VANOS
JOURNAL OF MECHANICAL ENGINEERING EDUCATION
http://jurnal.untirta.ac.id/index.php/vanos
ISSN 2528-2611, e-ISSN 2528-2700
Volume 7 Number 1, May 2022, Pages 1-11

The Development of an Application to Design a Solar Updraft Tower Power Plant and to Estimate its Power Generation

Moch. Faqih[1], Nu Rhahida Arini[2]

[1]Departement of Chemical Engineering, Universiti Teknologi PETRONAS, Malaysia
32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia
[2]Departement of Mechanical Engineering and Energy, Politeknik Elektronika Negeri Surabaya, Indonesia
Raya ITS Sukolilo Street, Surabaya, 60111, Indonesia

Corresponding author: mochammad_22000035@utp.edu.my

Received: 25 January 2022. Accepted: 10 March 2022. Published: 01 May 2022

ABSTRACT

A solar thermal converter is an alternative device to optimize the generation of electricity. One implementation of it is Solar Updraft Tower (SUT) which has some advantages such as easy installation, zero-emission, and long-life investment. This paper aims to describe a method to design the process of a SUT power plant which can be used to predict the expected mechanical power output. The application is built using an open-source computation software, GNU Octave, to produce an interactive user interface. In this paper, data is collected experimentally from SUT prototype in laboratory scale. The operational data is processed using the proposed application to analyze the effect of the variation of inlet diameter on mechanical power output. From the result, the power output increases along with the increasing inlet diameter. The highest power output is produced by a SUT diameter of 0.165 m. This study contributes to increasing the development of renewable energy technology of solar thermal power plants.

Keywords: Renewable energy, Solar Updraft Tower, GNU Octave

INTRODUCTION

The growth of renewable energy utilization becomes increase over the world. Implementation of clean energy is being a prospective alternative to minimize the use of conventional power plants which has several negative impacts on the environment. Solar energy is one of the renewable energy resources which has a large potency, especially in tropical countries. Currently, the most common solar energy converter used is photovoltaic. This kind of solar converter is widely used due to its easiness in installation and long lifetime. However, the technology of solar converter should be improved to meet sustainable energy and fulfill the electricity consumption. Another potential solar power plant is Solar Updraft Tower (SUT).

SUT harnesses the concept of convection due to heat transfer process gained from solar radiation to create a differential of air density and produce airflow. SUT has several primary components such as a solar collector, a tower or chimney, and a wind turbine coupled with an electricity generator as shown in Figure 1. The airflow is produced when solar radiation reaches the collector. In this condition, the heat is transferred to the air inside the collector and thermal expansion influences the decrease of air density. Subsequently, the hot air flows from the bottom to the top of the tower and drives the wind turbine to produce electricity. The concept of SUT had been proven and validated by Haaf et al [1][2], with a test result of a SUT prototype in Manzanares, Spain.

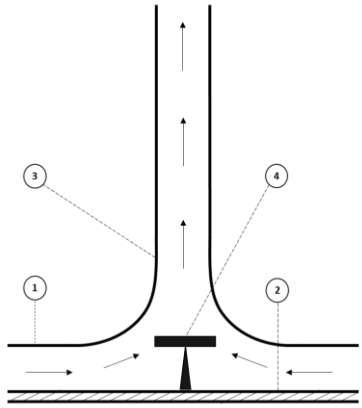

Figure 1. SUT Scheme: 1. Solar collector, 2. Ground, 3. Tower, 4. Wind Turbine

SUT had commonly been discussed by previous researchers. Jörg et al conducted a study of commercial SUT design based on theory, practical experience, and economic consideration [3]. The study found that the height of the tower increases the thermodynamic efficiency. Ayub et al proposed that a large range of the ratio of the collector and tower diameter is more effective to obtain a better performance [4]. The study also recommends the use of glass as the material of solar collector to trap the heat effectively. The previous studies implied that the geometry and material of SUT components influenced the power output. Other studies tried to improve the SUT technology through several novel concepts. Bilgen and Rheault proposed a Sloped Solar Updraft Power Plant (SSUPP) which has a thermal performance slightly higher than the conventional SUT with the optimum slope of collector range from 5° to 7° smaller than the altitude [5]. However, only conventional SUT will be discussed in this paper.

This study aims to propose an application to design a solar updraft tower which provides several features that can be used for both expert and beginner of solar thermal technology researchers. The algorithm was built using an open-source software, GNU Octave version 6.1.0, to produce a user interface which is easy to use. Subsequently, the application is used to analyze the performance of SUT prototype. The operational data was collected from previous study [6] and processed using the proposed application to identify the mechanical power and several output parameters with respect to the variation of inlet tower diameter.

RESEARCH METHOD

This study follows a research flowchart as shown in Figure 2. Starting with literature study and problem identification, this research discovered the necessary of power generated from SUT calculation to be more feasible and easier. The algorithm is then developed using mathematical equations as described in this section. Subsequently, an interactive interface is developed and linked to the algorithm. Operational data is applied to the application in order to estimate the mechanical power. After the calculation is done, the next steps is data analysis to discuss the result. Lastly, conclusion is gained to point out the findings.

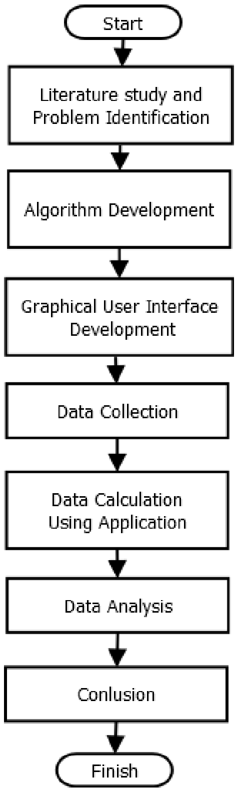

Figure 2. Research flowchart of SUT

The power output produced by SUT depends on solar energy ($\dot{Q}_{solar}$) and system efficiency (η_{system}). The value of solar energy varies over time due to the intensity of solar radiation. The system efficiency is calculated by multiplying the efficiency of the collector, tower, and turbine. However, in this paper, the system is accustomed to neglect the turbine. The formula of power output expressed by Equation (1).

$$P_{out} = \dot{Q}_{solar} \cdot \eta_{system} \quad (1)$$

The value of $\dot{Q}_{solar}$ determined by solar radiation (G) and area of collector (A_{coll}) as expressed by Equation (2).

$$\dot{Q}_{solar} = G \cdot A_{coll} \quad (2)$$

In heat transfer process, the energy balance principle is applied. Therefore, the

 ISSN 2528-2611, e-ISSN 2528-2700

quantity of heat transferred to the collector is equal to the heat of the air. The condition can be written by Equation (3).

$$\dot{Q}_{solar} \cdot \eta_{coll} = \dot{Q}_{air} \quad (3)$$

Where η_{coll} is the efficiency of the collector and $\dot{Q}_{air}$ is the heat of air. The hot air flows with a mass flow ($\dot{m}$) towards the exit of the tower by buoyancy principle. The difference in air density occurred due to thermal expansion at the entrance of the tower temperature (T_3) and tower temperature (T_1). The $\dot{Q}_{air}$ formula is expressed by Equation (4).

$$Q_{air} = \dot{m} \cdot C_p \cdot (T_3 - T_1) \quad (4)$$

Cp is the specific heat capacity of air obtained from properties table of air at 1 atm. The mass flow, $\dot{m}$, can be calculated using Equation (5).

$$\dot{m} = \rho_{in} \cdot A_t \cdot V_{max} \quad (5)$$

ρ_{in} is the density of inlet air obtained from properties table of air at 1 atm. A_t is the cross section area of the tower. V_{max} is the velocity of airflow through the tower without turbine. The solar energy is converted into kinetic and potential energy. The potential energy is represented by pressure drop (ΔP). In a tower without turbine system, the pressure drop can be written by Equation (6).

$$\Delta P = g \cdot H_t \cdot (\rho_{out} - \rho_{in}) \quad (6)$$

g, H_t, and ρ_{out} are the gravity acceleration, height of tower, and density of air at outlet tower. Based on the simplification of the system, the mechanical power output of SUT can be calculated using Equation (7).

$$P_{out} = \Delta P \cdot V_{max} \cdot A_{coll} \quad (7)$$

Equations 1-7 described the fundamental concept of SUT design used in this application. Therefore, the input and output design parameters are referred to as the equations. All parameter is summarized by Table 1.

Table 1. Input and output design parameters

Input	Output
Fill by user	Plot of mechanical power output and solar radiation over time
Geometry of collector : length (L) and width (B)	
Geomerty of tower : height (H_t), inlet diameter (d_{ti}) and outlet diameter (d_{to})	Plot of pressure drop and velocity of air over solar radiation
Temperature (T_1, T_3 and T_∞)	
Solar radiation (G)	Calculation result of mass flow rate
Velocity (V_{max})	
Data base	Calculation result of heat
Air density (ρ)	Calculation result of collector efficiency
Specific heat capacity (C_p)	
Gravity acceleration	Brief explanation of SUT
Theory of SUT	

In this paper, experimental data is collected from a previous study [6]. The experiment was conducted in Surabaya, Indonesia. Therefore, the condition related to solar radiation depends on the weather at the location.

The prototype was scaled to fit with laboratory dimensions. The tower was made of Polyvinyl chloride (PVC) which has smooth wall surfaces that prevent fluid resistance. PVC is also lightweight and flexible. The height of the tower is 2 m with vary inlet diameter of 0.048 m, 0.114 m, and 0.165 m. The frame of the collector was made of Aluminium which has several advantages such as lightweight, strong, and easy to form in any shape. The collector frame was a square-based pyramid with a height of 0.3 m and a base area of 1 m^2. The material of the solar collector is a mica plastic sheet. Mica plastic was used to forward the solar radiation due to its high specific heat.

Figure 3. 3D design of the prototype

In order to make the heat trapped perfectly, the ground of the prototype was covered by a zinc plate. The plate has an area of 1 m^2 and was coated using black paint to reach a better heat absorption. The thermal diffusivity was assumed to be 1. The prototype also using an isolation system to prevent heat losses and unwanted wind that interfere with the SUT system. The prototype computer design is shown in Figure 3.

The prototype used automatic data acquisition to collect data continuously. Operational data such as temperature and velocity were acquired over the preferred time. The data retrieval time determined due to optimal radiation in a day start from 9 AM to 3.30 PM of Western Indonesia Time. The solar radiation (G) data were obtained from the Meteorological, Climatological, and Geophysical Agency (BMKG) due to the unavailable solar radiation sensor of the prototype. To make an ease for inputting the data, the application has an interactive user interface as shown in Figure 4.

There are several features provided in this application such as introduction, start design, and about the author. The introduction contains a brief explanation of the basic theory of SUT, the history of SUT and its concepts, and several studies related to SUT. This feature aims to give the user an overview of SUT and its evolution. Therefore, this application is suitable for all types of user, i.e, those whom not familiar with solar thermal energy conversion. The user is also able to learn more deeply about SUT by review several related studies only by clicking the button. Users can start to design by getting on the start design button. The user should input several data to obtain the output design. The interface is shown in Figure 5.

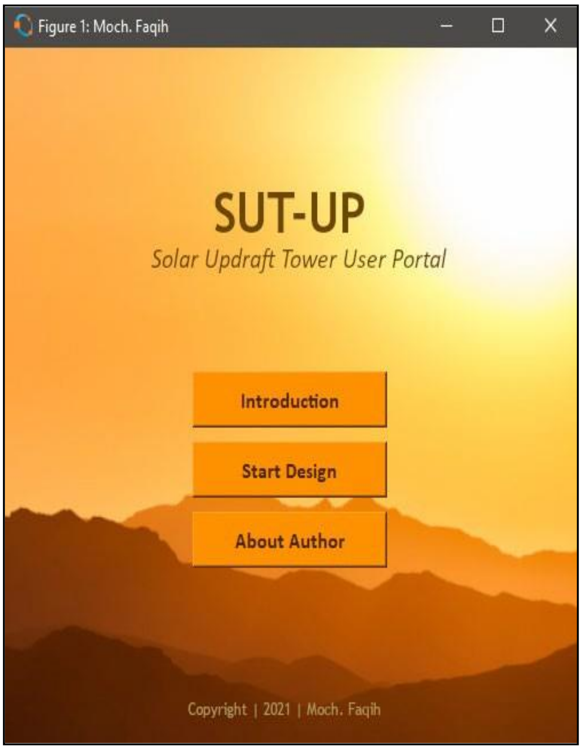

Figure 4. Application homepage

Two kinds of input data should be loaded including geometry parameters and operational data. Geometry parameters contain the length (L) and width (B) of the solar collector base, height of the tower (H_t), inlet (d_i), and outlet diameter (d_e) of the tower. The geometry data can be inserted directly into the column on the left side of the interface. The shape of the collector may be different depends on the design, i.e, F Ayub et al [4] used a cone-shaped collector which has a circle-shaped collector base. However, the prototype used in this study has a square-based pyramid collector. For operational data, the user can insert the data using a static data loader by clicking the browse button. This button will redirect to the user's directory and read-only *.csv file. The data file should contain solar radiation (G), the entrance of collector temperature (T_1), the entrance of tower temperature (T_3), ambient temperature (T_∞), and velocity of air inside the tower (V_{max}) sequentially. Subsequently, the data will be shown in the table as shown in Figure 6. This application also provides an automatic database to obtain density (ρ) and specific heat capacity (C_p) of air referred to as the air temperature. The table is collected from Appendix A-15 properties of air at 1 atm pressure [7].

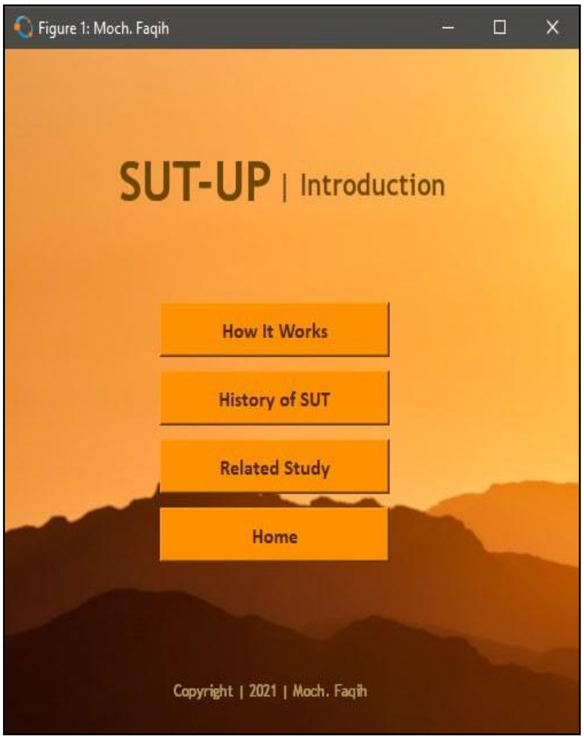

Figure 5. Features in introduction page

After inserting all data, the user can start the calculation by clicking the run button. It will process the calculation and plot the result. There are two plots, e.g, power output and solar radiation versus time, and pressure drop and velocity versus solar radiation. The first plot shows the mechanical power output generated by SUT.

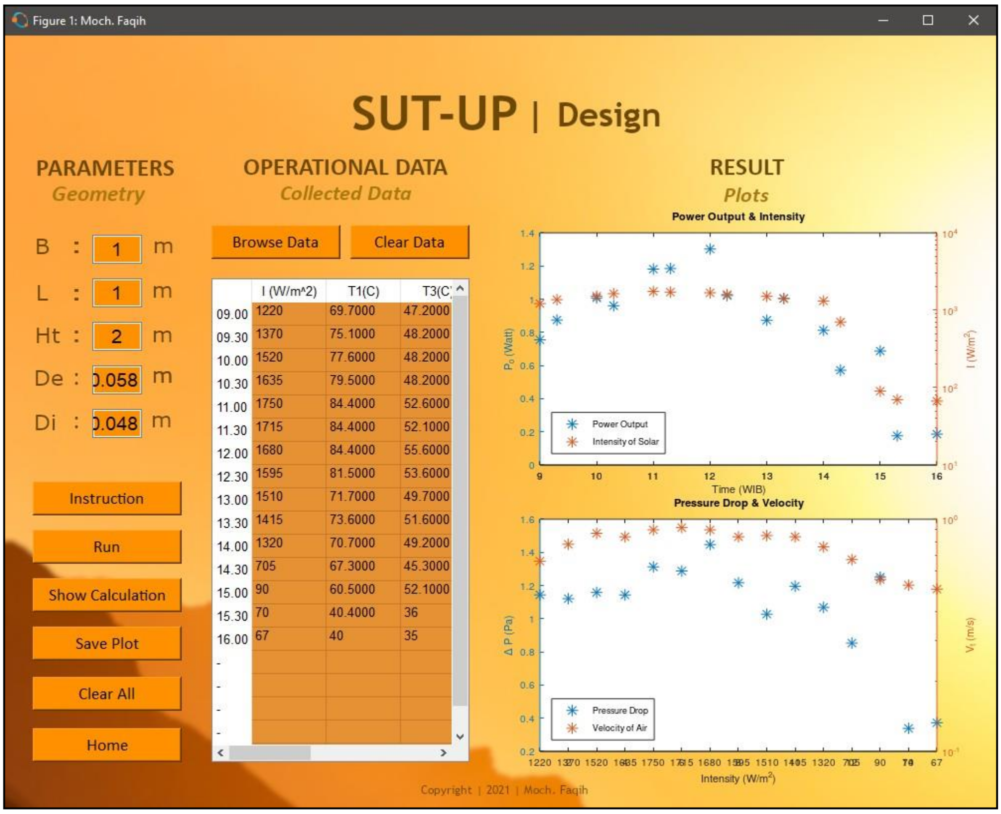

Figure 6. Features in start design page

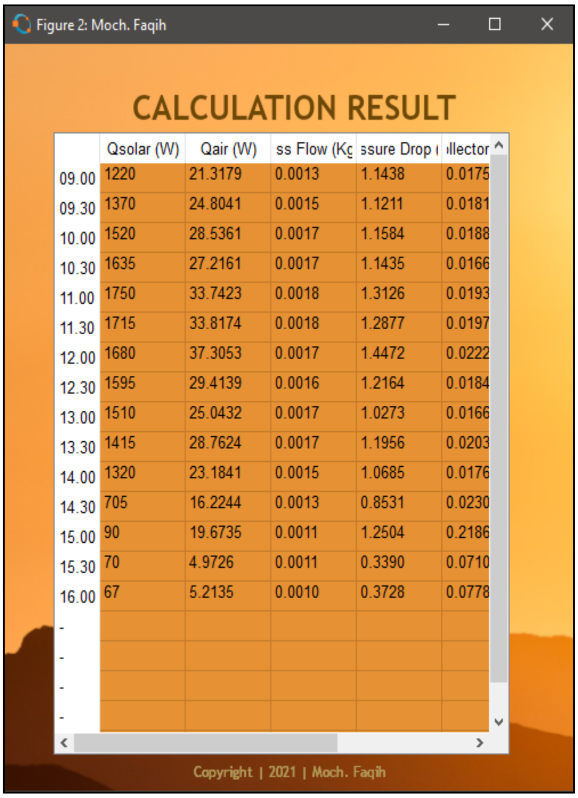

Figure 7. Calculation result display

The power output will be compared to the solar radiation at a certain time to represent the effect of radiation intensity on the power that can be generated. On the other hand, the second plot shows the effect of solar radiation to the pressure drop and velocity of air. Users can easily save the plots and export them into a *.png file by clicking the save button. For the detail of the calculation result, the user should click the show calculation button. The result will be displayed in a table as shown in Figure 7. After finishing the calculation, the application can reset the calculation automatically through a clear all button. In order to guide the user in using the design features, simple guidance was provided at the instruction button.

RESULT AND DISCUSSION

The effect of inlet diameter difference will be discussed in this section. Figure 8 shows the mechanical power output generated by SUT. The power output has a parabolic trend that changes over time. It reaches the highest peak value mostly at 12.00 WIB and the lowest at 15.30 WIB.

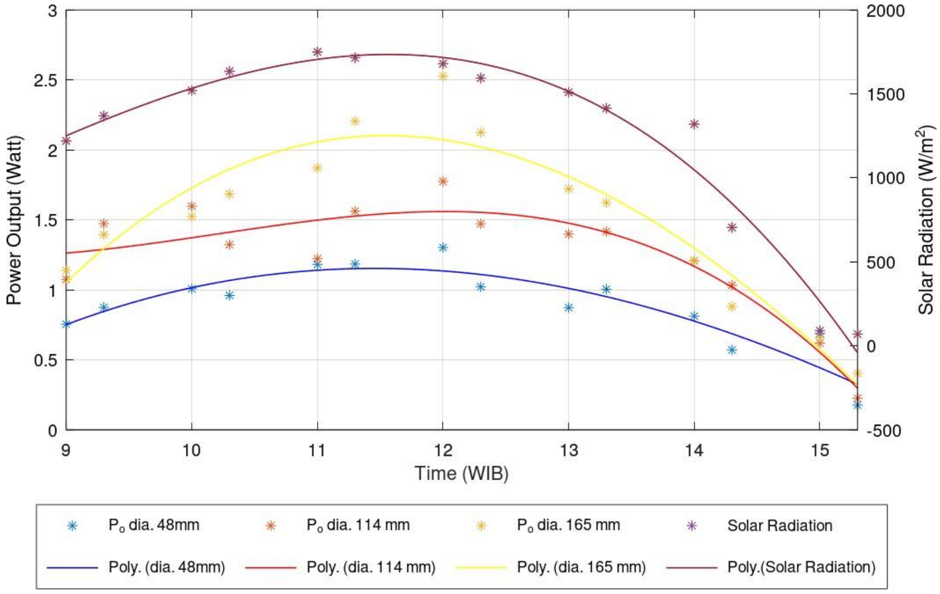

Figure 8. Power output and solar radiation VS time

Comparing with the power output, solar radiation also has the same trend which the intensity depends on the time. The intensity of solar radiation also strongly depends on the altitude and latitude of the location where the experiment was conducted. From the graph, the power output increases along the increasing inlet diameter. Based on Equation 7, the power output is influenced by the value of pressure difference across the chimney and the velocity of the airflow. Figure 8 represented the relation of pressure drop and velocity of air toward the intensity of solar radiation. The pressure drop and the velocity have a parabolic trend with the highest value gained at solar radiation of 1,680 W/m2 and the lowest at 70 W/m2. It can be inferred that the amount of solar radiation influenced the pressure drop and the velocity that is produced [8]. The SUT converted the solar energy which is absorbed by the collector into potential and kinetic energy. The increase in temperature generated an air density difference [9]. It works as a driving force to make the air flows from the collector to the top of the tower. In this condition, the higher potential energy is created, the higher kinetic energy will be. Therefore, the velocity of air will be increased along with the increase of the pressure drop [10][11][12].

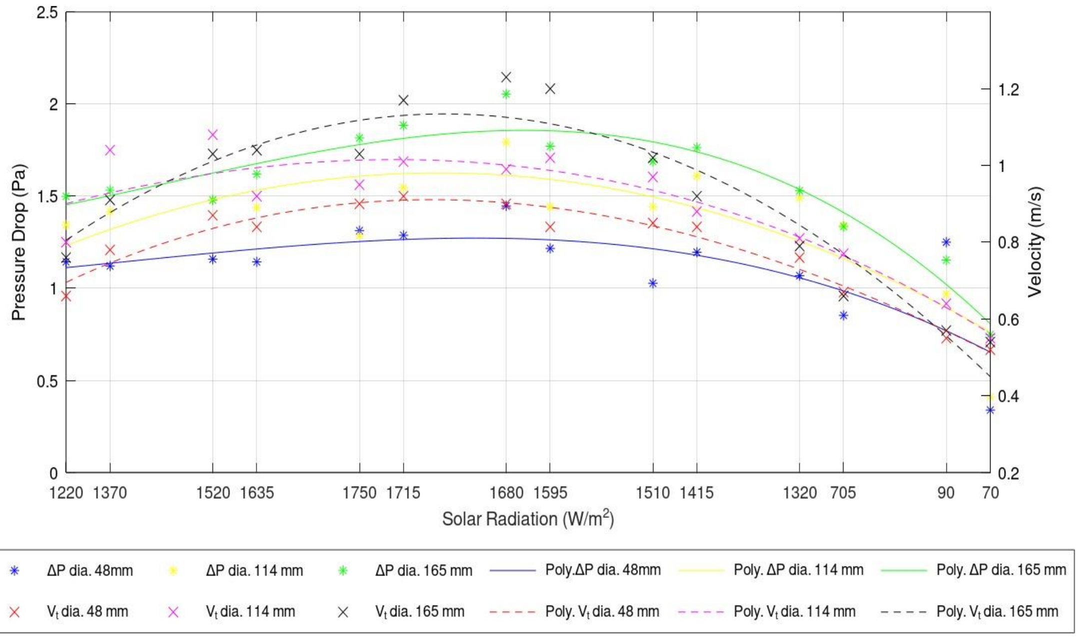

Figure 9. Pressure drop and velocity VS solar radiation

From Figure 9, the increase in inlet tower diameter produces an increase in the pressure drop and the velocity. A big diameter provides a larger area of the tower, thus the air mass flow rate becomes bigger and increases the velocity [13][14]. This condition is represented by Equation 5 and had been discussed in a previous study conducted by Salman [15].

The maximum power output related to the variation of diameter inlet is shown in Figure 10. The inlet diameter has a big role to involve the maximum power output of SUT. The tower with a diameter of 0.165 m has the largest maximum power output, whereas the lowest maximum power output is produced by a diameter of 0.48 m. Therefore, the diameter of the tower is being one of the significant factors in the production of power output on the SUT system.

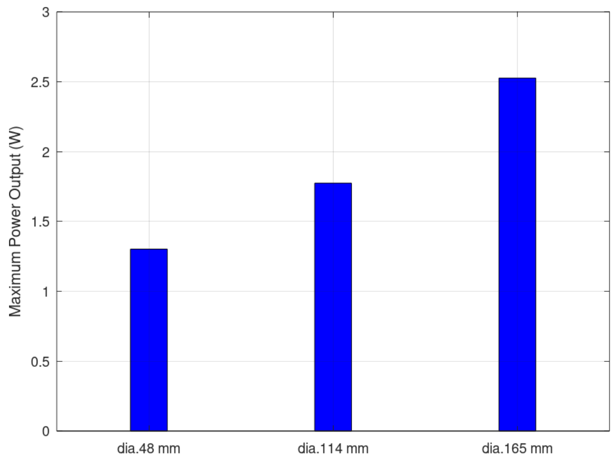

Figure 10. Maximum power output

CONCLUSION

The emphasis of this study is to develop an application to design a solar updraft tower that can be used to estimate the mechanical power output of the system. The application can be implemented in any region regardless of the solar intensity which makes this application is more applicable. From the result, the bigger tower diameter produces a larger capacity of power output. The maximum power output sorted from the higher to the lowest produces by the SUT with tower diameter of 0.165 m, 0.114 m, and 0.048 m. The algorithm was built using GNU Octave software which is compatible with MATLAB programming language. The code is planned to be shared in GitHub, so that can be used and give benefits for all. In this study, the implementation of SUT design is applied to investigate the effect of tower inlet diameter on the power output.

REFERENCES

[1] W. Haaf, K. Friedrich, G. Mayr, and ..., "Solar chimneys part I: principle and construction of the pilot plant in Manzanares," *International Journal of ...*, 1983, doi: 10.1080/01425918308909911.

[2] W. Haaf, "Solar chimneys: part ii: preliminary test results from the Manzanares pilot plant," *International Journal of Sustainable Energy*, 1984, doi: 10.1080/01425918408909921.

[3] J. Schlaich, R. Bergermann, W. Schiel, and ..., "Design of commercial solar updraft tower systems—utilization of solar induced convective flows for power generation," *J. Sol. Energy ...*, 2005, [Online]. Available: https://asmedigitalcollection.asme.org/solarenergyengineering/article-abstract/127/1/117/459203.

[4] F. Ayub, S. Akhand, A. S. Khan, and ..., "Design and Fabrication of Solar Updraft Tower and Estimation of Power Generation; Initially Focused on Bangladesh," *IOP Conference Series ...*, 2018, doi: 10.1088/1755-1315/150/1/012023.

[5] E. Bilgen and J. Rheault, "Solar chimney power plants for high latitudes," *Solar Energy*, 2005, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0038092X05000344.

[6] A.T. Adzani, "Experimental Study of Solar Updraft Tower with Variation of Diameter Inlet to Know The Effect on Mechanical Power Generated," *Electronic Engineering Polytechnic Institute of Surabaya*, 2015.Unpublished.

[7] T. L. Bergman, T. L. Bergman, F. P. Incropera, D. P. Dewitt, and ..., *Fundamentals of heat and mass transfer*. books.google.com, 2011. [Online]. Available: https://books.google.com/books?hl=en&lr=&id=vvyIoXEywMoC&oi=fnd&pg=PR21&dq=fundamentals+of+heat+and+mass+transfer&ots=8KshSZhXza&sig=7AcQs1dgANN137usdbrdAFD1cgs.

[8] D. K. Khidhir and S. A. Atrooshi, "Performance of a Solar Chimney With a Modified Collector Geometry: A Case Study From Erbil to the North of Iraq," *Journal of Solar ...*, 2020, [Online]. Available: https://asmedigitalcollection.asme.org

/solarenergyengineering/article-abstract/142/1/011010/955236.

[9] N. Mehla, K. Kumar, and M. Kumar, “Thermal analysis of solar updraft tower by using different absorbers with convergent chimney,” *Environment, Development and …*, 2019, doi: 10.1007/s10668-018-0087-1.

[10] P. Das and V. P. Chandramohan, “CFD analysis on flow and performance parameters estimation of solar updraft tower (SUT) plant varying its geometrical configurations,” *Energy Sources, Part A: Recovery …*, 2018, doi: 10.1080/15567036.2018.1477881.

[11] R. Balijepalli, V. P. Chandramohan, and ..., “Optimized design and performance parameters for wind turbine blades of a solar updraft tower (SUT) plant using theories of Schmitz and aerodynamics forces,” *… Energy Technologies and …*, 2018, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213138818302492.

[12] H. Nasraoui, Z. Driss, and H. Kchaou, “Effect of the chimney design on the thermal characteristics in solar chimney power plant,” *Journal of Thermal Analysis and …*, 2020, doi: 10.1007/s10973-019-09037-3.

[13] A. Jameei, P. Akbarzadeh, and ..., “Numerical study of the influence of geometric form of chimney on the performance of a solar updraft tower power plant,” *Energy & …*, 2019, doi: 10.1177/0958305X18802908.

[14] D. K. Khidhir and S. A. Atrooshi, “Performance of a Solar Chimney With a Modified Collector Geometry: A Case Study From Erbil to the North of Iraq,” *Journal of Solar …*, 2020, [Online]. Available: https://asmedigitalcollection.asme.org/solarenergyengineering/article-abstract/142/1/011010/955236

[15] S. H. Hammadi, “Solar updraft tower power plant with thermal storage,” *Basrah Journal for Engineering Research*, 2009, [Online]. Available: https://www.iasj.net/iasj/download/1be225300d6a0826.