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THE EFFECT OF HYBRID SAVONIUS AND DARRIEUS TURBINE ON THE CHANGE OF WAKE RECOVERY AND IMPROVEMENT OF WIND ENERGY HARVESTING

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The energy crisis encourages the development of renewable energy; one of the potential renewable energy is wind. In the field of wind turbine there is a two-way development of the utilization of wind energy, first by making a large wind turbine, the second by making a wind farm energy with a relatively small wind turbine.This hybrid VAWT wind turbine (Sultan Wind Turbine) is designed to work optimally on a farm array, on a wind turbine farm array will always cause a wake effect that will reduce overall wind turbine and farm array performance, an investigation with a CFD simulation is required to predict how far the wake effect will be before farm array build.The use of simulation software has been widely used to predict the effects of this wake, and experiments in the laboratory have also been done to predict the effects of a wake as well.This study'spurpose is to predict the distance area of the recovery wake behind the wind turbine, this distance which will be the reference distance between wind turbine units and determining the density of the turbine in a farm. Simulation using Computational Fluid Dynamics (CFD), with a method of Multi Frame Reference (MRF). Analysis using descriptive and inferential method in statistics such as mean, Kolmogorov-Smirnov Z and KruskalWalis test.From the analysis of simulation results and data processing descriptively and analytic statistic, it can be concluded from the data given, the distance of x/D=4, wind speed has recovery to the value near the input speed and no significant change to x/D= 9. Then it can be concluded that the distance between two wind turbines that can be used is a distance of 3.6 meters.These data suggest that the hybrid farm array VAWT savonius and darrieus have a higher power density compared to HAWT. From this power density calculation the hybrid VAWT has a greater electrical potential up to 300 percent compared to the HAWT farm array.

Key words: CFD, Wake effect, Power density, Farm array, Statistics

INTRODUCTION

Dabiriet. al. argues that the utilization of the small VAWT farm array can address the growing challenges of energy demand [1, 2]. Wake effect for HAWT causing the absorbed wind energy to drop by 31% at a distance of 3x blade diameter, and down to 35% at a distance of 5x the diameter of the blade [3], for VAWT at a distance of 2.5 x diameter, wind speed is reduced to only 41% of the original speed [4]. Many similarities between wake in VAWT and wake in HAWT [5], but the difference in recovery wake distance between the two types of turbine is not stated directly.Another research using 2D wake model for optimization of wind turbine layout [6].

The placement pattern and distance of a turbine in a wind farm is very important to improve the performance of the farm array. Research using methods such as genetic algorithm optimization [7], wind farm layout using biogeography-based optimization [8], grid-like layout [9] can significantly improve the performance of the farm array.

Investigation to co and counter-rotating 2 arrays and 3 arrays has been done to get the best efficiency [10] and propose for 2 array use backward counter-rotating and for 3 array use forward counter-rotating, Dabiri use forward counter rotating of 2 arrays [1], in this research using forward counter-rotating 2 arrays to get small wake spreading rate.

Several parameters have been studied that affect the efficiency and power generated by wind turbines such as tower height, rotor optimization and use of lightweight materials can be done to improve overall farm efficiency[11]. Another way to improve farm efficiency is by reducing recovery distance by increasing the tip speed ratio, also a concern to Cp while increasing tip speed ratio [12].

Sultan wind turbine, a hybrid savonius-darrieus [13] use as a prototype of hybrid VAWT in this project research. This hybrid is proposed to use in hybrid with biomass to improve the performance [34], another hybrid also introduced using solar and biomass for rice drying [35].

Wake arising from the single turbine will affect the overall wind farm performance [14] then the wake of each turbine should be reduced. Farm array will cause wake effect[3, 4, 14], wake effect greatly affect wind turbine performance and wind turbine performance will affect farm performance, therefore it is necessary to investigate the recovery effect of the wake as a reference in designing shape and size of the distance between turbine in the

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farm.In this study, wake recovery zone distance will become a reference in determining the distance and the shape of two wind turbines in a farm.

There has been no research that discusses the effects of wake generated by hybrid wind turbines VAWT especially hybrid savonius-darrieus and its influence on power density and comparison with HAWT.Ghosh A, did a CFD simulation research about combination of savonius and darrieus [22], but has different structure with our hybrid savoniusdarrieusVAWT.

This study aims to predict the wake recovery distance of the hybrid VAWT turbine savonius-darrieus, this position will be a reference in designing the shape and size of this VAWT hybrid farm array.

METHODOLOGY

This research will use CFD to simulate fluid movement around the turbine and wake effect that arise. Data of simulation result will be analyzed by the statistic method to compare significance differences of each distance group of data.

Computational Fluid Dynamic

A numerical study investigating hybrid wind turbine savonius-darrieus has been performed using RANS (SST k-ω) turbulence modelling [15-17]. The turbine's rotation is handled by the numerically robust Multi-Reference Frame technique, simulation with the CFD Fluent Software.

The MRF assumes that the volume used has a constant rotational speed with the surface of revolution with non-wall boundaries type. MRF performs a rotational simulation and observes the result at the equivalent position of the rotor. Also assumes a weak interaction between the volume of MRF and the volume around the stationary.

Some earlier researcher using MRF approaches to model the inner rotating reference frames in a stationary computational mesh and outer reference frame for the full wind turbine rotor simulations, MRF is also used in wake simulation on HAWT even in its result, sliding mesh method is better than MRF, but MRF is efficient in computing time[18]. From the simulation results can be seen a visualization of vortices or wake by using iso-surface of q-criterion or lambda2.

Mathematical Model

Statement of the problem

The physical problem being examined is the fluid flow through double VAWT hybrid wind turbines savonius and darrieus. This study examined the expansion of wake and initial predictions with the Multi Reference Frame CFD approach.

Governing equation

The continuity and conservation of momentumequations:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \bar{v}) = 0 \quad (1)$$

$$\frac{\partial \rho \bar{v}}{\partial t} + v.\nabla(\rho \bar{v}) = \nabla p + \nabla \tau + S_M \quad (2)$$

Multiple Reference Frame (MRF) formulation

The MRF approach is used in models with internal frames that rotate on a stationary reference frame.

Absolute speed in the internal frame reference uses í notation for inertia and r for rotation:

$$\vec{v_i} = \vec{v_r} + \vec{\Omega}.\ \vec{r} \quad (3)$$

Acceleration equation expressed as:

$$\frac{d\vec{u_i}}{dt}_{inertia} = \frac{d\vec{u_i}}{dt}_{rotating} + \vec{\Omega} + \vec{u_i} \quad (4)$$

By using equation (2) :

$$\frac{d\vec{u_i}}{dt}_{inertia} = \frac{d\vec{u_i}}{dt}_{rotating} + \frac{d\Omega}{dt}.r + 2\Omega\ .\mathrm{ur} + \Omega.\Omega.\mathrm{r} \quad (5)$$

Rotating frame ofreference in incompressible RANS equations as absolute velocityat the inertial frame of referenceis:

$$\nabla.u_i = 0 \quad (6)$$

$$\nabla.(u_i \otimes u_i) = -\nabla.\frac{p}{\rho} + V\nabla\ .\ \nabla\left(\frac{u}{i}\right) \quad (7)$$

At the rotating frame of reference is:

$$\nabla.u_i = 0 \quad (8)$$

$$\nabla.(u_i \otimes u_i) + \Omega\ .u_r = -\nabla.\frac{p}{\rho} + V\nabla\ .\ \nabla\left(\frac{u}{i}\right) \quad (9)$$

StatisticalTesting

Statistic method has been utilized in many fields in science, the combination of simulation and statistics is a powerful tool in drawing conclusions on cases that are difficult to decide with other methods.

Statistical methods are widely used in designing experiments of a simulation, such as full factorial research [19-21],a statistic is a powerful tool to analyze and make some conclusion from scattering data, a statistic used to estimate CFD result for drag prediction [30]. Combination of CFD and statistic technique has been used to guessspreading of airborne sea salt [31].

The Kruskal–Wallis test used to test statistical differences between lumen areas from CFD result in the medical application of stent coronary artery [32].

Descriptive And Deductive statistics that discuss how scattered postulate a set of data in a form that is easy to the analysis quick to provide information, presented in the form of tables, graphs, concentration values and spread values.

Mean

An average is a very frequently used cantering measure. The advantage of calculating the average is that the number can be used as a representation or representative of the observed data. The average is sensitive to the existence of extreme values or outliers.

$$\bar{X} = \sum_{i=1}^{n} X_i \quad (10)$$

Inferential Analysis

Kolmogorov-Smirnov Z Test,is a nonparametric test to see the normality of the data, if data normal, then continued with One Way ANOVA Test on the parametric test, and if not normal, it will be tested with Kruskal Wallis Test. The Kruskal Wallis test is a rank-based nonparametric test whose purpose is to determine whether there is a statistically significant difference between two or more independent variable groups in the numerical dependent variable (interval/ratio) and ordinal scale.

$$K = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_i \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij}-\bar{r})^2} \quad (11)$$

The next test is a comparison between each group to see significant differences between groups. Here followed by Test Two independent data groups with Mann Whitney U Test, is a non-parametric test used to know the median difference of two free groups, if the dependent variable data scale is ordinal or interval / ratio but not normally distributed.

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \quad (12)$$

Power density

Power density is a measure of electrical energy that can be generated per unit area of the farm array of wind turbine, the commercial HAWT flux limits theory is 2-3 Watts/m^2, while commercial VAWT can be up to 8 Watts/m^2.[1]

$$Power\ Density = \frac{4\ x\ rated\ power\ x\ capacity\ factor}{\mu\ (turbine\ diameter\ x\ turbine\ spacing)^2} \quad (13)$$

Power coefficient of VAWT is higher ≈6% than Betz Limits which is usually analyzed as the coefficient limit on HAWT [33].

RESULTS AND DISCUSSION

For statistical analysis required preparation of data to be analyzed, the data in the form of wind speed values from the simulation results at each point that has been determined. This data will also be displayed in the form of speed contour graphs in each field.

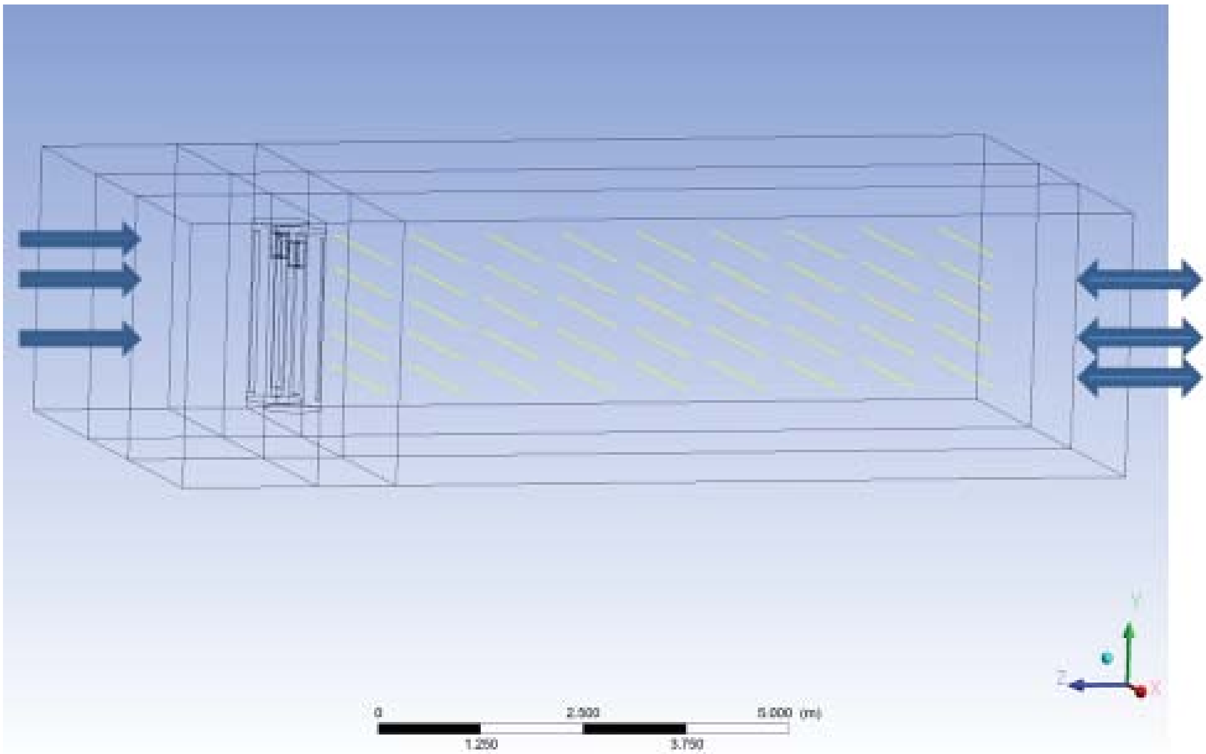

Figure 1: Simulation layout and field position of wind speed data retrieval

Figure 1 shown the experimental setup and wind data retrieval in a simulation. There are 9 fields, where each field has 5 lines of lines that line up vertically, and each line there are 50 points of data collection of wind speed. Incoming velocity is varying from 3 m/s to 9 m/s, with an outlet is ambient pressure.

The wind velocity data used in the simulated inlet is taken from a range of wind data measured directly in the field. The wind data sample was taken using an anemometer and data acquisition withan Arduino for 24 hours on August 3, 2017, the wind speed ranging from 0 m/s to 11 m/s.

Simulation data

With regard to the measured wind velocity contours, for simulated wind speeds set from 3 m/s to 9 m/s, the temperature and pressure are set to default. The working fluid is air. With variations of rotational speed of the rotor from 80 rpm to 175rpm. Domain sized is 12.000mm x 5696mm x 5350 mm.

Another setup, speed measurement distance ranging from 1 times to 9 times the diameter of the rotor darrieus.

In Figures. 2, Speed contour in x/Dd= 4 in two elevation positions, one in the middle of darrieus and another in the middle of savonius, with a wind speed of 6 m/s. The two graphs above show that savonius has a higher wake effect than darrieus. So the idea of varying the position of the savonius on the shaft arises to reduce the wake effect that resonates on the farm array if the position of savonius at the same level.

Analysis

Taking into account the 3D contours of wake from 3 m/s up to 9 m/s above, it supports 2D data result, that the wake effect on savonius is greater than that of darrieus. The wake effect also gradually disappears moving to the top-sided with increasing distance from the shaft, only it is difficult to determine at what distance position there has been recovery wake.

[23] analyzes and sets wake region based on a guest on an analysis dimensional graph without using any tools to analyze and determine wake region position. In this analysis, statistical analysis tools are used to determine the wake region position based on 3D graphics and data from simulated CFD results.

From the result of the test of data normality (Kolmogorov-Smirnov Z Test) with a result of Pval (0.000) <0,05 indicates that data is not normal, so do follow-up testing with Kruskal Wallis Test. Tests with 9 groups yielded Pval (.971) > 0.05 indicated as individuals, no statistically significant group of data.

The next test with 2 groups of data with Mann Whitney U, the result can be viewed in table 1.

From the result of the test of data normality (Kolmogorov-Smirnov Z Test) as a result of Pval (0.000) <0,05 indicates that data is not normal, so do follow-up testing with Kruskal Wallis Test. Tests with 9 groups yielded Pval (.971)> 0.05 indicated as individuals, no statistically significant group of data.

The next test, with 2 groups of data analyzed with Mann Whitney U, shows that for the data presented, there is a significant difference between the data group distance x/Dd=1-3 with the data group x/Dd= 4-9.

From two analyses, descriptive and Mann Whitney U, showing that at a x/Dd= 4, the wind velocity that descends behind the shaft recover and rises to an initial velocity such as before the shaft, or wakes affected zone only happen up to a x/Dd=3. The division of these two zones can be seen in Figure 3.

Wake that occurs behind the turbine, there is one important region that moves to the top, this is because of the position of the savonius that is at the top of the rotor. Whereas if the only darrieus then there are two parts of the region that one moves up and the second moves down [24].

$$PD = \frac{4\,x\,0.0005\;MW\,x\,0.3}{\mu\,(1.2\;m\,x\,4\,)^2} = \;8.29\;\mathrm{W}m^2$$

For rated of hybrid VAWT at 500 watts, and turbine spacing x/D = 4, show that Power Density is about 8.29 W/m^2.

Discussion

So far from the results of simulations and experimental results on wake, it will be quite difficult to determine the boundary area between wake effect and the recovery wake area. This research aims to determine the distance of wake recovery in hybrid VAWT. Dabiri states that the wake recovery VAWT is much shorter than HAWT the and power density of VAWT is higher than HAWT[1, 25]. This statement, however, is slightly different from that of other researchers suggesting that the characteristics of VAWT and HAWT have many similarities, but do not specifically state the equations on wake recovery distance [5]. Several other studies have suggested that VAWT wake recovery occurs at a distance ofx/Dd = 3-5[4, 23]. Slightly different from VAWT's research in this paragraph, this study investigates the wake recovery of VAWT hybrids, and for determining the wake recovery distance to compare the analysis of simulation results and statistical analysis. The results of this study are important because the distance obtained will determine the number of wind turbines in a farm array and the power density performance of the VAWT hybrid. Hybrid savoniusdarrieus VAWT hass been analised by using CFD [22] with different structure with tis research and the result is wake recovery at savonius is less than darrieus, slightly different with this research result that shown wake recovery at savonius is bigger than darrieus. This happen because different position of savonius, in Ghosh A research savonius placed at bottom and darrieus at top, in this research savonius is placed at top side of the structure, and form vortices result shown that savonius wake is moving to upside of the frame.

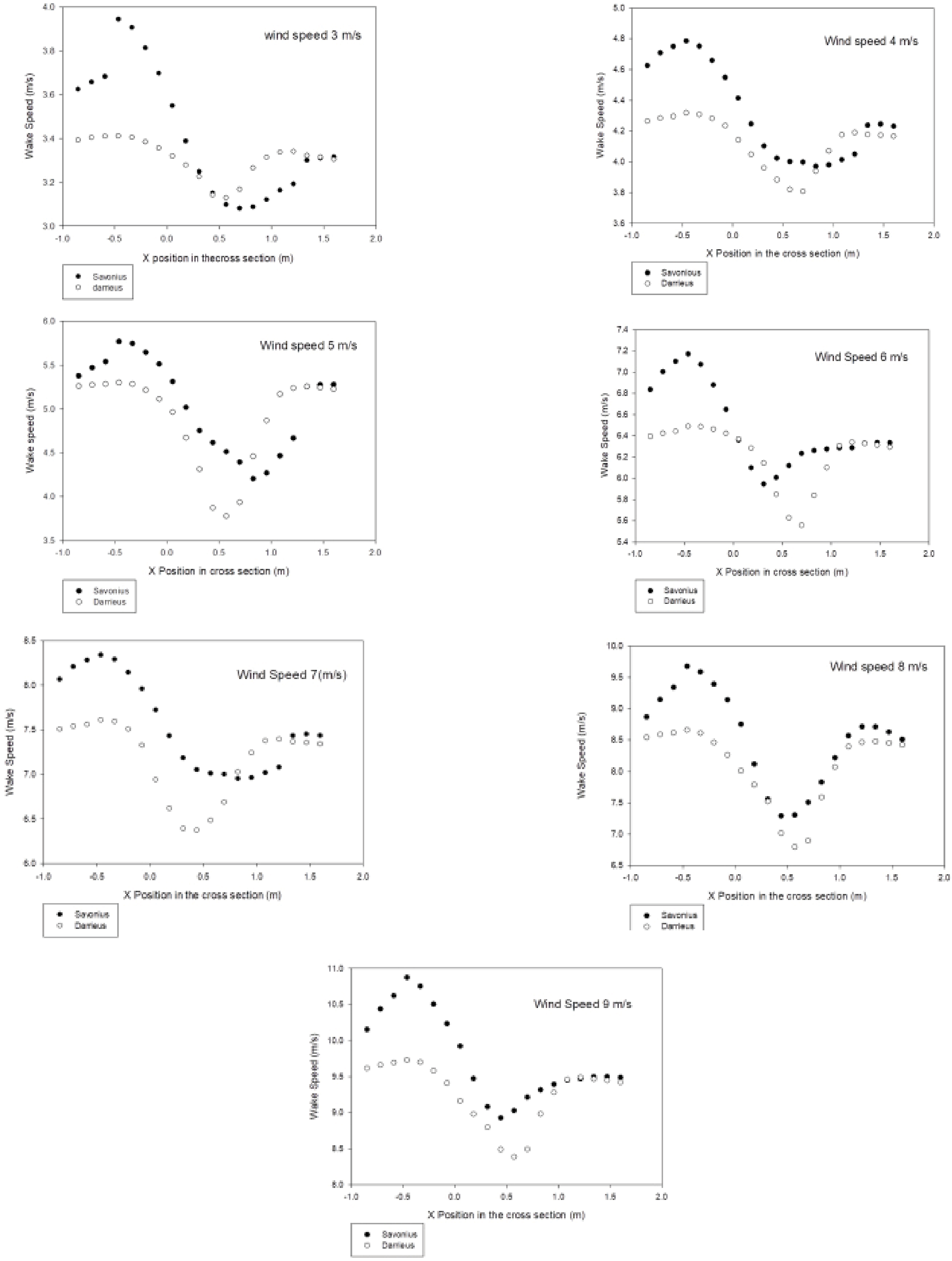

Figure 2: Contour wake speed in center of darrieus and savonius at x/D = 4, for wind speed 3-9 m/s

Table 1: Statistical analysis

Data group	Mann-Whitney U	Limit Pval	Conclusion
(1-4 and 5-9)	(.230)	>0.05	there was no statistically significant difference
(1-6 and 7-9)	.447	>0.05	there was no statistically significant difference
(1 and 2-9)	.000	< 0.05	there is a statistically significant difference
(1-2 and 3-9)	.000	< 0.05	there is a statistically significant difference
(1-3 and 4-9)	.000	< 0.05	there is a statistically significant difference

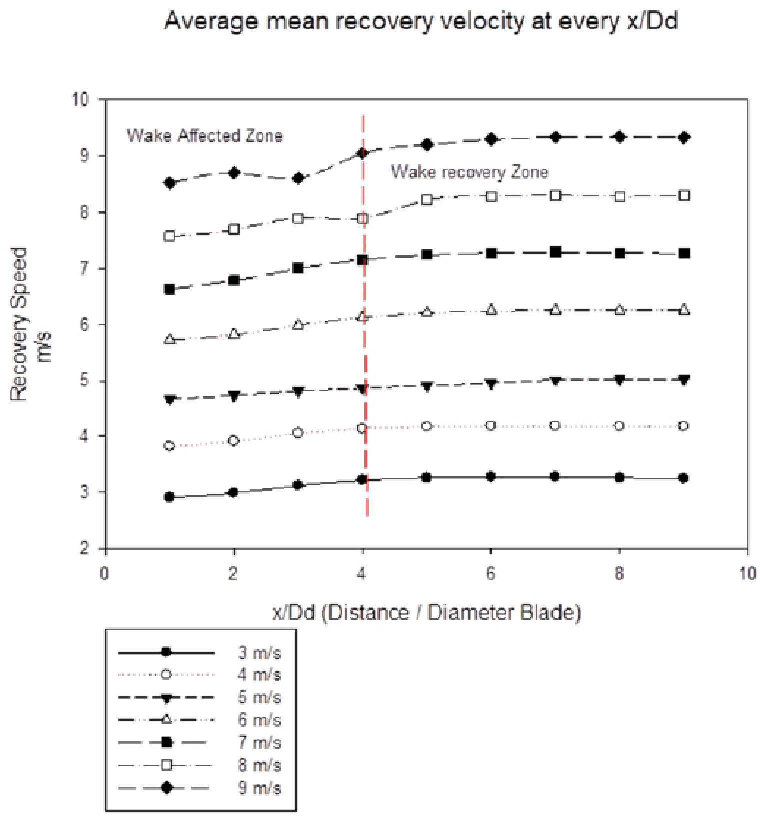

Figure 3: Descriptive test, average mean velocity at every x/Dd

CONCLUSIONS

The statistical method descriptive and inferential method, has been implemented to analyze the simulation results, and it has been shown that based on the above analysis, that at the x/Dd= 4 of the turbine or at the distance 3.6 meters from hybrid VAWT at the front, significantly for the given data indicates that each wind turbine will get an average wind speed equally at this distance, and it is expected that each wind turbine can produce the same electric rotation and energy on every wind turbine. The analysis also using post processing to examvorticesfor wind speed 9m/s with the Q Criterion[26]method shows the same trend that recovery has begun to occur about x/Dd = 4. This result is compatible withthe single VAWT simulation result which provides wake recovery occurring in the range of x/Dd = 5 [23], and based on experiment, wake recovery from straight-bladed Vertical Axis Wind turbine occurs in the range x/Dd = 3.3 and x/Dd = 4.5 [4] which much shorter than HAWT wake recovery that happens in x/Dd= 15 [27-29].This indicates that with the area of the wind sweep cross-section similar to the HAWT, hybrid VAWT has a higher power density than HAWT. Based on the calculation of Power density its show that for hybrid VAWT produce power density 8.29 W/m2over 300 percent than HAWT.

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