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Numerical Analysis for Optimizing Solar Updraft Tower Design Using Computational Fluid Dynamics (CFD)

J. H. Y. Too and C. S. N. Azwadi*

Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai Johor, Malaysia
*jfytoo@gmail.com

Abstract – *This paper presents and explains the working principle of solar updraft tower system. It also describes the major components of the system. The system utilizes solar thermal technology by heating up the air below the solar collector through solar radiation, convection and greenhouse effect. The heated up air tends to travel to the bottom of the tower and rises up the chimney due to differential temperature. The upward velocity is used to turn a turbine installed at the bottom end of the tower either vertical or horizontal to generate power. A parametric study on the geometry of the solar updraft tower is carried out by inclining the solar collector, studying the effects of an inclined chimney and also the effects of different solar radiation for 400 W/m^2, 600 W/m^2, 800 W/m^2 and 1000 W/m^2. A validated model is compared with the experimental prototype constructed by the University of Zanjan, Iran. The study is to maximize the power generation of the existing utilized land for optimum power generation by sloping the collector and updraft tower angle to evaluate the performance in terms of updraft tower velocity and estimated power generation improvement. The result shows a remarkable improvement in the power generated by just sloping the collector and without inclining the updraft tower. The findings and results are discussed and suggested for future* works.

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

1.0 INTRODUCTION

During the pass few couples of decades, the solar power technology is categorized as a viable source of clean energy. There has been considerable advancement to the solar photovoltaic (PV) power generation system development throughout the years. Currently electricity power generation from fossil fuels such as oil or coal is damaging our environment. Nuclear power stations are an unacceptable risk in most locations [1]. Therefore we need to diversify away from this non-renewable energy sources and look for alternatives. Many developing countries including Malaysia cannot fully rely on these conventional methods as we are aware on the damaging effect of the CO_2 emission and try to source for other types of green and renewable energy source. With a good amount of rainfall in our country, hydroelectric is one of our power generation source and we also have good amount of sunlight throughout the whole year where it is a good opportunity for solar harvesting. The need for a green and environmental friendly electricity power generation method is thus obvious and will further expand in near future.

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Currently the overall power generation in Peninsular Malaysia is totally relying on coal and natural gas and it has been the mainstay of source of power generation for more than two decades and we foresee that it will continue to be an important source for years to come unless a more reliable alternative and sustainable power source generation in large scale can be identified. The solar updraft tower is another alternative renewable energy source for areas that are rich in sunlight where it can be also considered as alternative to solar concentrating or solar PV cell (Solar PV farms) power generation facilities. There are several successfully implementations, such as several large towers being constructed in countries with well-developed energy infrastructures. This paper focuses on the potential of implementing a smaller scale solar updraft towers in remote area in Malaysia for power generation [2].

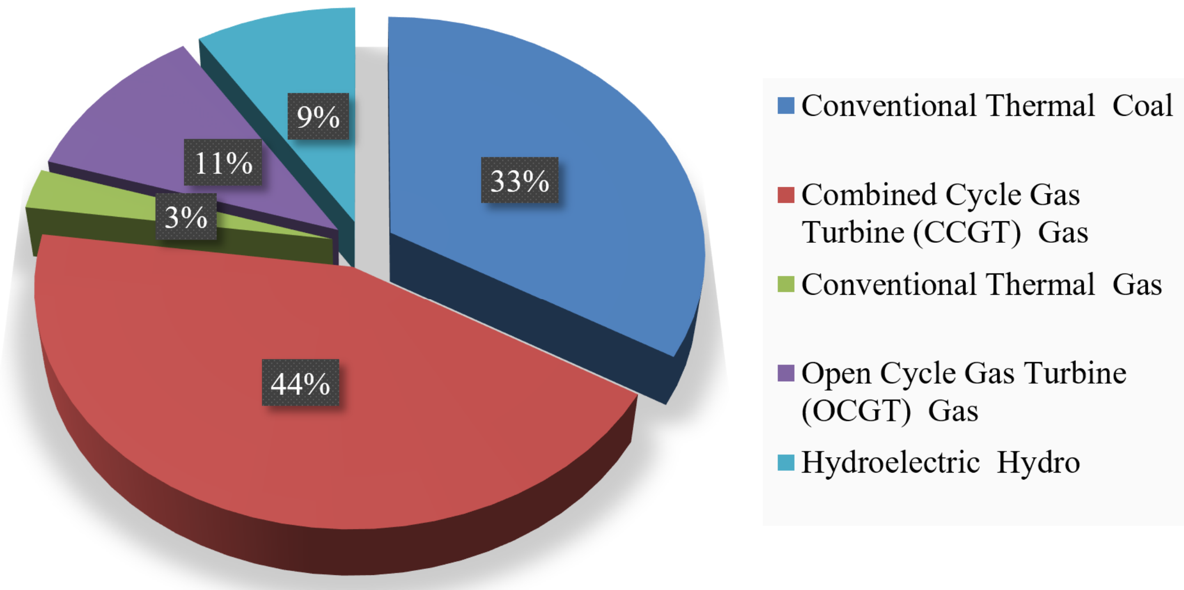

Figure 1: Percentage of type of power generation in Malaysia [2]

2.0 SOLAR UPDRAFT TOWER

2.1 Description

The Solar updraft Tower utilizes the concept of converting the solar radiation from the sun to electricity by using three types of working principle which consist of the Greenhouse effect, the rising tower and wind turbine generator. During the sunny day, when the solar radiation falls upon the solar collector which is usually made out of large pieces of glass roof similar to glass skylight. Hot air is produced by the sun when the solar radiation lands on the glass roof [3]. The buoyant air rises up into the tower of the solar updraft tower, thereby creates a drawing effect for air from the collector perimeter to enter into the collector region and thus initiating forced convection which heats the collector air more rapidly. Through mixed convection, the warm collector air heats the underside of the collector roof.

Some of the energy absorbed by the ground surface is conducted to the cooler earth below, while radiation exchange also takes place between the warm ground surface and the cooler collector roof. In turn, via natural and forced convection, the collector roof transfers energy from its surface to the ambient air adjacent to it. As the air flows from the collector perimeter towards the tower its temperature increases while the velocity of the air stays approximately constant because of the increasing collector height. The heated air travels up the tower, where it cools through the tower walls. The tower converts heat into kinetic energy. The pressure difference between the tower base and ambient pressure at the outlet can be estimated from the density difference. This in turn depends upon the temperatures of the air at the inlet and at the top of the tower. The pressure difference available to drive the turbine can be reduced by the friction loss in the tower, the losses at the entrance and the exit kinetic energy loss [3]. As the collector air flows across the turbine, the kinetic energy of the air turns the turbine blades which in turn drive the generator [4].

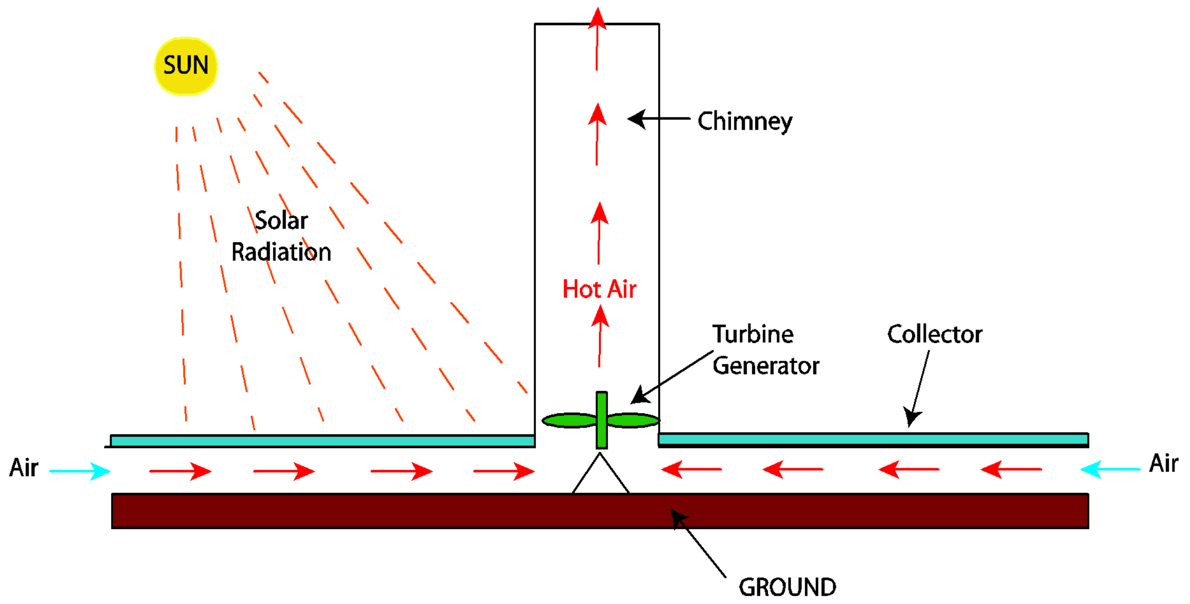

Figure 2: Solar Updraft Tower Schematic Diagram [5]

2.2 The Solar Updraft Tower

The solar updraft tower is the most important component in the solar updraft power station. The solar tower acts as a large rising tube located at the centre of the glass collector. The solar updraft tower is also defined as the thermal engine. The updraft tower consists of two temperature differential between the hotter air at the bottom of the tower and the ambient air temperature at the exit of the tower. When the air reaches the bottom of the updraft tower, it will be hotter compared to the ambient air temperature due to the air absorbing the heat when it flows through the collector. The hot air will rise up the tower due to the buoyancy effect of difference in air density. The design criteria of the solar updraft tower should also minimize the friction loss on the internal surface finishing and to maximize the differential pressure of the tower [5].

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2.3 The Solar Collector

The component that takes up the most footprint of the solar updraft tower power generation system is the collar collector. Therefore, it is considered the major component of the whole system. The solar collector acts as a heat exchanger that converts the solar radiation energy to internal energy in the air that passes through between the bottom of the collector and the ground [6]. The solar collector utilizes the greenhouse effect. The collector is made out of transparent material such as glass or plastic film where the radiation is allowed to pass through but part of it will be reflected back. The collector allows short wave radiation to pass and prevents them from exiting, and insulation which resists back and rear side heat losses. This heats up the ground / soil under the collector where it acts as a thermal storage and transfers its heat to the air flowing horizontally in between the bottom of the collector and the ground surface [5].

2.4 The Power Generation Turbine

The most important component for the solar updraft tower power plant is the power generation turbine. The function of the turbine is to convert the energy from the air flow and transmitting it to a generator for power generation. It has significant influence to the turbine pressure drop and transmits it to the generator. The specification of the wind turbine has many similarities to the large wind turbine but the principle of operation is slightly different. The pressure turbine relies on differential pressure which results on the shrouded blades to move and then the conversion of kinetic energy to power [5].

2.5 The Soil Energy Storage

The soil beneath the solar collector behaves as a storage medium, and it can be heated up by the air for a significant time frame after the sunset until the temperature reaches equilibrium with the ambient. The efficiency of the solar tower power plant is below 2% and depends mainly on the height of the tower. Due to the wide coverage required by the solar collector, the solar updraft tower can only be built on cheap land which is usually on the outskirt of the city. However the area under the solar collector can be used for agricultural purposes since it utilizes the greenhouse effect [7].

3.0 LITERATURE REVIEW

Numerical studies using CFD are becoming an indispensable computing tools for engineers. The CFD simulation provides insight to the details of how the solar updraft tower works and allows modification and new concepts to be evaluated using a computer simulation. The output of the solar updraft tower can be predicted before the actual plant is being constructed. The simulation also allows engineers to locate and identify problems in the design and further optimize the system before the construction. It is very suitable for large scale products such as the solar updraft tower to be simulated and results to be obtained near to the actual based on the assumptions made. It is impossible to build a large prototype within this kind of scale. Therefore CFD simulation is the solution.

Several researchers have contributed into the construction, numerical simulation of the solar tower collector. Pasumarthi & Sherif [8] have tested two different types of collector which are the extensions of the collector base and also the intermediate absorber is being introduced. The

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results of the experiment show that the temperature reported is higher than the theoretically predicted temperatures. The results indicate the fact that the experimental temperature reported is the maximum value of the temperature attained inside the solar updraft tower where the theoretical model predicts the bulk air temperature [8].

This is the first known attempt to simulate the convective flow in a solar updraft tower using CP. Bernardes presented a solution using Navier-Stroke and Energy Equation for the natural laminar convection in steady state, predicting its thermo-hydrodynamic behaviour [9]. Schlaich [10] also presented an analytical model of the solar updraft tower system. A boundary layer analysis was performed to determine the pressure differential due to frictional effects and the heat transfer coefficient during turbulent flow between two approximately parallel disc and surface where it applied to the flow at the inlet of the collector of the solar updraft tower collector [11]. A comprehensive analysis of the helio-aero-gravity concept, power production, efficiency, and estimating the cost of the solar tower power plant set up in developing nations was conducted [12]. Padki, Sherif [13] and Pasumarthi [8] developed a mathematical model of differential equations to study the effects of various environment and geometry conditions on the heat and flow characteristics and power output.

Earlier numerical models had been presented by Backström [4], where tower friction, system turbine and exit kinetic energy losses were introduced. Other researches also contributed in the improvement on the solar updraft tower numerical analysis by Hedderwick [14] and Beyers [15]. Pretorius & Kröger [6] also evaluated the influence of a developed convective heat transfer equation, more accurate turbine inlet loss coefficient, various types of soil and quality collector glass roof and the performance of a large scale solar tower power plant.

Bernardes [16] developed a comprehensive analysis of the solar updraft tower both analytical and numerical model to describe the performance of the system based on estimated power output of the solar updraft tower as well as to evaluate the effects of various types of ambient condition and structural dimension of the tower to the power output of the plant.

A mathematical model was proposed that could predict the affects parameter of the solar updraft tower such as tower height, the collector radius and the effects of the solar radiation from the sun, on the relative static pressure, the driving force, the power output and the efficiency of the solar updraft tower [17]. Another simulation study was carried out to investigate the performance of the power generating system based on a developed mathematical model. The simulated power outputs in steady state were obtained for different global solar radiation intensity, collector area and tower height [18]. The effects of the solar radiation intensity on the flow of the solar updraft tower were analyzed by Huang [19] where a Boussinesq model was adopted for natural convection, a discrete ordinate radiation model (DO) was employed for radiation and ground under collector cover was seen as a constant inner heat source. Koonsrisuk [20] compared theoretical models from previous works to study the accuracy of those theoretical models for the prediction of the solar updraft tower performance varying the plant geometrical. Computational fluid dynamics (CFD) studies were conducted to compare the results with these theoretical models and found that the results were very well compared with the CFD results and thus were recommended for the prediction of solar updraft tower performance

Maia [21] who presented the development of a model using airflow turbulent simulation in the solar updraft tower, found that the most physical element in the solar updraft tower system was the tower dimension as it caused the most significant variation in the flow behavior. A numerical model was presented for the process of laminar natural convection in a solar tower. They have focused on airflow and heat transfer inside the system and analyzed the effect of the geometry and Rayleigh number [22]

A mathematical model based on the Navier–Stokes, continuity and energy equations was developed to describe the solar tower power plant mechanism in detail. Numerical simulation was performed using the CFD software FLUENT that can simulate a two-dimensional axisymmetric model of a solar tower power plant with the standard *k*-epsilon turbulence model [23] . A comprehensive theoretical model had been developed by taking account of the detailed thermal equilibrium equations in the collector, the system driving force and the flow losses based on existing experimental data or formulas for the tower height and collector radius [24]. The effect of the geometric dimensions on the fluid dynamics and heat transfer was investigated. The thermal efficiency of the collector was found to improve with increasing scale, due to an increase of the heat transfer coefficient [25].

Regarding recent works for a few years back, Tayebi [26] conducted a detailed numerical analysis of solar tower power plant system with a curve junction. The results were related to the temperature distribution and the velocity field in the tower and in the collector. The performance evaluation of solar tower power plant was done by FLUENT software by changing three parameters including collector slope, tower diameter and entrance gap of collector. The results were validated with the solar tower power plant which was constructed in Zanjan [27] .

Another numerical research was conducted to study the influence of solar radiation and ambient temperature on the electrical energy produced by a solar tower in the region of M'Sila (Algeria). The results indicated that the production of electrical energy is closely related to solar radiation and ambient temperature [28]. Up until recently, a mathematical model based on the Navier Stokes, continuity and energy equations were developed to describe the solar updraft power plant mechanism. Two different numerical simulations were performed. The first one was transient simulation for the geometry of the prototype in Manzanares, Spain under Dire Dawa climate condition. The numerical simulation was performed using the CFD software FLUENT that can simulate a two-dimensional axisymmetric model of a solar tower power plant with the standard *k*-epsilon turbulence model and Discrete ordinates irradiation model [29]. Sandeep [30] presented their work for optimizing the geometry of the major components of the solar updraft tower power plant using a computational fluid dynamics (CFD) software ANSYS-CFX to study and improve the flow characteristics inside the solar updraft tower power plant.

The researches were now mainly to optimize the previous design such as performance evaluation of a solar updraft tower which was carried out based on the parameters such as roof angle, inlet height and for different irradiation values using ANSYS Fluent [31] . A 3D CFD (Computational fluid dynamics) model of a Solar Updraft Tower Power Plant was developed and validated through comparison with the experimental data of the Manzanares plant. Then, it was employed to study the system performance for locations throughout Tunisia [32].

A 3D numerical approach that incorporates the radiation model, solar load model, and a real turbine was used in this study. Variations in turbine performance with rotational speed were studied to investigate the power regulating strategy option for solar tower turbines [33]. A mathematical model was developed to estimate the performance of SUPP based on tracking solar collector consideration in Malaysia. The objective was to verify the suggested model and to optimize the slope angle of tilted tracking solar collector and the results were promising for implementation in Malaysia [34].

Lately Computational Fluid Dynamics modelling was used to calculate the specific parameters, energetic and exergetic efficiencies of the solar updraft tower where the results from experimental and simulation were statistically assessed and very close to the measured data [35]. A model for time dependent analysis of solar towers was presented. The energy balance equations for three components of solar towers, absorbing plate, cover glass and air-gap were discretized with respect to time using an implicit finite difference model. The discretized nonlinear energy balance equations were solved for numerous time steps over a 24 hours period using the Newton–Raphson method [36].

In this article, we will promote new solar renewable energy for reducing the conventional type of power generation, this has motivated us to look for alternative technologies and try to improve existing current system of the solar updraft tower. The objective of resolving the energy crisis motivate us to

a) Study and derive a numerical model for validation of previous works
b) Conduct a study on the effects of inclination of the angle of the solar collector
c) Conduct a study on the effects of inclination of the angle of the updraft tower with a fixed outlet diameter
d) Conduct a study on the effects of inclination of the angle of the updraft tower with a fixed tower entrance
e) Conduct a study on the effects of solar radiation towards the velocity profile at the center of the chimney.

4.0 NUMERICAL ANALYSIS

4.1 CFD Modeling

In this paper, a CFD model was developed to conduct a parametric study on the geometry of the solar updraft tower. A validated model was used for this paper to analyse the effects of changing the geometry of the collector and tower where an angle was applied to the original configuration. The geometry and configuration used for this research correspond to the experimental prototype setup by the University of Zanjan, Iran [27]. In this paper, ANSYS FLUENT was used for modelling and comparison will be analysed for different types of configuration to obtain the best results in terms of velocity since the power generation is a pressure turbine where the power generation depends on the velocity flowing through the turbine

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4.2 Model Simplification

The model needs to be simplified to ease the computation of the simulation. As the sun's radiation intensity changes within the day and the peak solar radiation will be near noon time of the day and during that time it should be a very stable point for a fair weather condition. For the model validation purposes, we have used the same time at the experimental data collected which is 11am based on the longitude and latitude of Zanjan, Iran. The numerical study requires a steady state condition therefore the mathematical model can be simplified with the following assumption.

a) The modelled fluid is Newtonian and incompressible
b) The flow is a Three (3) dimensional flow and it is assumed as turbulent
c) The viscous dissipation and compressibility properties of the fluid are assumed negligible
d) The solar radiation intensity is uniform throughout the surface of the collector ($I_o = 800W/m^2$)
e) The Solar radiation transmittance is 100%
f) Heat is being absorbed into the ground with an absorption of 0.8
g) The ambient temperature at the inlet and outlet are assumed as 300 K.
h) There is no heat loss at the inner wall of the collector, soil cover and tower wall
i) The air density changes using Boussinesq hypothesis and properties of air is assumed to be constant in all formulations
j) The fluctuation of wind effects is neglected
k) The overall process is at steady state
l) Loss of head due to the strutting and support columns for the solar collector and the loss of head for the pressure type turbine are neglected.

Based on the assumption above, the solar updraft tower will be assumed as a three dimensional steady compressible force convective heat transfer system. Therefore the standard *k*-*e*psilon turbulence model is used with the radiation model of discrete ordinates.

4.3 Governing Equation

As explained in previous chapter, the solar updraft tower consists of the solar collector and the updraft tower which function is to increase the energy in the air by utilizing the greenhouse concept where the air flow is driven by the buoyancy effect due to the vertical column of hot air at the updraft tower.

The modelled fluid which flows within the system is described through the conservation equation of mass, momentum and energy. The unknowns in the equations can be computed by the application of suitable turbulence model. . The standard *k*-epsilon models are used to solve the equations and standards values for constants are adopted. With the above assumptions and the system is assumed as steady state condition, the basic equations can be written as following:-

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Continuity Equation

$$\frac{1}{r}\frac{\partial}{\partial r}(ru) \quad + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Momentum Equation

$$\rho\left(u\frac{\partial u}{\partial r} - \frac{v^2}{r} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial \rho}{\partial r} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) \quad - \frac{u}{r^2} + \frac{\partial^2 u}{dz^2}\right] \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial r} - \frac{uv}{r} + w\frac{\partial v}{\partial z}\right) = \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v}{\partial r}\right) \quad - \frac{v}{r^2} + \frac{\partial^2 v}{dz^2}\right] \tag{3}$$

$$\rho\left(u\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial \rho}{\partial z} + \rho g\beta(T - T_c) + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right) \quad + \frac{\partial^2 w}{dz^2}\right] \tag{4}$$

Energy Equation

$$\frac{1}{r}\frac{\partial}{\partial r}\,(\rho ruT) + \frac{\partial}{\partial z}(\rho vT) = \frac{1}{r} * \frac{\partial}{\partial r}\left(r\frac{\lambda}{C_P}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{\lambda}{C_p}\frac{\partial T}{\partial z}\right) \tag{5}$$

4.4 Turbulence Modelling

A turbulence model is a method of computational procedure to close the system of a mean flow equations. For most of the engineering application in the industry, it is unnecessary to resolve the details of the turbulent fluctuations. Therefore the turbulence models enable the calculation of the mean flow without first calculating the full time-dependent flow field. The reason is to identify and know the affects by the turbulence to the mean flow. Therefore to justify that the flow within the updraft tower is of turbulence flow, the Reynolds number shall be more than 2,300 for internal pipe flow. The Reynolds number equation is listed below:-

$$N_{Re} = \frac{\rho v D}{\mu} \tag{6}$$

where
P = density of air (kg/m3)
v = velocity of the fluid (m/s)
μ = Dynamic viscosity of air (kg/m.s)
D = Diameter of pipe (m)

From the above calculation, the Reynolds number at the centre of the updraft tower indicates that the flow is turbulent. Therefore a turbulent model can be used for this application. The selection type of turbulent model must fulfil the following criteria

- Must have a wide applicability and also similar usage on previous works
- Results obtained must be accurate
- Simplicity of the model

- Must be economical to run

The standard *k*-epsilon equations are used for this paper. It is the simplest and complete of turbulence using two-equation models in which the solution of two separate transport equations allows the turbulent velocity and length scales to be independently determined.

- The most widely-used engineering turbulent model for industrial applications
- Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations.
- Leads to stable calculations that converge relatively easily.
- Reasonable predictions for many flows
- Contains sub-models for compressibility, buoyancy, combustion, etc.

For this paper, the turbulent kinetic energy which is the transport equation are obtained from the exact equation, also is its rate of dissipation and the transport equation are derived using physical reasoning [27]:-

***k* equation**

$$\rho\left(\frac{1}{r}\frac{\partial(ruk)}{\partial r}+\frac{\partial(kv)}{\partial z}\right)=\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right)+G_k-\rho\in \tag{7}$$

Epsilon equation

$$\rho\left(\frac{1}{r}\frac{\partial(ru\varepsilon)}{\partial r}+\frac{\partial(\varepsilon v)}{\partial z}\right)=\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right)+\frac{\varepsilon}{k}(c_1G_k-c_2\rho\varepsilon) \tag{8}$$

Referring to the standard *k*-epsilon equations above, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients [37]. The variable r, which stands for the radial coordinate, corresponds to the radial direction in the collector, and the variable z, which represents the axial coordinate, corresponds to the tower axial direction [23]. The standard *k*-epsilon equation was used when calculating, the wall adopted standard wall function method and also the simple method was used to treat pressure-velocity coupling.

The equations also consist of some adjustable constants σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$. The values of these constants have been arrived at by numerous iterations of data fittings for a wide range of turbulent flows [38]. These are as follows σ_k = 1.00, σ_ε = 1.30, $C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ =1.92 & C_μ = 0.09.

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4.5 Geometry Generation

The geometry was constructed using the ANSYS design modeller. The solar updraft tower is split into three different zones. There are three different zones which are

a) The Solar Collector
b) Transition Section in between solar collector and tower
c) Tower

The mesh of each part is generated separately and the parts where the face size is too wide, a secondary mesh refinement is being introduced to provide smooth and better quality mesh. The transition zone is the most sensitive area of the computational domain as it is a very small area on which there is a strong pressure gradient [10]. Therefore refinement is also added to this area to improve the mesh quality. The overall mesh quality is checked to reduce the skewness ratio to approximately 0.8. The system geometry consists of a tower with 12.0 meters height and 0.25 meter diameter surrounded by a collector with 5 meters radius and 0.15 meter height. The physical domain was modelled and meshed using the ANSYS mesh editor. Grid generation is considered as the first necessary step for CFD modelling and has an impact on numerical results.

Table 1: Main Component of Solar Updraft Tower Prototype in Zanjan, Iran

Name of Component	Parameters
Collector square	78.54 m^2
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

4.6 Parametric Study on existing geometry

The original design of the experimental prototype geometry will be used as a base for this parametric study. By conducting this study, we can further optimize the characteristic of the existing system. The parametric study is to alter the existing geometry in terms of angle and still maintaining the actual footprint of the collector and height of the tower. It is split into three section which is listed as following

a) Stage 1: The existing non inclined collector will be introduced with a slope angle inclining from the centre of the tower base sloping out to the end of the collector. The height of the entrance between the solar collector and the ground surface remains unchanged where it is fixed at 0.15 meter. For this study the angles of inclination of 0 degree, 1.5 degrees, 3.0 degrees, 5.0 degrees and 7.0 degrees will be modelled for result comparison.

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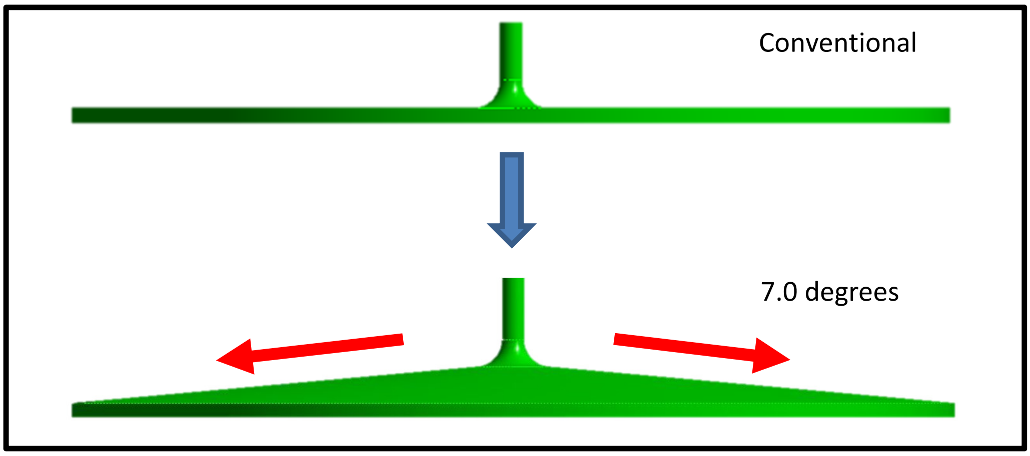

Figure 3: Sloping of Collector towards the outer side of the collector

b) Stage 2: After confirmation the best angle of inclination for the solar collector, the straight updraft tower will be inclined to form a taper where the outlet of the tower is maintained at 0.25 meter hence increasing the special area at the base of the updraft tower. For this study the angle of inclination of 0 degree, 1.0 degrees, 3.0 degrees, 5.0 degrees and 7.0 degrees will be modelled for result comparison.

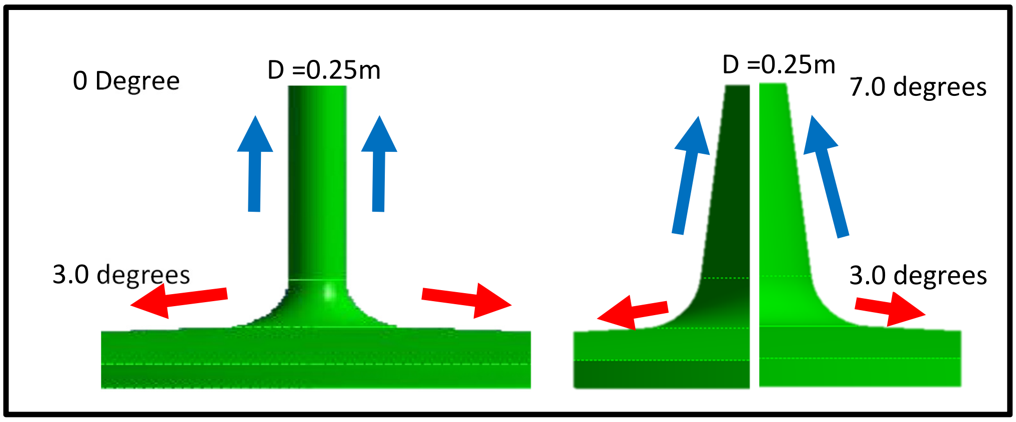

Figure 4: Sloping of Collector towards the outer side of the collector from 0 degree to 7 degrees

c) Stage 3: Is an alternative geometry model of stage 2 where the entrance of the updraft tower is fixed at 0.25 meters and the outlet of the tower is tapered to the inside. For this study the angle of inclination of 0.15 degree, 0.3 degree, and 0.5 degree will be modelled for result comparison.

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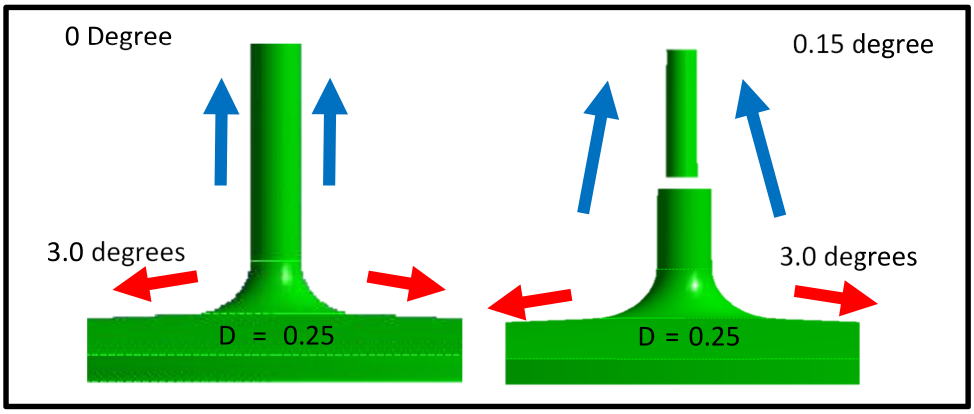

Figure 5: Sloping of chimney with fixed chimney inlet diameter and fixed collector angle of 3.0 degrees

5.0 MODEL VALIDATION

5.1 Grid Independence Study

Table 2: Summary of Grid Configuration & Mesh Information

Grid	Cell	Face	Nodes	Velocity (m/s)
1	293,845	609,146	60,269	4.503
2	296,250	623,096	65,226	4.194
3	365,169	758,450	75,554	4.208
4	390,145	813,442	82,480	4.209
5	615,430	1,280,044	127,839	4.202

Grid independent study is performed to get a favourable number of mesh for the model selected. Grid independent study was conducted for a total of five grids, named Grid 1, Grid 2, Grid 3, Grid 4 and Grid 5 whose description is explained in the table below until consistent results are achieved.

After completion of the geometry from the design modeller, the geometry is edited using the mesh editor by FLUENT. The geometry is divided into three (3) different major sections which are listed as following:-

a) The solar collector & soil cover
b) The curvature area zone
c) The updraft tower

The judging criteria for the five (5) different types of configuration is the outlet velocity at the centre of the updraft tower. From the results, we noticed that when we compared the Grid results of Grid 3 & Grid 4, the difference between the results was approximately 0.019% and compared with Grid Result of Grid 4 & 5, it was approximately 0.175%. Since the difference is less than 1% and having a very fine mesh would not have the benefits as it will only increase the computational time of the simulation, we have adopted Grid 4 as the selected Grid for this paper as the computation time to complete all the simulations within the provided time frame is compulsory.

5.2 Model Validation

An experimental sample was built in University of Zanjan, in 2010. The tower height is 12.0 meters and the collector has a 10.0 meters of diameter. The collector angle must be designed in a way that the most possible heat could be absorbed. Zanjan city has the attitude of 36º, 68´ and longitude of 48º, 45´ [27].

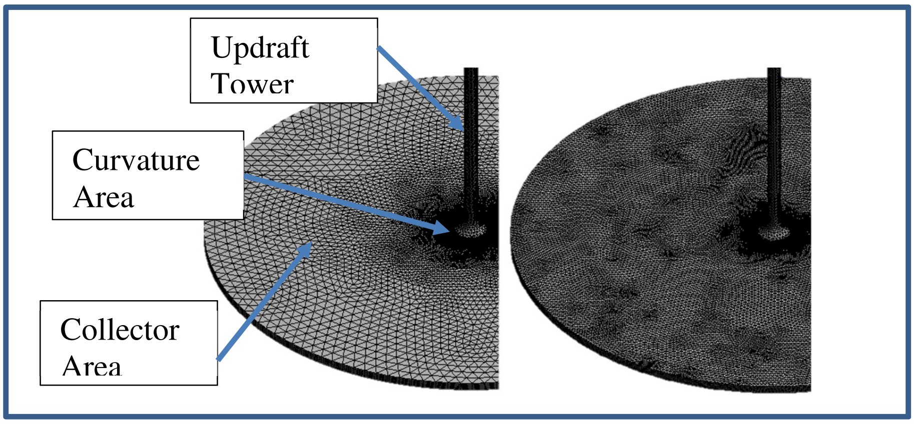

Figure 6: Mesh Configuration for the Solar Collector, curvature zone and chimney - Coarse (left) - Extra Fine (Right)

To validate the numerical results, the temperature increase in the collector is compared with the experimental data of the Zanjan prototype [27]. The experimental results indicate that, when the solar radiation is approximately 800 W/m^2 and the temperature increase through the collector with no-load condition reaches 20 K with ambient temperature of 300 K.

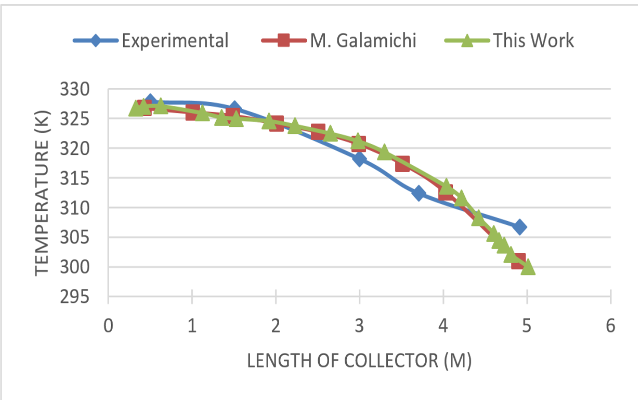

Figure 7: Comparison for Model Validation of previous work [27] and current numerical model result

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A good quantitative agreement was obtained between the experimental data of the Zanjan prototype and both of the numerical results obtained from previous work by [27] and the experimental result from the prototype. Slight difference may be due to error from the sensors and the location of the mounting of the sensors may result on some data deviation with numerical results. Therefore, this CFD modelling via 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.

6.0 RESULT AND DISCUSSION

The numerical modelling was conducted as per the requirement of the parametric study for studying the effects on the slope angle for the solar collector, effects of a taper tower either fixed outlet diameter (type A) or taper tower with a fixed entrance diameter. All the models have been successfully completed.

6.1 Effects on Slope Angle of Collector

The conventional type of solar updraft tower does not have any slope on the collector where it is usually installed at 0 degree. For this study we have introduced several angles for the inclination of the collector which are 1.5 degrees, 3.0 degrees, 5.0 degrees and 7.0 degrees. The inlet of the collector remains the same as 0.15 meter high and the inner collector is raised based on the angle inclination. We will be looking into the effects on the temperature of the collector where the temperature of the 0 degree slope is compared with the sloped collectors

6.1.1 Temperature distribution along the collector

As the air flows through the collector, we notice that the air is heated up by absorbing the heat from the Solar Radiation (800 W/m^2) and also part of the heat released from the ground based on the absorption of 0.8. As the air approaches the bottom of the entrance to the vertical updraft tower, the temperature difference between the inlet and outlet of the updraft tower creates the draft due to differential in air density where the Boussinesq approximation is introduced.

Referring to Figure 8: Collector temperature profile (X= 0.075m), we notice that the initial temperature at the centre of the tower was approximately 340 K. Then the angle of inclination starts to drop down. When the angle increases the volume at the end of the collector tends to increase therefore the temperature will go down as the point of the temperature does not increase with the angle.

6.1.2 Velocity Profile at the centre of the tower

The velocity at the centre of the tower is monitored to determine the best location for installation of the turbine. The turbine power generation power mainly depends of the diameter of the turbine blade, efficiency of the turbine and velocity through the turbine. For this case since the updraft tower diameter is 0.25 meter and there are no angles of inclination, therefore the higher the velocity will result on the higher power being generated but there will be some minor increase of the head loss since the velocity is higher.

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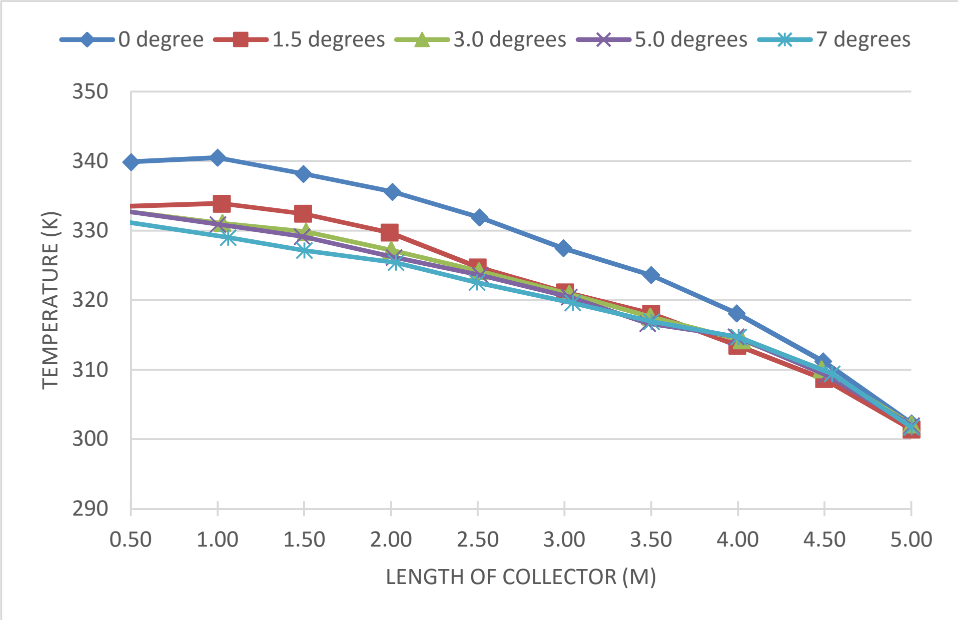


Figure 8 : Collector Temperature Profile (X=0.075m) showing half of the collector

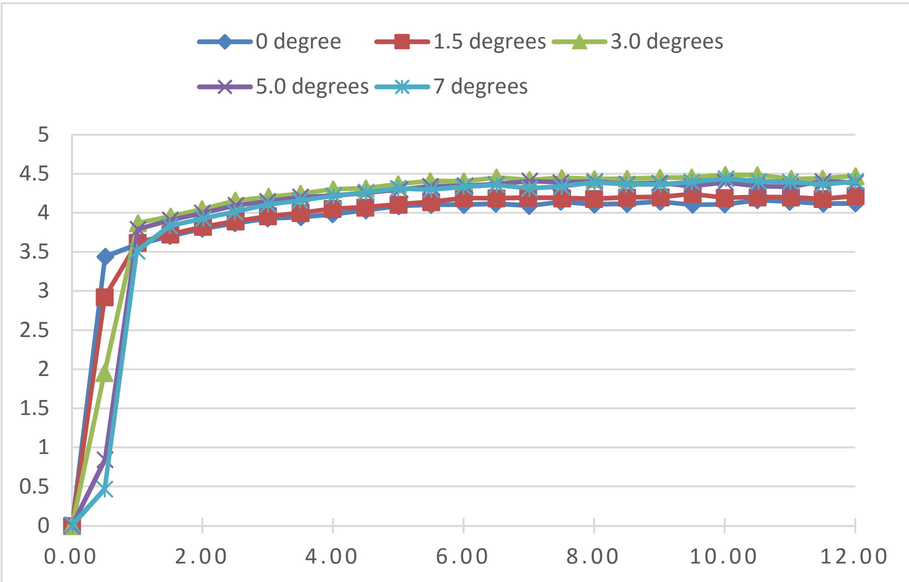


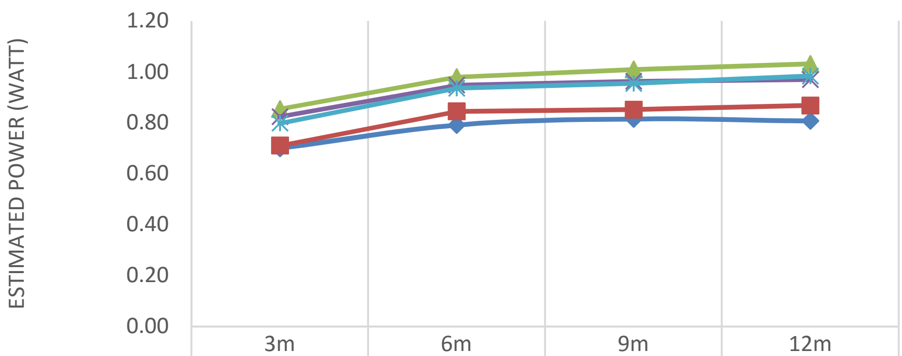
Figure 9: Comparison of the velocity profile at the centre of the tower for the various slope angles of the collector

From the Figure 9: Comparison of the velocity profile at the centre of the tower for the various slope angles of the collector, we notice that the there is a rapid acceleration at the entrance of the tower and a gradual increase after 1.0 meter from the entrance of the updraft tower. From the graph, we notice that when the collector is inclined with the angles of 1.5 degrees, 3.0

degrees, 5.0 degrees and 7.0 degrees all show improvement. Therefore to analyse the suitable location of the turbine generator, we assume that it will be suitable for installing it at the location where there is the highest possible achievable velocity profile.

With reference to the Figure 9: Comparison of the velocity profile at the centre of the tower for the various slope angles of the collector, for the collector inclination of 1.5 degree and 3 degree, it shows improvement compared to the non-inclined collector. From the results, it shows that the 3.0 degrees inclination angle could achieve the optimum velocity in the four (4) different locations of the tower. As the inclination angle increases to 5.0 & 7.0 degrees, the velocity tends to reduce compared to the velocity profile of 3.0 degrees inclination angle. Hence this shows that the optimum angle of inclination for the collector is 3.0 degrees. The highest increase of velocity of 8.52% is observed at the outlet of the tower and if the turbine is to be installed at the height of 3.0 meters from the ground level, it will have approximately of 6.88% increment compared to the non-inclined collector.

The following table indicates the conversion of power based on the velocity profile after consideration of the area of the turbine and the efficiency of the generator which are indicated in Figure 10: Estimated Power Generation for each Slope Inclination Angle of the Collector.



	3m	6m	9m	12m
0 Degree	0.70	0.79	0.82	0.81
1.5 Degree	0.71	0.84	0.85	0.87
3 Degree	0.85	0.98	1.01	1.03
5 Degree	0.82	0.95	0.96	0.97
7 Degree	0.80	0.94	0.95	0.98

Figure 10: Estimated Power Generation for each Slope Inclination Angles of the Collector

In terms of power generation, the conventional system with a non-inclination angle for the collector and non-inclination angle for the tower can generate approximately 0.70 W based on the geometry setup. The result shows that the peak value at the point of 3.0 meters from the ground with the inclination angle of 3.0 degrees of the solar collector where the estimated power generation is approximately 0.85 W which is approximately 22.11% of increment from the non-inclination angle collector. Hence the 3.0 degrees inclination of the slope collector has the highest performance increment compared to the rest of the modelled angle of inclination where the tower with angle inclination is being modelled.

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6.2 Effect of Varying the Angle of Tower (Type A) for fixed 3 Degree Sloped Collector

The 3.0 degrees collector slope has been determined and now the tower will be sloped for optimization of the output of the solar updraft tower. The tower configuration for of type A fixes the outlet diameter of 0.25 meter and varying the base of the tower. Simulation has been conducted for 1.0 degree, 3.0 degrees, 5.0 degrees and 7.0 degrees slope. The results of the velocity magnitude at the centre of the tower are shown in the Figure 11: Comparison of the velocity profile at the centre of the chimney for the various inclination angles of the Chimney (Type A).

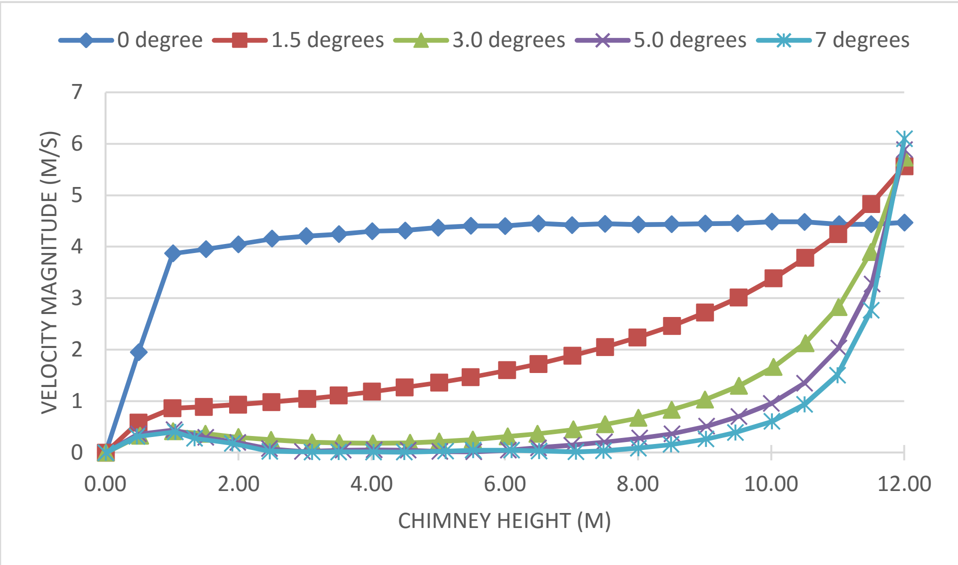

Figure 11: Comparison of the velocity profile at the centre of the chimney for the various inclination angles of the Chimney (Type A)

It is observed that by introducing a slope for the tower type A, the velocity at the entrance tends to drop. As the conical area increases the velocity will drop until a very low flow velocity. Then the velocity rises above the non-inclined tower at 1m before the exit of the tower hence exceeds the non-inclined tower max velocity. A jetting effect is observed at the exit of the tower. The figures below indicate the velocity profile at difference heights of the tower for determining the suitable location of the turbine.

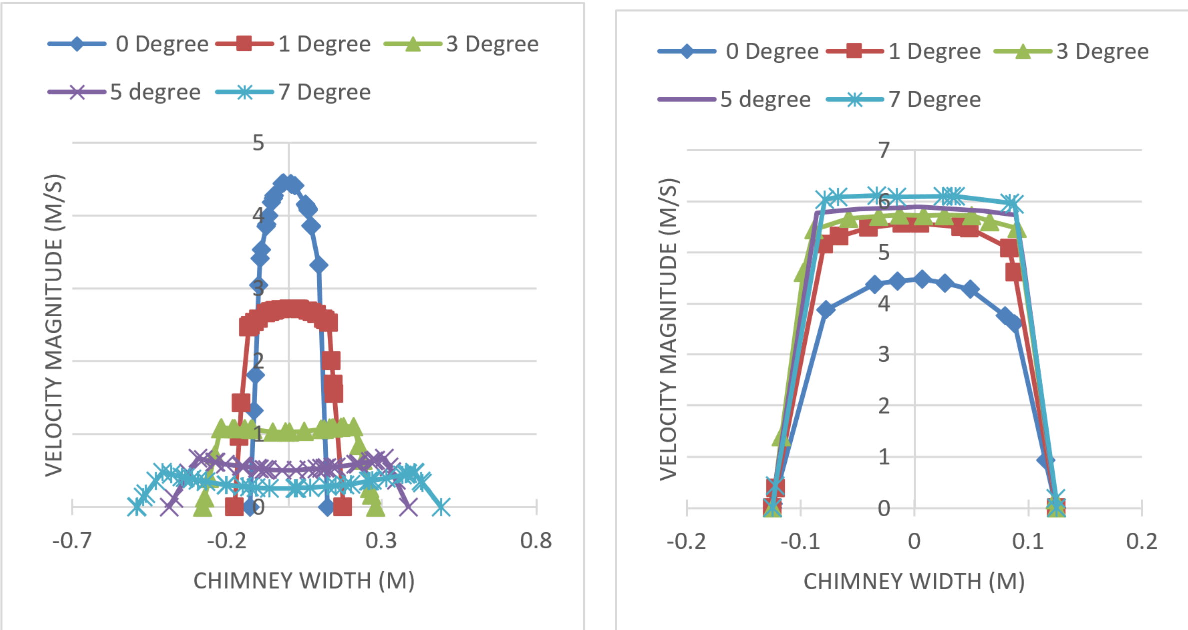

Figure 12: Inclined Chimney (Type A) Velocity Profile at 3.0 m (Left) and Chimney Velocity Profile at 6.0 m (Right)

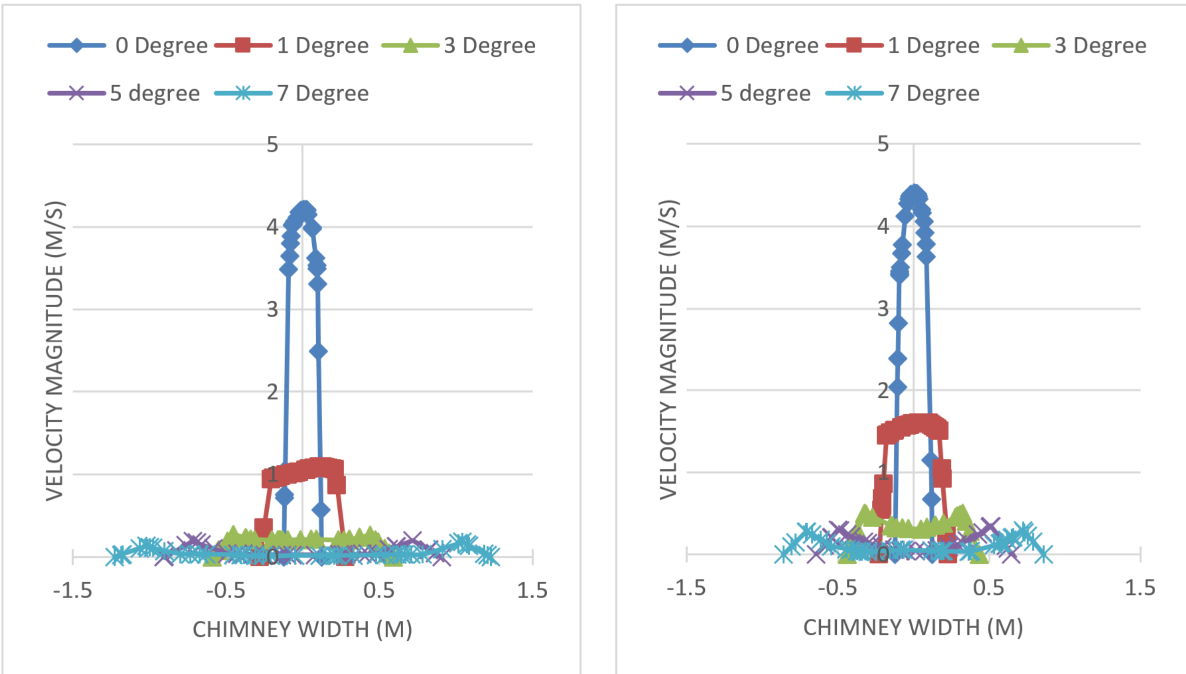

Figure 13: Inclined Chimney (Type A) Velocity Profile at 9.0 m (Left) and Chimney Velocity Profile at 12.0 m (Right)

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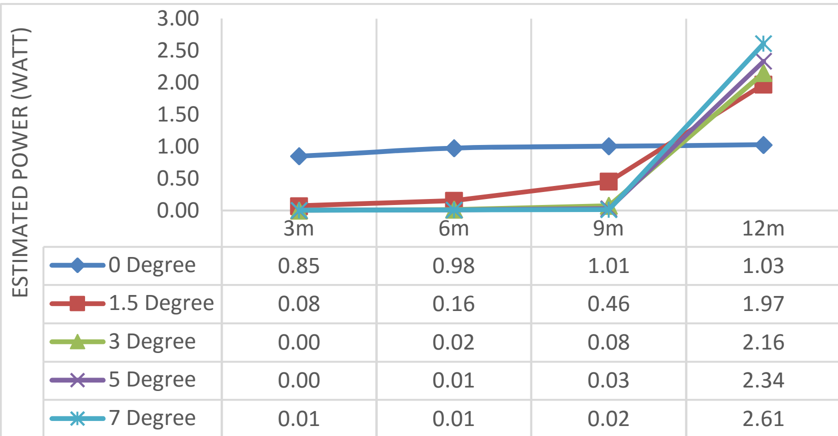
With references to the Figure 12 & Figure 13, the only advantages of getting higher velocity is to install the turbine at the exit of the Updraft Tower where the 7.0 degrees inclined angle of the tower (Type A) can achieve an outlet velocity up to 6.11 m/s which is an increase of approximately 36.35%. The 1.0 degree inclination angle shows the lowest improvement of merely 24.19% at the outlet of the updraft tower compared to the rest of the inclination angle. All inclination angles show positive improvement at the outlet of the updraft tower. Unfortunately if the turbine is installed at the remaining 3 locations, there is a tremendous drop in the velocity. The following table indicates the conversion of power based on the velocity profile after consideration of the area of the turbine and the efficiency of the generator. This is indicated in Figure 14: Estimated Power Generation for each inclination angle of the tower (Type A) with 3.0 degrees slope collector.



	3m	6m	9m	12m
0 Degree	0.85	0.98	1.01	1.03
1.5 Degree	0.08	0.16	0.46	1.97
3 Degree	0.00	0.02	0.08	2.16
5 Degree	0.00	0.01	0.03	2.34
7 Degree	0.01	0.01	0.02	2.61

Figure 14: Estimated Power Generation for each inclination angles of the tower (Type A) with 3.0 degrees slope collector

6.3 Effect of Varying the Angle of Tower (Type B) for fixed 3 Degree Sloped Collector

The 3.0 degree collector slope has been determine as per type A configuration and now the tower will be sloped for optimization of the output of the solar updraft tower. The Tower configuration for type B fixes the tower inlet diameter at 0.25 meter and varies the exit of the updraft tower. Simulation has been conducted for 0.15 degree, 0.3 degree, and 0.5 degree. The results of the velocity magnitude at the centre of the tower is shown in the following figure:-

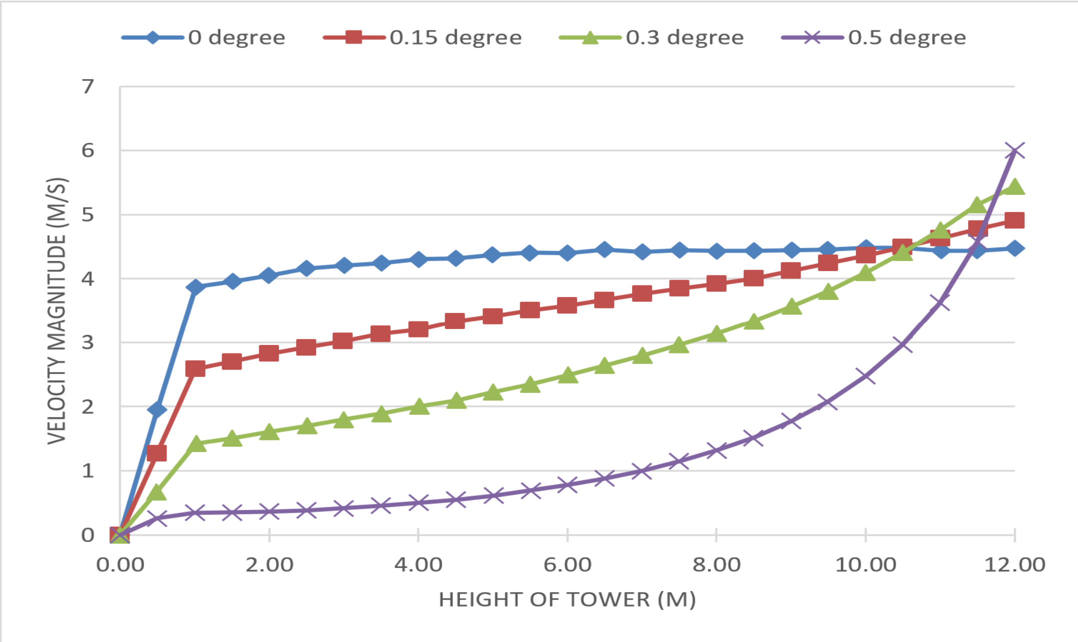


Figure 15: Comparison of the velocity profile at the centre of the tower for the various inclination angles of the Tower (Type B)

It is observed that by introducing a slope for the tower type B, the velocity at the entrance tends to drop only slightly compared to Type A. As the tower taper towards the exit, the velocity will starts to improve. Then the velocity rises above the non-inclined tower at approximately 1.5 meters before the exit of the tower hence exceeds the non-inclined tower max velocity. A jetting effect is observed at the exit of the tower. The figures below indicate the velocity profile at difference heights of the tower for determining the suitable location of the turbine.

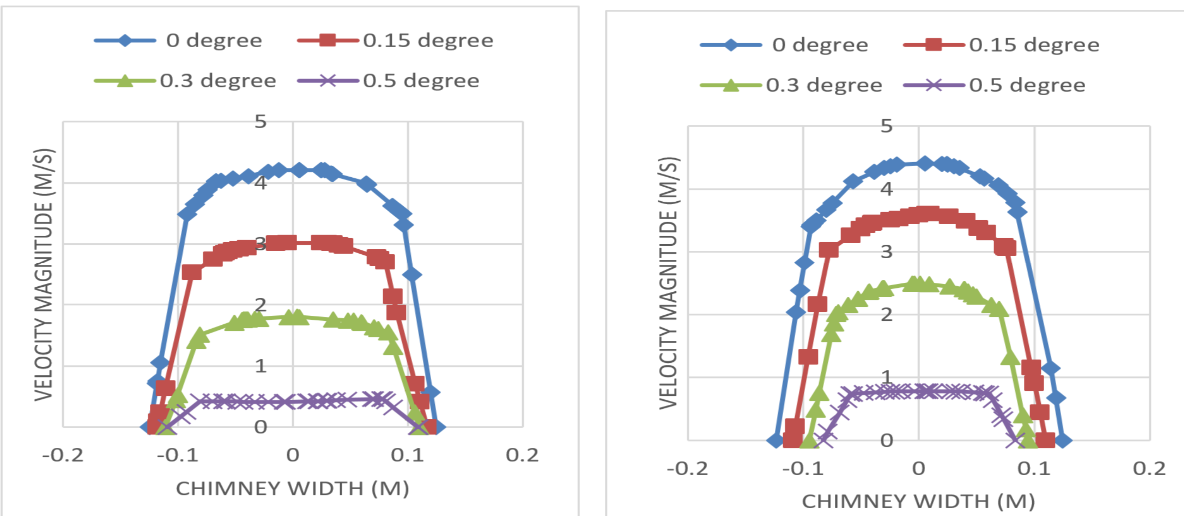


Figure 16: Inclined Chimney (Type B) Velocity Profile at 3.0 m (Left) and Chimney Velocity Profile at 6.0 m (Right)

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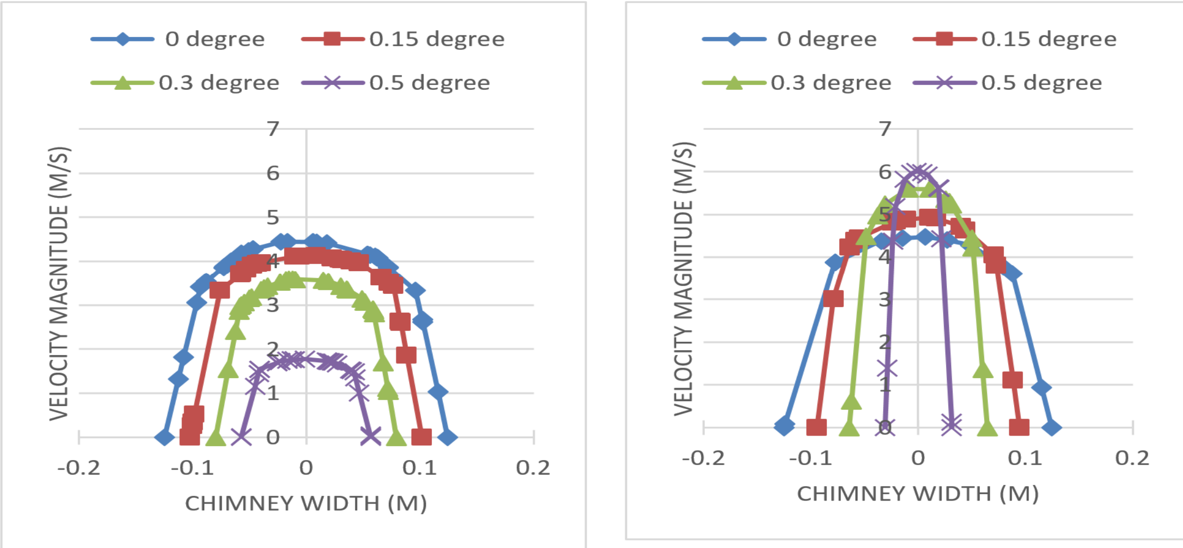
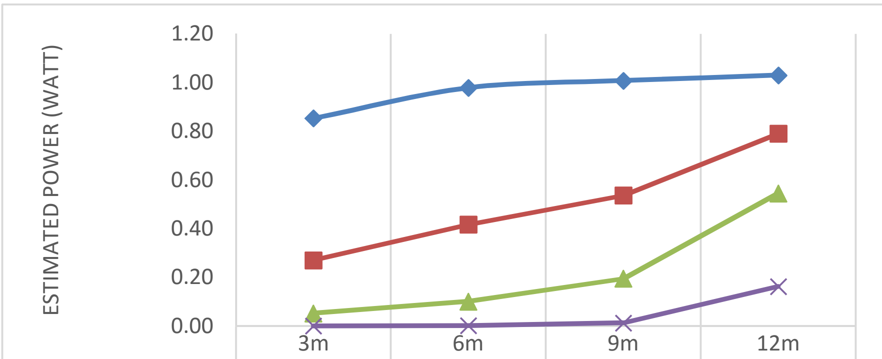


Figure 17: Inclined Chimney (Type B) Velocity Profile at 9.0 m (Left) and Chimney Velocity Profile at 12.0 m (Right)

The following figure indicates the conversion of power based on the velocity profile after consideration of the area of the turbine and the efficiency of the generator. The maximum power generation is only achievable at the outlet of the chimney.



	3m	6m	9m	12m
0 degree	0.85	0.98	1.01	1.03
0.15 degree	0.27	0.42	0.54	0.79
0.3 degree	0.05	0.10	0.20	0.55
0.5 degree	0.00	0.00	0.01	0.16

Figure 18: Estimated power generation for each inclination angle of the chimney (Type B) with 3.0 degrees slope collector

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6.4 Effect of Varying the Solar Radiation

In this paper, the solar radiation is assumed peak at noon time where average solar radiation of 800 W/m^2 can be achieve during this time period on a fair weather day. But during the day, the solar radiation will fluctuate and this will affect the performance of the solar updraft tower. The following figure indicates the Hourly Solar Radiation in Malaysia.

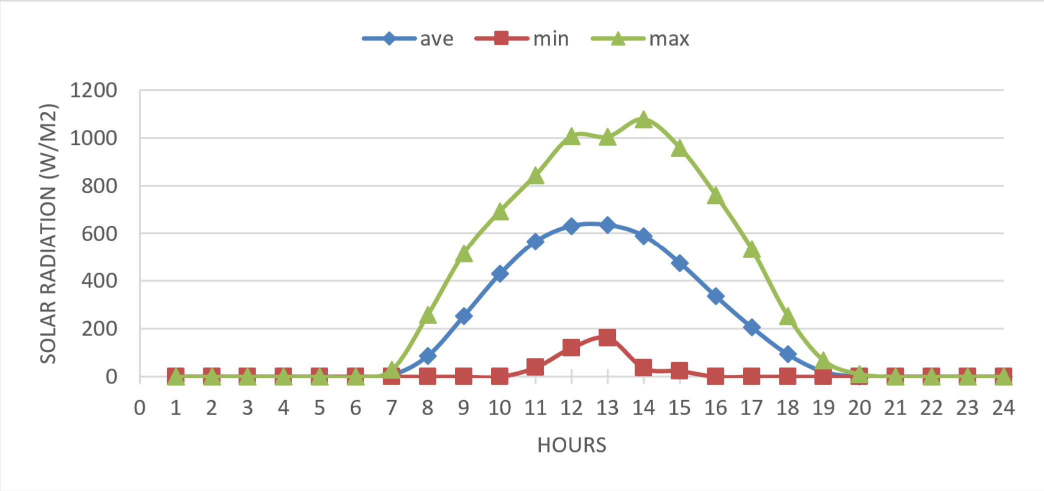

Figure 19: Hourly Solar Radiation Estimated in Malaysia

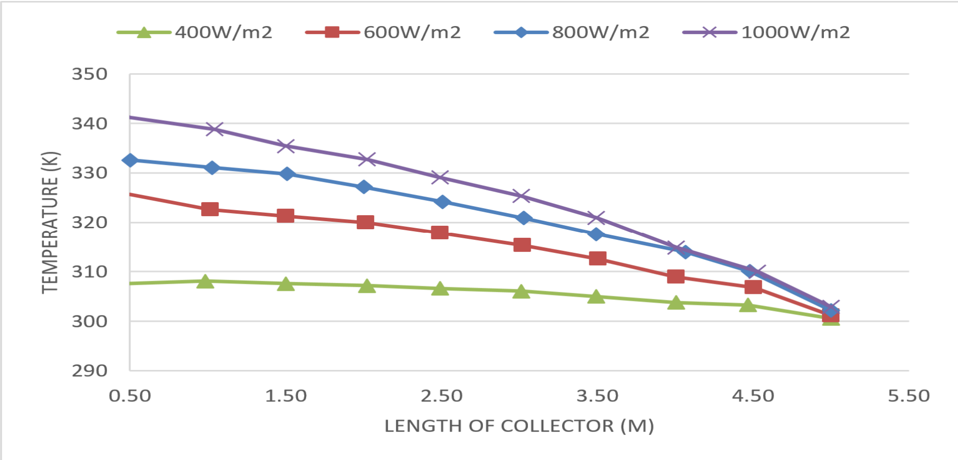

Figure 20: Comparison of Collector Temperature 3.0 degrees slope angle during different solar radiation

From the above figure, the solar radiation will start to increase from 8 am in the morning, and peak out during noon time and will start to decrease in the evening. When the solar updraft tower is exposed to different solar radiation, the temperature of the collector will be affected as well. The following figure shows the velocity profile of the centre of the tower in various solar radiation conditions.

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From figure 21, we notice that under different solar radiations and the effects to the temperature at the inlet and outlet temperature of the collector, the solar updraft tower could not have much temperature increase when exposed to 400 W/m^2 which is approximately 7.58◦C. As the solar radiance increases, the temperature difference increases and the highest differential temperature between inlet and outlet is achieved when solar radiation is 1000 W/m^2.

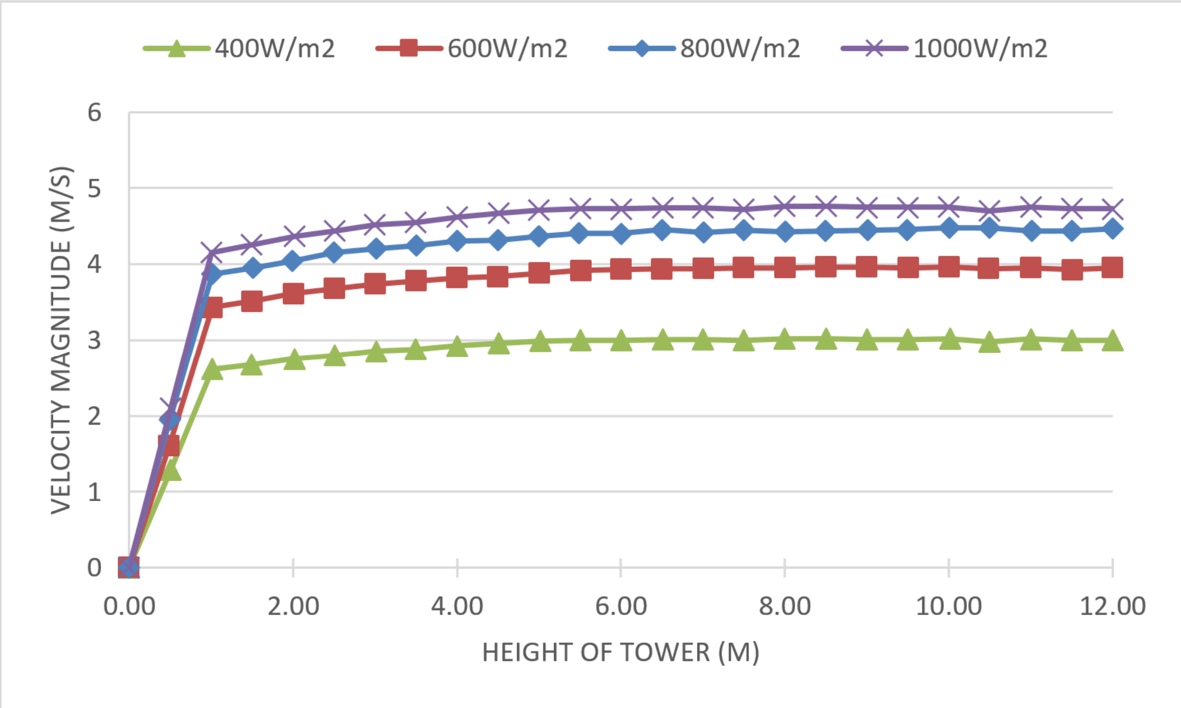

Figure 21: Velocity Profile at the centre of updraft tower subjected to various solar radiation

Based on the graph and consideration that the turbine is installed at 3.0 meters above the ground level, the highest velocity achieved during 1000 W/m^2 where it is approximately 4.52 m/s and lowest velocity during 400 W/m^2 where the velocity drops to 2.85 m/s. The overall percentage of decrease in velocity is approximately -36.84%. In terms of power drop, it will be approximately -74.80%. The following figure shows the temperature of the collector during different solar radiations.

Based on the hourly radiation graph, the solar updraft tower may only operate at 400 W/m^2 to 600 W/m^2 between 10:00 to 11:00 and 14:00 to 16:00 and peak average solar radiation of 600 W/m^2 to 800 W/m^2 between 11:00 to 14:00. For duration out of this period, the overall power generation will be much lower inclusive of the heat release from soil as thermal storage. The following figure shows the actual power generation at four different turbine locations when exposed to different solar radiation.

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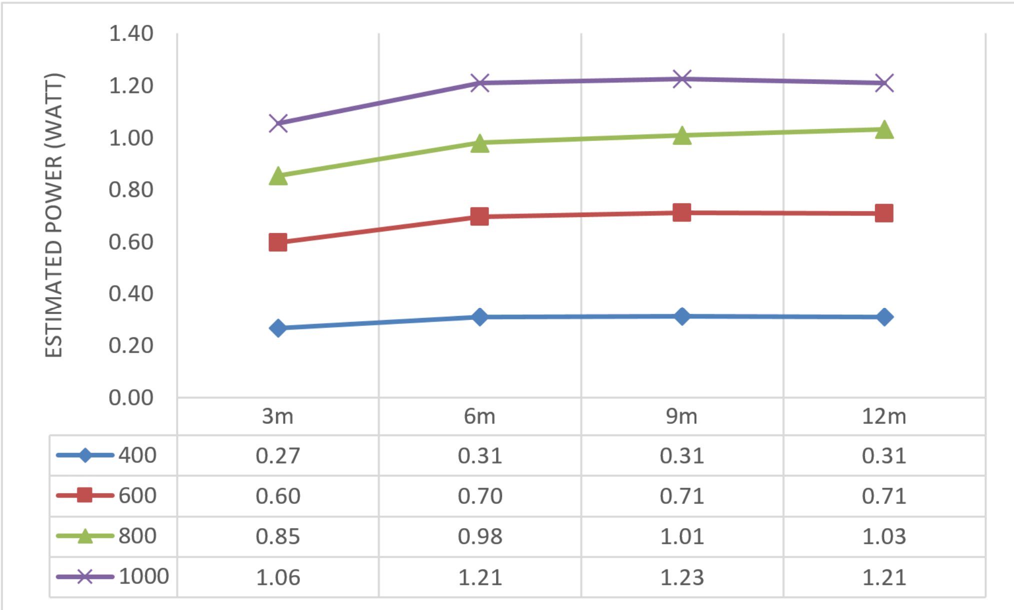

Figure 22: Estimated Power Generation based on different Solar Radiation

From the above figure, we notice that the actual power generation will be changed at different locations of the turbine and subject to the solar radiation at the certain time period. It will have fluctuation during the hourly changing solar radiation.

7.0 CONCLUSION

In this paper, 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 as to be turbulent where it was simulated with the *k*-epsilon turbulent model using ANSYS Fluent software. The geometry used for the base and validation was from the prototype constructed by the University of Zanjan, Iran.

Numerical simulation was conducted using the ANSYS FLUENT software, which solved the momentum equation using the Boussinesq approximation. The standard *k*–epsilon turbulence model was used together incorporating the solar ray tracing model for a more accurate result.

A 3D solar updraft tower was designed based on the geometry of the prototype installed by the University of Zanjan, Iran where the numerical model and experimental results were in good agreement with this paper. The inlet and outlet ambient temperature was assumed at 300 K. All walls were considered as adiabatic except for the solar collector and the soil cover beneath the solar collector. The solar collector modelling parameters were defined as non-slip, convective heat transfer and radiation. And as for the soil layer, it was assumed as a thermal storage with a heat absorption coefficient of 0.8. The numerical model was also validated using previous numerical results obtained from the Zanjan prototype. Then the numerical model was used to model the actual operation of the solar updraft tower operating in Malaysia which also shows that it is feasible for this system to be implemented in Malaysia.

The parametric study was conducted for the angle of inclination of the slope collector, the taper updraft tower configuration with either a fixed entrance or a fixed exit and different solar

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radiation for the optimized geometry. The objective of varying these parameters is to determine the four (4) different points at the centre of the updraft tower at intervals of 3.0 meters, 6.0 meters, 9.0 meters and 12.0 meters from the ground level to determine the most suitable position for installation of the power generation turbine. It was important to have a high velocity at the upstream of the turbine. The power generation turbine utilized the updraft velocity, which means the greater the velocity, the faster the turbine can turn to generate more power.

With the introduction to the slope collector, we can maximize the full advantage of the provided land for the solar collector. In Malaysia, we have frequent rain fall and by introducing the slope angle, it will create a self-cleaning effect when the rain water runs down from the collector where majority of solar PV system in Malaysia has the problem of maintenance and cleaning of the surface where it lowers down the efficiency of the power generation.

As for the taper tower configuration for Type A and B, the results showed a jetting effect at the exit of the tower where it could have a relatively high exit velocity. For tower type A configuration, the velocity increased approximately 36.35% and for type B configuration, the velocity increased approximately 34.27%. Both of the outlet velocity were at the exit of the tower.

Another critical factor that will affect the overall output of the solar updraft tower power output is the environmental factor. It is the most important environmental parameters which consist of different weather conditions and various latitudes. For this paper, the geometry of the model was analysed based on the longitude and latitude of Malaysia, It was assumed that the solar radiation peak was 800 W/m^2 which was sufficient to raise the temperature of air in between the solar collector and soil surface with an ambient temperature.

Therefore, after taking into consideration all the points mentioned, we concluded that providing the slope collector will be sufficient when paired with a conventional straight rising updraft tower without any requirement of inclination for ease the construction method and also construction cost. Therefore by sloping the collector at 3.0 degrees and installing the wind turbine at 3.0 meters to 6.0 meters above the ground, we can improve the velocity profile from 6.88% to 7.38%. In terms of power generation, it will be approximately 22.11% to 23.81% which is consider as convincing as in terms of the construction cost, the steel columns have to be raised up accordingly to the slope requirement and the increase in area of collector is not so significant. Through the analysis, it is found that the geometrical parameters proposed have increased the overall performance of the overall system and the system performance efficiency will be controlled by the solar radiation on the solar updraft tower where this will be the determination factor of the overall power output of the system especially during rainy and wet seasons at the end of the year.

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