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THE EXPERIMENTAL STUDY OF WASTE KINETIC ENERGY RECOVERY SYSTEM (WKERS)

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ABSTRACT

This project is intended to convert waste kinetic energy into electrical energy from the source of wind energy discharged from a cooling tower. The design of the blade of the vertical axis wind turbine (VAWT) is inspired by the pectoral fin of the Humpback whale (Megapteranovaeangliae) with its tubercles. After the process of flow simulation of the whale-inspired blade with the geometry of aerofoil BACXXX-il, a prototype is fabricated by 3D printing for further evaluation process. The experiment is illustrated using a floor fan which produces an average wind speed of 4.37 m/s, which is compatible with the wind speed produced by a small size cooling tower. According to the pitch angle setting from 0° to 90° for every interval of 5°, the best angle of attack is selected based on the highest rotational speed of the wind turbine produced by the wind, eventually coming to an end where the highest output voltage generated by the generator is considered.

Keywords: whale-inspired, vertical axis wind turbine, regenerative system, humpback whale's tubercles.

INTRODUCTION

Energy resources are limited since world energy demand increases in accordance to population growth and the economic development. Growing concern in Malaysia has arisen about the energy consumption and its adverse environmental impact. There are plenty industries that use high energy-consuming cooling tower in Malaysia due to the humid environment and hot weather, lead to the release of waste energy into environment, mostly in terms of kinetic and heat energy. No matter which method is used to transfer heat from machinery or heated process materials, the heat energy has always been rejected to the atmosphere as a waste energy. Moreover, the function of a cooling tower is well known to do the heat transfer process, hence indirectly create wind energy and reject it to the atmosphere which is considered as waste energy.

All those energy are extracted from the fossil fuels (eg: coal, natural gas, petroleum etc.), which are also the primary source for energy in the world(U. S. Energy Information Administration, 2015). Overharvesting of fossil fuels brings negative impacts on human health and environment by the emissions of greenhouse gas (W. T. Chong, 2014). For developing sustainability in long term, the utilization of renewable energy such as solar, wind, rain, tides and waves was encouraged. To minimize the negative impacts on energy supply chain in Malaysia, renewable energy is considered as the fifth energy under the Fifth Fuel Policy which was launched in 2000(C. Chong *et al*. 2015).

The wind energy in Malaysia is not suitable for generating electricity because the wind is not uniformly blown. Even though there are some regions in Malaysia that could reach up to 15 m/s of wind speeds, but the mean annual wind speed in this country is analyzed to be 1.8 m/s (G. Basil, 2013). Taking that into considerations, cooling tower has the most suitable wind speed, being produced when it operates. Indeed the best thing is, the source is constant (A. M. Najib, 2015). A wind turbine could not rotate without a good lifting blades, even if the finest generator is installed. Therefore, the design of the blades to harvest the best lift effect is the most important part to be proposed.

REVIEW OF WKERS INSTALLATION

Speaking about the blade design of the wind turbine which is the main role of the regenerative system, there are two classes of wind turbine, which are vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). There are some theoretical methods which will affect the efficiency and also performance of the regenerative system, such as propulsion, gravitational, gyroscopic, centrifugal, aerodynamic and more (P. J. Schubel and R. J. Crossley, 2012). VAWT faces any direction of wind and it uses straight or curved bladed rotor with rotating axes perpendicular to the wind stream (M. Mahmood, 2012). Above all, the Bernoulli's Principle is taking into consideration as the primary concept of the aerodynamics, where the low wind speed on the aerofoil surface will perform high static pressure or vice versa. Consequently, the pressure gradient between suction surface (upper surface) and pressure surface (lower surface) contributes to the lift force for the aerofoil.

The motive of three blades turbine

The number of blade is one of the important issues that need to be concerned before developing a wind turbine (S. Muluk, 2014, F. Wenehenubun *et al*., 2015). A turbine with only one blade will be the cheapest costing for development, but the presence of unbalancing is one of the considerations. However, the one-bladed turbine is able to rotate at high tip-speed ratio. The even number of blade will affect the stability of the turbine and has a lower inertia moment. Thus the lesser the number of blade, the higher the efficiency of a wind turbine (S. Muluk , 2014).

Figure-1 shows the graph power coefficient C_p variation against tip-speed ratio for the computational result of two, three and four blades of Savonius wind turbine.

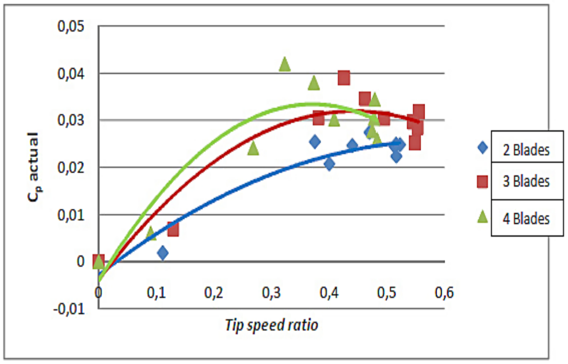

Figure-1. Power coefficient C_p variation with tip speed ratio [9].

The wind turbine with four blades performed the good at lower tip-speed ratio, but the three blades has the best performance at high tip-speed ratio. In other words, the four blades is the best choice of the wind speed of 6m/s; but when coming to the wind speed of 6 m/s to 8 m/s, the three blades turbine will have the advantages (F. Wenehenubun *et al.* , 2015). Therefore, a total number of three blades is proven to become a criterion wind turbine for the current industries based on the aerodynamic concept (P. J. Schubel and R. J. Crossley, 2012, S. Muluk, 2014, F. Wenehenubun *et al.,* 2015). The stiffer blade will encounter higher lift on the blades.

Beneficial of inspired design idea

The idea of whale-inspired blade design came from the pectoral fin of the humpback whale (Megapteranovaeangliae) which is extraordinary large among the other whales. With the help of its aquatic maneuverable extended flippers and leading-edge tubercles, the humpback whale would be able to be a harmful predator to the prey (F. E. Fish and J. M. Battle, 1995). Blade design to be incorporated in the wind turbine is based on the utilization of Whale-Inspired Tubercles. Figure-2 shows the results of the whale inspired design on field which has been transformed into the wind turbine design, tested by Wind Energy Institute of Canada (WEICan). From the cut-in wind speed of 5 m/s and 35 kW of power limit, the whalepower blade shows the better performance than the Wenvor published data, indeed that the power output of the whalepower blade is achieved at lower wind speed than that of Wenvor's (L. E. Howle, 2009).

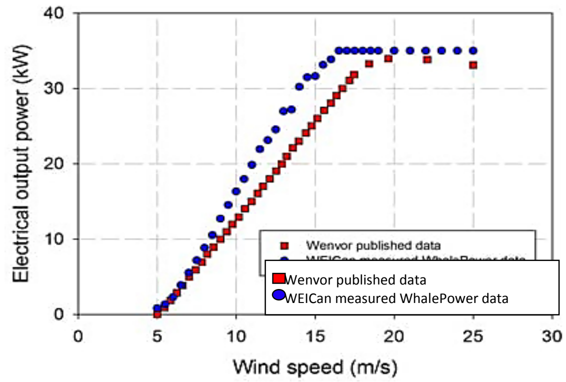

Figure-2. Comparison of electrical power produced between Wenvor published data and WEI can whale power data (L. E. Howle, 2009).

Moreover, the big curved tubercles along the leading edges of the wing-like flipper which is helping the humpback whale in turning and banking, the tubercles presenting an increasing of lift coefficient (C_L) and decreasing of drag coefficient (C_D) (F. E. Fish *et al.,* 2011, D. S. Miklosovic *et al.,* 2004). The drag coefficient experimentally shows the scalloped flipper is decreased compared to the baseline geometry. Eventually, the aerodynamic efficiency shows a great increase in lift to drag (L/D) ratio for the scalloped flipper which is considered the flipper producing a high lift low drag performance (F. E. Fish *et al.,* 2011-K. L. Hansen *et al.,* 2009). Presence of tubercles is to produce a delay in the angle of attack until stall, thereby increases a maximum lift with the decrease of drag (A. Farouk and A. Gawad, 2013). More power at slower speeds can be generated by this Whale-Inspired blade compared to the conventional one, with lesser noise.

METHODOLOGY

The primary progress of the WKERS implementation for the cooling tower system require the process of design, simulation, fabrication, finishing, and data collection. The design and simulation process is done by using SolidWorks design software, followed by the fabrication process of the blades that is printed by UP Plus 3D printer. After the finishing process, the experimental output data collection is evaluated and analyzed. By any means necessary, the small lab-scale prototype has to be tested indoor in the laboratory before the attachment on the real cooling tower on the roof top for the sake of some safety issues such as the broken blade fly off or bird crash by mistake.

Mechanical design & working principle

The SolidWorks design software is the main tool of the whole design process. The first step for the design process is the design of the housing for the center generator. The design of the housing included the function of setting the blade angle, θ which is the angle between the chord line and the airflow direction. Blade angle is practically a complementary angle with pitch angle, β such as;

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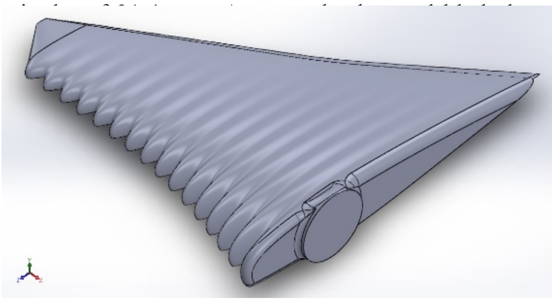
$$\theta + \beta = 90° \quad (1)$$

In addition, the blade angle is designed to be set from 0° to 90° for every interval of 5°. The aerofoil geometry for designing the blade, aerofoil BACXXX-il is imported from UIUC Airfoil Coordinates Database.

The whale-inspired blade planform designed in 226.45 mm along in tapered feature included 7.076 mm long of transition section from the root to the aerofoil BACXXX-il. The wingtip is attached with a tapered



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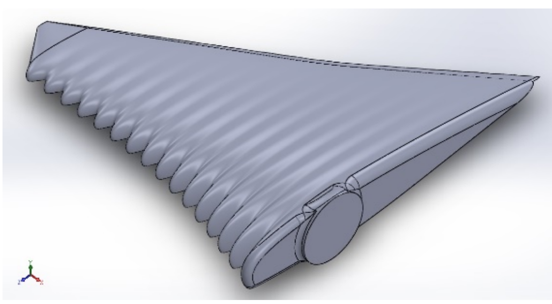

Figure-3. Whale-inspired blade design.

It could be a blocking effect after the whale-inspired WKERS is placed on top of the cooling tower's outlet. Hence, the discharged flow rate need to be taken into consideration and an important parameter to determine the present of blocking effect. It is calculated by:

$$Q = V_{outlet} \times A_{out} \quad (2)$$

where is the discharged flow rate, V_{out} representing the discharged airflow speed from cooling tower, and A_{out} will be the outlet area.

Development & refinement

The fabrication part is organized by 3D printing and then go through the underwater polishing to get the smoother surface which achieved the mirror effect. Thenceforth the printed parts is assembled including the SHIMANO DH-3N30 dynamo hub as generator for the wind turbine. For the reason of the relativity between airflow speed and the height above cooling tower outlet (A. M. Najib *et al*., 2005), the distance above the floor fan to the wind turbine is set at 130.0 mm on behalf of the highest airflow speed that is measured in that position. The whole system is mounted on a frame which is built with 20mm × 20mm extruded aluminium profile, indeed the frame is clamped on the ground to reduce vibration caused during the turbine rotation. The masterpiece of lab-scale prototype for indoor test is shown in Figure-4.

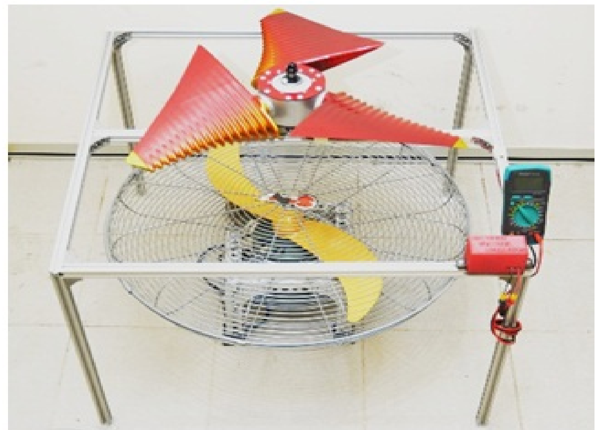

Figure-4. Whale-inspired WKERS.

Monitoring system

For the observation and evaluation parts, the accuracy of the instrument is important to prevent instrumental error, hence the result obtained will be precised. The digital multimeter is used to measure the output voltage from 200 mV up to 200 V which has the accuracy of ±1.0%. The full-wave rectification circuit controller convert the output of the SHIMANO 6V-3W dynamo from alternating current (AC) to direct current (DC). With the present of capacitors, the output voltage V is more stable then the one that examined with the digital multimeter.

Eventually, a digital anemometer is able to measure the wind speed from 0 m/s up to 30 m/s which is having the resolution of ±0.1 m/s and used to determine the airflow speed of the floor fan in ±5% of accuracy. The average of the airflow speed is taken by measuring from a few positions along the radial distance of the floor fan propeller from the root to the tip to reduce random error. The measurement of RPM by using digital tachometer has an accuracy of ±1 rev/min for measuring the rotational speed from 30 rev/min to 12,499 rev/min. All data has to be measured after the turbine rotation, fan propeller or both had been stabilized.

A digital clamp meter with a measurement current range of 200 A is used to measure the current drawn for the floor fan to produce the wind source. The digital clamp meter has a resolution of 100 mA and ±3% accuracy in 50 Hz to 60 Hz frequency.

RESULTS AND DISCUSSION

Computational results

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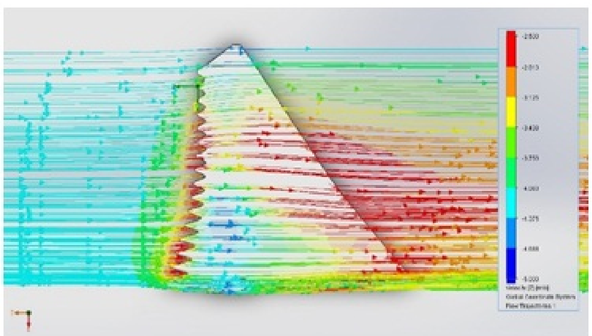
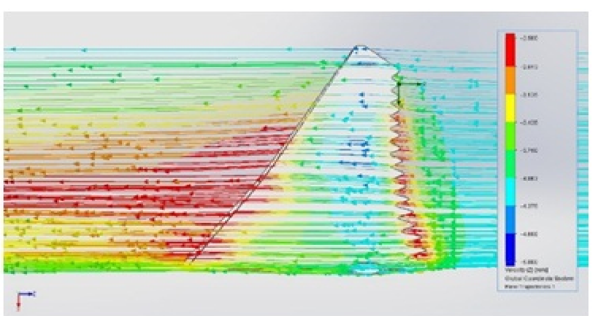
To demonstrate the study of the new development whale-inspired blade, Solid Works design software is used to carry out the simulation. The flow velocity and static pressure simulated the wind flow from leading edge to trailing edge through the surface of the whale-inspired blade presented in **Error! Reference source not found.** and **Error! Reference source not found.**. A comparison is made between **Error! Reference source not found.** (a) and (b), where higher average velocity on suction surface than that of the pressure surface can be seen.

On the other hand, the static pressure on the pressure surface is higher than that on the suction surface in **Error! Reference source not found.** (a) and (b). Therefore, the pressure gradient is relatively creates the lift force on the blade, so the Bernoulli's Principle is proven. Besides, it is clearly seen that the scalloped design split up the stream when its reach the leading edge, all at once flow through the cleavages in between the humps to concentrate the flow. For this reason, whale-inspired blade is believed to reduce the vortices created ahead to the tip, hence the drag will be reduced.

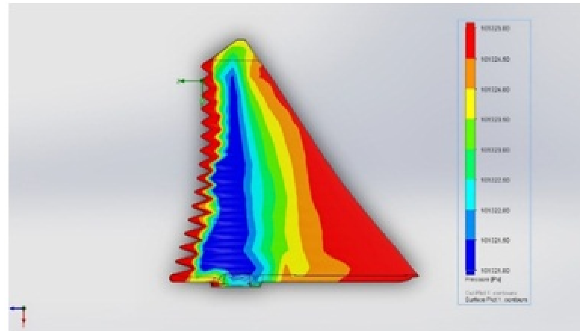


(a)

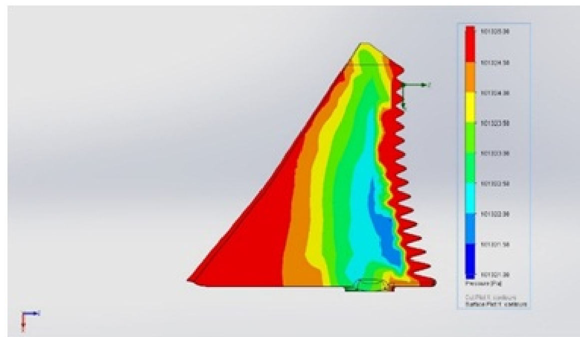


(b)

Figure-5. Whale-inspired blade surface flow velocity simulation.



(a)



(b)

Figure-6. Whale-inspired blade surface static pressure simulation.

Indoor experimental results

Firstly before staring the indoor lab test, the prefect way to handle the measurement instrument is well trained to avoid gross error caused by the tester. The average airflow speed from the source of the floor fan is measured to be 4.37 m/s from the fan propeller root to the tip for preventing unwanted random error. The measurement is taken after the fan propeller spinning had stabilized to reduce the random error.

Meanwhile, the measurement of the rotational speed and output voltage is collected after the spinning of the wind turbine had become stabilized, then the result data is tabulated and plotted into a graph shown in **Error! Reference source not found.**. The result shows the generator produced an output voltage of 3.9 V and 19 rev/min rotational speed, but the blade is rotated in opposite direction which is considered as a negative effect. However, there is no rotation created in between 5°, 10°, 15°, 80°, 85° and 90° blade angles, this is because of less lift force to overcome the generator starting torque to push the blade and turn the turbine.

Furthermore, both the rotational speed and output voltage increased steadily from 20° to 70° blade angle and reached the peak with 372 rev/min and 58.4 V respectively. The rotational speed and output voltage is then start descending at the blade angle of 75°, the whale-inspired blade is exceeded the stall point of maximum lift. Particularly, the blade angle of 75° is relatively outreached the critical angle of attack.

Based on the given result in **Error! Reference source not found.**, the rotational speed increased grammatically relative to the output voltage from the generator, this proved that the electrical power generated by the generator and the wind turbine rotation are proportional to each other. Simultaneously, the peak of turbine RPM is slightly higher than that of the maximum output voltage, this is no doubt that the optimum performance of generator is achieved, yet the wind turbine rotation still progressively performed.

Another average airflow speed measurement is taken above the wind turbine. The measurement is taking into consideration to determine the difference airflow speed before and after the whale-inspired WKERS. As a result, the whale-inspired WKERS produces a minimum blocking effect on the cooling tower system since the average airflow speed discharged is reduced from 4.37 m/s to 4.28 m/s. The airflow speed is reduced about 2.06%, but there is no significant of extra current drawn when measured with the digital clamp meter. Therefore, the real scale of whale-inspired WKERS is needed for an accurate and precise test in order to observe the extra current drawn due to the blocking effect.

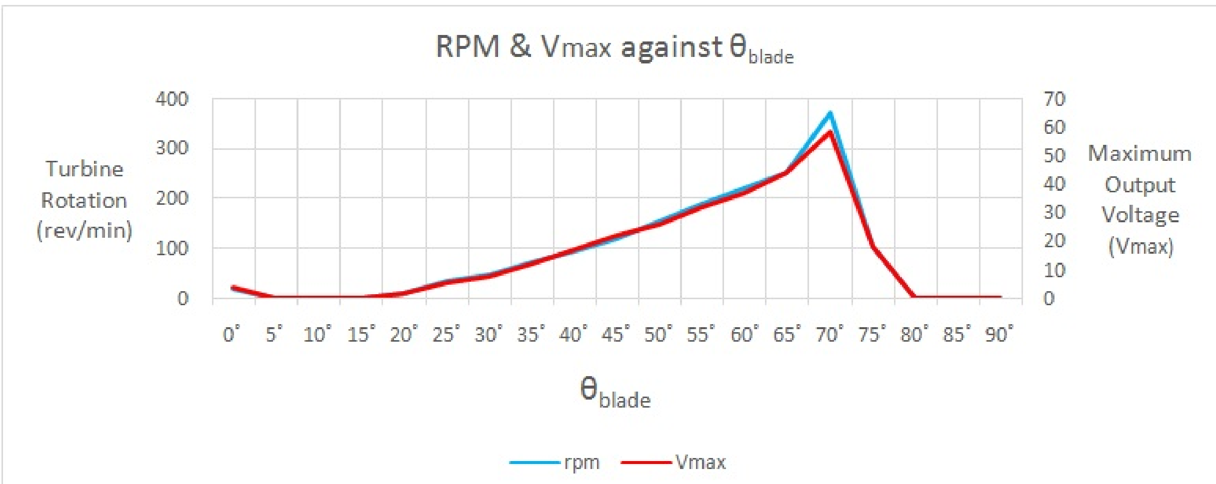


Figure-6. Relationship between rotational speed (RPM) and maximum output voltage (V_{max}) to the blade angle (θ_{blade}).

CONCLUSIONS

This research work highlights the ability to maximize the whale-inspired wind turbine potential to improve the performance of a WKERS by varying its blade angle. By analyzing from 0° to 90° of blade angle, the result represents the effect of blade angle to the turbine rotational speed. The best performance identified for whale-inspired is the 70° blade angle, under amplitude A = 0.1C and wavelength λ = 14.152 mm.

The indoor lab-scale prototype is able to generate output voltage up to 58.4 V with 372 rev/min. However, there is a blocking effect which reduced 2.06% of the airflow speed when conducting the indoor lab test. Hence, further study for the energy conservation law is needed to improve the efficiency of the whale-inspired WKERS. Nevertheless, the lost airflow could be any outflow to atmosphere and caused the reduction of airflow speed. Thus, an enclosure may need for further design and development. This study idea could then be applied to power a lightning system for a building or fed into existing gridline with authority imposed tariff. This innovative green technology product possesses good market potential.

FUTURE RECOMMENDATIONS

Further enhancements and modifications will be carried out to improve the efficiency of the whale-inspired wind turbine:

i. A better design and proper dimension of the winglet.
ii. A better combination of the amplitude-to-wavelength ratio for the scalloped design.
iii. Scaled-up prototype to actual dimension compatible to the real cooling tower for more effective validation.
iv. Replacement of the generator to get the optimum energy outcome.
v. Study of the minimizing the blocking effect of WKERS on the cooling tower system.

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This product and its images of WKERS are protected by legal copyright laws by the Intellectual Property Corporation of Malaysia under application number: LY2016000528.

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iii. UTeM Research and Innovation Expo (UTeMEX 2015)

iv. Mini UTeM Research and Innovation Expo (MINI UTeMEX 2014)

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