Effect of Geometric Parameters on the Performance of Water in Glass Evacuated Tube Solar Heater*

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Kyekyere, E., Ndiritu, H., Hawi, M. and Mwambe P. (2022), "Effect of Geometric Parameters on the Performance of Water in Glass Evacuated Tube Solar Heater", *Ghana Mining Journal*, Vol. 22, No. 2, pp. 43-49.

Abstract

Performance improvement of water in glass evacuated tube solar water heaters has received attention from many researchers yet the effect of geometric parameters on the performance of the system has not been fully explored. In this work, the effect of collector tube length, diameter and tilt angle on the temperature and velocity distribution was studied using computational fluid dynamics (CFD). The results of the CFD model were validated against experimental data. The collector tube length was found to have a significant influence on both the temperature in the storage tank and the velocity distribution. The longest collector tube (2000 mm) achieved the highest temperature compared to collector lengths of 1800 mm and 1600 mm. A larger collector tube diameter of 52 mm enhanced the average temperature in the storage tank compared to collector tube diameters of 42 mm and 47 mm. The effect of tilt angle on velocity distribution was analysed using tilt angles of 10, 23, 30, and 45 degrees and the results showed that the average flow velocity for lower tilt angles was high, however, the maximum flow velocity which occurs at regions close to the boundary between the collector tube and the storage tank was higher for high tilt angles.

Keywords: Solar water heater, Water-in-Glass Evacuated Tube, Collector Tube, Tilt Angle

1 Introduction

Solar water heaters offer a cost-effective, limitless and ecologically friendly approach to hot water generation. Research has shown that the performance and reliability of evacuated tube solar collectors are better as compared to flat plate solar collectors (Liu *et al.*, 2017). Evacuated tube solar collectors are classified mainly as a heat pipe, u-type and water in glass solar collectors (Arturo *et al.*, 2015). However, water-in-glass evacuated solar water heater is one of the most commonly used solar water heaters due to their simplicity and cost-effectiveness.

Water in glass evacuated tube solar water heater generally consists of a storage tank mounted horizontally and about 10– 40 evacuated glass tubes. Each tube is made up of a transparent outer glass tube larger in diameter, as well as an inner glass tube, smaller in diameter and selectively coated to enhance solar irradiation absorption (Kyekyere *et al.*, 2021). The heat energy absorbed by the collector tube is then transferred to the water inside the collector tubes. When the water in the collector tube gets heated, its density reduces and it is pushed up by the dense cold water from the storage tank.
Research on the performance of water in glass evacuated tube solar water has received interest from many researchers due to its cost-effectiveness and simple design. Arturo et al. (Arturo *et al*., 2015) conducted a numerical simulation using CFD to predict the performance of water in glass evacuated tube solar water heater using a variation of the properties with temperature (VPT) and Boussinesq approximation (BA). Results from their simulation revealed that the Boussinesq approximation has high accuracy in predicting the performance of the system as compared to the variation of properties with temperature. Sato *et al*. (2012) modified the conventional water in glass evacuated tube collector by the addition of inferior and lateral connections to form a double-ended collector tube. The inferior connection greatly improved the stratification effect in the storage tank. However, the temperatures recorded in the new designs were lower than the conventional design.

Yao *et al*. (2015) simulated the performance of an all-glass evacuated tube solar water heater using a single collector tube with twist tape inserts. The twist tape inserts were found to be suitable for high-temperature operations since it enhances the uniformity of the temperature field. Morrison *et al*. (2005) used a single-ended evacuated tube connected directly to a storage tank to investigate the circulation flow rate and the heat transfer in water in glass evacuated tube solar water heater. The temperature of water in the storage tank was found to have a significant influence on the rate of water circulation through the tubes. Additionally, the intensity of solar irradiation on the surface of the absorber greatly contributes to the circulation flow rate.

Morrison *et al*. (2004) predicted the possibility of a stagnant region at the bottom of collector tubes longer than 2.4 m from their preliminary investigations. The experimental investigation of Zhang *et al*. (2014) on the performance of water in

**Manuscript received September 25, 2022*
Revised version accepted December 24, 2022
https://dx.doi.org/10.4314/gm.v22i2.7

glass evacuated tube solar water heaters predicted the optimum polyurethane insulation of the storage tank to be around 50 mm. Furthermore, the capacity of the collector was found to have an impact on the performance of the solar water heater. The tilt angle of the collector tube significantly influences the daily heat gain and the flow patterns within the tank, however, the influence of tilt angle on the daily conversion efficiency is negligible as observed by Tang *et al*. (2011) and Bracamonte *et al.* (2015).

Shah and Furbo (2007) investigated the effect of collector length on the performance of all glass solar water heaters using a horizontal collector connected to a vertical channel. The results revealed that the shortest collector length achieved the highest thermal efficiency. Nevertheless, little is known about the influence of collector tube length on the temperature distribution and flow patterns in the tube of tilted collectors.

In this study, the effect of collector tube length and diameter on the temperature distribution and flow patterns in tilted water in glass evacuated tube collectors is evaluated using CFD.

2 Resources and Methods Used

2.1 Design and Sizing of Model

To reduce the computational time and resources required for the simulation process, a single-ended tube connected directly to a corresponding portion of the tank was modelled. The length of the collector was 1800 mm and its diameter was 47 mm. The transparent outer glass tube of the collector was not modelled physically in the study, however, its effect on the performance of the water in glass evacuated tube solar water heater was incorporated in the boundary condition. The collector tube was inclined at an angle of 23 degrees to the horizontal. The tank has a diameter of 376 mm, a length of 90 mm and a volume of 10 litres. These specifications were chosen based on the experimental setup of the study conducted by Kyekyere *et al*. (2021). Fig. 1 shows the computational domain of the CFD model.

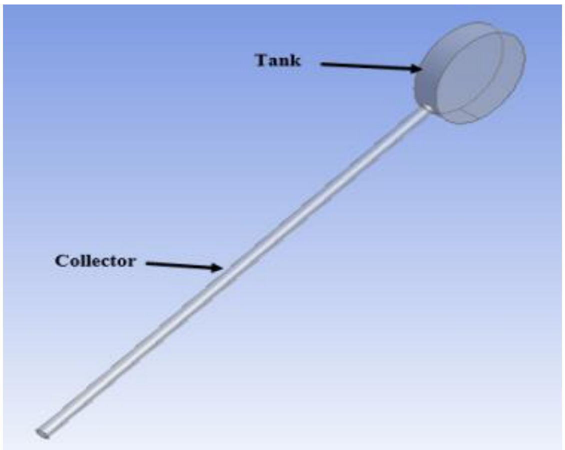


Fig. 1 Computational Domain

2.2 Discretization of the Computational Domain

In numerical simulations, the stability and accuracy of the predictions are determined by the grid size of the computational domain. To ensure a solution that is independent of the mesh size, stable and accurate, a grid-independent test was conducted taking into account various mesh sizes.

A grid independence test was conducted for the average temperature in the storage tank using five different grid resolutions. The grid resolutions used were 66 829, 224 811, 526 528, 908 785 and 1 776 526 cells corresponding to mesh sizes of 12 mm, 8 mm, 6 mm, 5 mm and 4 mm respectively. Based on the grid independence test, a grid system with 908 785 cells was used to discretise the computational domain since no appreciable change in the results occurred when the cells were increased from 908 785 to 1 776 526 as observed in Table 1.

Table 1 Mesh independence Test for Simulation

Mesh Size [mm]	**Number of Elements**	**Average Temperature in Tank [^{o}C]**	**Highest Temperature in Collector [^{o}C]**
12	66829	68.3	74.9
8	224811	68.1	74.5
6	526528	67.9	74.2
5	908785	67.9	74.2
4	1776526	67.9	74.2

Residual values of the momentum, continuity and energy equations were monitored to ensure solution convergence. Residual values were less than 10^{-4}, 10^{-5} and 10^{-11} respectively for the continuity, momentum and energy equations.

2.3 Flow Governing Equations

In this analysis, the flow system was assumed to be 3- dimensional, laminar and transient. The following continuity, momentum and energy equations governing fluid flow in the tensor form were used.

Continuity Equation

$$\frac{\partial P}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

Momentum Equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial(u_i)}{\partial x_j}\right) - \frac{\partial P}{\partial x_i} + \rho g_i \quad (2)$$

Energy Equation

$$\frac{\partial \rho T}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i C_p T - k\frac{\partial T}{\partial x_i}\right) = 0 \quad (3)$$

2.4 Boundary Conditions and Solution Method

Correct specification of the boundary conditions in numerical simulation represents its approximation of the physical system and ensures the accuracy of the simulated results. The Solar ray-tracing model which is in-built into the ANSYS software was used as the source of solar irradiation. Atmospheric conditions including the day of the year, time of the day, time zone, latitude and longitude of the area were specified together with the sunshine factor. The location has a latitude of -1.03326 and a longitude of 37.06933.

The working fluid was water and the initial temperature of water in the system was set as 27 °C. The system was assumed to be full of water and no inlet and outlet conditions were assumed. The circulation of water in the system was a result of the difference in water density at various portions due to uneven heating of water. The thickness of the collector tube was set as 1.6 mm while the thickness of the tank wall was set as 0.005 m. The wall thickness of the tank takes into account the thickness of the polyurethane insulation. These values were selected based on the dimensions of the experimental set-up of Kyekyere *et al.* (Kyekyere et al., 2021). The collector absorptivity and transmissivity were 0.96 and 0.04 respectively. The initial direct normal solar irradiation was 728 W/m^2 and the solar irradiation was updated after every 10-time step. The walls of the tank were assumed to be adiabatic.

The finite volume method was used to solve the governing equations in this study. The coupled algorithm which is suitable for transient conditions with large time steps was used to deal with the pressure velocity coupling. Body weighted force was set as a spatial discretization scheme for pressure due to its ability to account for the gaps in pressure that occurs in natural convection flows. Both the momentum and energy equations were discretized using the second-order upwind scheme.

2.5 Model Validation

The results from the simulation were compared with the experimental results of Kyekyere *et al.* (Kyekyere *et al*., 2021) to determine the reliability, accuracy and validity of the numerical model. The numerical model in this study was developed using the specifications of their experimental setup. Also, the initial and boundary conditions used in the simulation were similar to the environmental and operating conditions present in their study. Figure 2 shows a comparison of the experimental results of Kyekyere *et al.* (Kyekyere *et al*., 2021) obtained on 28th January 2021 with the simulation results in this study. The data shows an average deviation of 0.23% of the simulated results from the experimental results. This close agreement proves the validity and accuracy of the simulation model and hence can be used to represent the real system for further studies. Fig. 3 shows the temperature and velocity distribution in the numerical model.

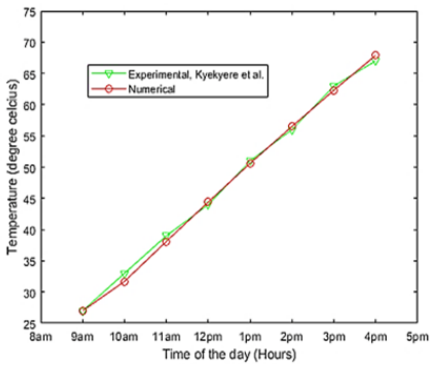
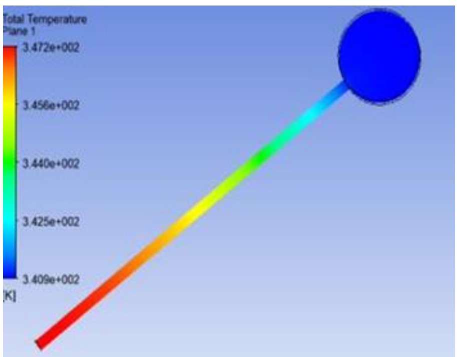
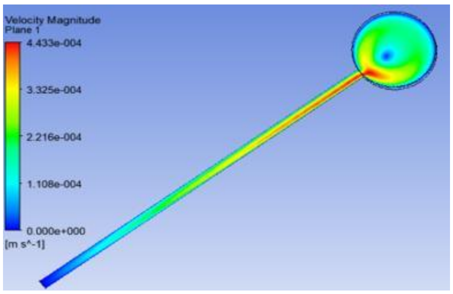


Fig. 2 Comparison of Experimental and Simulated Results on 28th January 2021.



(a)



(b)

Fig 3. Temperature (a) and Velocity Distribution (b) in the Numerical Model at 4 pm on 28th January 2021.

3 Results and Discussion

3.1 Effect of Collector Tube Length on Temperature Distribution

Collector tube lengths of 1600 mm, 1800 mm and 2000 mm were used to investigate the effect of the collector length on the performance of the water in glass evacuated tube solar water heater. All other geometric parameters were held constant while varying the length of the collector tube. The results indicated that the length of the collector tube has a significant influence on the performance of the solar water heater as observed in Fig 4.

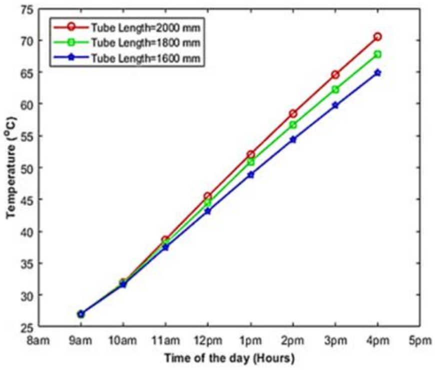


Fig. 4 Effect of Collector Length on Temperature Distribution in the Storage Tank

The longest collector tube (2000 mm) achieved the highest average tank temperature while the shortest collector tube achieved the lowest average temperature. This result can be attributed to the increased surface area of longer collector tubes for absorption of solar irradiation. This result agrees. with the findings of the study by Shah and Furbo (Shah & Furbo, 2007), who reported high average temperatures for longer horizontally mounted evacuated tubes. A temperature change of about 6 ℃ was recorded when the collector length was increased from 1600 mm to 2000 mm. Hence, to increase the outlet water temperature of the water in glass evacuated tube solar water heater, longer collector tubes are desirable. However, in the determination of the optimum collector length, the installation space and ease of transportation must be taken into account.

3.2 Effect of Collector Diameter on Temperature Distribution

The effect of the collector tube diameter on the performance of the water in glass evacuated tube solar heater was investigated using tube diameters of 42 mm, 47 mm and 52 mm while keeping all other parameters constant. The collector tube diameter was found to influence the temperature distribution in the storage tank as observed in Fig. 5**.**

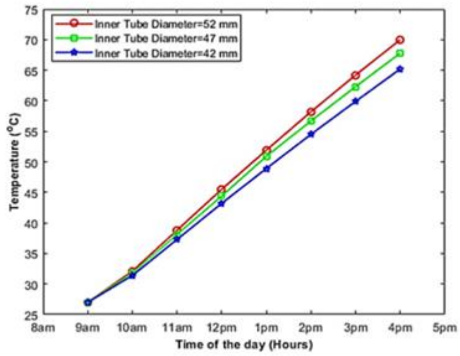


Fig. 5 Effect of Collector Diameter on Temperature Distribution in the Storage Tank

The collector tube with the largest diameter (52 mm) performed better as compared to the other two. The largest collector tube diameter of 52 mm achieved an average temperature of about 5 ℃ higher than the collector tube with a 42 mm diameter. An increase in the collector tube diameter results in an increased surface area for solar irradiation absorption. It also increases the quantity of water in the collector tubes for the extraction of thermal energy.

However, in the determination of the optimum diameter of the collector tube, several factors including the number of collector tubes, the length of the storage tank and the distance between the centres of the adjacent collector tubes must be taken into consideration.

3.3 Effect of Collector Diameter and length on Velocity Distribution

The effect of the collector tube length and collector tube diameter on the velocity distribution of the water in glass evacuated tube solar water heater was investigated. From Figures 6 and **7**, the average flow velocity increases steadily to a maximum at around 11 am where the flow velocity begins to decrease gradually. This behaviour is a result of the high-temperature gradient between the cold water in the storage tank and the hot water in collector tubes resulting from the natural circulation of water in the system. As the mixing of the hot water and cold water continues through the natural circulation process, the temperature gradient reduces which in turn reduces the flow velocity.

The average flow velocity in the longest collector tube (length=2000 mm) was observed to be higher than for shorter collector tubes. An increase in the collector length increases the surface area for solar absorption. This increases the temperature in longer collector tubes which in turn increases the temperature gradient between the water in the collector tube and the water in the storage tank. The high-temperature gradient in longer collector tubes accounts for the higher average flow velocity for longer collector tubes as observed in Fig. 6. An increase in the flow velocity increases the kinetic energy of the flow. This enhances the penetration of the hot water from the collector tube to the bottom of the storage tank reducing the stratification effect.

On the other hand, an increase in the inner collector tube diameter resulted in a decrease in the average flow velocity of water in the system as observed in Fig. 7. The largest collector tube diameter (52 mm) achieved the lowest average flow velocity while the smallest tube diameter achieved the highest flow rate.

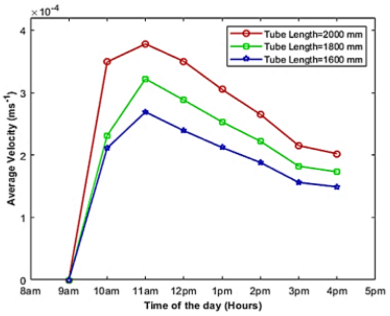


Fig. 6 Effect of Collector Length on Velocity Distribution

Though an increase in the collector tube diameter increases the average water temperature in the storage tank, the decrease in the average flow velocity reduces the kinetic energy which affects the penetration of the hot water from the collector tube to the bottom of the storage tank. This increases the temperature stratification in the storage tank

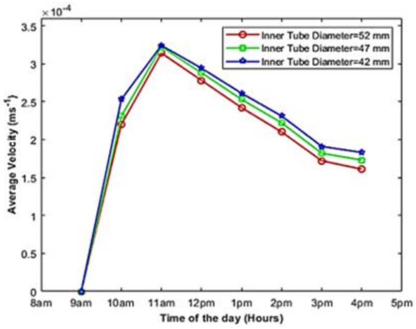


Fig. 7 Effect of Collector Diameter on Velocity Distribution

3.4 Effect of Tilt Angle on Velocity Distribution in the Collector Tube

The effect of tilt angle on the velocity distribution in the collector tube was studied using tilt angles of 10, 23, 30 and 45 degrees. Results from the study showed that the collector tilt angle has a significant influence on the velocity distribution in the collector tube which influences the stratification effect in the storage tank. The average flow velocity for lower tilt angles was found to be higher than that of higher tilt angles. As observed in Fig. 8, the average flow velocity for a tilt angle of 10 degrees was higher as compared to the others.

The maximum flow velocity in the collector tube occurs at the upper portions of the collector tube, and at the regions near the storage tank. Though the average flow velocity was higher for lower tilt angles, the maximum flow velocity increases with an increase in tilt angle. From Fig. 9, the maximum flow velocity for the tilt angle of 30 degrees is higher than for the tilt angle of 10 degrees.

These results are in agreement with the study findings of Bracamonte *et al.* (Bracamonte et al., 2015) who stated that the velocity of flow increases with an increase in tilt angle. However, it is established from this study that the average flow velocity decreases with an increase in tilt angle but the maximum flow velocity which occurs at regions close to the opening of the collector tube increases with an increase in tilt angle.

This accounts for increased kinetic energy and momentum at the regions close to the opening of the collector tube which increases the penetration energy of the hot water in the storage tank for higher tilt angles. Due to the increased kinetic energy and momentum at the upper portion of the collector tube for higher tilt angles, the hot water from the collector tube can penetrate the bottom of the storage tank leading to reduced stratification.

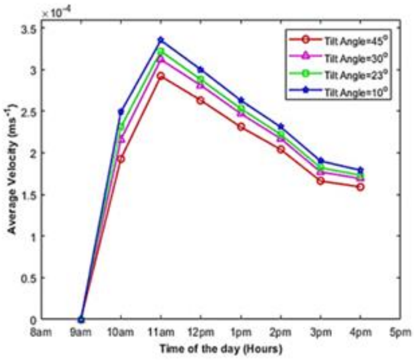


Fig. 8 Effect of Tilt Angle on Average Velocity Distribution in the Collector Tube

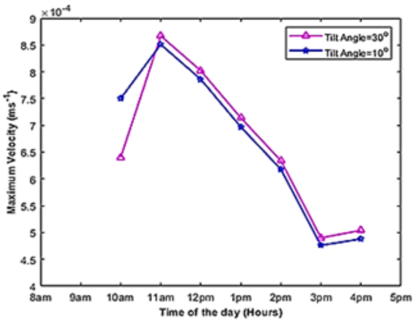


Fig. 9 Effect of Tilt Angle on Maximum Velocity in the Collector Tube

4 Conclusions and Recommendations

Numerical results from this study revealed that the length of the collector tube of water in glass evacuated tube solar water heater significantly affects the performance of the system. The results also showed that longer collector tubes enhance the solar irradiation absorption which increases the outlet water temperature of the storage tank as compared to shorter collector tubes. The average flow velocity of water in longer collector tubes was found to be better than for short collector tubes.

Larger collector tube diameters achieved higher temperatures than collector tubes with smaller diameters. However, the average flow velocities decrease with an increase in the collector diameter. These findings indicate that to maximise the water outlet temperature of water in glass evacuated tube solar water heater, determination of the optimum collector length and diameter taking into account all necessary factors is critical.

The average flow velocity for lower tilt angles was found to be higher as compared to higher tilt angles, however, the maximum flow velocity which occurs at regions close to the boundary between the collector tube and the storage tank was higher for high tilt angles. This leads to increased momentum and kinetic energy at the opening of the collector tube which enhances the mixing of the cold water and the hot water in the storage tank.

Further research study on the optical properties of the collector material as well as the cost-benefit analysis of increasing the collector length and diameter is essential in improving the performance of the system.

Acknowledgement

The authors express their profound gratitude to the Pan African University Institute for Basic Sciences, Technology and Innovation for the financial support. The authors acknowledge also technical support from Mr Shem of Advanced Research Laboratory, JKUAT.

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