure and thermal stratification in the fluid tank. To the authors knowledge, the TiO_2-water nanofluid has not been applied to date as an absorbing medium in thermosiphon evacuated tube solar collector.

4.0 PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

The geometry adopted in this study is a three-dimensional model that comprises of a cylindrical tube of length 1420mm and diameter of 47mm attached to a 150liter circular reservoir tank containing the fluid as shown in Fig.6. Constant heat flux of $500W/m^2$ is applied at the top half of the tube which corresponds to a solar irradiance of $1000\ W/m^2$. TiO_2-water nanofluid with nanoparticles volume fraction ranging from 0.05-1% was used. Basically, the flow in the tube is associated with interaction between liquid and solid along the boundaries. It can be observed that when fluid flow in any cylindrical-like shape, there may exist several ways to which the fluid flow behaves inside or outside the boundary. Nevertheless, the fluid flow behaviour in this study is assumed to be internal flow, the nature of flow is laminar, unsteady, and incompressible. the heat transport is mainly by the natural convection.

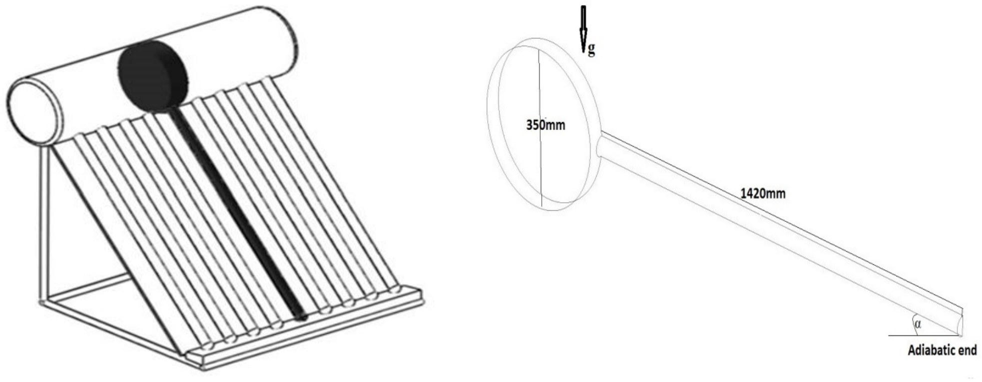

Figure 6: Schematic diagram of water-in-glass evacuated tube solar collector (left) [59]. Geometry of an evacuated tube solar collector.

Considering the above problem, the governing equations can be expressed as the follows:

The continuity equation:

$$\frac{du}{dx}+\frac{dv}{dy}+\frac{dw}{dz} \tag{1}$$

The momentum equations in x, y and z directions are as follows:

$$\rho_{nf}\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial x}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\rho_{nf}g_x\beta_{nf}\left(T-T_{ref}\right) \tag{2}$$

$$\rho_{nf}\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial x}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\rho_{nf}g_y\beta_{nf}\left(T-T_{ref}\right) \tag{3}$$

$$\rho_{nf}\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial x}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\rho_{nf}g_z\beta_{nf}\left(T-T_{ref}\right) \tag{4}$$

The energy equation is given as below:

$$\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial x}\right)=\frac{k_{eff}}{\left(\rho c_p\right)_{nf}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

The density of nanofluid can be obtained based on the volume fraction and densities of both based fluid and nanoparticles respectively [60]. The correlation is given as

$$\rho n_f=(1-\varphi)\rho_f+\varphi\rho_s \tag{6}$$

The specific heat capacity of the nanofluid can be estimated based on the correlation given by:

$$\left(\rho c_p\right)_{nf} = (1\text{-}\varphi)\left(\rho c_p\right)_f + \varphi\left(\rho c_p\right)_s \tag{7}$$

The coefficient of thermal expansion coefficient is expressed as

$$(\rho\beta)_{nf}=(1\text{-}\varphi)(\rho\beta)_f + \varphi(\rho\beta)_s \tag{8}$$

The thermal conductivity of nanofluid can be calculated based on Maxwell model [61], which can be expressed as

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f+2\varphi\left(k_f-k_s\right)}{k_s+2k_f-\varphi\left(k_f-k_s\right)} \tag{9}$$

Brinkman correlation of effective dynamic viscosity was used throughout this study [62].

$$\mu_{nf}=\frac{\mu_f}{(1-\varphi)^{2.5}} \tag{10}$$

The evacuated tube is divided into top and bottom parts. The heating is only applied on the top part where as the bottom part is unheated throughout this study. Top part is expected to receive 50% to 57% of solar radiation where as the bottom received less unless the use of a reflector under it. The heat fluxes were measured on the 1st-Oct-2015 under latitude 1.5333^0N and longitude 103.6667^0E at Skudai, Johor Bahru, Malaysia. The solar irradiance of the sun were taken at different time from morning 8.00am to evening 5.00pm. As can be observed in Table 3, the maximum solar insolation was obtained 980W/m^2 during the noon at approximately

12:00 pm, eventually the solar insolation after an hour begins to decrease. Therefore, in this research, the heat flux around the half tube was taken as 500W/m^2.

Table 1: Solar irradiance at different time taken in Skudai, Johor Bahru on 01/10/2015

Time (hr)	Solar Insolation (W/m^2)
8:00am	832.426
9:00am	916.332
10:00am	956.473
11:00am	975.415
12:00pm	980.684
13:00 pm	974.074
14:00 pm	953.313
15:00 pm	909.913
16:00 pm	818.108
17:00 pm	576.684

5.0 RESULTS AND DISCUSSIONS

Grid dependency test and model validation

A good quality and quantity of mesh size are very important to ensure the accuracy and time of CFD numerical computation. In this study, few three-dimensional meshes were generated using ANSYS to investigate the effects of grid numbers on the maximum temperature inside the tank. From Table 3, it can be clearly observed that a maximum temperature inside the tank was converged at 308K. Similar finding was also reported in experimental study by Morrison et al [26]. Therefore, the element size of 586275 is independent and accepted for the computational domain in this study.

Table 3: Rid sizes at the tank temperatures

Mesh (element size)	Temperature (K)
174658	308.85
267523	308.70
400037	308.50
523911	308.30
586275	308.10
831754	308.10
973645	308.10

Figure 7 shows the comparisons between the predicted velocity magnitude of water and the experimental data at the joint opening of the tube to the tank. It can be seen that the predicted velocity in this study has a good agreement with the experimental value given by Morrison et al [26]. Besides, in order to further evaluate the prediction performance of the numerical model, the magnitude of velocity was plotted at steady state condition.

Figure 7 shows the results of velocity contour inside the tube and the tank. From the figure, we can notice the flow behaviour is identical to that obtained through the previous experimental work [26]. This indicates that the computation method and numerical procedure are reasonable and reliable. In this study, nanofluid containing TiO$_2$ nanoparticles with volume concentration from 0.05% to 1% was used as an absorbing medium in an evacuated tube solar collector. The thermophysical properties of base fluid, nanoparticles and nanofluid are shown in Table 4.

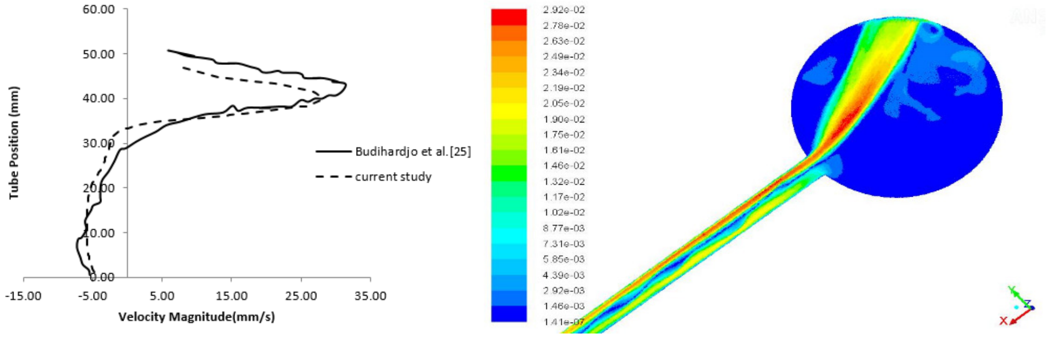

Figure 7: Comparison of velocity magnitude and velocity contour inside the manifold

Table 4: Thermophysical properties of based fluid, nanoparticles and nanofluids

	Water	TiO_2	0.05vol.%	0.1vol.%	0.5vol.%	1vol.%
Density , ρ (kg/m3)	998.2	4175	999.826	1001.452	1014.459	1030.718
Specific heat capacity Cp((J/kgK)	4182	773	4174.544	4167.112	4108.773	4037.357
Thermal conductivity, k (W/mK)	0.6	8.4	0.600741	0.601482	0.607435	0.614931
Coefficient of volume expansion,β 1/k	0.00021	0.9E-5	0.00021	0.000209	0.000206	0.000202

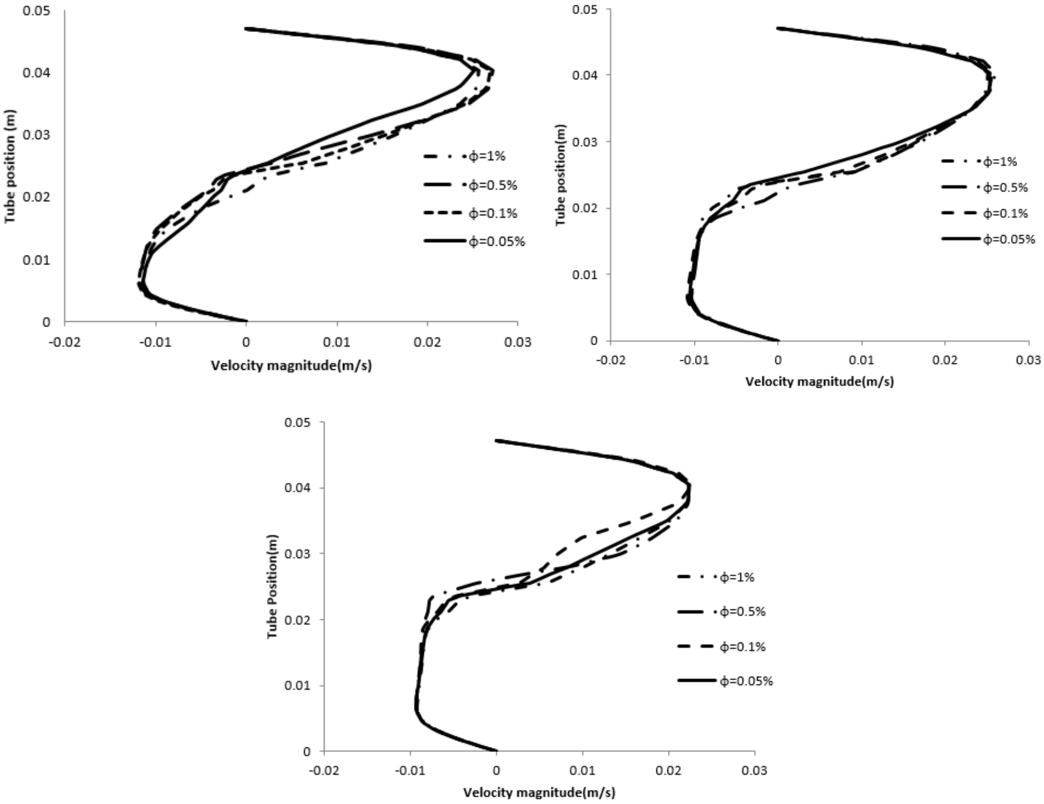

Figure 7: Velocity profile at the tube opening for 30°, 45° and 60° at various nanofluid concentration

Figure 8 presents velocity magnitude at the tube opening at different inclination angles of single tube evacuated solar collector (STESC) with various concentration of nanofluid. The flow in the tube is bi-filament in nature with the hot fluid rising to the top of the tank replacing the cold water flowing from the reservoir tank into the tube. It is noticeable that as the inclination angle of STESC increases from 30°to 60°, the velocity decreases due to lower buoyancy force generated near the joint of the tube and tank. We also noticed that at volume fraction of 0.5%, the highest velocity magnitude can be obtained at all inclination angles.

Figure 9 shows the plot of velocity magnitude at tube opening for 0.5vol% of nanofluid and three different inclination angles. The results clearly showed that the inflow and outflow velocities from the tube is the highest when the inclination angle of 30^o. At this angle, it is believed that the fluid received the maximum effect of thermosyphon phenomenon which could lead to the obtained results. Similar findings were also reported by previous researchers [64,65].

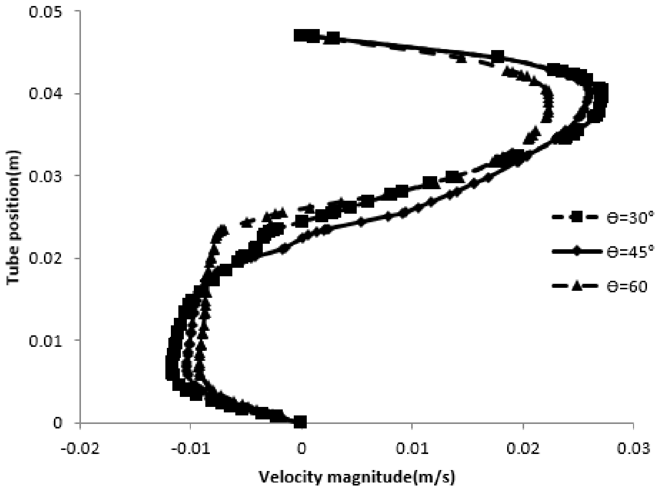

Figure 8: Comparison of Velocity profile at the tube opening at φ=0.5 for 30°, 45° and 60.

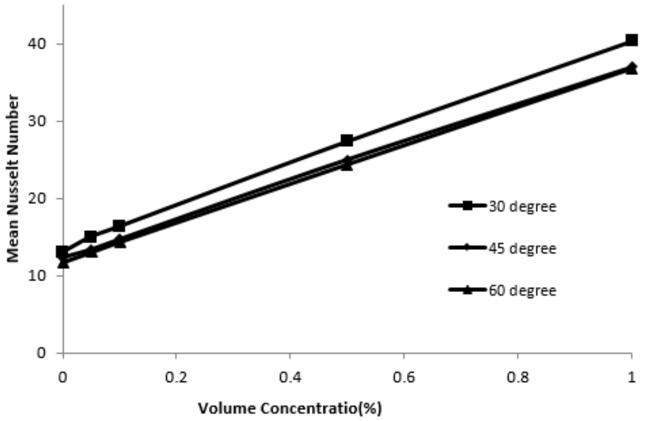

Figure 9: Effect of inclination angle on mean Nusselt number at different Volume fractions.

The variation of mean Nusselt number with volume fraction for different inclination angles of 30° to 60° is demonstrated in Fig 10. For all values of inclination angles, as the volume fraction increases, the mean Nusselt number also increases. However, it can be observed that increasing inclination angle decreases the mean Nusselt number for all volume fraction concentration. These are caused by the formation of weak secondary recirculation at the higher inclination angles and thus, decreasing the mean Nusselt number.

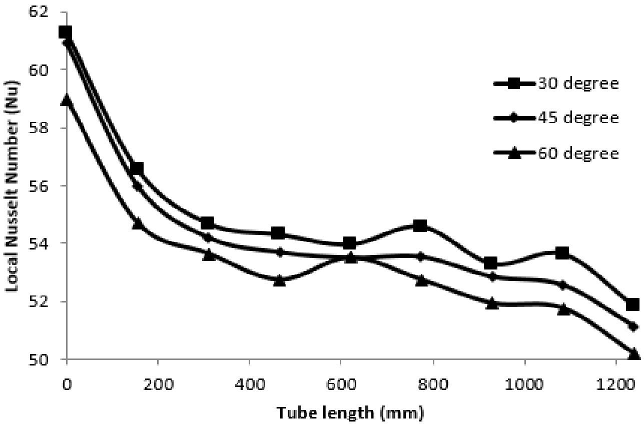

Figure 10: Comparison of local Nusselt number at φ=0.5 volume fractions along the heated wall for 30˚, 45˚and 60˚

The variation of local Nusselt number along the heated wall at different inclination angle for the 0.5vol% is given in Figure 11. Here we confirmed previous finding that higher value of Nusselt number can be obtained at small inclinations angle [66].

Effect of Tank Thermal Stratification

Thermal stratification of evacuated tube solar collector refers to the change in temperature at different depth in the tank volume as a result of density variation of fluid inside the tank. Cold nanofluid is denser than warm nanofluid as such it will be stratified at the bottom of the tank reservoir. Moreover, thermal stratification is very important in studies related to natural convection and, therefore, the more stable the thermal stratification the more efficient the collector. Figure 12 shows the development of temperature changes inside the reservoir tank. At steady state condition, it is found that the temperature above the tube opening point is homogeneous and that the temperature gradient was found below these openings. The hot water was fully mixed above the opening of the tubes. These results agree with experimental work of Behnia and Morrison [67-69] and Tang et al [70].

6.0 CONCLUSIONS

Numerical prediction using commercial software of ANSYS has been conducted on thermosyphon evacuated tube solar collector with TiO_2/water nanofluid as an absorbing medium. The effect of volume fraction of nanoparticles on thermal performance of collector was investigated for different inclination angles of tube. Some of the most important results that have been achieved in this study are as follows:

1. Increase of nanoparticles volume fraction enhances the thermal conductivity of fluid and mean Nusselt number of evacuated tube solar collector
2. Inclination angle of tube plays an important role in thermal performance of evacuated tube which enhance the thermosyphon effect.

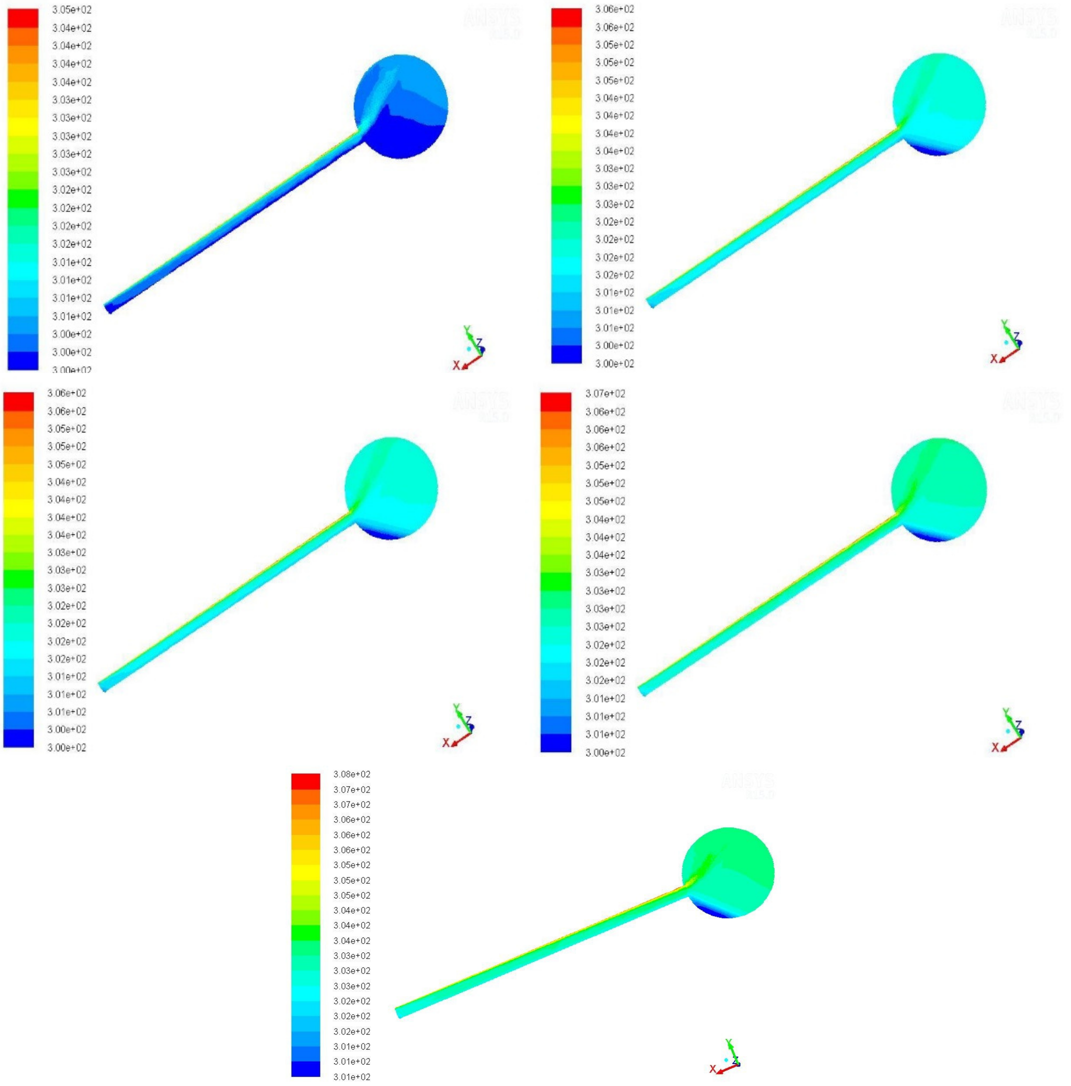

Figure 11: Tank Thermal stratification for (a) 400s (b) 1200s (c) 2000s (d) 2800s (e) 3600s

3. The highest velocity magnitude and maximum enhancement of heat transfer enhancement can be seen when the nanoparticles volume fraction and inclination angle of 0.5% and 30 degree respectively
4. The temperature above the tube opening point is homogeneous (fully mixed) and that the temperature gradient was found below these openings.

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