Design and Simulation of a Rectangular Solar Collector for the Green Tower Development

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ABSTRACT.

Solar chimneys generally have large size solar collectors. This is because of the solar chimney output is directly proportional to the input. The more solar energy is harvested, the higher the output. Aside from the size, most of a big solar collector is in a cylindrical shape. Thus, this study proposes the role of solar collectors which has a rectangular build at a smaller size and known as Green Towers. The main purpose of this study is to determine the performance of the rectangular solar collectors for Green Tower development. This report presents the numerical simulation and validates with the field experiment of the Green Tower. Various analyses were carried out for investigating the Green Tower performance and the result was very promising. The resulting air velocity increases with various geometrical sizes of the Green Tower. In summary, using the rectangular shaped solar oven's collector has significantly increased the temperature distribution for the Green Tower thus improve its efficiency and overall performance.

Keywords: *Green Tower, Solar Oven, solar radiation, solar thermal*

1.0 Introduction

The solar chimney is also known as the solar updraft tower is the technologies which were being studied by various researchers[1] and being acknowledged to generate electrical energy from solar energy[2]. As acknowledged for it clean energy, it offers highly interesting opportunities in generating pollution free resources of energy [3]. The solar chimney structure consists of solar air collector and central updraft tube for generating solar

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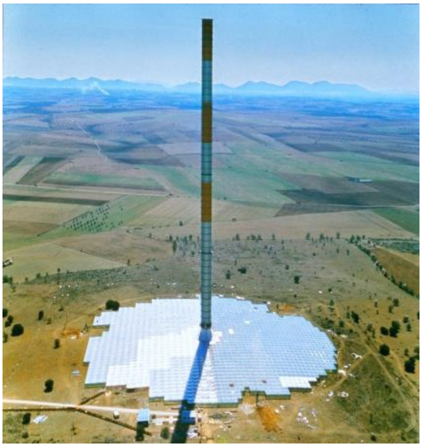
induced convective flows of which drive the turbines that could generate the electrical power[4]–[6].

The first researcher who has investigated the concept of solar chimney plant in 1903 was Isidaro Cabanges, and he had published the idea in the La Energia Electrica magazines [3], [7]. From Isidaro's idea, it has opened many researchers' interest and the first prototype of the design was proposed by two German engineers, Jorg Schlaich and Rudolf Bergerman in 1976[7], [8]. In 1993, Hanns Gunther had conceived the concept of the operation of a pilot plant and it was constructed until proven successful in Manzanares, Spain[5]. The prototype in Spain had ignited researchers' interests in the development of an experimental and mathematical model to study the variation of parameters and the effect of environmental climate. Also, the surrounding conditions with regard to the dimensional geometry of the solar chimney model as well as the flow and heat transfer characteristics of the solar chimney were investigated [2], [4], [9]–[14].

In this work, the Green Tower's working principle is adopting the Solar Chimney operating system that was built in Manzanares, Spain by Hanns Gunther that uses solar energy to generate electricity from the updraft wind [1], [15]–[17]. The Solar Chimney in Manzanares deploys solar oven and chimney that uses thermal energy as its primary energy source; Figure 1(a) refers. The Green Tower uses a solar oven that acts as the solar collector and a chimney that acts as the central updraft tube to generate a solar induced convective air flow, which drives pressure to develop artificial wind. Figure 1(b) is the improved version of the Solar Chimney idea and is called Green Tower.



(a)

(b)

Figure 1: (a) Solar Updraft Tower or Solar Chimney in Manzanares, Spain. (b) Green Tower

The Solar Chimneys generally have large solar collector size and cylindrical in shape. This is because the temperatures inside the solar chimney need to be increased to obtain high buoyancy[10]. The collector has cylindrical sides and opens at the bottom. Schailch [18] and other researchers use the bottom open space as a thermal energy storage[11], [18]–[20]. On the other hand, the open part can also contribute to the loss of energy. The large size of the collector is not suitable for a small country; therefore, the rectangular solar collector has been introduced in order to reduce the size of the collector. To ensure an acceptable distribution of solar energy to the extent possible, the rectangular solar collector can receive solar energy from its side and has insulator at the bottom, compared to the cylindrical solar collector that is open on the side and energy loss from the bottom of the energy storage layer[19]. Therefore, the main objective of this study is to determine Green Tower efficiencies and overall performance using a rectangular solar collector.

2.0 Model

Green tower concept which combines a solar oven and a solar chimney is a technology that uses renewable energy. Thus mathematical analysis is essential in order to develop the simulation process according to different model parameters. The analysis begins with the development of solar ovens as heat collectors[21], followed by analysis of heat transfer pipes and chimneys. Theoretically, the natural air is flowing through the collector tubing that is connected to the tower’s chimney at ambient temperature. Instantaneously, upon entering the tubing and approaching towards the updraft level the air was warmed up by the heat that was generated inside the solar collector.

The Green Tower as mentioned in the above paragraph is the improvised model that combined both solar oven and solar chimney idea; Figure 1 (b) refers. The Green Tower model comprises tower’s piping that made of aluminum tube and connected to the outlet tower that made of PVC tube [14]. Here, the air was being heated up through solar radiation[22] inside the rectangular transparent solar oven[23]. It is also performed as a solar collector replacing the conventional cylindrical solar collector as proposed by Hanns Gunther in the solar chimney study [5]. In the middle of the solar collector or solar oven is a vertical tower with the air inlet. The air inlet is towering at a four-meter height from the base of the solar oven level. The joint that connecting between the solar oven and the tower base is airtight [5]. As hot air is lighter than cold air, it rises up the tower. The thermal energy is converted into kinetic energy through rapids air movement [24] thus creates the suction effect. The suction effect is resulting from the convective and buoyancy phenomena inside the chimney tower. Hence, the more hot air was drawn from the collector so as the cold air was driven in from the ambient. This has resulted in artificial wind.

The experimental Green Tower model was constructed and series of experiments have been conducted. Refer [25], [26]. Data collected from these experiments were used as a validation model for this simulation study and being referred as ‘Experiment’ in Table 1. The Green Tower model is measuring at 1meter wide, 1 meter long and 4.5 meters height; is the height of the collector together with its chimney. The chimney is positioned at the approximately 1-meter length of the collector’s surface area cross-section. The chimney is measuring at 4 meters high with 0.075 meters radius. Thus the ratio of chimney height to collector’s cross section area is 4:1 compared to physical model from Kasaein of 1.2:1[27], Zhou[14] model of 0.8:1 and Manzanares prototype of 0.8:1[18].

In this simulation study, the Green Tower simulation models were constructed based on several assumptions. The mathematical model is representing analysis model level, it is assumed that the air flow inside the chimney pipe is ideal and at steady states, such as the model developed by other researchers [28], [29]. Friction factor inside the tube of the chimney tower was neglected[5].

The solar oven acts as a collector and thermal energy storage[23]. Data that were collected to measure the performance of the Green Tower is the speed of moving air inside the chimney; air flow rate [5], [9], [10], [14], [19], temperature[10], [19], [20] and solar radiation[10], [14]. The main concept of the Green Tower's design is operating without a turbine or no load conditions. The concept used is similar to the solar chimney power plant system made by Zhou[14]. Detailed size and dimension for simulating the Green Tower models can be obtained in Table 1.

Data of the air velocity and temperature are measured at the collector’s level; Figure 2 refers. Reason being, at this level the wind turbines were normally installed. Based on the prototype made in Manzarannes, wind turbine height level is at the level of solar chimney’s collector.

The compiled data of air velocity and temperature ranges during simulation study were gathered and converted into efficiency.

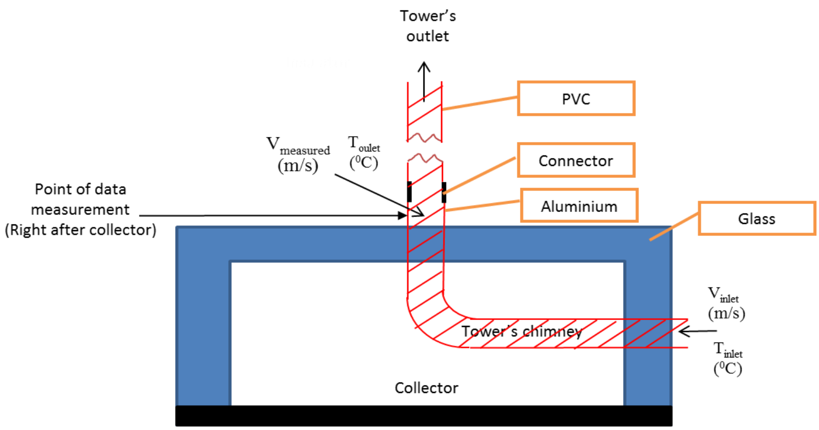


Figure 2: Schematic diagram of Green Tower

Table 1: Green Tower simulation models

Model	Collector size (m^3)	Tower Height (m)	Chimney Heat Exchanger Length (m)	Collector medium	Working Fluid
Experiment	0.500	4	0.40	Air	Air
CFD 1	0.500	4	0.40	Air	Air
CFD 2	0.500	4	0.82	Air	Air
CFD 3	0.500	4	1.23	Air	Air
CFD 4	0.625	4	0.40	Air	Air
CFD 5	0.750	4	0.40	Air	Air
CFD 6	0.875	4	0.40	Air	Air
CFD 7	1.000	4	0.40	Air	Air

2.1 CFD Approach

Development of mathematical models for the Green Tower employs several energy equations. Some parameters such as temperature, heat, air velocity, and dimensions must be determined for each model configuration. Mathematical models were translated into three-dimensional drawings in solidwork. Green Tower model size used in the experiment was used as the basis of the reference models in simulation methods. Various configurations and sizes are deployed in the simulation analysis as in Table 1; the simulation data were then validated against the experimental methods. The second stage involves the conversion of a three-dimensional model into Computational Fluid Dynamics (CFD) elements to generate elements meshing; the CFD software from ANSYS[8] is used. Then the successful meshing model was exported to FLUENT for thermal analysis. Analysis of air flow characteristics for various size and dimensions as well as the amount of heat energy has been carried out at the final stage using CFD simulation.

2.2 Governing Equation

The governing equations of the air flow inside the chimney were studied by various researchers[8], [9], [19], [22]. Solar chimneys that have solar collectors and cylindrical chimney can be modeled using 2D equation[19]. This is because the Solar Chimney has the symmetrical cross-section. Therefore, 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 is used to solve the differential equations that govern the transport of mass, momentum and energy equation[8], [30], [31]. 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 determine the course of simulation in good condition. To solve these problems, Rayleigh number was used[19].

$$Ra = g\beta(T_h - T_c)L^3/\alpha v \tag{1}$$

Where α is the thermal viscosity, v is the kinematic viscosity, g is the acceleration due to gravity, β is the coefficient of thermal expansion whereas T_h and T_c are temperatures maximum and minimum respectively. Boussineqq equations are used in the analysis to solve different density in the chimney. The analysis found that Ra > 10^{10} and with it, the flow of air inside the chimney may be interpreted as turbulent[19], [20].

The characteristics of air turbulence inside the chimney are also represented by a modified k-ε model[19]; taking into account the air flow near the wall.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{3}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + v\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \qquad (3)$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + v\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{5}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{u_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{6}$$

Where G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, where G_b is the generation of turbulence kinetic energy due to buoyancy of $\beta g_i \frac{u_t}{Pr_t} * \frac{\partial T}{\partial x_i}$ with Pr_t is the turbulence Prandtl number for energy. Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate of which $Y_M = 2\rho\epsilon M_t^2$, and has been neglected as the flow is not considered as Mach-number. $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants at 1.44 and 1.92. Whereas σ_k and σ_ε are the turbulent Prandtl numbers of 1.0 and 1.3 respectively. Sk and $S\varepsilon$ are user-defined source terms. As there is no diffusion and high speed flow that made the conversion of kinetic energy into thermal energy, general energy equation reduce to :-

$$\rho Cp\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = k_{eff}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial^2 z}\right) \tag{7}$$

Where k_{eff} is the effective conductivity ($k_{eff} = k + k_t$) and k_t is the turbulent thermal conductivity. Energy equation is solved for the temperature distribution inside the chimney

2.3 Boundary condition

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). The heat distribution is induced upon harvesting the solar energy from the sun. The solar energy used in this simulation is based on the energy harvested and recorded during the experiment. Solar energy was recorded from 8 am to 6 pm. It is 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 take into account the earth rotational effect.

(1) Heat balance of the collector

The Green Tower design concept is not the same as the solar chimney. The Green Tower has a new design of solar collector. Thus, the boundary conditions must be modified. The solar chimney structure has been constructed with an opening at the bottom and utilizes the land as a heat storage [8], [14], [18], [19], [22], [32]. In contrast, the Green Tower has a rectangular collector with insulated bottom section so that the heat loss could be minimized. Therefore, heat flux distribution in the collector can be determined from Fourier’s Law:

$$from\ side, q_x^{"} = \mathrm{k}\frac{\mathrm{dT}}{\mathrm{dx}}, q_y^{"} = \mathrm{k}\frac{\mathrm{dT}}{\mathrm{dy}}\ \ and\ at\ the\ top\ q_z^{"} = \mathrm{k}\frac{\mathrm{dT}}{\mathrm{dz}} \quad (8)$$

As the bottom is insulated,

$$0 = -\mathrm{k}\frac{\mathrm{dT}}{\mathrm{dz}} \quad (9)$$

Where q" is the solar energy from the sun and its movement is based on the altitude and azimuth angles. Heat flux distribution can be referred to[25], [26].

$$\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = 0 \quad (10)$$

The rectangular shaped solar collector is represented by the expression of the Laplace equation as in equation (10) above; the temperature distribution in the collector can be obtained. The equation used with the assumption that there is no energy either stored or generated in the solar collector.

(2) The boundary conditions for Green Tower chimney

The second boundary condition is to represent the air flow inside the chimney. The inlet air flow rate is determined by measuring or calculating the rate of ambient air flow. Heat is transferred from the solar collector leads to the calculation of the velocity of the air inside the chimney. The velocity of the air intake can be obtained from Solihin [26]. Where $v_{inlet} = measured\ during\ experiment$. The pressure at the inlet is set as ambient pressure.

2.4 Efficiency

The Green Tower efficiency can be determined by knowing the energy output per solar energy as an input[18], [33]–[36]. In this study, the output energy that is generated by the Green Tower is the Kinetic Energy with solar energy input [22], [37], [38].

$$\eta = \frac{1/2(\rho A_{tower})V^3}{IA_{Collector}} \qquad (11)$$

Where *I*, is the solar irradiation received by the collector. In determining the efficiency of the Green Tower, temperature and air velocity (Air Speed) are two important parameters. The temperature distribution is required to determine the density of air.

3.0 Results

Figure 3 shows the experimental results that were carried out on the rooftop of Tower 1, UiTM Shah Alam Complex Engineering; Solihin 2015 refers [26]. The experimental data was collected from 0800hour to 1800hour [39]. The equipment used to capture the experimental readings is Yokogawa Solarimeter.

The average distribution of solar energy indicates a less favorable output. The cloudy sky in Malaysia region shading the pure solar energy from reaching the earth's surface. In Figure 3, the highest reading of solar energy harvested is approximately 623 W/m^2 compared 800-1000w/m^2 in other countries. Also, from the irradiation plot (Figure 3) it is noticeable that the highest reading is at 2 pm and decreased dramatically from 623 w / m^2 to 436 W/m^2. This trend causes the air velocity fluctuations in the Tower Green.

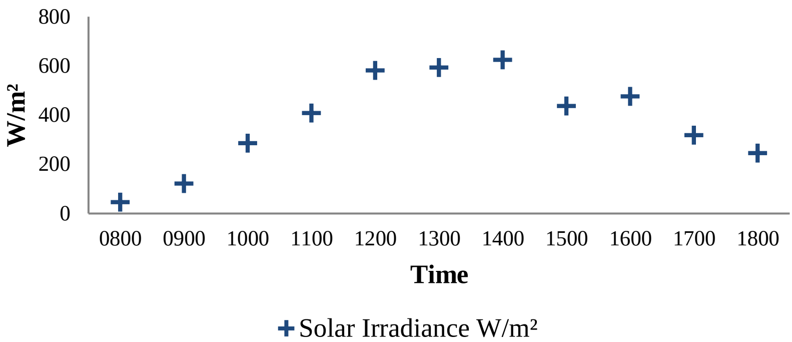


Figure 3: Solar irradiance received during experiment

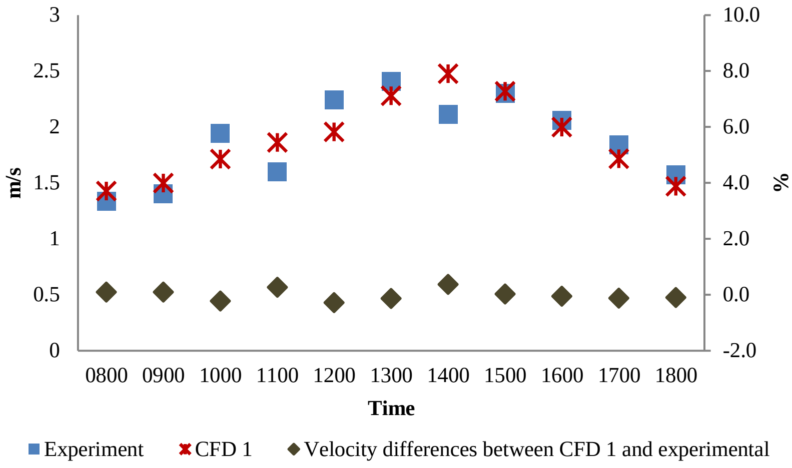


Figure 4: Relative air velocity inside chimney

Figure 4 shows the computer simulation (CFD1) and experimental air velocity results. Data obtained from computer simulation CFD1 is validated against the experimental result that has the same parameter settings (model size and dimension) as the experimental model. The simulation results show very good agreement with the experimental results with almost zero differences in average.

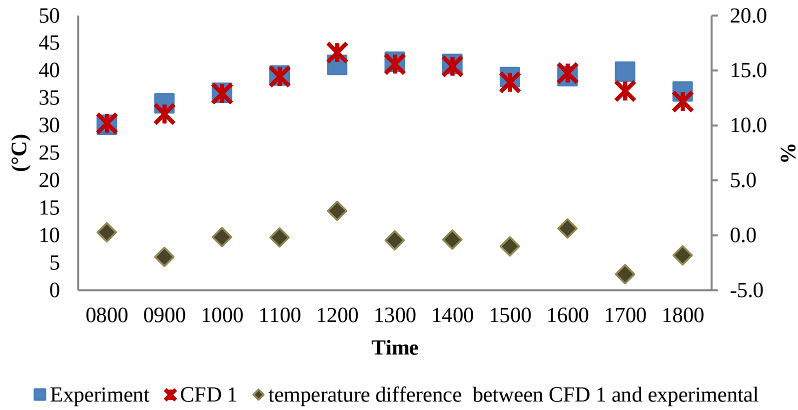


Figure 5: Temperature reading in the chimney

The graph in Figure 5, shows that the highest temperature recorded during the experiment was 41.5ºC at 1300hour. Within the same time slot, by referring to Figure 3 the air velocity also recorded at the highest, 2.4m/s. For CFD1, the highest temperature recorded was 60°C at 1200 hour, with the highest air velocity is 2.43 m/s at 1400hour. The temperature differences between the CFD1 and the experimental highest temperature is observed at 1200hour. This could be due to the external factors prompted the equipment error reading during the experiment. In addition, simulation is based on several assumptions mathematical formulae, of which might influence the output results hence its accuracy.

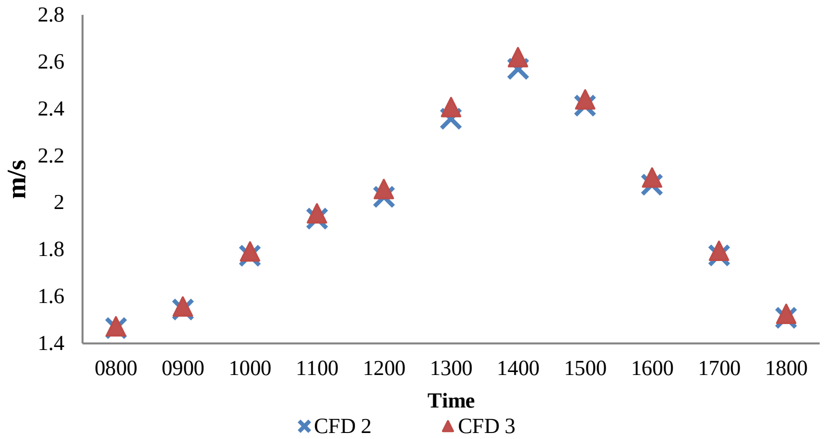


Figure 6: The Air Velocity variation with the effect of Heat Exchanger

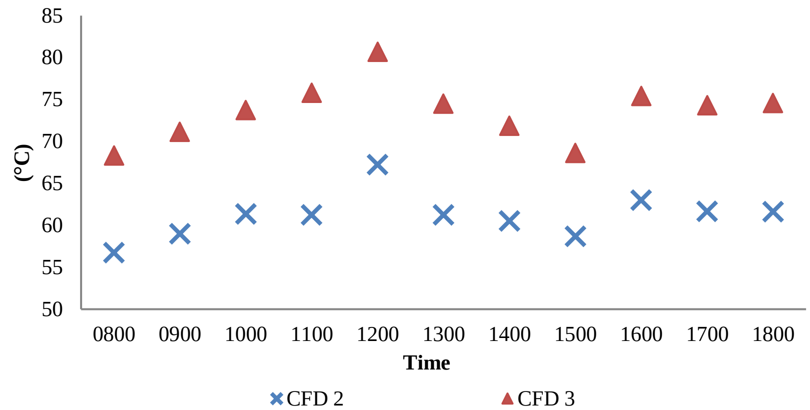


Figure 7: Temperature Variation from Different Length of Heat Exchanger

Figure 6 and 7 above shows CFD2 and CFD3. The model has the size and dimensions similar to CFD 1 except for the length of the heat exchanger is longer but same diameter. The difference in the heat exchanger barely affected the readings of air velocity inside the Green Tower. The results show the data of air velocity at 1400 of CFD2 and CFD3 were recorded at 2.57m/s and 2.62m/s, respectively. The temperature readings were also recorded 10-30% higher for both CFD2 and CFD3 as compared against the CFD1. The CFD2 average recorded temperature around 60°C and CFD3 recorded a temperature of about 70°C; Figure 7 refers. The higher temperature is caused by differences in length size of the heat exchanger. In contrast, the air velocity inside the Green Tower is not affected by this geometrical shape differences.

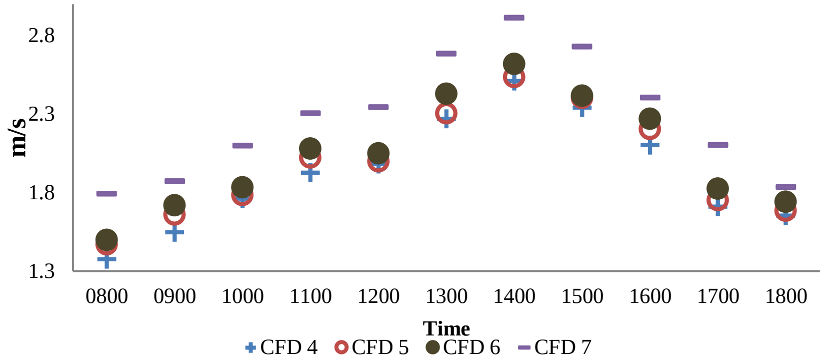


Figure 8: Air Velocity Variation with Different Collector Volume

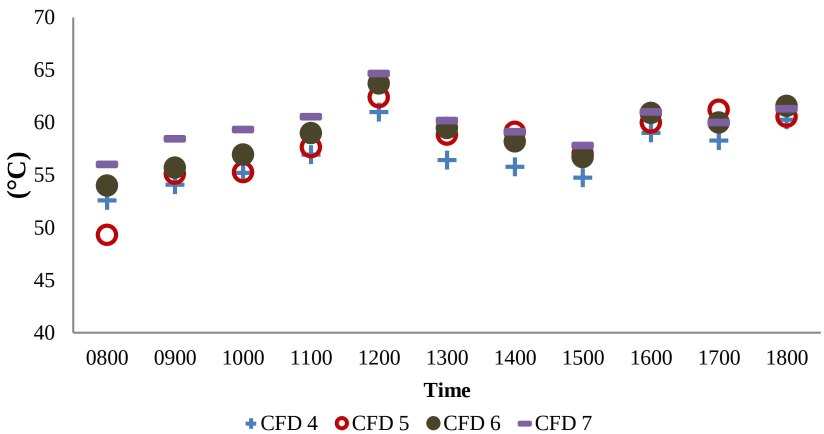


Figure 9: Temperature Distribution with the Effect of Collector Volume

Figure 7 and 8 show simulation output results for 4 models which are CFD4, CFD5, CFD6, and CFD7. Each model has different collector volume sizes; CFD4:0.625m^3, CFD5:0.75m^3, CFD6:0.875m^3, and CFD7:1m^3. The purpose of varying the collector volume sizes is to investigate the effect of the heated volume inside the solar collector towards the Green Tower performance. Mathematical modeling of the air density inside the chimney is based on Bousineqq Equation. Figure 8 shows the CFD7 which has the biggest volume generates the highest air velocity. The air velocity was recorded as high as 2.9m / s at 1400hour. It is also observed that during the same time (1400hour) the temperatures were recorded at 59^{o}C inside the chimney. This behavior indicates that the volume of heat supplied by solar collectors to the heat exchanger has a significant impact on the air velocity performance inside the chimney.

4.0 Discussion

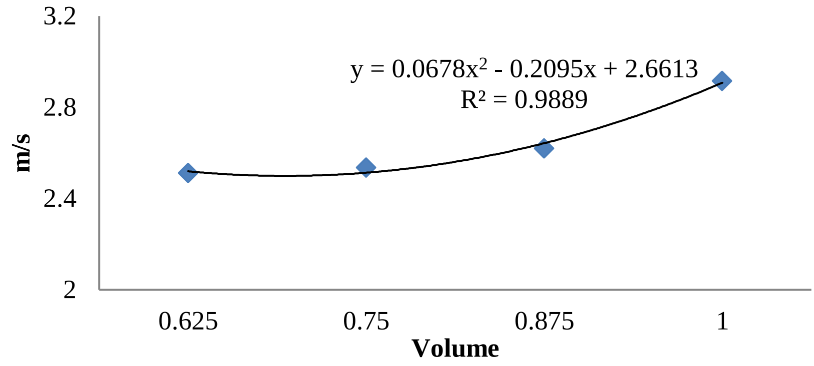


Figure 10: The Effect of Air Velocity toward Collector Volume

Figure 10 shows the effect of the volume of solar collectors on the velocity of the air inside the chimney. The velocity of the air is taken in at 1400hour. This comparison is made for the effect of the volume of the collector to the temperature and velocity of air in the chimney. The plot shows a parabolic trend with a coefficient of determination approaches 1. This trend shows that the larger the volume of solar collectors, the effects of air velocity and temperature in the chimney is also higher. In the future, various studies can be done by varying the sizes and dimensions of the solar collector. One important finding highlights that the larger the size of the solar collector the more heat volume can be accommodated thus higher temperature can be generated resulting in higher air velocity performance inside the Green Tower.

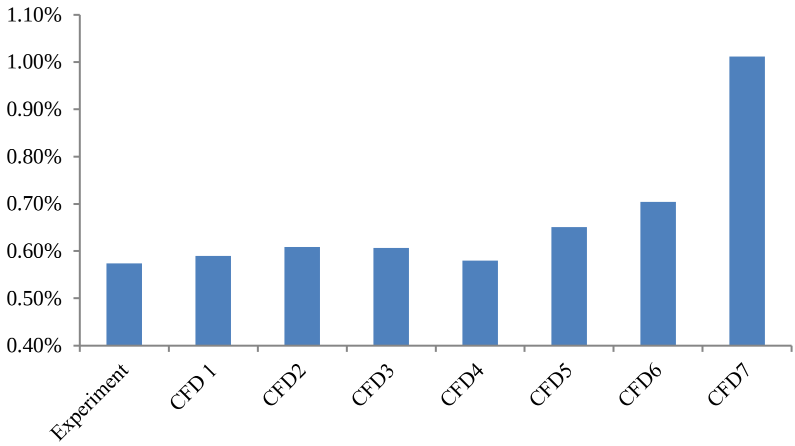


Figure 11: Average efficiencies for all models

The solar chimney efficiency was studied by Atit [8], [22], [37], [38] and the result shows the efficiency of approximately 0.5% has been achieved. Figure 11 shows the efficiency of the Green Tower from 0.574% to 1.012%. CFD7 shows the highest efficiency compared with other models. This result is mainly due to its solar collector is bigger thus directly influenced heat generation inside the chimney and finally pushing air toward a higher speed. These important findings indicate that the rectangular solar oven is viable to be used as a solar collector in energy conservation work.

5.0 Conclusion

Based on the experiments and the analysis done, it can be conferred that the objective of this study has been achieved by determining the efficiency of the rectangular solar collector and studying its effect towards the Green Tower performance. The simulation model has been validated. The study involved a variety of solar collector models and CFD models. Finally, it can be concluded that:-

a) The results CFD1 show good agreement with the experimental data with the difference of about 5%. This shows that the results obtained from the simulation are reliable.

b) Although the temperature measurement indicates significant differences in different length of the heat exchanger, the effect of temperature on the air velocity irrelevance.
c) The results from different solar collector size indicate bigger collector size gives a better improvement in air velocity recorded and also better efficiencies.
d) This indicates that increasing the length of the heat exchanger would result in the heat stored in the collector reduced at a faster rate.
e) In order to have better heat supplied from the collector to heat exchanger, bigger collector size is needed. Thus it can be seen from the efficiency recorded by CFD7 which has the biggest collector generate better efficiency compared to other models.
f) Overall, the Green Tower optimal size can be studied in the future in order to obtain optimal efficiency

It can be concluded that the laboratory size solar chimney has been successfully deployed in establishing the parametric data of investigating the existence of wind speed updraft using Green Tower technology. The Green Tower technology has a great potential to be implemented in Malaysia.

6.0 Acknowledgement

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