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by Dena Hendriana

Design Comparison of Wind Turbines for Low Wind Speed

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Abstract: Wind energy is one of the potential renewable energy, but the applications have to be adjusted to the available wind characteristic in the area. In Indonesia, the wind speed is in average not very high, only around 4 m/s. Therefore the wind turbine design have to be adjusted for usage in Indonesia. In this research, two wind turbine designs are compared. One design is of the form Horizontal-Axis Wind Turbine (HAWT) and the other is of the form Vertical-Axis Wind Turbine (VAWT). Both designs are optimized for wind speed of 4 m/s. The comparisons are done using computer simulation software OpenFOAM. The result shows VAWT design can produce similar power with smaller turbine dimension than the HAWT design.

Keywords: CFD, OpenFOAM, VAWT, HAWT, turbine, low speed wind

1. Introduction

Wind energy is being developed all over the world, since it is one of the potential renewable energy resources. Large and medium scale turbines have been developed alot in America and Europe, especially in England and Gemany. The development of small scale wind turbines, on the other hand, have just begun (Thorstensson, 2009).

Indonesia has potential in wind energy. Indonesia Wind Energy Society (2012) has published a map showing the potential of wind energy in Indonesia. According to this map, the areas with the most wind energy potential in Indonesia are Nusa Tenggara Timur, Nusa Tenggara Barat, south Papua, Sulawesi, and south coastal region of southern Indonesia. It is estimated that the potential power that can be generated from wind energy in Indonesia can reach 150 MW.

Badan Pengkajian dan Penerapan Teknologi (BPPT, Agency For The Assessment And Application Of Technology) has produced a report detailing the wind energy potential in 10 java regions (Badan Pengkajian dan Penerapan Teknologi (BPPT), 2014). The map is shown in Figure 1. In all the regions surveyed in that report, the maximum wind speed is only 8 m/s, and in average the wind speed is only around 4-6 m/s.

Figure 1. Wind energy potential in several areas in Java, Indonesia (Badan Pengkajian dan Penerapan Teknologi (BPPT), 2014)

Based on this result, it is clear that the common wind turbine, which is usually designed for high speed wind (10 m/s or more), will not perform well in Indonesia. What is needed is more wind turbines which are optimized for low speed wind (around 4 m/s). Low speed wind turbine also usually means that the power generated is only small scale. But it is better than large scale wind turbine, with high power generating capacity, which cannot operate well due to lack of wind speed.

Wind turbine design can be done using computer simulation. OpenFoam is one of the open source software that can be used for this purpose (OpenFoam, 2018). This software has been used to optimize wind turbine design by analyzing the air flow in the turbine, e.g. in (Hendriana et al., 2015). The basic difference between wind turbine designs for high and low wind speed is in the area of the blades. Low speed wind turbine will have larger blade area. The larger area is needed because the momentum of the low speed wind is lower than for the high speed wind. The power of wind momentum is proportional to the the cube of the wind velocity (Rosa, 2009).

There are two possibilities of wind turbine design: Horizontal-Axis Wind Turbine (HAWT) and Vertical-Axis Wind Turbine (VAWT). For each of this type, a design is simulated using OpenFoam. The turbines are designed to be optimal at wind-speed 4 m/s.

2. Methods

2.1. Horizontal-Axis Wind Turbine (HAWT) Design

Horizontal axis wind turbine (HAWT) is a wind turbine with rotation axis parallel to the wind direction. This kind of turbine is usually mounted on a tower, and can be aligned to the wind direction by using a back fin (Moreno, 2008). In many literatures it is mentioned HAWT can have higher efficiency than any other wind turbine (Castillo, 2011).

The HAWT design which is tested in this research is a modification of the design made by Hendriana et al. (2015), which is a HAWT with 6 blades with diameter 7.5 m each. This HAWT has a good efficiency of 52%. The design can be seen in Figure 2.

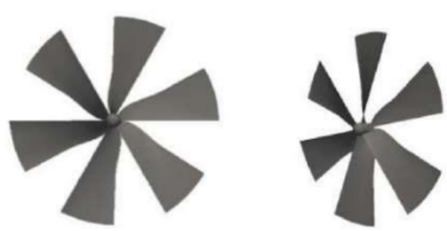


Figure 1. Wind energy potential in several areas in Java, Indonesia (Badan Pengkajian dan Penerapan Teknologi (BPPT), 2014)

In this research, the HAWT designed by Hendriana et al. (2015) is modified, so it has now only 3 blades with smaller diameter of 5 m. These modifications are done to reduce the weight and cost. Further simplification is taken by simplying the profile of the blade with straight line along radial direction to simplify the manufacturing process. The modified design can be seen in Figure 3.

Figure 3. Modified design of HAWT

2.2. Vertical-Axis Wind Turbine (VAWT) Design

Vertical-Axis Wind Turbine (VAWT) has axis of rotation perpendicular to the wind direction. The main axis is then usually set to be vertical (Castillo, 2011). VAWT has the advantage that it can rotate independent of the wind direction. This kind of turbine is suitable for places where wind direction often changes.

The VAWT which is used in this research is of the type Savonius, where the momentum of the wind is converted into high pressure, which then move the blades, just like for the sails in a sailing boat. Two VAWT designs are combined. The first one is made by Susanto (2017) which can be seen in Figure 4 (a), and the second one is made by Clements (2017) shown in Figure 4 (b).

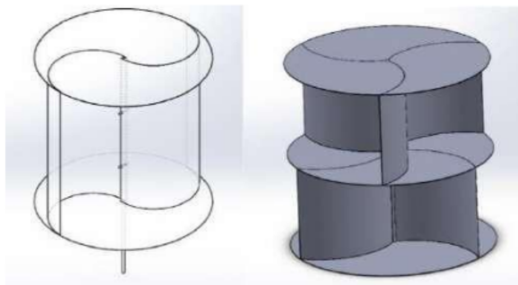


Figure 4. Two VAWT designs: (a) Susanto (2017) and (b) Clements (2017)

The design in Figure 4(a) is relatively simple, and need less material, and has high efficiency but the torque is not stable (going up and down in one rotation). On the other hand the design in Figure 4(b) has a stabile torque and high efficiency, but it needs more material due to too many blades. The modified VAWT used in this research has just two blades arrangement like in Figure 4(a), but the turbine is divided in two vertically like in Figure 4(b). Using only two blades should decrease the material cost, and the two layers should increase the stability of the torque. The resulting modified design can be seen in Figure 5. The height is designed to be 2 m and the total outer diameter is 2.4 m. The size of the turbine is chosen to maximize the utilization of plate material in the market with the size of 2.4m x 1.2m.

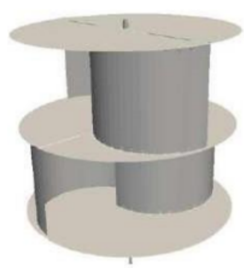


Figure 5. Modified design of VAWT

2.3. Computational Fluid Dynamics

Computer simulation analysis is performed using RANS turbulence method with the software called OpenFOAM. This is an open source CFD software and for more details, we can refer to OpenFOAM user guide (2018). This software has been undergoing lots of tests and validations by the CFD community in the world and good results have been reported everywhere. Furthermore, open source base software gives the opportunity for researchers to develop and improve the software. Besides, it is a free software license too.

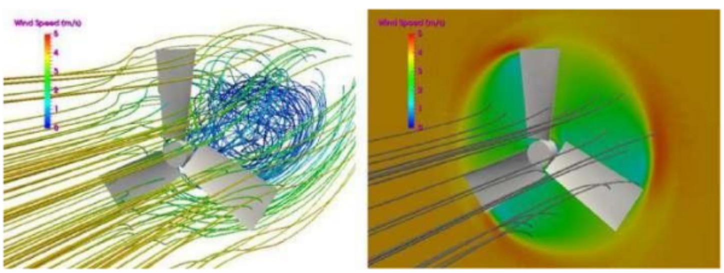
In this analysis, incompressible solver with Reynolds Averaged Navier-Stokes (RANS) and k-ω turbulence model is used. The module name in OpenFOAM is simpleFoam and simulation is run to get steady-state solution. Setup of the simulation is sketched in the following figure.

Figure 6. Simulation boundary conditions for turbine CFD analysis.

3. Results and Discussions

3.1. Horizontal-Axis Wind Turbine (HAWT) Results

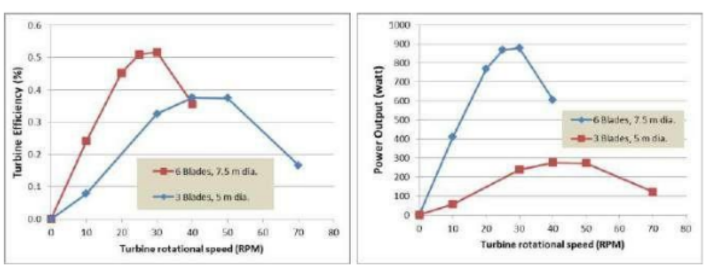
Simulation result for HAWT to show air streamlines and air speed distribution behind the wind turbine is shown in Figure 7. Large turbulence which is indicated by low air speed with blue color, behind the turbine is predicted. This area will be the location of turbine nacelle. The size of turbine back fin needs to be large enough to reach outside this turbulence area.



(a) (b)

Figure 7. Simulation result for HAWT, (a) Air streamlines colored by air speed (b) slice to show air speed distribution behind turbine

Comparing the performance of original HAWT design with 6 blades, diameter of 7.5 meter, smooth radial blade profile to the simplified HAWT design with 3 blades, diameter of 5 meter, straight line radial blade profile, turbine efficiency and output power curves as a function of turbine rotational speed can be seen in Figure 8.



(a) (b)

Figure 8. Turbine performance comparison between HAWT original design and simplified design (a) Turbine efficiency (b) power output.

Figure 8(a) shows that the peak turbine efficiency for the original design is 52% while the simplified design is 38%. This reduction of turbine efficiency is mainly influenced by the blade reduction from 6 to 3 blades. Notice that the peak turbine efficiency for original design is at around 30 rpm while for the simplified design at around 45 rpm. This shift of peak rpm is influenced by diameter reduction from 7.5 to 5 meter. The smaller the diamater, the higher is the peak rpm.

Figure 8(b) shows that the peak power output for original design is 890 watt at 30 rpm while for the simplified design is around 290 watt at 45 rpm. This power reduction is due to the turbine diameter reduction and lower turbine efficiency. The larger the diameter, the larger is the power output of the turbine.

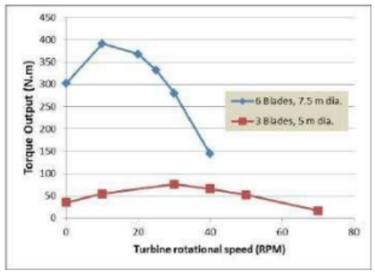


Figure 9. Turbine torque output performance comparison between HAWT original design and simplified design.

Figure 9 shows that the peak torque output for original design is 395 N.m at 10 rpm while for the simplified design is around 75 N.m at 30 rpm. This torque reduction is due to the turbine diameter reduction and lower turbine efficiency. The larger the diameter, the larger is the torque output of the turbine.

3.2. Vertical-Axis Wind Turbine (VAWT) Results

Simulation for VAWT is done with 2 different angle of turbine rotation, 0 degree and 45 degree angle. The sketch with turbine upper blade cross section for 2 different attitudes is shown in the following Figure. Note that the turbine attitude of 0 degree will be symmetrical to 90 degree attitude because the upper blade attitude is 90 degree difference to lower blade attitude. When the turbine attitude is 90 degree, the upper blade attitude will be the same as 0 degree lower blade attitude.

Figure 10. Simulation conditions for 2 different attitude of VAWT turbine.

Simulation result for VAWT to show air streamlines and turbine surface pressure distribution for 2 different attitude is shown in Figure 11. Turbulence area, indicated by low air speed behind the turbine is predicted. Air acceleration close to the rounded blade is seen indicated by higher air speed, red color. Close to this air acceleration is lower pressure on the blade surface, blue color. High pressure is seen in the open cup area of the blade, indicated by red color.

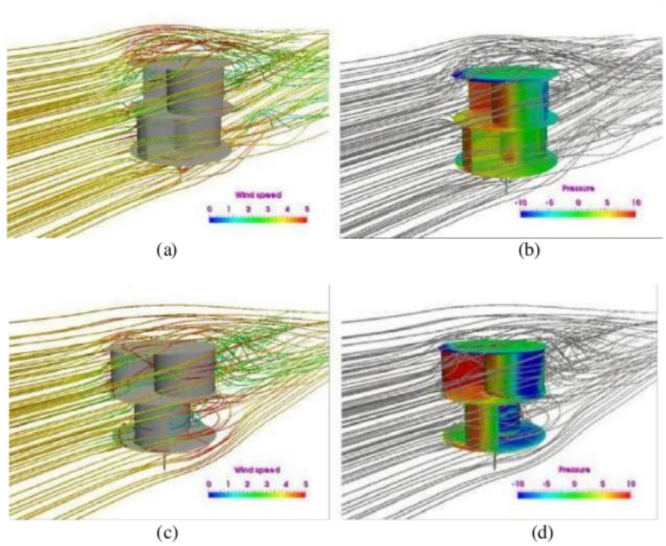


Figure 11. Simulation result for VAWT, (a) Air streamlines colored by air speed for 0 degree angle, (b) surface pressure distribution on the turbine for 0 degree angle, (c) Air streamlines colored by air speed for 45 degree angle, (d) surface pressure distribution on the turbine for 45 degree angle

Turbine torque and power output curves as a function of turbine rotational speed for 0 degree and 45 degree angle are shown in Figure 12. Estimated total torque and power output curves will be the average of 0 and 45 degree curves.

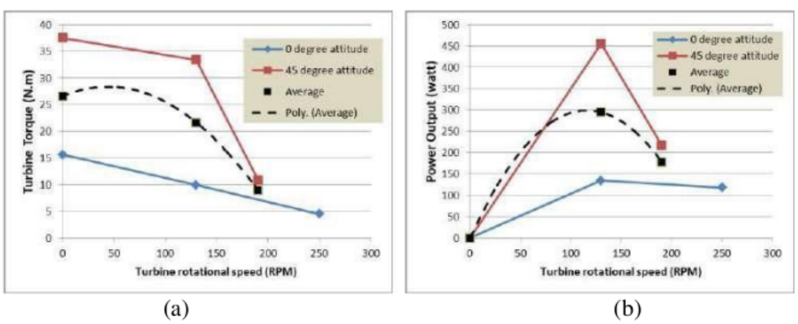


Figure 12. VAWT Turbine performance for 0 and 45 degree angle and its average (a) Turbine torque output, (b) Turbine power output.

Figure 12(a) shows that torque output for 45 degree angle is larger than for 0 degree angle. This will lead to pulsation of turbine rotation. However, mass inertia of the turbine will smooth the turbine rotation due to this torque pulsations.

Higher torque output lead to higher power output as shown in Figure 12(b). The 45 degree angle gives larger power output than 0 degree angle. The total expected power output of the turbine will be the average power output of turbine. VAWT turbine gives a peak power output of 300 Watt at 130 rpm.

3.3. *Turbine Comparison*

Dimension and predicted performance of Turbine HAWT and VAWT evaluated at the wind speed of 4 m/s is summarized in the following table.

Table 1. Comparison between HAWT and VAWT for wind speed 4 m/s

Parameter	HAWT	VAWT
Image		
Geometry	Outer diameter: 5 meter Sweep area: 19.6 m^2	Total height: 2 meter Total outer diameter: 2.4 meter Frontal area: 4.8 m^2
Maximum power output *(from computer simulation)*	290 Watt at 45 rpm	300 Watt (average) at 120 rpm
Maximum torque output *(from computer simulation)*	75 N.m at 30 rpm	28 N.m (average) at 50 rpm

As can be seen in Table 1, the VAWT can produce about the same output power as HAWT with much less frontal area. However, VAWT is running in higher rpm than HAWT. This is due to the size of the turbine. The smaller the size of turbine the higher rpm it will run. Due to its size, VAWT gives smaller maximum torque output as well.

4. Conclusion

The sizes of HAWT and VAWT turbines considered in this project are reasonable for transportation and manufacturing. Although VAWT turbine size is smaller than HAWT, they both are producing almost the same power of 300 Watt for low wind speed of 4 m/s. VAWT turbine is not very popular in Indonesia and the simulations show its potential for the electric generation application in low wind speed area. Nevertheless this simulation results must be verified using experiments.

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