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Investigation on the effect of diffuser and guide-vanes on an exhaust air energy recovery turbine for energy conservation

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ABSTRACT

An enclosure which was built with several guide-vanes and diffuser-plates as power-augmentation features for an on-site energy conservation system is investigated. Two vertical axis wind turbines (VAWTs) that are integrated with the enclosure are installed above an exhaust air outlet to recover a part of the discharged wind energy for electricity generation. On-coming airflow is guided to an optimum angle of the VAWT blades by arranging four guide-vanes at pre-defined angles between the VAWTs and the exhaust air outlet. Diffuser-plates are tilted at 7^{o} relative to its vertical axis to create a venturi-effect which accelerates the discharged airflow. Laboratory test (cooling tower scaled model with 0.3 m diameter of a 5-bladed H-rotor) was conducted to investigate the effect of integrating the enclosure with the VAWTs. From the test, optimum matching of guide-vane angle and VAWTs is achieved for optimum performance and higher efficiency of the VAWT. Significant improvements on the VAWTs' rotational speed (7 – 8 % increment) together with their self-starting behavior (42 – 60s faster) were observed when the guide-vanes are adjusted at their optimum angle. Meanwhile, intake air speed into the cooling tower was increased by 33%. This product can contribute to the reduction of greenhouse gases emission and conservation of the environment for a healthier life since fossil fuel consumption for energy generation is reduced.

1. INTRODUCTION

Nowadays, due to the decreasing availability of economic wind energy sites along with increasing urban density, there are plans to install wind turbines closer to

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populated areas for on-site clean energy generation. In order to site wind turbines out from rural areas, the current problems of wind turbines need to be resolved, especially visual impact, poor starting behavior in low wind speeds and danger caused by blade failure. Most of the wind turbines are designed for high wind speed since they are rated at 10 – 15 m/s and meanwhile, they start to operate in 3 m/s of wind speed. As a result, conventional wind turbines are not commercially viable for Malaysian applications as wind speed in Malaysia is relatively low most of the hours all over the year (annual wind speed is in the range of 0 – 3 m/s) (Khatib, Sopian, Mohamed, & Ibrahim, 2012).

In such a case, an efficient solution to generate greater amount of energy from wind would be by increasing the wind speed. Hence, an enclosure was designed as a power augmentation device (which was built with 2 diffuser-plates and 4 rows of guide-vanes) with the objective to improve the local wind flow. Providing that, the wind speed discharged from the cooling tower was recorded up to 18 m/s (measured at a distance of 0.3 m above the cooling tower outlet) and is favorable for electricity generation. Two vertical axis wind turbines (VAWTs) integrated with the enclosure are properly positioned above a cooling tower outlet as an exhaust air energy recovery system. A portion of the exhaust fan motor consumption is expected to be conserved by converting the wasted discharged wind energy from the exhaust air system. There are numerous cases of forced ventilated situations available globally such as ventilated exhaust from air conditioning systems (Chilugodu et al., 2012). Consequently, these situations will result in the developed system having a high market potential.

In this study, the effect of both diffuser-plates and guide-vanes were investigated with two VAWTs by conducting laboratory tests. An optimum matching of guide-vane angle together with the diffuser-plates and VAWTs is achieved for optimum performance and higher efficiency of the VAWTs.

2. WIND POWER AUGMENTATION DEVICES

2.1 Diffuser design

Theoretically, an increase in wind speed across the turbine rotor significantly increase the wind power output since wind power is directly proportional to the cubic power of the wind speed approaching a wind turbine. There are many researches being done in attempts to effectively enhance the approaching wind speed. Diffuser augmented wind turbine (DAWT) is among the most tested devices to improve the overall output power of a wind turbine. Efficiency of a wind turbine is increased by using a shrouded funnel-shape structure (acts as a separation region) to increase suction at the rear of the turbine as a result from the increased differential pressure across the rotor. The low pressure region will draw more wind and allow it to accelerate (Foreman, Gilbert, & Oman, 1978). Furthermore, wind turbines are operated at lower wind speed since cut-in wind speed is improved. Over a period of time, there are various kinds and geometries of diffusers that have been developed. With appropriate and optimum design of the structure for the diffuser, velocity augmentation is about 1.2 times the upstream wind speed (Kishore, Coudron, & Priya, 2013). It was reported that power augmentation of the wind turbine can be significantly improved up to 4 – 5 times with the flanged diffusers (Ohya, Karasudani, Sakurai, Abe, & Inoue, 2008). Based on the test results processed by M. Kardous et al., the increased rate of wind velocity for diffuser without flange is about 58% while for the flanged diffuser, the rate is extended at the range of 64% – 81%. The effect of adding the flange is tabulated to be in between 13% and 23% since vortex formation increased at the exit path of wind flow, thus more mass flow was drawn to the wind turbine (Kardous, Chaker, Aloui, & Nasrallah, 2013).

2.1 Guide-vanes design

Guide-vane is a set of fixed structure arranged around the rotor that guides the oncoming wind into the moving blades of a turbine with minimum loss of energy. The vanes divide the fluid into several flow channels which guide the flow to an optimum angle of attack of the turbine blades (W. T. Chong, Fazlizan, Poh, Pan, & Ping, 2012). According to a study conducted by Takao et al., performance of the straight bladed VAWT can be enhanced by the directed guide-vane row in terms of power coefficient and torque coefficient. Guide-vanes generate wake in its downstream and whirl velocity of inlet flow to the rotor is increased (Takao et al., 2009). The increase in the power output with the guide-vanes installed is dependent on the geometry of the guide-vane and the VAWT position relative to the guide-vane (Kim & Gharib, 2013). Optimum configuration of guide-vanes can increase the power output coefficient by more than 27% (Mohamed, Janiga, Pap, & Thévenin, 2010). To further extract the output power from the wind, an omni-direction-guide-vane has been developed which is able to collect the on-coming wind from any direction. It was observed that the output power of a VAWT was enhanced by 206% at a tip speed ratio of 0.4 with the presence of the ODGV through CFD simulations (Wen Tong Chong, Poh, Fazlizan, & Pan, 2012).

3. DESIGN DESCRIPTION AND GENERAL ARRANGEMENT

An exhaust air energy recovery system which consists of two VAWTs (in cross wind orientation) that is integrated with an enclosure is depicted in Fig. 1. It is installed above the outlet of a cooling tower to capture the discharged wind energy for electricity generation. VAWTs are carefully positioned at their respective optimum position to assure none or minimum of negative effect exerted on the original system.

The enclosure is designed to extract the maximum possible of the discharged wind for energy conservation. It is formed with two diffuser-plates which are installed inclined outwardly at 7^o relative to their vertical axis at both sides of the VAWT. Based on Bernoulli's principle, a venture-effect is created allowing wind velocity augmentation to be achieved as a result from a drop in pressure within the diffusers. This feature is beneficial to VAWTS in terms of their performance as they are capable of self-starting sooner and rotating closer to its rated speed. In addition to that, several rows of guide-vanes are arranged in between the VAWTs and the cooling tower outlet at their respective optimum angle to further increase the wind power output. The installed guide-vanes provide optimized and smooth airflow which matches with the optimum angle of attack of the turbines blades. As a result, the wind turbines move with higher thrust force since maximum lift force is created.

The enclosure design takes into account the safety of personnel by installing both of the VAWTs inside the enclosure. The enclosure acts as a protective cover to the entire system from public or maintenance worker hazards. Chances of blade flying off whenever there is blade failure could be minimized. The electricity generated from this system can be utilized for local commercial or sold back to the grid based on feed-in tariff.

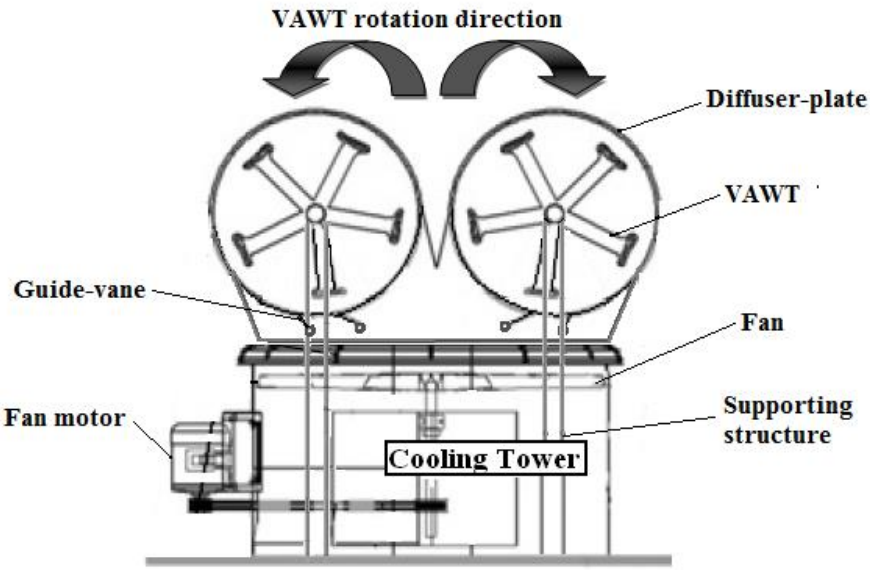

Fig. 1 General arrangement of the exhaust air energy recovery system

4. EXPERIMENT SET- UP FOR LABORTORY TEST

The effect of adding diffuser-plates and guide-vanes was examined in laboratory test. Fig. 2 shows the laboratory test set-up on a scaled model of cooling tower. A 0.7 meter diameter cooling fan which was enclosed in a 0.8 meter diameter circular duct was treated as a scaled down model of a cooling tower. Two 5 bladed H-rotor wind turbines (each with 0.3 meter rotor diameter) are located at a height of 0.26 meter (measured from fan outlet to the center of the wind turbine). At the bottom of the cooling tower, there was a gap of 0.195 meter from the floor (with the air inlet area of 0.5329 m^2).

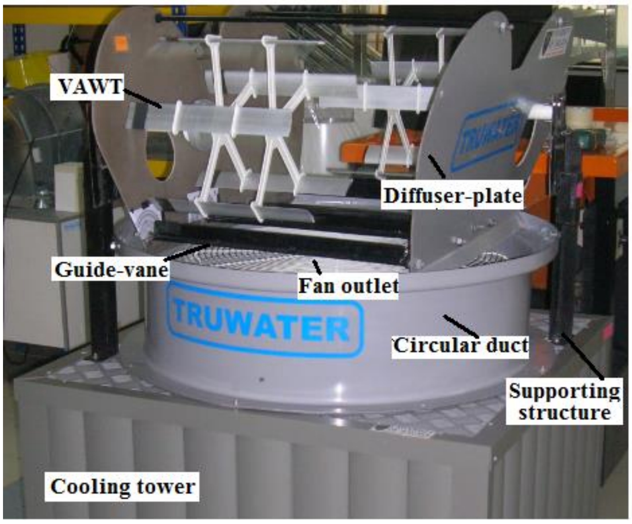

Fig. 2 Laboratory test set-up

4.1 Diffuser-plates effect test

The first part of the test is to examine the effect of adding the diffuser-plates on the VAWT performance. Diffuser-plates were mounted on the outlet of the circular duct with a slant of 7° relative to its vertical axis as suggested by Abe et al. (Abe et al., 2005). Several measurements had been recorded to identify the difference between both with and without diffuser-plates. The fan motor current input was measured by using a current clamp meter at the LIVE wire. A hot wire anemometer was used to measure the air intake speed of the scaled model of cooling tower at four intake points of the air inlet area labelled in A, B, C and D as shown in Fig. 3 after the rotational speed of the wind turbine had stabilized. Then, the rotational speed of the VAWTs and fan was measured with two hand held laser tachometers.

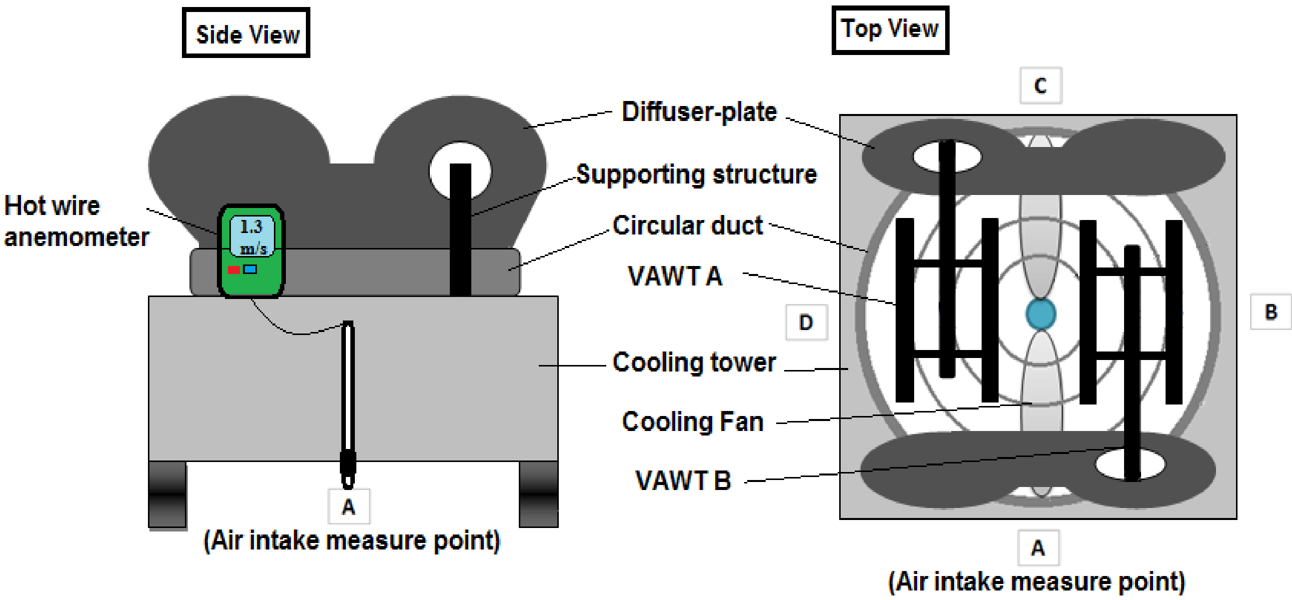

Fig. 3 Air intake speed measurement method of the cooling tower

4.2 Guide-vanes effect test

Four guide-vanes have been positioned below the VAWTs within the diffuser-plates. The optimum angle of each guide-vane was first determined by measuring the wind turbine rotational speed while varying the angle of each guide-vane. The angle of guide-vane A was adjusted first to start from 0°until 180° as shown in Fig. 4 to determine the optimum angle which gives maximum rotational speed while guide-vane B, C and D remained at angle 90° (assuming 90° is similar with scenario without guide-vane). These procedures were repeated for the remaining guide-vanes once the optimum angle for guide-vane A was obtained. Similar with diffuser effect test, readings for intake wind velocity, power consumption of fan motor and VAWT rotational speed were obtained to study the effect of guide-vanes for the test condition when there are no guide-vanes and when the guide-vanes are adjusted at their respective optimum angle.

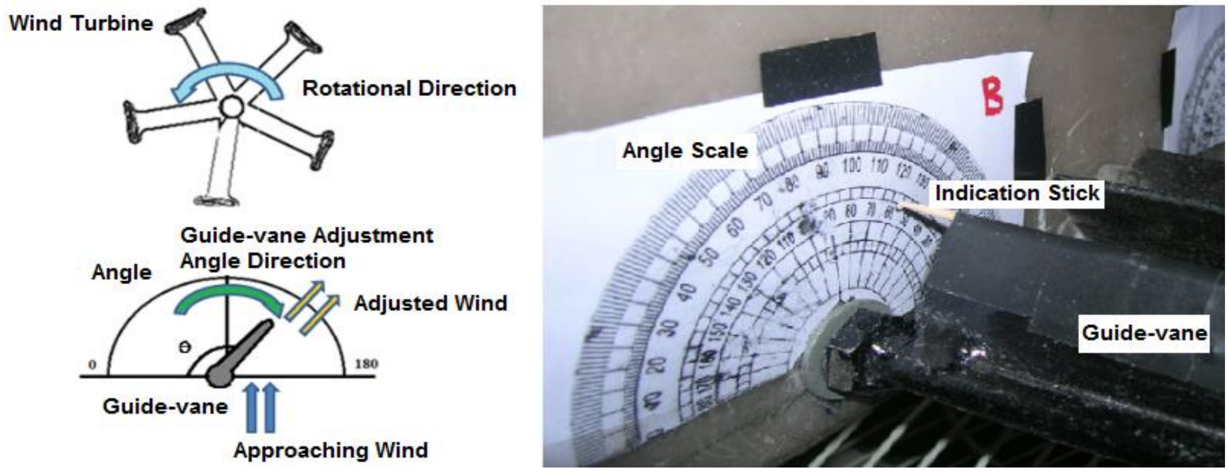

Fig. 4 Guide-vanes adjustment method

5. RESULTS AND DISCUSSION

Table 1 presents the measurement results for all the test conditions from the laboratory test. The measured results for the first test condition (small scale model of the cooling tower only) will be considered as the baseline for the entire experiment. The discharged wind speed from the cooling tower's outlet was recorded at 5.35 m/s. After the installation of both VAWT A and B, it was observed that both VAWTs are capable of self-starting with the rotational speed for VAWT A at 438 rpm and VAWT B at 444.7 rpm at free-running condition (no loading). A decrease in fan power input was observed as low pressure region was created around the rotor of the VAWTs when they are rotating above the cooling tower.

After the inclusion of diffuser-plates, a significant increase in the air intake speed was recorded with the average value of 30% (compared with the condition of cooling tower only). This increment was observed due to the suction effect increased as a result from the increase in differential pressure around the rotor of the VAWTs. On the other hand, the power consumption of the fan motor was reduced from 203.84 W (cooling tower only) to 199.51 W (with diffuser-plates). These results show that the suction effect resulting from the diffuser-plates installation helps to reduce the work load of the fan by drawing more air into the cooling tower (recorded at 2.47 m/s). In addition, the tip speed ratio for the VAWTs was tabulated with the value of 1.28 - 1.29. This means that both the VAWTs are rotating about 1.29 times faster compared with the oncoming wind speed.

From guide-vanes effect test, the optimum angles arrangement for guide-vanes A – D are achieved which is 40°, 70°,70°, and 40°. When the 4 guide-vanes were installed at their respective optimum angle together with the diffuser-plates, about all the measurement parameters show positive effect especially in the rotational speed of both VAWTs (7 – 8% increment) and their self-start time (about 42 – 60s faster in order for the VAWTs to reach 430 rpm) when comparing with the results obtained for test condition of cooling tower. Additionally, intake air speed into the cooling tower was increased by 33%. However, a minimum increment in power input to the fan motor was detected with the value of 0.3 W as compared with the test condition of diffuser-plates installation. This scenario occurred due to guide-vanes causing a minimum blocking effect to the fan motor. The slight increase in power may be also due to the increase in intake air flow rate that is handled by the fan motor. Since the increment value of the fan power is lower as compared with the condition for cooling tower only (1.97% lower compared to original system's power consumption), the small negative effect as a result from the guide-vanes does not affect the original performance of the cooling tower and no additional load was exerted on the motor. Besides, the small increment in fan motor input power can be compensated by the power generated by the VAWTs.

Table 1 Laboratory test results

Test Condition	**Rotational Speed (rpm)**		**Intake wind speed (m/s)**	**Fan motor power input , P_{in} (W)**	**Self-start time (s)**	
	VAWT A	**VAWT B**			**VAWT A**	**VAWT B**
Cooling Tower only	-	-	1.90	203.84	-	-
VAWT A and B only	438.0	444.7	2.15	200.20	101.7	150.0
Diffuser-plates	465.6	468.6	2.47	199.51	83.3	110.5
Diffuser-plates and Guide-vanes	474.7	475.3	2.52	199.81	59.6	87.8

6. CONCLUSIONS

This paper investigates the effect of adding diffuser-plates and guide-vanes on an exhaust air energy recovery turbine which is placed on top of an exhaust air system. As a result, the optimum configuration of the enclosure is identified with the diffuser-plates installed slant at 7^{o} relative to its vertical axis and the 4 guide-vanes are arranged at angles of 40^{o}, 70^{o}, 70^{o} and 40^{o} counting from guide-vanes A – D.

Based on the laboratory test results on the scaled model of cooling tower, it was observed that the VAWTs rotational speed was significantly improved in the range of 7 – 8 % when the enclosure design was optimized. Besides, inclusion of the enclosure also helps to improve self-starting behavior of the VAWTs (about 42 – 60s faster for the VAWTs to reach their stable rotational speed) which solves the conventional problem for low wind speed countries. A slight reduction in the workload of the fan motor was observed with the value of 1.97% lower compared to the original system's power input to the motor can be achieved by integrating the enclosure with the exhaust air energy recovery turbines.

By turning the discharged wind energy from the cooling tower outlet to electricity, this system is an on-site energy conservation system that is capable of directly supplying a portion of the energy demand of a metropolis. It does not cause any kind of pollution and furthermore, lesser greenhouse gases will be emitted to the atmosphere leading to a healthier city and environment.

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REFERENCES

Abe, K., Nishida, M., Sakurai, A., Ohya, Y., Kihara, H., Wada, E., & Sato, K. (2005). "Experimental and numerical investigations of flow fields behind a small wind turbine with a flanged diffuser." *Journal of Wind Engineering and Industrial Aerodynamics*, **93**(12), 951-970. doi: 10.1016/j.jweia.2005.09.003

Chilugodu, N., Yoon, Y.-J., Chua, K., Datta, D., Baek, J., Park, T., & Park, W.-T. (2012). "Simulation of train induced forced wind draft for generating electrical power from Vertical Axis Wind Turbine (VAWT)." *International Journal of Precision Engineering and Manufacturing*, **13**(7), 1177-1181. doi: 10.1007/s12541-012-0156-6

Chong, W. T., Fazlizan, A., Poh, S. C., Pan, K. C., & Ping, H. W. (2012). "Early development of an innovative building integrated wind, solar and rain water harvester for urban high rise application." *Energy and Buildings*, **47**(0), 201-207. doi: 10.1016/j.enbuild.2011.11.041

Chong, W. T., Poh, S. C., Fazlizan, A., & Pan, K. C. (2012). "Vertical axis wind turbine with omni-directional-guide-vane for urban high-rise buildings." *Journal of Central South University*, **19**(3), 727-732. doi: 10.1007/s11771-012-1064-8

Foreman, K. M., Gilbert, B., & Oman, R. A. (1978). "Diffuser augmentation of wind turbines." *Solar Energy*, **20**(4), 305-311. doi: 10.1016/0038-092x(78)90122-6

Kardous, M., Chaker, R., Aloui, F., & Nasrallah, S. B. (2013). "On the dependence of an empty flanged diffuser performance on flange height: Numerical simulations and PIV visualizations." *Renewable Energy*, **56**(0), 123-128. doi: http://dx.doi.org/10.1016/j.renene.2012.09.061

Khatib, T., Sopian, K., Mohamed, A., & Ibrahim, M. Z. (2012). "Sizing of a wind charger at minimum cost for remote housing electrification: A case study for nine coastal sites in Malaysia." *Energy and Buildings*, **51**(0), 185-190. doi: http://dx.doi.org/10.1016/j.enbuild.2012.05.001

Kim, D., & Gharib, M. (2013). "Efficiency improvement of straight-bladed vertical-axis wind turbines with an upstream deflector." *Journal of Wind Engineering and Industrial Aerodynamics*, **115**(0), 48-52. doi: http://dx.doi.org/10.1016/j.jweia.2013.01.009

Kishore, R. A., Coudron, T., & Priya, S. (2013). "Small-scale wind energy portable turbine (SWEPT)." *Journal of Wind Engineering and Industrial Aerodynamics*, **116**(0), 21-31. doi: http://dx.doi.org/10.1016/j.jweia.2013.01.010

Mohamed, M. H., Janiga, G., Pap, E., and Thévenin, D. (2010). "Optimization of Savonius turbines using an obstacle shielding the returning blade." *Renewable Energy*, **35**(11), 2618-2626. doi: http://dx.doi.org/10.1016/j.renene.2010.04.007

Ohya, Y., Karasudani, T., Sakurai, A., Abe, K.-i., and Inoue, M. (2008). "Development of a shrouded wind turbine with a flanged diffuser." *Journal of Wind Engineering and Industrial Aerodynamics*, **96**(5), 524-539. doi: 10.1016/j.jweia.2008.01.006

Takao, M., Takita, H., Saito, Y., Maeda, T., Kamada, Y., and Toshimitsu, K. (2009). "Experimental Study of a Straight-Bladed Vertical Axis Wind Turbine With a Directed Guide Vane Row". *ASME Conference Proceedings*, 1093-1099.