Experimental Study of Circular Tunnel of Vertical Axis Wind Turbine of Savonius Type-U

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Keywords: Vertical Axis Wind Turbine (Vawt), Savonius Type-U, Circular Tunnel.

Abstract: Much research has been conducted to develop the construction of wind turbine thus produces the optimum electrical power. The construction development that has been carried out is by varying the shape of blade, angle of blade, number of blades, staging blade, shield, and deflector. Author tried to optimize the use of shield construction (guided-box tunnel) by making the variation of circular shape. By guiding wind to the blade that is dragged can increase turbine power proportional to the torque value. Therefore, the aim of this research is to find Coefficient of Power (Cp) and torque value of deconstructed Savonius wind blade type U using circular tunnel. The designed rotor is a savonius type -U of 2 blade rotor. The dimensions of the rotor are designed to be smaller than the previous research which has the diameter of savonius rotor of 250 mm and an aspect ratio of 1: 1. Circular tunnel dimensions was slightly widened, with the diameter of 270 mm and height of 400 mm. Cp with circular tunnel increase 2,5 times of the value Cp without circular tunnel. Meanwhile, the addition of circular tunnel caused the decrease of torque value even though it was not significant.

1 INTRODUCTION

The Savonius wind turbine is a type of Vertical Axis wind Turbine (VAWT). This turbine has been already studied since 1920 until now by many researchers. The working principle of this turbine is based on the difference of drag force that hit the surface of semicircular of the rotor. The sum of this drag force, if it is positive, can rotate of the turbine shaft (D.S.Hasan, et al., 2013). Theoretically, the relation between Cp value and Tip Speed Ratio (TSR) for Savonius Turbine is shown in Figure 1.

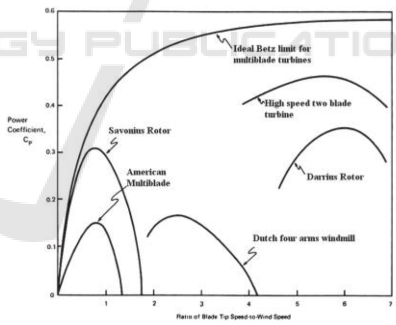

Figure 1: Relation between Cp and TSR.

Much research has been conducted to develop the construction of wind turbine thus produces the optimum electrical power. The construction development that has been carried out is by varying the shape of blade, angle of blade, number of blades, staging blade, shield, and deflector. Therefore, there are many types of blades of this turbine, such as type U that is the conventional type, type L, twisted blade, multistage blade, or various radius and width of the arc.

There are some methods to increase the performance of the Savonius U-type wind turbine. One of which is by applying guide-box tunnel, that can be seen in Figure 2(a), as wind deflector to prevent returning blade. By using this type, Cp can increase until 50% for three blades but the

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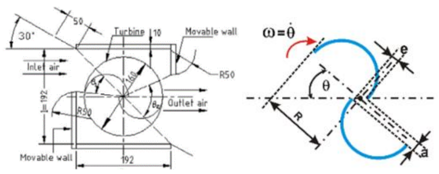
disadvantage of this type is its complex construction. The sixth method is by modifying the blade by applying geometrical parameter value difference, such as overlap and angle between blades as can be seen in Figure 2(b). This can increase the Cp value up to 60% dan producing high vibration (Mohamed Hasan A. M, 2011). The sixth method is always used to design the turbine blade because it is proven to increase Cp more significantly than the conventional blade design (Delffika Canra. et al, 2018).



(a) (b)

Figure 2: (a) Guide-box tunnel (b) Overlap geometri rotor

Author tried to optimize the use of shield construction (guided-box tunnel) by making the variation of circular shape. By using this method, it is intended to increase the Cp and torque value on the wind blade. This tunnel construction can guide the wind to the surface of the blade and prevent the wind to push the returning blade. By guiding wind to the blade that is dragged can increase turbine power proportional to the torque value. Therefore, the aim of this research is to find Cp and torque value of deconstructed Savonius wind blade type U using circular tunnel.

2 RESEARCH METHODS AND PREPARATION

The research method that is used, is experiment with the steps are explained in Figure 3.

Figure 3: Research flow.

The first step was designing prototype model by using CAD software to produce design model and drawing. The drawing is used to make the prototype (wind turbine). The designed rotor is a savonius type -U of 2 blade rotor. The dimensions of the rotor are designed to be smaller than the previous research which has the diameter of savonius rotor of 250 mm and an aspect ratio of 1: 1. Circular tunnel dimensions was slightly widened, with the diameter of 270 mm and height of 400 mm as shown in Figure 4.

This circular tunnel was varied by applying guide on the inlet of the wind as seen in Figure 5. There was variation of guide angle by 0° and 45°. By applying this guide, it was intended to increase the wind power to rotate the wind turbine.

Wind tunnel was prepared with the dimension of 750 mm x 20 mm x 250 mm and equipped with honeycomb inside. The function of honeycomb is to guide the wind to be homogeneous in one direction. The material of the rotor that was used was aluminium due to its lightness and ease of formation and fabrication. Meanwhile, the material of the Circular Tunnel was the steel plate with the thickness of 1 mm.

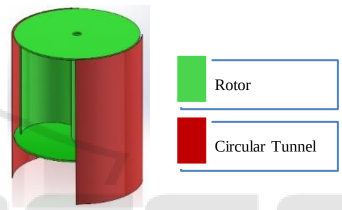
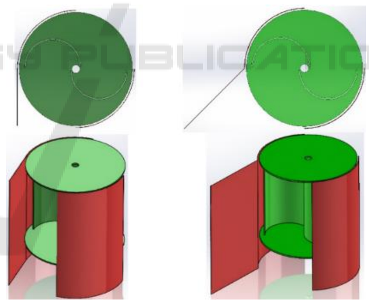


Figure 4: Design of Rotor and Circular tunnel.



(a) (b)

Figure 5: Variation of Design of Circular tunnel (a) guide of inlet 0^0 (b) guide of inlet 45^0.

Prototype design and research was done in the laboratory of Mechanical Engineering Department of Polindra while the turbine was manufactured in the workshop of Mechanical Engineering Department of Polindra. The process was then continued to the data retrieval. The wind speed used for this research was 4-9 m/s with the resolution of 0,5 m/s by using Axial Blower Fan. The wind speed was measured when the wind flowed through and exited from the rotor by using anemometer. The other required data was the rotational speed of rotor by using tachometer. Meanwhile, to know the produced torque, load addition to the rotor system was needed and the load was measured by using small weight scale as can be seen in Figure 6.

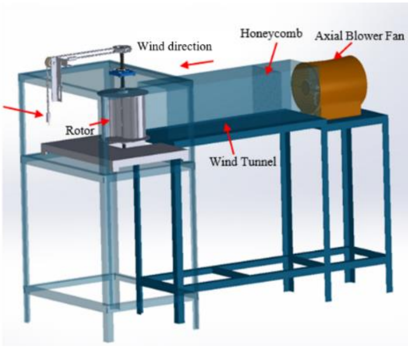


Figure 6: Prototype Design.

The collected data then were processed according to the basic theory of wind turbine, such as turbine power calculation, wind power and the produced torque. By using Betz momentum theory in which the wind speed v_1 flowing through the turbine blades experiences the speed change of v_2, the mechanical power then could be calculated by using the following formula.

$$P = \frac{1}{4}\rho A(v_1 - v_2)(v_1{}^2 - v_2{}^2) \quad (1)$$

Where: P = turbine mechanical power (W)
ρ = density of wind (kg/m^3)
A = sweep area (m^2)
v = velocity of wind (m/s)

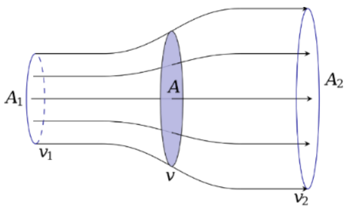


Figure 7: Change of wind speed after flowing through the turbine blade.

The Cp defines the performance of the wind turbine and the wind power defines the amount of kinetic power of the wind that flow through the wind turbine blade and can be formulated by

$$P_0 = \frac{1}{2}\rho A v^3 \quad (2)$$

where P_0 = wind power (W)
Therefore, the Cp of the turbine was calculated by

$$C_p = \frac{P}{P_0} \quad (3)$$

Calculating the amount of torque is also important. Torque can be defined as the measure of force effectiveness to produce the rotation around the axis. The amount of torque can be formulated by

$$T = (m_1 - m_2).g.r \quad (4)$$

Where : T = Torque (Nm)
m = mass (kg)
r = radius of pulley (m)
g = gravitation (m/s^2)

Meanwhile the tip speed ratio can be calculated by

$$\lambda = \frac{\pi D n}{60 v} \quad (5)$$

Where : D = diameter of blade (m)
v = velocity of wind (m/s)
n = blade rotation speed (rpm)

3 RESULT AND DISCUSSION

3.1 Experiment-1 (E-1): Rotor Without Circular Tunnel

The first experiment is testing the turbine withour using the circular tunnel. The result of data processing of turbine power, wind power and Coefficient of Power can be represented in Table 1 and Figure 8, where the author used Equation 1.

The highest Coefficient of power (Cp) was obtained at the wind speed of 6,5 m/s. After that, the Cp decreases as the wind speed increases.

The construction ratio of 1:1 caused the Cp value lower than that of the construction ratio of 1:4. This is proven by the highest Cp value that was obtained was 0,1031. The typical Cp value of Savonius Type C is usually up to 0,3 (Mohamed Hasan A. M, 2011). However, in this research, the author focused on the difference of Cp value in the utilization of circular tunnel.

Table 1: Data Processing Result of Cp (E-1).

v [m/s]		P [watt]	P_0 [watt]	Cp
1 (in)	2 (out)			
9	6,8	1,5414	29,3878	0,0524
8,5	6,2	1,5674	24,7569	0,0633
8	5,8	1,3463	20,6400	0,0652
7,5	5,3	1,2487	17,0068	0,0734
7	4,6	1,3468	13,8272	0,0974
6,5	4,2	1,1409	11,0708	0,1031
6	4	0,8063	8,7075	0,0926
5,5	3,9	0,4850	6,7070	0,0723
5	3,8	0,2554	5,0391	0,0507
4,5	3,8	0,0820	3,6735	0,0223
4	0	0,0000	2,8500	0,0000

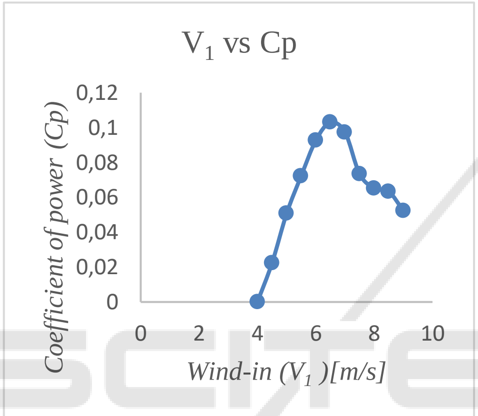


Figure 8: The Graph of the Relation between v_1 and Cp (E-1).

By using equation 4 and 5, the author processes the data of wind speed, rotational speed of rotor, and the given load to the system. The result of this was the torque value (T) and Tip Speed Ratio (λ) that can be seen in Table 2 and Figure 9.

Table 2: Result of Data Processing of Torque and TSR (E-1).

v_1 [m/s]	n [rpm]	m [kg]		T [Nm]	λ (TSR)
		m_1	m_2		
9	580	0,725	0,39	0,1027	0,9443
8,5	530	0,68	0,355	0,0996	0,9137
8	490	0,645	0,34	0,0935	0,8975
7,5	440	0,545	0,3	0,0751	0,8597
7	359	0,485	0,28	0,0628	0,7515
6,5	280	0,41	0,24	0,0521	0,6312
6	180	0,295	0,17	0,0383	0,4396
5,5	105	0,155	0,13	0,0077	0,2797
5	75	0,07	0,07	0,0000	0,2198
4,5	50	0	0	0,0000	0,1628
4	0	0	0	0,0000	0,0000

The resulted torque increased proportionally as the inlet wind speed increased, and inversely related to the increase of Cp. This concluded that the torque was not affected by Cp.

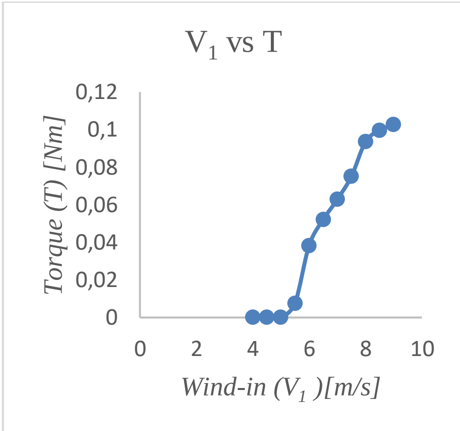


Figure 9: The Graph of the Relation between v_1 and T (E-1).

The data of the first experiment became the comparison value to the next experiment.

3.2 Experiment-2 (E-2): Rotor with Circular Tunnel

The second experiment was the turbine simulation with circular tunnel. The result of data processing of turbine power, wind power, and Cp can be represented on Table 3 and Figure 10, where the equation 1,2, and 3 were used.

Table 3: Data Processing Result of Cp (E-2).

v [m/s]		P [watt]	P_0 [watt]	Cp
1 (in)	2 (out)			
9	5,5	1,7901	14,6939	0,1218
8,5	4,9	1,7502	12,3785	0,1414
8	4	1,9350	10,3200	0,1875
7,5	3,2	1,9939	8,5034	0,2345
7	2,9	1,6772	6,9136	0,2426
6,5	2,5	1,4513	5,5354	0,2622
6	2,4	1,0971	4,3538	0,2520
5,5	2,3	0,8050	3,3535	0,2400
5	2,2	0,5689	2,5195	0,2258
4,5	2,1	0,3831	1,8367	0,2086
4	2,05	0,2318	1,2900	0,1797

The trend of the graph line was not significantly different from the first experiment, but the highest Cp value increased by three times at the wind speed of 6,5 m/s. From this data, it could be proven that the circular tunnel could increase the Cp of turbine.

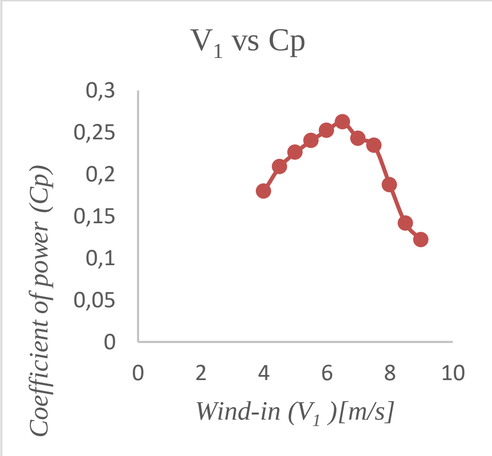


Figure 10: The Graph of the Relation between v_1 and Cp (E-2).

Torque (T) dan Tip Speed Ratio (λ) result can be seen in Table 4 and Figure 11. The result of data processing of wind speed, rotational speed of rotor, and the given load to the system used Equation 4 and 5.

The second experiment shows that the torque value increased as the wind speed increased which was identical with the first experiment. The torque decreased compared tto the first experiment at the same wind speed though. This could be caused by the decrease of wind volume flowing through the turbine and it was suspected that there was turbulence around zje circular tunnel plate thus the rotational speed of rotor decreased dramatically.

Table 4 : Result of Data Processing of Torque and TSR (E-2).

v_1 [m/s]	n [rpm]	m [kg]		T [Nm]	λ (TSR)
		m_1	m_2		
9	230	0,5	0,275	0,0690	0,3745
8,5	223	0,475	0,255	0,0674	0,3844
8	206	0,44	0,22	0,0674	0,3773
7,5	188	0,395	0,215	0,0552	0,3673
7	169	0,33	0,205	0,0383	0,3538
6,5	139	0,25	0,16	0,0276	0,3134
6	95	0,155	0,12	0,0107	0,2320
5,5	75	0,08	0,065	0,0046	0,1998
5	63	0	0	0,0000	0,1846
4,5	40	0	0	0,0000	0,1303
4	23	0	0	0,0000	0,0843

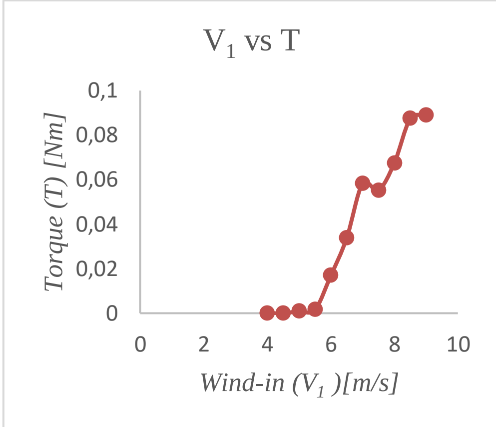


Figure 11: The Graph of the Relation between v_1 and T (E-2).

3.3 Experiment-3 (E-3): Rotor with Circular Tunnel Inlet 0^0

The third experiment was the turbine simulation with circular tunnel inlet 0°. The result of data processing of turbine power, wind power, and Cp can be represented on Table 5 and Figure 12, where the equation 1,2, and 3 were used.

Table 5: Data Processing Result of Cp (E-3).

v [m/s]		P [watt]	P_0 [watt]	Cp
1 (in)	2 (out)			
9	4,5	2,7551	14,6939	0,1875
8,5	4,3	2,2756	12,3785	0,1838
8	4	1,9350	10,3200	0,1875
7,5	3,9	1,4890	8,5034	0,1751
7	3,7	1,1743	6,9136	0,1699
6,5	3,5	0,9070	5,5354	0,1639
6	3,3	0,6833	4,3538	0,1569
5,5	3,1	0,4992	3,3535	0,1489
5	2,9	0,3511	2,5195	0,1394
4,5	2,8	0,2126	1,8367	0,1158
4	2,7	0,1141	1,2900	0,0885

Circular tunnel with inlet 0° resulted in the Cp up to 0,1875 at wind speed of 9 m/s and the trend increased as the wind speed increased. During the data collection at simulated turbine, there was indeed the turbulence that caused the decrease of turbine power and wind power compared to the second experiment.

Looking at Figure 12, the Cp increased as the wind speed increased and there was no decrease sign. The was possibility that the Cp peak was not reached. Due to the limitation of axial fan blower, the data collection could not be proceed further.

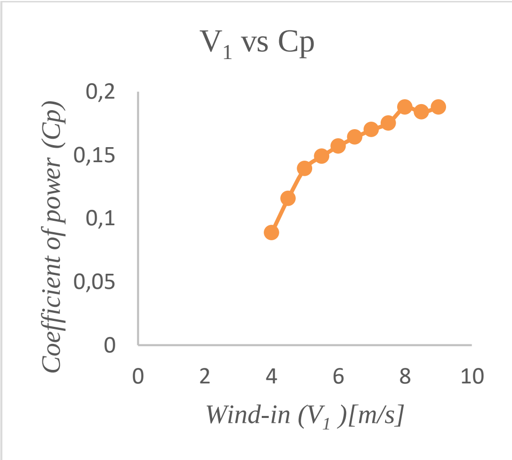


Figure 12: The Graph of the Relation between v_1 and Cp (E-3).

Table 6: Result of Data Processing of Torque and TSR (E-3).

v_1 [m/s]	n [rpm]	m [kg]		T [Nm]	λ (TSR)
		m_1	m_2		
9	230	0,5	0,275	0,0690	0,3745
8,5	223	0,475	0,255	0,0674	0,3844
8	206	0,44	0,22	0,0674	0,3773
7,5	188	0,395	0,215	0,0552	0,3673
7	169	0,33	0,205	0,0383	0,3538
6,5	139	0,25	0,16	0,0276	0,3134
6	95	0,155	0,12	0,0107	0,2320
5,5	75	0,08	0,065	0,0046	0,1998
5	63	0	0	0,0000	0,1846
4,5	40	0	0	0,0000	0,1303
4	23	0	0	0,0000	0,0843

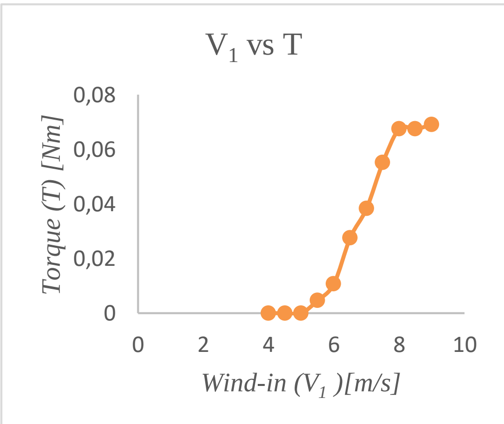


Figure 13: The Graph of the Relation between v_1 and T (E-3).

The third experiment shows that the torque value increased as the wind speed increased that can be seen in Figure 13 and was identical with the first and second experiment. The highest torque value that was obtained was 0,0690 at the wind speed of 9 m/s that can be seen in Table 6. The torque decreased compared to the first experiment at the same wind speed but equivalent to the torque value of second experiment.

The resulted torque value of the third experiment was insignificantly different from that of the second experiment. By adding the guide of inlet 0°, it caused more turbulence but did not affect the torque much.

3.4 Experiment-4 (E-4): Rotor with Circular Tunnel Inlet 45^0

The fourth experiment was the simulation of turbine by using circular tunnel with inlet 45°. The result of data processing of turbine power, wind power, and Cp can be represented on Table 7 and Figure 14, where the equation 1,2, and 3 were used.

Table 7: Data Processing Result of Cp (E-4).

v [m/s]		P [watt]	P_0 [watt]	Cp
1 (in)	2 (out)			
9	5,3	1,9730	14,6939	0,1343
8,5	5,1	1,5844	12,3785	0,1280
8	4,9	1,2494	10,3200	0,1211
7,5	4,6	1,0256	8,5034	0,1206
7	4,3	0,8302	6,9136	0,1201
6,5	4,1	0,6153	5,5354	0,1112
6	3,8	0,4780	4,3538	0,1098
5,5	3,5	0,3628	3,3535	0,1082
5	3,2	0,2678	2,5195	0,1063
4,5	2,9	0,1909	1,8367	0,1039
4	2,6	0,1304	1,2900	0,1011

Circular tunnel with inlet 45° resulted in the Cp up to 0,1343 at wind speed of 9 m/s and the trend increased as the wind speed increased as seen in Figure 14. This Cp was lower than that of the third experiment. The same case might occur as the third experiment that there was much turbulence causing the decrease of turbine power and wind power.

The result of the fourth experiment was identical with the third experiment. However, there was decrease of Cp in the fourth experiment the experiment cannot be conducted further due to the limitation of the experiment apparatus.

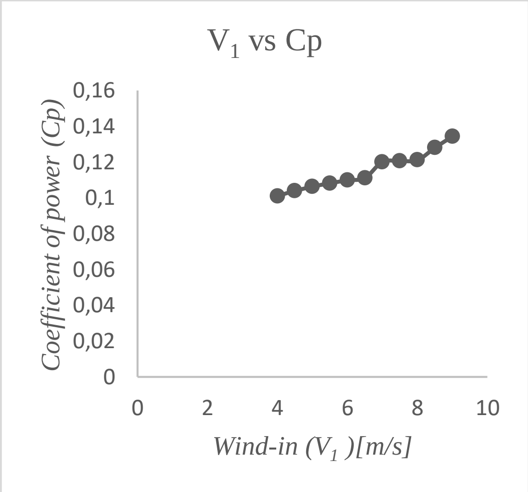


Figure 14: The Graph of the Relation between v_1 and Cp (E-4).

Because the fourth experiment was identical to the third experiment, the torque value was thus not different much. The highest torque was 0,0797 at the maximum wind speed of 9 m/s as seen in Table 8. This proves that the addition of inlet, either inlet 0° or inlet 45°, did not affect the torque value even though the turbulence increased a little.

Table 8: Result of Data Processing of Torque and TSR (E-4).

v_1 [m/s]	n [rpm]	m [kg]		T [Nm]	λ (TSR)
		m_1	m_2		
9	290	0,545	0,285	0,0797	0,4722
8,5	250	0,49	0,265	0,0690	0,4310
8	225	0,465	0,24	0,0690	0,4121
7,5	200	0,405	0,2	0,0628	0,3908
7	172	0,345	0,17	0,0536	0,3601
6,5	147	0,325	0,165	0,0491	0,3314
6	115	0,25	0,15	0,0307	0,2809
5,5	96	0,13	0,08	0,0153	0,2558
5	70	0	0	0,0000	0,2051
4,5	52	0	0	0,0000	0,1693
4	32	0	0	0,0000	0,1172

Figure 15 shows the same case as the previous experiment. There was no significant difference between them. The torque value increased as the wind speed increased.

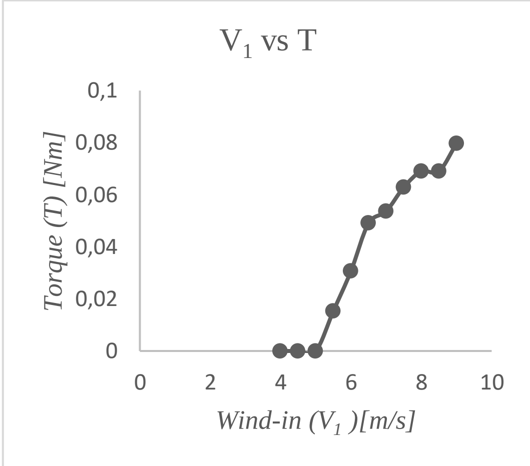


Figure 15: The Graph of the Relation between v_1 and T (E-4).

3.5 Comparison of all Experiment Results

As can be represented by Figure 16, the highest Cp value was obtained in the second experiment by 0,2622 at the wind speed 6,5 m/s while the Cp of 0,1031 was obtained at the same wind speed in the first experiment. This differed from the third experiment, where the highest Cp were 0,1875 and 0,1343 respectively.

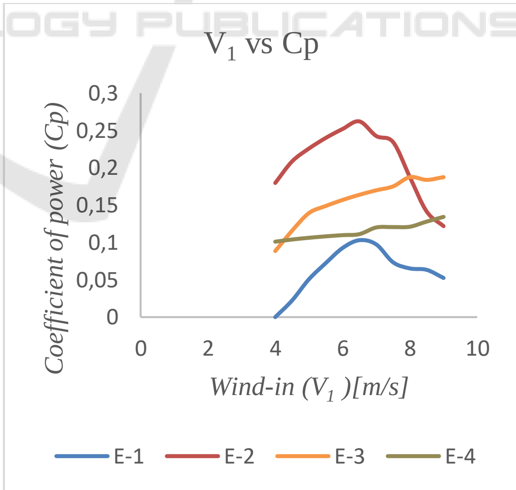


Figure 16: The Graph of the Relation between v_1 and Cp.

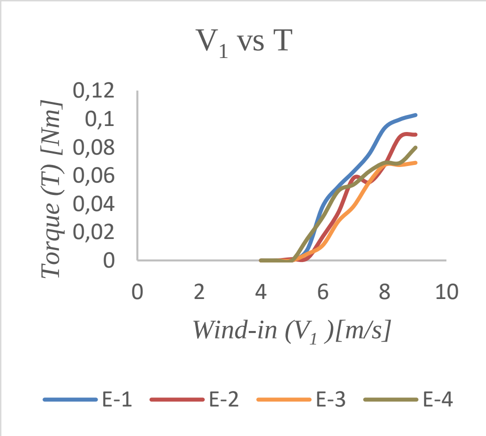


Figure 17: The Graph of the Relation between v_1 and T.

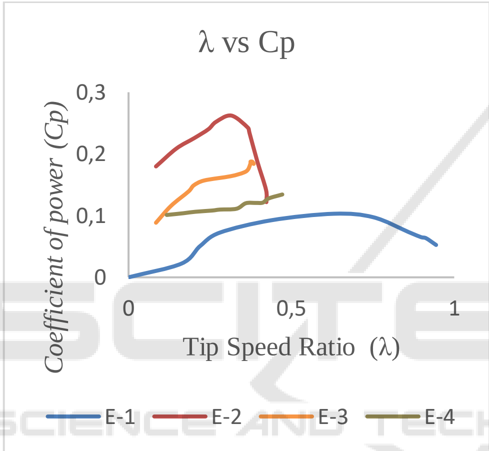


Figure 18: The Graph of the Relation between λ and Cp.

The torque value in all experiment increased as the wind speed increased but the highest torque was obtained in the first experiment as seen in Figure 17. In the second until the fourth experiment, there was decrease of torque compared to the first experiment but this was not significant. This was suspected that the cause of this was circular tunnel.

Looking at the comparison graph of Cp and TSR in Figure 18, only the first and second experiment that had the typical Savonius wind turbine graph characteristic in general. Meanwhile, in the third and fourth experiment, there was still possibility of increase then decrease of value until the TSR reached 1 or more.

4 CONCLUSION

From the result of all experiment, it can be concluded that the use of circular tunnel affects the Cp increase, especially in the second experiment, where there was increase of value of Cp by 2,5 times of the value of Cp in the first experiment, which was 0,2622 at the wind speed of 6 m/s. The same case occurred in the third and fourth experiment, that the obtained Cp was higher than the Cp in the first experiment by 1,8 and 1,3 times respectively. Another word that Cp with circular tunnel increase 2,5 times of the value Cp without circular tunnel.

Meanwhile, the addition of circular tunnel caused the decrease of torque value even though it was not significant.

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