Jurnal Riset Sains dan Teknologi
Volume 8 No. 2 September 2024, 127-135
e-ISSN: 2549-9750
p-ISSN: 2579-9118

The Effect of the Number of Baffles on the Performance of Solar Updraft Tower: A Numerical Study

Teguh Hady Ariwibowo[1*], Arrad Ghani Safitra[2], Paradya Nabilah Ismah[3], Muhammad Muslih Hidayatullah[4], Firyal Nisa Amelia[5]
[1,2,4,5]Department of Power Plant Engineering, Politeknik Elektronika Negeri Surabaya,
Jl. Raya ITS, Surabaya, 60111, Indonesia
[3]PT Honda R&D Indonesia,
Summarecon Kelapa Gading, 14240, Jakarta

*Corresponding author: teguhhady@pens.ac.id

DOI;
10.30595/jrst.v8i2.19553

Histori Artikel:

Diajukan:
09/10/2023

Diterima:
23/09/2024

Diterbitkan:
30/09/2024

ABSTRACT

Enhancing the amount of flow field and heat transfer characteristic is an effective way to increase the performance of SUT plants. The velocity magnitude and heat transfer characteristic can be increased by adding passive flow control in the form of baffles. This study investigated the SUT prototype's flow field and heat transfer characteristics numerically using one, two, and three baffle variations through 2D axisymmetric analysis with the standard k-epsilon turbulence model using a Computational Fluid Dynamics (CFD) method. The results of the CFD solution obtained profiles of temperature distribution, velocity, streamline, kinetic power, and turbulent kinetic energy of each baffle variation. SUT with two-baffle variation is superior to the others by having a maximum air velocity of 6.248 m/s and increasing SUT performance by 104.769 %, while the three-baffle variation has the highest temperature profile and the most circulating flow effect with an increase in SUT performance of 51.524%. As the number of baffles in the SUT increases, the pressure drop also increases, but the effect of the pressure drop is not significant.

***Keywords**: Solar Updraft Tower, Baffle, Heat Transfer, Velocity Distribution, Temperature Distribution, Turbulent Kinetic Energy*

1. INTRODUCTION

Solar updraft tower (SUT) is examples of the use of solar energy technology with low-temperature differences (Saini et al., 2022). Solar updraft tower (SUT) is a renewable energy power plant that works on the principle of heat transfer by natural convection. In a conventional SUT, there is a collector that is mounted around-horizontally on the ground, a chimney located in the center of the collector, and a turbine inside the tower (Lee et al., 2018; Zhou & Xu, 2016).

The SUT collector absorbs and collects solar radiation to heat the ground beneath it. The heat collected in the ground causes the air to have a velocity called the natural convection phenomenon (Ming et al., 2013). The temperature gradient causes the air to have a buoyancy to pass through the chimney. The buoyancy-driven airflow drives the turbine and converts kinetic energy into mechanical energy so that the turbine can rotate and generate electricity.

Solar updraft tower has been developed as a type of large-scale power plant by previous researchers. From the results, the main parameters proposed for the first time were the performance and efficiency of the SUT. Continuing the subsequent study, the assessment of SUT performance through a numerical approach study was adopted as a function of geometrical parameters. The study results show that the performance of the SUT varies according to those geometrical parameters. Thermal performance can be improved by component addition in the SUT.

Ming et al. (2013) simulated the addition of blockage in a 3D SUT model with the same geometry as a 50 kW SUT prototype in

Manzanares, Spain. The results showed that the blockage was able to improve the velocity, pressure, and temperature distribution better than the SUT without blockage. When installing a blockage at the collector channel, the effect of crosswinds on the SUT performance is significantly reduced.

Nia and Ghazikhani, (2015) conducted a study regarding the potential improvement in the flow field and heat transfer characteristics of the SUT by using passive flow control. They performed a 2D axisymmetric incompressible steady with CFD solutions. From the results, it can be shown the improvement in energy output of SUT. (Lee et al., 2018) conducted a study regarding the addition of baffle variations. With geometric parameters and baffle placement points, SUT with baffles can play a role in the phenomenon of heat transfer by producing a vortex.

The requirements for high-performance thermal systems lead to the development of various methods to improve efficiency. Several experiments with the addition of different components and geometries for heat exchanger applications have been conducted (Awais et al., 2021; Awais & Bhuiyan, 2019; da Silva et al., 2019; Fugmann et al., 2018; Wu et al., 2022; Xiao et al., 2019; Zeeshan et al., 2018).

By using a vortex generator, the heat transfer coefficient can be increased (Mokrani et al., 2020; Sheikhnejad & Gandjalikhan Nassab, 2021). Baffles can disrupt flow by creating a vortex and affecting airflow velocity. A vortex generator induced a flow pattern to increase the rate of heat transfer by convection (Ramanathan et al., 2020). (Abdelkader & Zubair, 2019) experimented to determine the effect of the number of baffles, baffle cuts, mass flow rate, and type of tube layout on the pressure drop and heat transfer coefficient in the shell and tube heat exchanger.

The results the greater the number of baffles used, the higher the pressure drop on the shell side and the higher the heat transfer coefficient. Hoseini et al. (Hosseini et al., 2017, 2018) have studied several fin shapes used in solar heating and chimney related systems. The fin shapes tested included rectangular, elliptical, and triangular. The results showed that the best thermal performance was achieved with the use of rectangular fins. This is due to the larger heat transfer surface area, so that the thermal efficiency is significantly increased when fins are used compared to systems without fins. In addition, the induced mass flow rate increased by 7 to 14%. The results also showed higher temperatures in heaters with rectangular fins compared to other fins.

In this study, previous research (Lee et al., 2018; Nia & Ghazikhani, 2015) became a reference for assessing the baffle variation capabilities when installed in SUT. By using the CFD solution, profiles of velocity and temperature distribution, streamline, kinetic power, and turbulent kinetic energy were obtained which can be used to clarify the effects of using baffle variations.

The purpose of this study is to determine the characteristics of the effect of using the number of baffles at the SUT on thermal phenomena and airflow. Through this research, the aim is to find out the appropriate number of baffles for performance improvement, especially to increase the heat transfer coefficient and the phenomenon of airflow in the SUT.

2. RESEARCH METHOD

a. Base case

The geometry of this study refers to (Lee et al., 2018; Nia & Ghazikhani, 2015). The geometry of SUT has an inlet height (a) 0.15 m, a ground radius (b) 5 m, a chimney entrance height (c) 1 m, a chimney entrance height (d) 13 m, and a chimney radius (e) 0.125 m as shown in Figure 1.

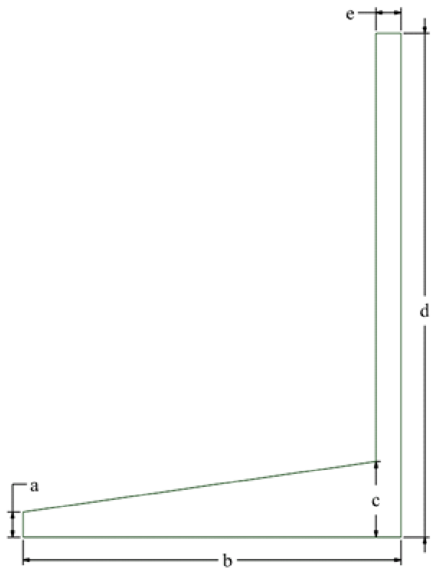
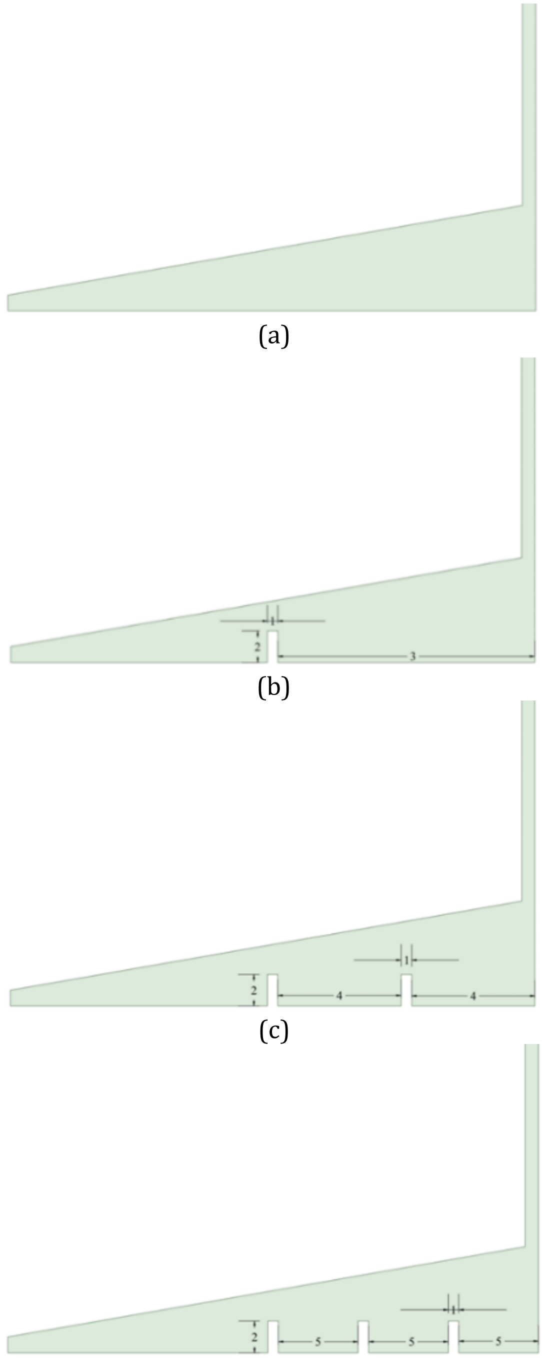


Figure 1. Solar updraft tower geometry without baffles variation

A collector with radius of 4.875 m, 13 m chimney height, the collector roof is angled 9.891° from the inlet channel. To determine the effect of the number of baffles on flow and performance, the baffles are varied by the number of one, two, and three.

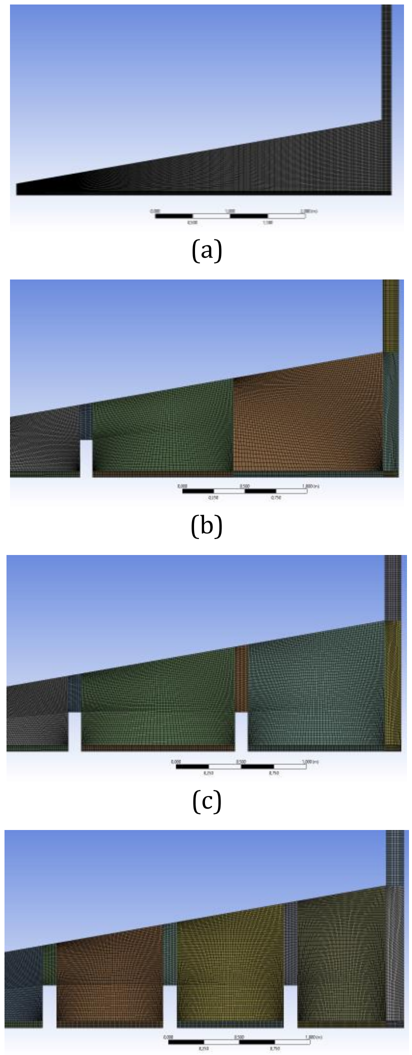
b. CFD simulations

This research was conducted using the 2D axisymmetric model using solutions from commercial CFD software. In Figure 2, the data is related to the geometry as follows: baffle thickness (1) is 0.1 m, the baffle height (2) is 0.3 m, and there are 3 variations of baffle spacing (3), (4), and (5) are 2.45 m, 1.175 m, and 0.75 m, respectively. In the meshing process, all geometry uses a number of divisions and face meshing to produce a structured mesh with a quadrilateral grid type. The results of the meshing structure are shown in Figure 3.



(a)
(b)
(c)
(d)

Figure 2. Location baffle for case (a) plain, (b) one baffle, (c) two baffle, and (d) three baffles



(a)
(b)
(c)
(d)

Figure 3. The meshing structure in (a) no baffle, (b) one-baffle, (c) two-baffles, (d) three-baffles

The data input for simulation refer to (Nia and Ghazikhani, 2015). The flow is assumed to be steady-state and turbulent. Air is considered an incompressible Newtonian fluid. The thermophysical properties of air are assumed to be constant. The air density is a temperature function incorporated in the temperature and flow fields, and the Bousinessq approach is carried out. The solar radiation flux absorbed by the collector plate is assumed to be constant.

For simplification of the density calculation, the Boussinessq method can provide better convergence than an ideal gas model or an incompressible ideal gas model. The Boussinesq assumption can be used to assume that the difference in inertia is negligible, but gravity is strong enough to make the masses differ enough between two fluids (Lee et al., 2018). The following equation determines the density of the buoyancy section in the momentum equation, shown in equation (1).

$$(\rho - \rho_0)g \approx -\rho_0\beta(T - T_0)g \qquad (1)$$

Where:
ρ : Fluid density (m³/kg)
ρ_0 : Reference fluid density (m³/kg)
β : Coefficient thermal expansion
T : Temperature (K)
T_0 : Reference temperature (K)
g : Gravity (m/s²)

c. Grid Independence

In order to obtain accurate simulation results, verification is carried out by grid independence. The temperature at the tower inlet is used as a reference parameter. Figure 4 shows the grid independence result and Table 1 shows the relative error. Relative errors are less than 1%, so the grid remains above 31225. In this study, mesh number 31225 is used.

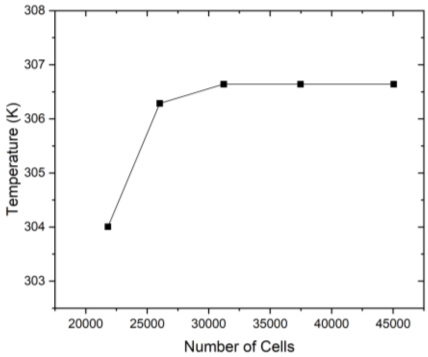


Figure 4. Number of meshing for three baffles

Table 1. Grid Independence Test

Grid Numbers	Temperature (K)
21810	304.007
26021	306.287
31225	306.641
Richarson Extrapolation	306.730
Relative Error (%)	0.029

3. RESULTS AND DISCUSSIONS

This study used the effect of the number of baffles on the performance of the solar updraft tower evaluated based on the visualization of temperature contours, velocity, and streamline in the collector. The simulation needs to be validated with a numerical approach to the experimental data recorded at predetermined points (Amirkhani et al., 2015; Nia & Ghazikhani, 2015). The sensors include temperature data at the points that have been placed above the surface of the ground. The temperature distribution along the ground collector sensor points is shown in Figure 5.

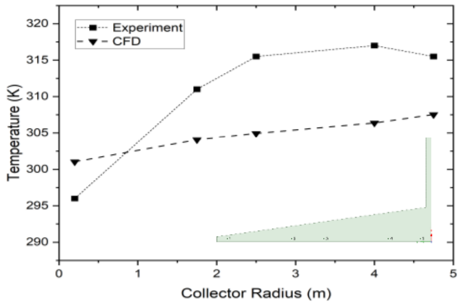


Figure 5. Plot of the temperature distribution along the ground collector sensor points.

Tabel 2. The temperature data for CFD evaluation

Point	Experimental (K)	CFD (K)	Error (%)
1	296	301.045	1.704
2	311	304.080	2.225
3	315.5	304.934	3.348
4	317	306.378	3.351
5	315.5	307.527	2.527

a. Velocity and Temperature Distribution

Figure 6 is a streamline visualization of the SUT simulation results with variations without baffles, one baffle, two baffles, and three baffles. It can be seen that there are two airflows in each variation, namely the main flow and transversal vortex. The main flow is the flow that leads directly to the chimney and the circulating flow is generally formed behind the baffle. Circulating flows are formed because of the reversed flow shown in Figure 7.

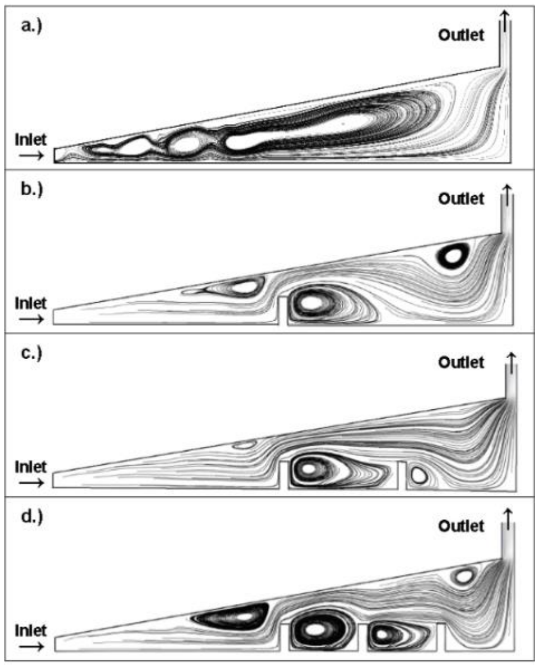


Figure 6. Streamline of velocity on the SUT with variations (a) without baffle SUT, (b) one-baffle SUT, (c) two-baffles SUT(d) three-baffles SUT

In SUT without baffle (Figure 6a), there is a circulating flow around the inlet and close to the collector. In one-baffle SUT (Figure 6b) there are three circulating flows which are under the collector, behind the baffle, and close to the inlet chimney. Whereas for two-baffles SUT (Figure 6c) there is a circulating flow at the bottom near the collector and behind the baffle.

At three-baffles SUT (Figure 6d) there is circulating flow near the collector, behind the baffle, and near the inlet chimney. Two-baffles SUT has a more dominant main flow and smaller eddies. Whereas for one-baffle SUT and three-baffles SUT there is a vortex near the collector and inlet chimney. In Figure 7 it can be seen that the most eddies are formed at three-baffles SUT.

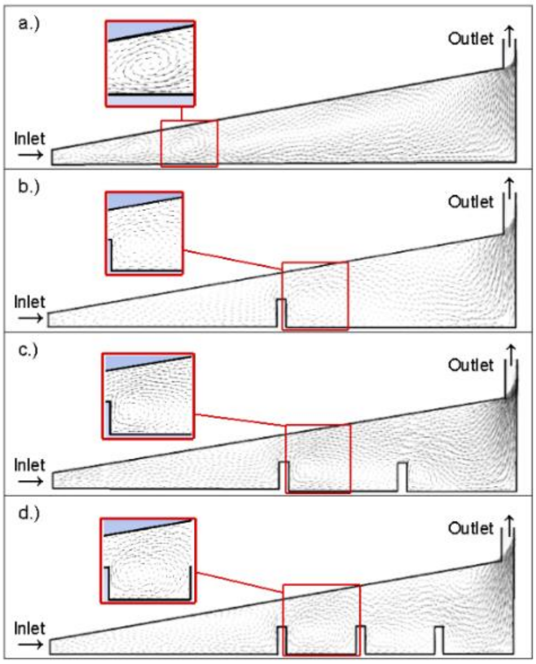


Figure 7. Velocity vector on SUT with variations in the number of baffles (a) without baffle SUT (b) one-baffle SUT (c) two-baffles SUT (d) three-baffles SUT

The buoyancy effect causes this backflow. A change in fluid density causes the bouncy force on the airflow. Ground which absorbs solar radiation, causes the air from the inlet side to experience an increase in temperature.

So that the air near the ground has a higher temperature than the air that leads to the collector. Air that has a higher temperature causes the density value to change to be smaller. The movement of hot air becomes upward until it reaches a certain limit and experiences flow deformation. This is what causes the airflow in the SUT to form a vortex.

Figure 8 is a visualization of the simulated velocity distribution with variations of one baffle, two baffles, and three baffles. In Figure 8 it can be seen the differences in the three variations of the velocity distribution. There is a change in velocity for each variation, this is because in the solar updraft tower there is a natural convection phenomenon.

The presence of heating on the ground side causes the air near the ground to have a greater temperature than the air under the collector. This increase in air temperature causes a change in density. As a result, the air that is close to the ground moves up and the air below the collector moves down due to the influence of gravity. This is what causes the air to have velocity and can move towards the chimney.

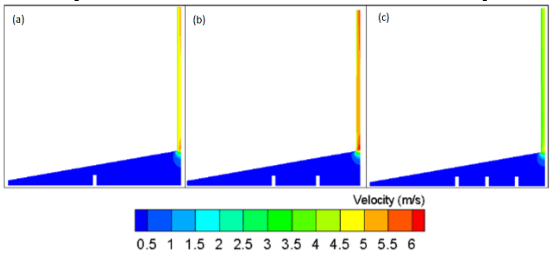


Figure 8. Contours of velocity magnitude(a) one-baffle SUT (b) two-baffles SUT (c) three-baffles SUT

The maximum air velocity at each variation is shown in Figure 9 and Table 2. Figure 9 is a plot of the average air velocity along the chimney for each variation. The maximum air velocity in the SUT is also shown in Tabel 2. It is known that there is an increase in velocity with the addition of baffles.

Based on Figure 9 and Table 2, the greatest air velocity is at two-baffles SUT. It can be seen in Figure 9, that two-baffles SUT has the highest velocity distribution, while three-baffles SUT has the smallest velocity distribution on the chimney side compared to the other variations. This is related to the character of the airflow as shown in Figure 6.

Two-baffles SUT has a higher velocity distribution because there is no circulating flow that interferes with air velocity. The main flow that goes into the chimney is more stable when compared to one-baffle SUT and three-baffle SUT. This can be caused because the air velocity vortex near the inlet chimney is not formed so that the airflow entering the inlet chimney has a more stable velocity.

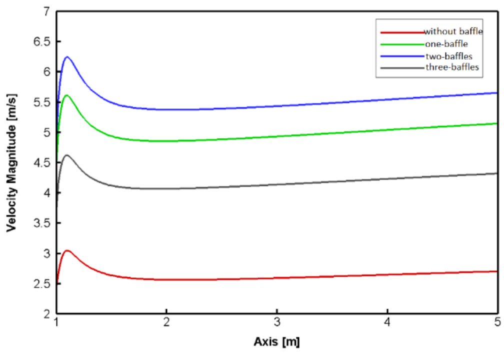


Figure 9. Plot of velocity distribution with variations in the number of baffles

Table 3. Maximum velocity that passes through the SUT

Variation	Maximum velocity (m/s)	Increment (%)
without baffle SUT	3.051	0
one-baffle SUT	5.614	83.994
two-baffles SUT	6.248	104.769
three-baffles SUT	4.623	51.524

The performance of the SUT can be known as one of them from the parameter of the amount of generated kinetic power. From these results, the kinetic power obtained for each variation can be seen in Figure 10. Comparison of average air velocity and SUT performance improvement based on variation in number of baffles can be seen in Table 3. It can be seen that two-baffles SUT has the greatest power capacity compared to other variations.

This is because the magnitude of the kinetic power is proportional to the air velocity. The greater the velocity of the incoming air, the greater the value of the kinetic power. The installation of baffles not only has a positive effect in increasing the performance of the SUT but also has a negative effect, namely an increase in pressure drop. Based on Figure 11, it is known that the pressure drop value is produced in each baffle variation.

Figure 12 is a graph of turbulent kinetic energy (TKE) along the collector on the solar updraft tower. In the centerline area, each variation has an increased TKE value. TKE values from smallest to largest are three-baffles SUT, one-baffle SUT, two-baffles SUT, and without baffle SUT.

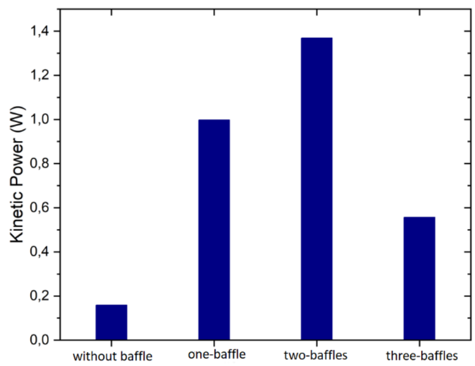


Figure 10. Kinetic power each baffle variations

Table 4. Comparison table of average air velocity and SUT performance improvement based on variation in number of baffles

Variation	Average air velocity (m/s)	Performance improvement (%)
without baffle SUT	2.578	-
one-baffle SUT	5.193	760.598
two-baffles SUT	5.698	527.298
three-baffles SUT	4.273	250.031

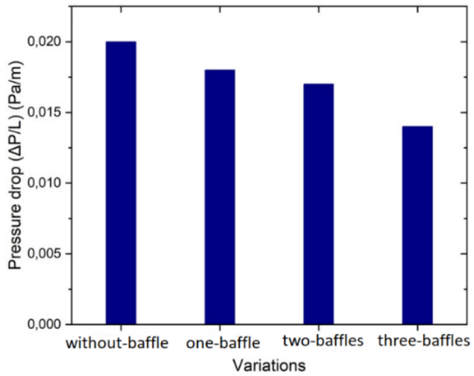


Figure 11. Pressure drop per length

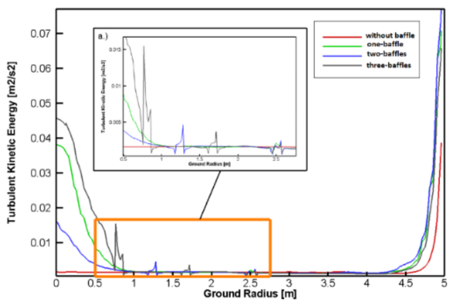


Figure 12. Turbulent kinetic energy along the collector on the SUT

An increase in the TKE is related to the phenomenon in Figure 6. A TKE value that is too large can worsen airflow conditions, thus changing the original flow pattern. The existence of streamline deformation causes the velocity of air entering the chimney to decrease. Based on Figure 12, it can be seen that the closer the baffle is to the centerline (axis), the greater the TKE value.

Figure 13 is a visualization of the temperature distribution of the baffle variations. It can be seen that there is a change in temperature inside the Solar updraft tower. This is because the ground surface was heated and heat transfer occurs to the air above it, so that the air has a greater temperature.

The increase in temperature from the inlet to the chimney is caused by natural convection heat transfer. This phenomenon occurs because the air from the inlet side experiences changes in temperature and velocity. With the same heat flux, but an increase in mass flow rate, the temperature difference will be smaller. The temperature difference profile of each variation can also be seen in Figure 14.

It can be seen that the higher the distance between the ground and the collector, the lower the air temperature. Figure 14 shows that without baffle SUT has the highest temperature distribution and two-baffles SUT has the smallest temperature distribution. Without baffle SUT has the largest temperature distribution because the flow is not disrupted by the effect of using baffles.

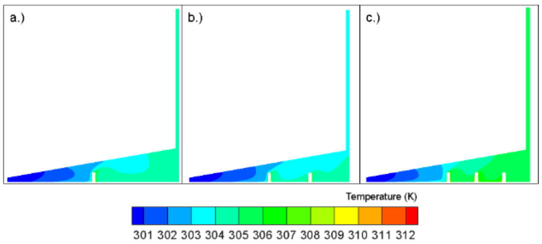


Figure 13. Plot of temperature distribution (a) one-baffle SUT (b) two-baffles SUT (c) three-baffles SUT

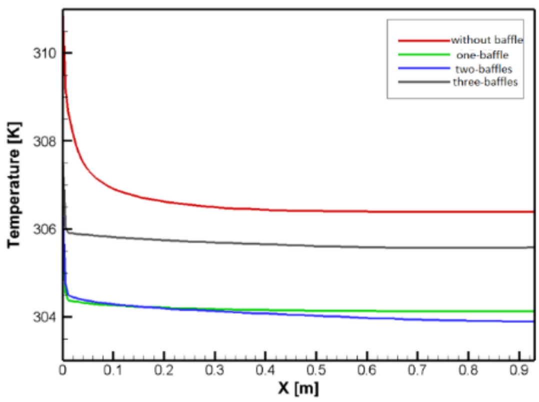


Figure 14. The temperature profile along a line located 0.5 m from the axis

4. CONCLUSIONS

In this study, a numerical method is presented using ccomputational fluid dynamics (CFD) to analyze the effect of using the number of baffles on the performance of a solar updraft tower to improve performance. Based on the analysis of the research data it can be concluded that solar updraft towers with two baffles are able to improve the best performance compared to solar updraft towers with one or three baffles.

SUT with two-baffle variety is predominant to the others by having a greatest velocity of 6.248 m/s and improving SUT performance by 104.769 %, whereas the three-baffle variety has the most elevated temperature profile and the foremost circulating air flow impact with an increment in SUT performance of 51.524%. By increasing the number of baffles in the SUT it causes an increase in the amount of circulating flow. The pressure drop also increases, but the pressure drop effect is insignificant.

There are several suggestions to develop this research. First, predetermine the optimal baffle placement position and the effect of the distance between baffles on the SUT to obtain better performance. Second, the use of longitudinal vortex application and its effect on SUT performance. Third, the modification of the baffle shape and its effect on the thermal-hydraulic phenomena on the SUT.

ACKNOWLEDGMENT

The authors would like to thank the Department of Power Plant Engineering, Politeknik Elektronika Negeri Surabaya for supporting the research and Research and Community Service Unit Politeknik Elektronika Negeri Surabaya for funding this research under applied scheme with the decree number 1758/PL14/PG/2021.

REFERENCES

Abdelkader, B. A., & Zubair, S. M. (2019). The Effect of a Number of Baffles on the Performance of Shell-and-Tube Heat Exchangers. *Heat Transfer Engineering*, *40*(1–2), 39–52. https://doi.org/10.1080/01457632.2017.1404806

Amirkhani, S., Nasirivatan, Sh., Kasaeian, A. B., & Hajinezhad, A. (2015). ANN and ANFIS models to predict the performance of solar chimney power plants. *Renewable Energy*, *83*, 597–607. https://doi.org/10.1016/j.renene.2015.04.072

Awais, M., & Bhuiyan, A. A. (2019). Enhancement of thermal and hydraulic performance of compact finned-tube heat exchanger using vortex generators (VGs): A parametric study. *International Journal of Thermal Sciences*, *140*, 154–166. https://doi.org/10.1016/J.IJTHERMALSCI.2019.02.041

Awais, M., Ullah, N., Ahmad, J., Sikandar, F., Ehsan, M. M., Salehin, S., & Bhuiyan, A. A. (2021). Heat transfer and pressure drop performance of Nanofluid: A state-of- the-art review. *International Journal of Thermofluids*, *9*, 100065. https://doi.org/10.1016/j.ijft.2021.100065

da Silva, F. A. S., Dezan, D. J., Pantaleão, A. V., & Salviano, L. O. (2019). Longitudinal vortex generator applied to heat transfer enhancement of a flat plate solar water heater. *Applied Thermal Engineering*, *158*, 113790. https://doi.org/10.1016/j.applthermaleng.2019.113790

Fugmann, H., Di Lauro, P., Sawant, A., & Schnabel, L. (2018). Development of Heat Transfer Surface Area Enhancements: A Test Facility for New Heat Exchanger Designs. *Energies*, *11*(5), 1322. https://doi.org/10.3390/en11051322

Hosseini, S. S., Ramiar, A., & Ranjbar, A. A. (2017). Numerical investigation of rectangular fin geometry effect on solar chimney. *Energy and Buildings*, *155*, 296–307. https://doi.org/10.1016/j.enbuild.2017.09.017

Hosseini, S. S., Ramiar, A., & Ranjbar, A. A. (2018). Numerical investigation of natural convection solar air heater with different fins shape. *Renewable Energy*, *117*, 488–500. https://doi.org/10.1016/j.renene.2017.10.052

Lee, S., Kim, Y., & Park, J. (2018). Numerical Investigation on the Effects of Baffles with Various Thermal and Geometrical Conditions on Thermo-Fluid Dynamics and Kinetic Power of a Solar Updraft Tower. *Energies*, *11*(9), 2230. https://doi.org/10.3390/en11092230

Ming, T., Gui, J., de Richter, R. K., Pan, Y., & Xu, G. (2013). Numerical analysis on the solar updraft power plant system with a blockage. *Solar Energy*, *98*, 58–69. https://doi.org/10.1016/j.solener.2013.02.027

Mokrani, O. B. E. K., Ouahrani, M. R., Sellami, M. H., & Segni, L. (2020). Experimental investigations of hybrid: geothermal water/solar chimney power plant. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–18. https://doi.org/10.1080/15567036.2020.1810830

Nia, E. S., & Ghazikhani, M. (2015). Numerical investigation on heat transfer characteristics amelioration of a solar chimney power plant through passive flow control approach. *Energy Conversion and Management*, *105*, 588–595. https://doi.org/10.1016/j.enconman.2015.07.030

Ramanathan, S., Thansekhar, M. R., Kanna, P. R., & Gunnasegaran, P. (2020). A new method of acquiring perquisites of recirculation and vortex flow in sudden expansion solar water collector using vortex generator to augment heat transfer. *International Journal of Thermal Sciences*, *153*, 106346. https://doi.org/10.1016/j.ijthermalsci.2020.106346

Saini, M., Sharma, A., Singh, V. P., Dwivedi, G., & Jain, S. (2022). *Solar Thermal Receivers—A Review* (pp. 311–325). https://doi.org/10.1007/978-981-16-8341-1_25

Sheikhnejad, Y., & Gandjalikhan Nassab, S. A. (2021). Enhancement of solar chimney performance by passive vortex generator. *Renewable Energy*, *169*, 437–450. https://doi.org/10.1016/j.renene.2021.01.026

Wu, J., Liu, P., Yu, M., Liu, Z., & Liu, W. (2022). Thermo-hydraulic performance and exergy analysis of a fin-and-tube heat exchanger with sinusoidal wavy winglet type vortex generators. *International Journal of Thermal Sciences*, *172*, 107274. https://doi.org/10.1016/j.ijthermalsci.2021.107274

Xiao, H., Wang, J., Liu, Z., & Liu, W. (2019). Turbulent heat transfer optimization for solar air heater with variation method based on exergy destruction minimization principle. *International Journal of Heat and Mass Transfer*, *136*, 1096–1105. https://doi.org/10.1016/j.ijheatmasstransfer.2019.03.071

Zeeshan, M., Nath, S., Bhanja, D., & Das, A. (2018). Numerical investigation for the optimal placements of rectangular vortex generators for improved thermal performance of fin-and-tube heat exchangers. *Applied Thermal Engineering*, *136*, 589–601. https://doi.org/10.1016/j.applthermaleng.2018.03.006

Zhou, X., & Xu, Y. (2016). Solar updraft tower power generation. *Solar Energy*, *128*, 95–125. https://doi.org/10.1016/j.solener.2014.06.029