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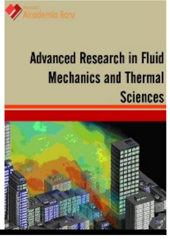

Design and Optimizing of Geometric for Solar Updraft Tower using Computational Fluid Dynamics (CFD)

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ABSTRACT

There are many experimental and analytical approaches that have been physically proven in the last few decades for the Solar Updraft Tower (SUT) concept to provide energy from solar radiation. Solar chimneys with their potential advantages have gained more attention by fully utilising solar radiation energy to generate air movement by stack pressure. This movement is driving the heated air through the chimney channel and then drawing colder air through the building in a continuous cycle. A parametric study on the geometry of the solar updraft tower is carried out with a different slope angle of collector, different inlet height of collector and different diameter of chimney collector inlet height with fixed solar radiation at 800 W/m^2. A validated model is compared with the experimental prototype constructed by the University of Zanjan, Iran. The result shows an incredible improvement in the power generated by a collector with 0 degree and the best entrance gap of collector and chimney diameter at 0.05 m and 0.05 m respectively. The findings and results are discussed and suggested for future works.

Keywords:
Solar Updraft Tower, Solar Chimney Power Plant, CFD, Renewable Energy

1. Introduction

The need for a green and environmentally friendly electric power generation method is apparent and will be further expanded shortly with the decrease of fossil fuel. Currently, electrical power generation from fossil fuels, such as oil or coal, is damaging our environment while nuclear power stations are an unacceptable risk in most locations and radiation exposure [1,19]. This phenomenon is making renewable energy sources the primary factor for a sustainable development of the worldwide economy. A renewable energy is obtained from natural and persistent flows of energy occurring in the immediate environment. Obvious examples include solar energy, wind energy, biomass energy and water which repetitively refer to the 24-hour significant period. Solar energy is clean and one of the renewable energy resources which can be replenished. Electricity can be

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obtained from solar energy by two means; through photovoltaic effect and solar thermal cycle. Solar updraft tower (SUT) power plant is one of the valuable renewable energy-based power suppliers on a large scale. Solar tower power plants have been studied since the 1970s and the potential for a significant scale energy generation is high [2]. Schlaich [3] initially proposed a successful prototype of the solar chimney in 1968. In the 1980s, the solar updraft power plant principle was proven through eight years of continuous operation with a 50 kW experimental prototype which was built in Manzanares, Spain [4]. In 2005, to improve solar collector efficiency, Bilgen and Rheault [5] proposed to build a collector component in a sloppy and tapered section.

Several researchers have contributed to the construction and numerical simulation of the solar tower collector. The accuracy regarding distribution behaviour of the flow in the SUT system offered by simulation software has to increase the CFD application in this area. Bernandes *et al.,* [6] performed CFD with numerical analysis to simulate the flow in the solar chimney on a natural convection in a radial solar heater. They studied the different junction shapes at the collector base to predict the thermos-hydrodynamic behaviour. With the advantage of CFD software to predict the performance of a large scale solar chimney, a commercial CFD software, such as ANSYS-CFX, was used to verify the experimental data of the scaled model. Due to the excellent agreement between the experimental and numerical results, Kirstein and Backstrom [7] have studied the flow inside a collector and chimney at the transition part by using numerical analysis.

Other researches were conducted by Tingzhen *et al.,* [8] and Sangi *et al.,* [9]. Tingzhen had validated their CFD code and performed a numerical simulation on the Manzanares SUT which was integrated with a three-bladed turbine. Both experimental and numerical approaches using the CFD code showed a good quantitative method. To provide a reference for the design of large-scale SUT systems, five-bladed turbines were tested with a MW-grade SUT. A mathematical model of the SUT-based on the Navier–Stokes, continuity and energy equations was also developed to perform with numerical simulations. Sangi *et al.,* [9] also studied on Manzanares SUT using a commercial CFD software FLUENT. The result showed a good agreement between the experimental data, numerical and mathematical model.

A convergent SUT was designed and built by Pasumarthi *et al.,* [10,11]. Padki and Sherif [12] have developed a simple analytical model and showed that the convergent SUT was helpful to increase the plant power output with a turbine installed in the system. Regarding a specific part, the effect of tower area changes on a SUT was investigated by Koonsrisuk and Chitsomboon using CFX [13]. They have concluded that the mass flow rate and kinetic energy can be increased when using a divergent tower due to the different tower areas. With a convergent tower design, the velocity is higher while the mass flow rate decreases at the tower outlet, causing the kinetic energy to be similar with a constant area tower. They also stated that the maximum kinetic energy occurs at the tower inlet. In 2014, the optimum divergent angle was determined by Patel *et al.,* [14] by using CFD simulations with a divergent angle of 2°.

A recent study was conducted regarding the influence of ambient crosswind on the performance of SUT using CFD by Ming *et al.,* [15]. From their findings, the performance of SUT had a positive and adverse effect due to ambient crosswind. This phenomenon resulted in power output due to the flow field and mass flow rate changes. When flow field was deteriorated due to weak ambient crosswind, the SUT output power reduced and when the ambient crosswind was strong enough, the output power increased due to the increase of mass flow rate. This increase in mass flow rate was due to a wind suction effect on top of the chimney caused by the high velocity wind (Bernoulli principle). To overcome the negative effect of strong ambient crosswind, Ming *et al.,* [16] carried out another numerical analysis by employing a blockage a few meters away from the collector inlet opening. They stated that the obstructions helped to overcome the negative effects resulting from the strong ambient crosswinds.

The present work is to identify the performance of SUT due to various geometrical modification parameters on a fixed solar chimney height and collector diameter. The slope angle of the collector, inlet height of collector and diameter of chimney collector inlet height were varied and tested with different configurations to study and to investigate the airflow characteristics inside an SUT.

2. Methodology

A CFD model was developed to conduct a parametric study on the geometry of solar updraft tower using Ansys Fluent. Comparison between the current result and previous research will be analysed for different types of configuration to obtain the best results regarding velocity and temperature profile. The power generation is a pressure turbine where the power generation depends on the velocity flowing through the turbine while thermal energy storage needs higher temperature distribution. A validated model was used to analyse the effects of different geometry with some configurations applied to the original shape. The geometry and configuration used for this research corresponded to the experimental prototype setup by the University of Zanjan, Iran [17]. The specification of Zanjan geometry is described in Table 1.

Table 1
Main Component of Solar Updraft Tower Prototype in Zanjan, Iran [17]

Name of Component	Parameters
Updraft Tower Height	12.0 meters
Updraft Tower Diameter	0.25 meter
Solar Collector Diameter	10.0 meters
Solar Collector Entrance Height	0.15 meter

The geometry was constructed using ANSYS design modeller. To obtain easy mesh generating for the whole system, the collector and tower were modelled separately. A three-dimensional model was created by revolving the model around z-axis on the x-y plane. With a dimension of 8 m in diameter of the circle for the collector and 10 m in height for the chimney, the model was varied with some modifications. Each modification will give effect to the system and total power output. In this study, variations of slope angle of the collector, inlet height of collector and diameter of chimney collector inlet height were carried out as shown in Figure 1. The collector angle was varied from 0 to 15 degrees while the inlet collector height was varied from 0.05 m to 0.25 m. For the last modification, the chimney radius was varied from 0.05 m to 0.3 m. These combinations were simulated to obtain the optimum efficiencies and power output.

Meshing for each part was done by generating separately and for the regions where the face size was too wide, a subsequent mesh refinement was introduced to provide smooth and better quality mesh. The transition zone was the most sensitive area of the computational domain as it was a tiny area on which there was a high-pressure gradient. Therefore, refinement was also added to this area to improve the mesh quality. The overall mesh quality was checked to reduce the skewness ratio to approximately 0.8. The system geometry consisted of a tower with 12.0 m height and 0.25 m diameter surrounded by a collector with 5 m radius and 0.15 m height. The physical domain was modelled and meshed using the ANSYS mesh editor. Grid generation was considered as the first necessary step for CFD modelling and had an impact on the numerical results.

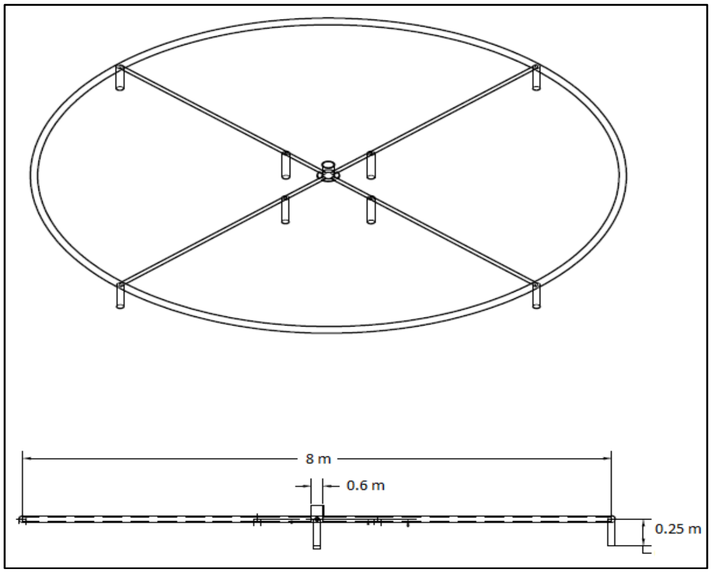

Fig. 1. Geometry configuration for the collector

Grid independent study was performed to obtain the number of mesh for the model selected. This process was conducted using five grids, namely Grid 1, Grid 2, Grid 3, Grid 4 and Grid 5 whose descriptions are explained in Table 2 until consistent values were achieved. The numerical modelling was conducted to analyse the performance of the solar updraft tower using a three-dimensional steady-state and energy equation. The air flow inside the updraft tower was assumed to be turbulent where it was simulated with the k-epsilon turbulent model using the ANSYS Fluent software.

Table 2
Summary of Grid Configuration & Mesh Information

Grid	Face Size, m	Cell	Face	Nodes	Velocity, m/s
1	0.1	300	766	300	3.61
2	0.05	1410	3151	1742	4.08
3	0.01	33116	67875	34760	4.79
4	0.005	130818	264958	134141	4.82
5	0.003	364718	734959	370242	4.83

3. Results

3.1 Model Validation

To validate the numerical results, the temperature increase under the collector was compared with the experimental data of the Zanjan prototype [17]. An experimental sample was successfully set up at the University of Zanjan, in 2010. The experimental results indicate that the temperature increase through the collector reached 25 K with no-load condition with solar radiation and the ambient temperature was approximately 800 W/m2 and 300 K respectively. A good quantitative agreement was obtained between the experimental data of the Zanjan prototype and numerical results obtained from a previous work by Ghalamchi [18]. The slight difference, as shown in Figure 2, was due to error from the sensors, the location of the mounting of the sensors and another external factor that may result in some data deviation with the numerical results. Therefore, this CFD modelling via the FLUENT software can be exploited to distinguish the best city for constructing a Solar Updraft Tower with the same dimensions and materials of Zanjan's plant, such as Malaysia.

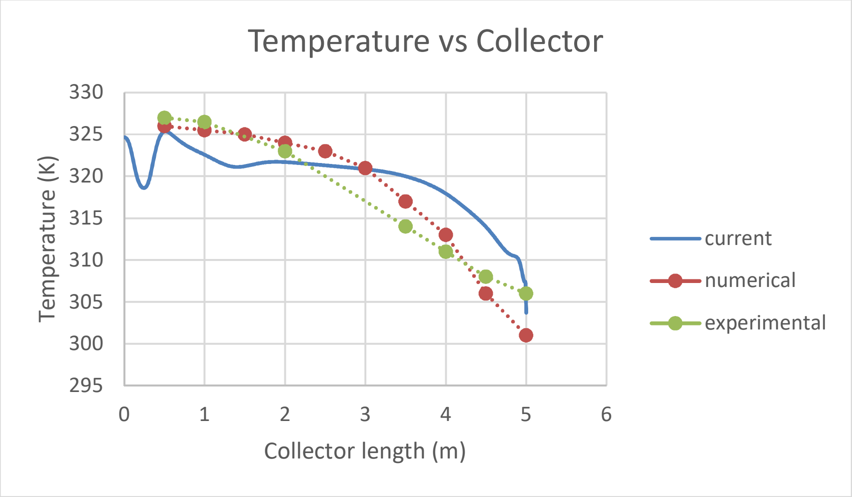

Fig. 2. Comparison for model validation current numerical model result with previous result by experiment [17] and numerical [18].

3.2 Effects on Slope Angle of The Collector

The initial temperature at the collector inlet was 300 K for all cases. With the angle of collector inclination increasing, the temperature started to drop down, as shown in Figure 3. This phenomenon occurred due to volume increasing at the end of the collector after some inclinations were made. Slopes 0 and 10 degrees indicated a higher temperature profile compared with other angles ranging from 330 K to 340 K. Another angle that showed a similar pattern with the average temperature was recorded at 323 K. As the air flowed through the collector, the air was heated up by absorbing the heat from the solar radiation and also part of the heat released from the ground based on the absorption coefficient of 0.8.

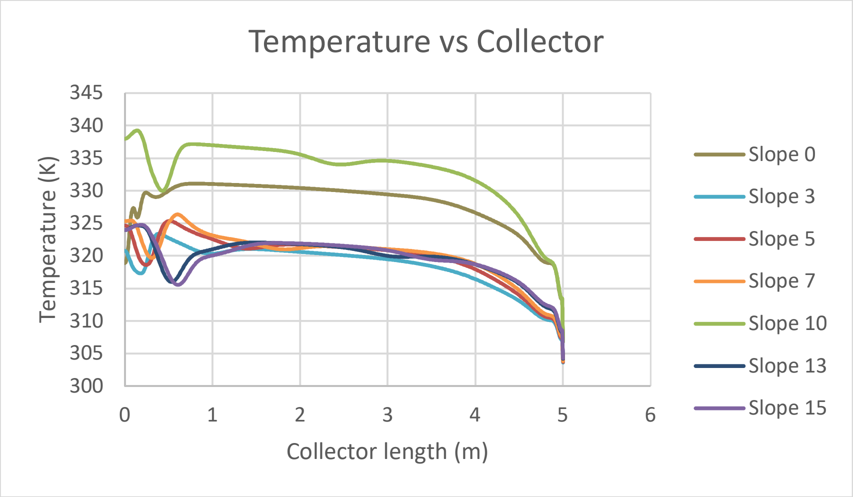

Fig. 3. The temperature profile for different slope collectors

The velocity was monitored to determine the best location for turbine installation. The turbine power generation power mainly depends on the diameter of the turbine blade, the efficiency of the turbine and air velocity through the turbine. Therefore, to investigate the suitable location of the turbine generator, the highest possible achievable velocity profile is ideal for installing it. Comparison of the velocity profile for various slope collector angles is demonstrated in Figure 4. From the observation, a rapid acceleration was formed at the chimney entrance and a gradual increase after 1.0 m. From the results, it shows that the 0 degree inclination angle could achieve the optimum velocity compared to others. As the inclination angle increased, the velocity tended to decrease compared to the velocity profile of 0 degree angle. Hence, this shows that the optimum angle of inclination at a higher speed for the collector is 0 degrees with 6.1 m/s.

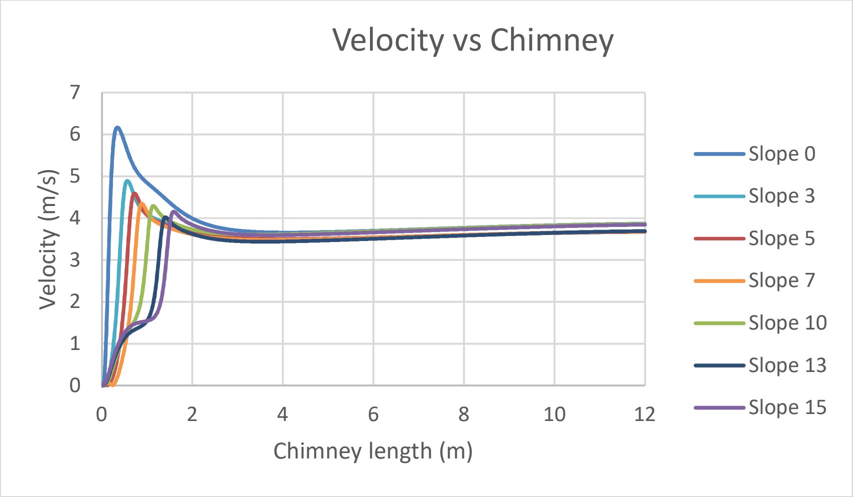

Fig. 4. Velocity profile for different collector slopes

3.3 Effects on Inlet Height of The Collector

From the angle variation cases, the 0 degree slope for the collector was determined as the initial parameter study due to higher velocity and temperature profile. To optimise the output of the solar updraft tower system, the inlet height of collector was varied. The study was conducted with 0.05 m, 0.1 m, 0.15 m and 0.2 m and 0.25 m of inlet heights. The results of the temperature distribution along the collector and velocity magnitude at the chimney centre are shown in Figure 5 and Figure 6 respectively.

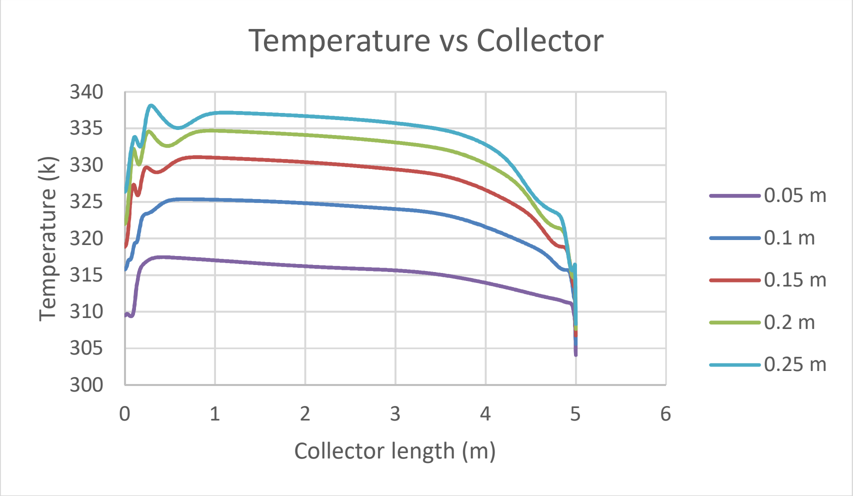

Fig. 5. The temperature profile for different entrance collector heights

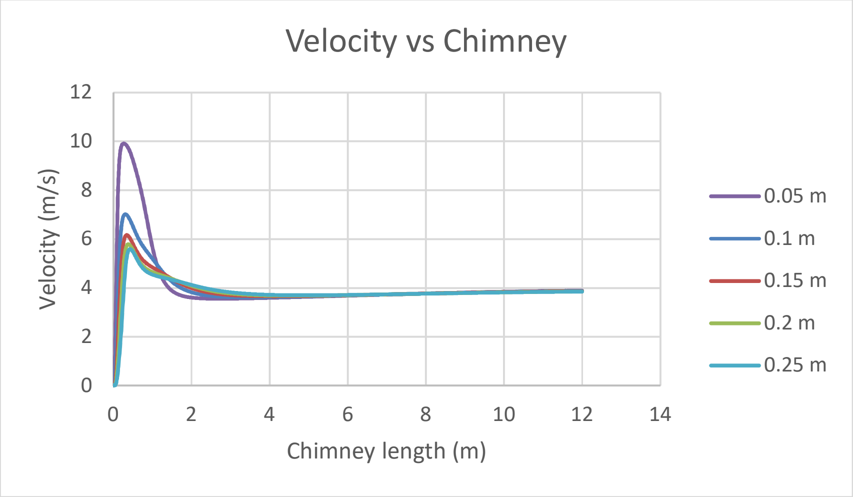

Fig. 6. Velocity profile for different entrance collector heights

By introducing different heights of the collector, temperature distribution was significantly affected while the velocity profile remained similar for all cases. From Figure 5, the highest temperature was recorded at 337 K when the height was set at 0.25 m from the ground. The temperature in the collector became low when the height was reduced. From here, increasing the inlet height of the collector will affect the temperature intensity in the collector due to the ratio between volume and radiation absorptivity. For output power generation, velocity magnitude in the chimney was a critical parameter to measure. The highest velocity magnitude was recorded at 0.05 m height of collector inlet with 10 m/s, and then slightly decreased for another height configuration, as shown in Figure 6. From the observation, all cases illustrated the same velocity magnitude of around 3 m/s from the beginning until it reached 3 m after the chimney entrance. This phenomenon occurred due to the similarity of section area and fully developed velocity profile from the initial condition.

3.4 Effects of Chimney Diameter

The 0 degree collector slope and 0.05 m collector inlet height was chosen for configuration and the tower diameter was varied for optimisation. Simulation process was conducted for six radius sizes which were 0.05 m, 0.1 m, 0.15 m, 0.2 m, 0.25 m, and 0.3 m. Similar to the earlier study, two main parameters were discussed, involving temperature profile and velocity magnitude for comparison. All cases with different chimney diameter sizes showed similar temperature profiles along the collector. The highest temperature was recorded at 317 K for all diameter sizes but the dropping rate at the chimney entrance was slightly different. From observation, the bigger the size of the chimney diameter, the faster the temperature started to decrease. From Figure 7, chimney diameter with 0.3 m shows that temperature began to drop from 317 K to 305 K after 4.5 m from the collector inlet. For the small diameter, 0.05 m indicated that the temperature started to decrease with just a tiny difference from 317 K to 314 K before entering 0.3 m from the chimney inlet.

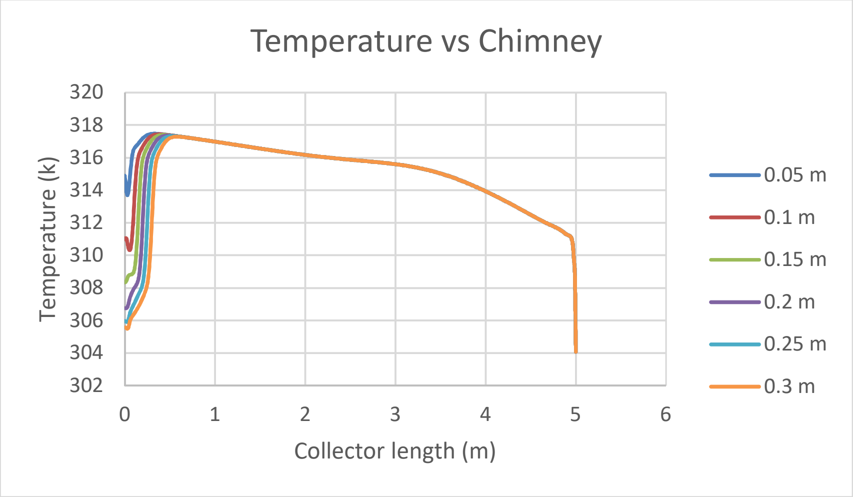

Fig. 7. The temperature profile for different chimney radius sizes

Figure 8 indicates that the highest velocity magnitude was 15 m/s for 0.05 m radius size and then significantly decreased for another radius size configuration. From observation, all cases illustrated different velocity magnitudes where the overshoot reading occurred at the tower until it reached 2 m after the entrance. 0.05 m and 0.1 m radius sizes demonstrated a higher reading at 15 m/s and 11 m/s, respectively. Other configurations showed a small difference in velocity reading at below than 1 m/s for each case.

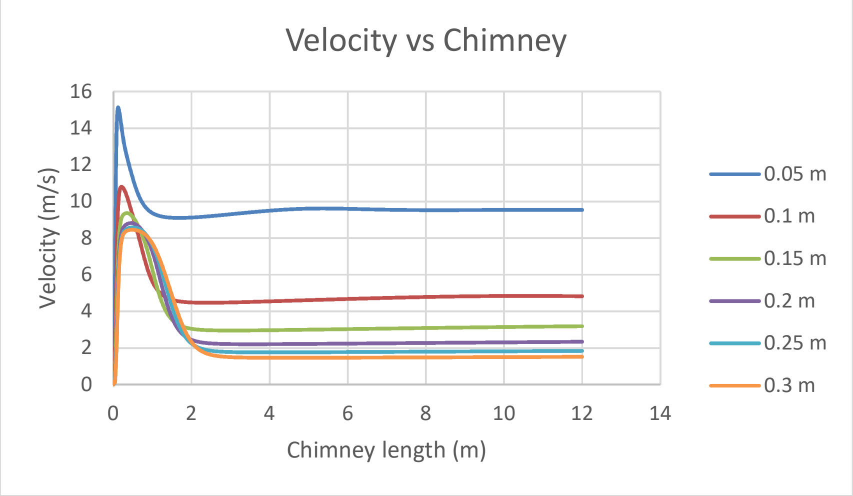

Fig. 8. Velocity profile for different chimney radius sizes

3.5 Power Output and Efficiency Estimation

The efficiencies and power conversion were based on the velocity profile after consideration of the effectiveness of the generator at 0.85. The results of three cases, involving slope of the collector, collector inlet height, and chimney diameter are illustrated in Figure 9, Figure 10 and Figure 11. The initial study focused on identifying the optimum angle for collector inclination to give the optimum power output. From Figure 9, slope 0 degree performed the highest power conversion and higher efficiencies around 6 W and 0.000095. This number is approximately two times compared with the other slope configuration which indicated a constant output of around 3 W. This phenomenon was presented with the contour of velocity distribution where the highest velocity occurs at the critical area of the chimney inlet.

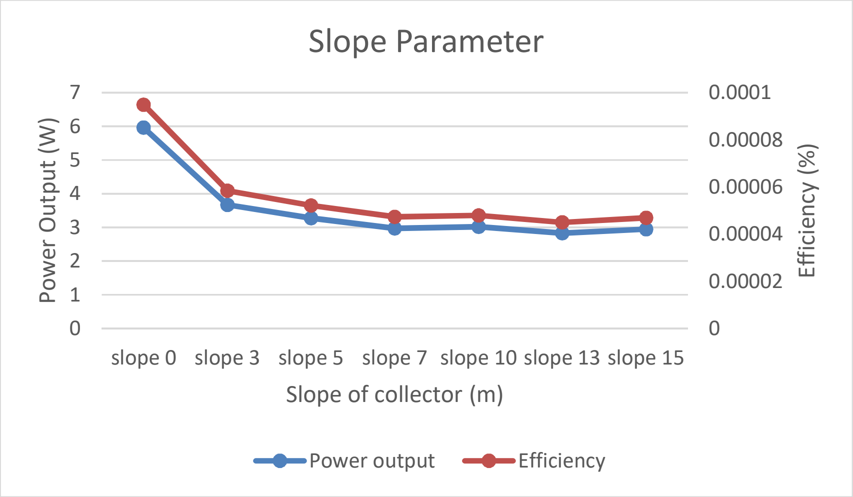

Fig. 9. Power output and efficiencies with different slope angles

Figure 10 indicates the power conversion based on the velocity profile and the efficiency of multiple inlet height parameters. Early data were interpreted during simulation and the maximum power generation was achieved at 0.05 m inlet height for approximately 26 W. The power output tended to decrease to 8 W and 5.1 W for inlet height 0.1 m and 0.25 m, respectively. Increasing the inlet height resulted in more volumetric creation, causing more ambient air from the surrounding to enter the collector, thus resulting in low air movement at the tower inlet.

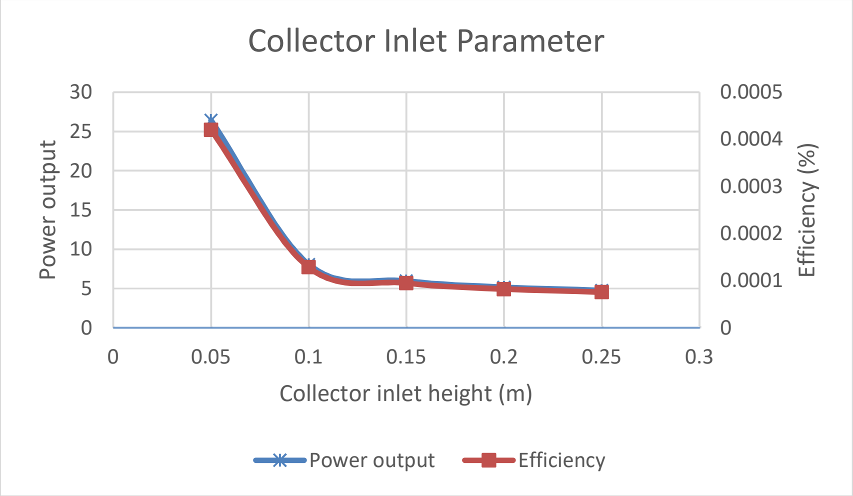

Fig. 10. Power output and efficiencies with different inlet heights of the collector

The final adjustment for the solar updraft tower improvement has been designed for this study where variable chimney sizes were performed. From observation, increasing the chimney size significantly improved in terms of power output and the efficiency of the system. Figure 11 shows that power generated increased from 4 W to 25 W for radius sizes 0.05 m to 0.3 m, respectively. This phenomenon demonstrated that chimney configuration is an important parameter to get the optimum output and performance. The results also reported that different chimney geometries led to obtaining higher efficiencies where the highest was recorded at 0.0004 with 0.6 m of chimney diameter configuration.

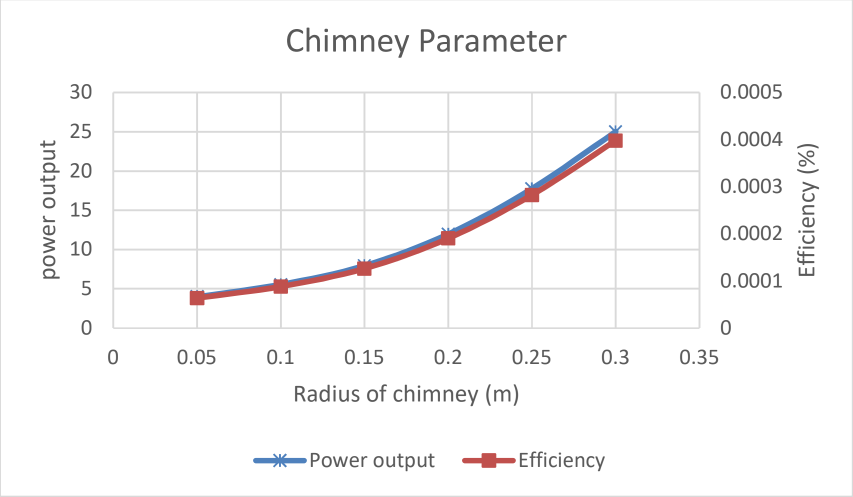

Fig. 11. Power output and efficiencies with different chimney diameters

4. Conclusions

From the simulation, the collector with 0 degree worked better and the best entrance gap diameter between the collector and chimney was 0.05 m and 0.05 m, respectively. Through simulation and numerical optimisation of many cases with dimensional variations, it is best to describe that any changes regarding chimney configuration will not significantly affect the temperature profile in the collector except in terms of power conversion and efficiency for the system due to high velocity produced in the tower. Therefore, in this initial attempt for any adjustment of chimney geometry, the speed and the pressure difference in the system were affected. The environmental effect can be defined as the primary factor that will affect the overall output of the solar updraft tower power output. In this paper, solar radiation peak was assumed at 800 W/m^2 based on the longitude and latitude of Malaysia and this solar radiation was sufficient to raise the temperature of air in between the solar collector and soil surface with an ambient temperature.

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