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Research paper

The Study of Water Media in Green Tower's Solar Collector

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Abstract

In general, the solar collector of a Green Tower is either air-filled or empty space. This condition allows the solar chimney to have constant air flow supply from the solar collector. In this study, water media is introduced inside the solar collector as an effort to increase the performance of the Green Tower. As solar energy is harvested, energy is stored inside the collector. Thus, this study investigates the Green Tower performance using the solar collector with water-filled media. The investigation is done by simulating the solar collector with water-filled condition using Computer Fluid and Dynamic (CFD) software. From here, the viability of employing the water-filled solar collector is validated. This report presents the mathematical model of the understudied conditions and compared against the experimental as well as simulation data. The simulation results show that the Green Tower's performance is very promising with good temperature output were recorded at 55°C and temperature difference between CFD2 (water medium) and CFD1 (air medium) was steadily recorded at approximately 12°C. Increased in the resulting temperature is observed by using the water-filled solar collector. However, the air velocity is recorded near identical between CFD1 and CFD2 due to thermal coefficient of water is higher compared to air thus resist the heat to be transferred into the heat exchanger. In conclusion, the temperature distribution inside the Green Tower is increased because of using water as a medium inside the solar collector. But, the heat stored inside the collector remains longer with water-filled medium thus, this condition allows the Green Tower to function during the night time as well; when the solar radiation is unavailable.

Keywords: *Green Tower; Water Media; Efficiency, Solar Energy; Solar Collector*

1. Introduction

The Green Tower study is originated from the solar chimney idea. It is a solar power plant that could generates large scale of electricity using solar energy. The Green Tower uses the solar energy as its main input and produces the main output in the form of mechanical energy [1]. It is also known as an artificial wind generator as the wind turbine is installed to produce electricity. The schematic of Green Tower is illustrated in Figure 1. Solar energy is harvested from the sunlight and it was then accumulated inside the solar collector which greenhouse effect occurs inside the solar collector thus, heating up the air inside the heat exchanger. The heated air inside the heat exchanger produces buoyancy effect therefore, push-es the hot air up through the chimney. Continuous hot air flow process inside the chimney creates the updraft shaft effect. The updraft shaft energy that was generated from thermal and kinetic energy was converted into electricity by wind generator.

The first concept of solar chimney plant was introduced by Isidaro Cabanges, in 1903. The idea was published in the La Energia Elec-trica magazines [2], [3]. Isidaro's idea has drawn research interest amongst the scholars and the first solar chimney prototype plant was built by two German engineers, Jorg Schlaich and Rudolf Bergerman in 1976 [2], [4]. Later, in 1993 Hanns Gunther had adopted the concept and built the first solar chimney pilot plant in Manzanares, Spain [5]. The solar chimney plant was a successful one thus, attracted more researchers to explore on the idea.

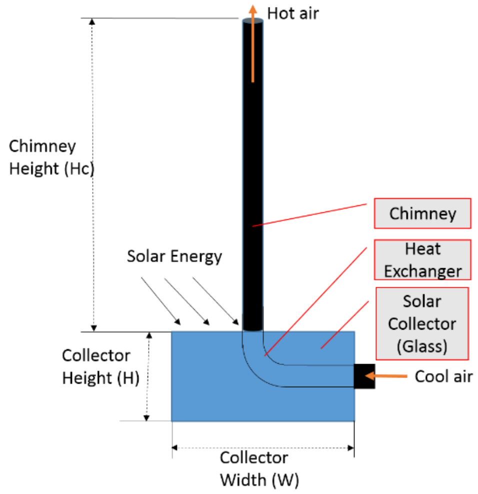

Fig. 1: Schematic layout of Green Tower.

Advancing from here, experimental study and mathematical model investigating the parametric effects of the solar chimney power plant were carried out. Correspondingly, the cost and benefit analysis were reported [6], [7].

The Solar Chimney configuration is usually massive, with large cylindrical shape solar collector spread around the solar chimney base perimeter [5]. This massive configuration helps to increase the temperature inside the solar chimney therefore, high buoyancy is obtained [1]. The common solar collector design has cylindrical shape with its sides and bottoms open. The bottom open system was employed by Schailch [2] and others [10]–[12]. The bottom open system utilizes the ground (earth) as its thermal energy storage[2]–[5]. However, it was reported that the open system solar chimney's collector caused the thermal energy loss [2]-[3]. Since the thermal energy storage is very critical in sustaining the Green Tower performance thus, the viability of using the water-filled solar collector is being explored. Therefore, the main objective of this study is to investigate the Green Tower performances using water-filled solar collector. The study explores whether the water-filled solar collector system can provide good solar energy distribution. Also, it confirms whether the system is viable to be deployed on the Green Tower structure.

2. Methodology

The experimental field work is illustrated in Figure 2. The experimental setup has been discussed in detailed in [6]. The basic principle of Green Tower's operation is by using solar oven as a heat collector. Solar oven has been proven its capabilities of receiving solar energy and used for cooking or drying purposes [7].
The work is aiming to evaluate the potential kinetic energy that is generated from the Green Tower system. Thus, the analysis is done according to the system without a turbine structure. This approach has been employed by Koonrisuk [8]; the purpose is to reduce the analysis complexity and uncertainty that come with the turbine structure. The analysis begins with the theoretical calculation using the established mathematical model.

Fig. 2: Green Tower physical model

2.1 Theoretical Model

As mentioned earlier, the Green Tower is a thermal power generating system that used solar energy as its main input. Theoretically, energy balance of the Green Tower is divided into two phases: The solar collector; received the input energy from solar radiation and converted it into heat energy. The chimney with heat exchanger received the heat from solar collector and drive the kinetic energy inside the chimney.
The general efficiency is derived by.

$$\eta = E_{kinetic} / E_{solar} \quad (1)$$

From general efficiencies, the heat energy is defined as.

$$Q_{col} = \dot{m} C_p \Delta T_{col} \quad (2)$$

Where Q_{col} is the heat energy inside the collector, C_p is the specific heat at constant pressure and ΔT_{col} is the temperature difference between temperature inside collector and ambient temperature. Thus, for heat exchanger, $Q_{h.e}$.

$$dQ_{h.e} = \dot{m}_{chim} C_p dT_{Chim} \quad (3)$$

Where $\dot{m}_{chim}$ is mass flow rate inside the chimney and T_{chim} is temperature difference between T_{oulet} and T_{inlet}. The energy balance is given by Equation (4),

$$E_{col} = E_{chim} \quad (4)$$

$$\int_0^L \frac{d\,(T_{col} - T_{chim})}{(T_{col} - T_{chim})} = -U\left(\frac{1}{C_{col}} - \frac{1}{C_{chim}}\right)\int_0^L dA_{h.e} \quad (5)$$

With $A_{h.e}$ is the area for heat exchanger, $C_{col} = \dot{m}C_p$ for collector, $C_{chim} = \dot{m}C_p$ for chimney, T_{col} is temperature inside the collector and T_{chim} is the temperature inside the chimney respectively.

$$Q = UA_{h.e}\left[\frac{\Delta T_{col} - \Delta T_{chim}}{\ln\left(\frac{\Delta T_{col}}{\Delta T_{chim}}\right)}\right] \quad (6)$$

Where $\Delta T_{col} = T_{col} - T_{amb}$ and $\Delta T_{chim} = T_{outlet} - T_{inlet}$, where U is the overall heat transfer coefficient and is defined as

$$U = \frac{h_{col} k_{chim} Nu_{chim}}{(k_{chim} Nu_{chim}) + h_{col} A_{chim}} \quad (7)$$

Where h is heat transfer coefficient NU_{chim} is Nusselt Number inside the chimney and k is the thermal conductivity. Therefore

$$Q_{h.e} = \frac{h_{col} k_{chim} Nu_{chim}}{(k_{chim} Nu_{chim}) + h_{col} A_{chim}} \cdot A_{h.e}\left[\frac{\Delta T_{col} - \Delta T_{chim}}{\ln\left(\frac{\Delta T_{col}}{\Delta T_{chim}}\right)}\right] \quad (8)$$

Where v is specific volume, $D_{h.e}$ is the heat exchanger diameter and $A_{h.e}$ is heat exchanger area. As E_{chim} is being defined as the energy generated inside the chimney and being governed by heat exchanger, the energy consists of P_{flow} and $Q_{h.e}$. Where is the total energy generated inside the chimney that consist of power contained in the flow, P_{flow} and heat contained in the flow, $Q_{h.e}$.

$$P_{flow} = Q_{h.e}$$

The power of the flow inside the chimney, with the total pressure difference and the volume flow of the air, the power contained in the flow[2] can be defined as.

$$P_{flow} = pV_{air} A_{h.e} \quad (9)$$

Where p is the total pressure difference and V_{air} is the air velocity inside the chimney. Combining equation (8) and (9).

$$V_{air} = \frac{h_{col} k_{chim} Nu_{chim}}{(k_{chim} Nu_{chim}) + h_{col} A_{chim}} \cdot A_{h.e}\left[\frac{\Delta T_{col} - \Delta T_{chim}}{\ln\left(\frac{\Delta T_{col}}{\Delta T_{chim}}\right)}\right] \cdot \frac{1}{pA_{h.e}} \quad (10)$$

Thus, the efficiency is derived from kinetic energy per solar radiation received by the solar collector is given by Equation (10),

$$\eta = \frac{0.5\,(\rho A_{chim}) V_{air}^{3}}{IA_{col}} \quad (11)$$

With V_{air} is being derived from equation (10).

2.2. Governing Equation

The governing equations of the air flow inside the chimney were presented by many researchers [3], [9]–[11]. Solar chimneys that have solar collectors and cylindrical chimney can be modeled using 2D equation [3]. This is because the Solar Chimney has the symmetrical cross-section. However, for the Green Tower development, the governing equations in 3D are used since the structure does not have the symmetrical cross-section. The simulation program that is used to solve the differential equations that govern the transport of mass, momentum and energy equation can be obtained in [12]. These equations are the three components in the 3D configuration and in a steady state condition. The flow of air inside the chimney has been analyzed in three components X, Y, and Z. The flow rate and the force of buoyancy are analyzed to determine the flow characteristics inside the chimney. This was done to ensure the course of simulation is in good condition.

2.2. Boundary Condition

The boundary conditions and the air flow for simulating the phenomenon inside the Green Tower is determined by several factors; the first is the determination of the temperature distribution in the Green Tower collectors that effortlessly supply the heat into the aluminum chimney (known as chimney heat exchanger). Solar energy was recorded from 8 am to 6 pm. It was found that during the experiment, the earth rotational effect around the sun; day and night occurrence does contribute to the solar harvesting performance. Thus, the boundary conditions for solar collectors must consider the earth rotational effect.
The Green Tower design concept is not the same as the solar chimney. The Green Tower structure was complemented with a new design of solar collector. Thus, the boundary conditions were modified accordingly. The solar chimney structure has an opening at the bottom and utilizes the land as a heat storage [2], [3], [9], [10], [13], [14]. In contrast, the Green Tower structure has a rectangular solar collector with insulated bottom section so that the heat loss could be minimized. Heat flux distribution can be referred to Solihin et al [6], [15].

2.5. Model

The Green Tower model has rectangular solar collector therefore, the governing equation of 3Dimensional is used. The experimental model is used to validate the the simulation result of CFD1. CFD1 simulation model is representing the actual experimental model; It was constructed using the similar size and measurement with the experimental model. Both conditions of the solar collector medium in experimental and CFD1 simulation model is set using the air (Refer to Table 1). Once the CFD1 simulation is validated, the medium inside the solar collector is changed to water and the simulation model is name as CFD2. The size and dimension of CFD2 is similar with CFD1 but differ in media inside the collector. Table 1 presents the Green Tower experimental and simulation models settings.

Table 1: Green Tower models

Model	Task			
	Collector Volume (m^3)	Chimney Height (m)	Medium	Remark
Experiment	0.5	4	Air	It is used as a validation model
CFD1	0.5	4	Air	It is used as a validation model
CFD2	0.5	4	Water	Investigate the effect of water as medium inside the collector

Figure 3 illustrates detailed reference points of measurements of the Green Tower structure. The inlet air velocity and the outlet temperature are measured at the inlet point and recorded respectively; refer to Figure 3. As the air leave the collector, another point of measurement is being placed for outlet air velocity and outlet temperature. The gathered data is tabulated the following section.

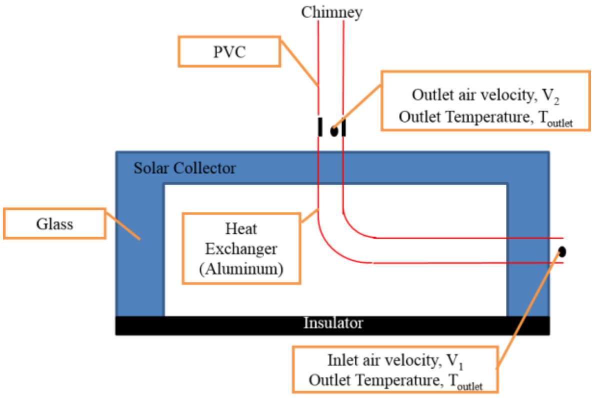

Fig. 3: Schematic of reference point measurement.

3. Results

Figure 4 shows the tabulation of solar energy (insolation) during the experimental work. This data is used as the input energy data for simulation process. The insolation received is observed at the highest, 600w/m^2 at 2 pm. The insolation received was low compared to others finding [16].

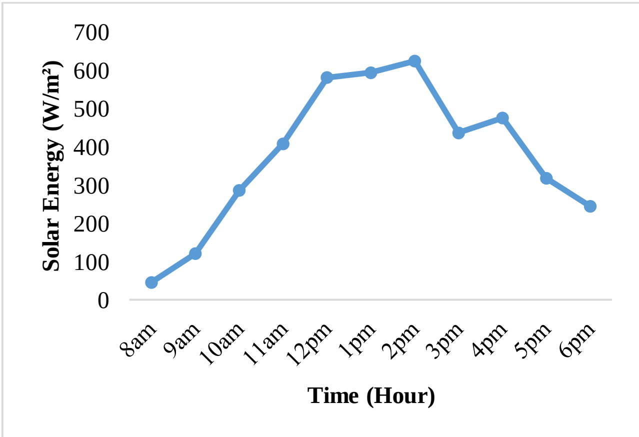

Fig. 4: Tabulation of solar energy of the experimental work

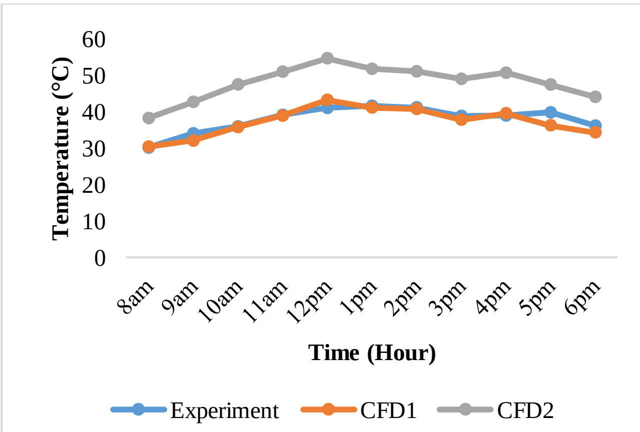

Fig. 5: Temperature variation for experiment, CFD1 and CFD2.

Figure 5 presents the temperature plots of the experimental, CFD1 and CFD2 data. The temperature is recorded at its highest for CFD2 is at 55°C compared to CFD1 at 43°C and experiment model at 42°C. Also, the graphs trends of experimental and CFD1 indicate that both graphs is almost identical hence validates the governing equation correspondingly the CFD1 model. It is also observed that the temperature difference between CFD2 and CFD1 was steadily recorded at approximately 12°C. This phenomena is influenced by the energy stored inside the water-filled collector. The temperature inside the water-filled collector remains higher compared to the average ambient temperature, 31°C even though the solar energy received was low (as approaching late afternoon).

The analysis continues with different temperature values between 6 pm and 8 am. The temperature remains high for CFD2. This finding confirms that that latent heat in the water-filled collector kept the temperature high even after 6 pm. This finding reveals that the Green Tower can be operated at night time with no solar energy received.

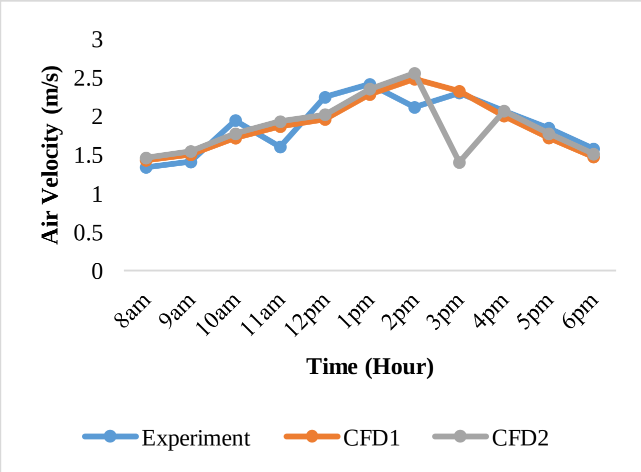

Fig. 6: Air velocity comparison between experimental, CFD1, and CFD2

Figure 6 tabulates the air velocity inside the chimney. The data showed near-identical figure for all the models. Although the temperature recorded high for CFD2, but no significant increment was observed on the air velocity. This phenomenon could be due to the lower conductivity property of water that affects the heat transfer process from collector to the heat exchanger. As the thermal property value of water is high, it takes longer to heat up the water from the solar radiation thus affecting the heat transfer rate to the air velocity in the chimney.

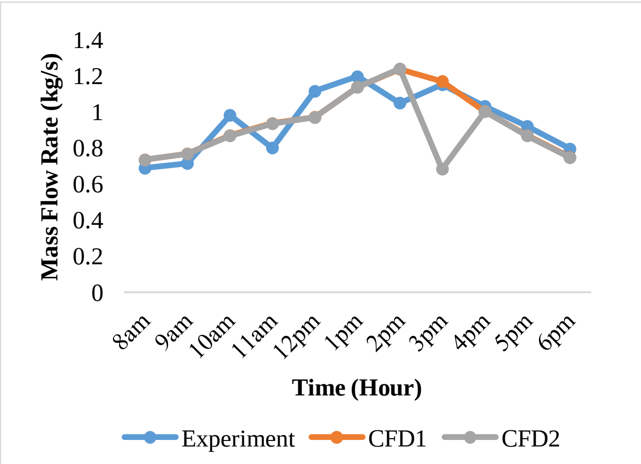

Fig. 7: Mass flow rate recorded for experimental, CFD1, and CFD2.

Figure 7 depicts the mass flow rate for all the understudied models. The experimental model shows higher fluctuation of mass flow rate. The graphs trend reveals that the governing equation is analogous with small errors observed. The data is nearly identical for CFD1 and CFD2 as the governing equation used for both models are similar; except for the water media inside the collector. These findings are true with high fluctuation for experimental model and small fluctuation for simulation models.

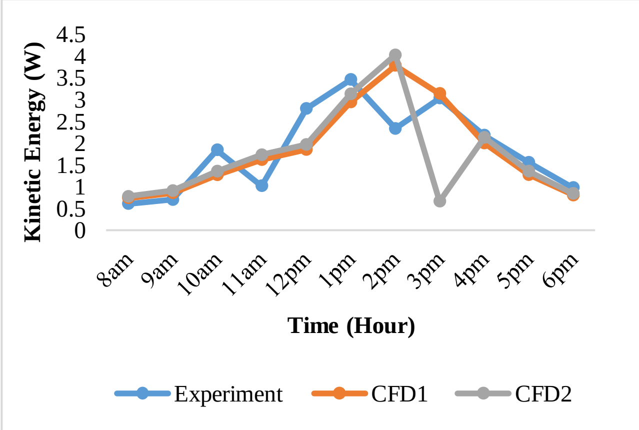

Fig. 8: Kinetic energy develop for experimental, CFD1, and CFD2.

Figure 8 highlights that the kinetic energy is recorded at its highest for CFD2 at 2 pm. High fluctuation trend is observed for the experimental data. In contrast to both simulation models; CFD1 and CFD2. Again, this is because the governing equation for both models using the same assumptions. Although the CFD2 results show highest kinetic energy at 2 pm but the trend highlights that before and after 2pm the kinetic energy is recorded lower; compared to experimental and CFD1. The 2pm kinetic energy is used to contrast the efficiency of all models.

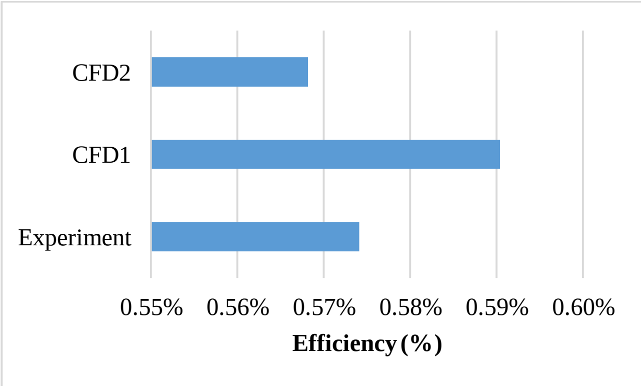

Fig. 9: The efficiencies for experiment, CFD1, and CFD2

The efficiencies of the entire model are being tabulated in Figure 9. The efficiencies are calculated by taking the average value from 8 am to 6 pm. Although the temperature was high for CFD2, the air velocity recorded was the lowest compared to the other models. Thus, this affecting the efficiency calculated for CFD2. Figure 9 indicates that the efficiency for CFD1 is the highest compared to the CFD2 and experimental models, almost 0.02%. As mentioned earlier, the CFD2 efficiency was merely due to the low air velocity performance recorded is compared to the CFD1 and experimental models.

This finding demonstrates that although consistent high temperature performance is recorded for CFD2, but the heat transferred effectiveness was low hence, resulting to lower efficiency. However, one important discovery that could be further explored is the Green Tower with water-filled collector deployment without the solar energy source.

4. Conclusion

A Green Tower with water-filled solar collector is being studied and its performance has been evaluated. The results show that the water medium helps to increase the temperature inside the collector up to 55°C. Temperature difference between CFD2 and CFD1 was steadily recorded at approximately 12°C, but due to water thermal coefficient is high compared to air, the heat transfer was interjected. This finding shows that the air velocity and the mass flow rate was the lowest for CFD2 due to the heat transfer effect. The CFD1 shows highest efficiency compared to the other models. The finding also reveals that the CFD2 has the highest heat stored and it can be used for Green Tower to operate during night time.

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