Experimental Investigation into the Influence of Turbulence Intensity on Aerodynamic Performance of a Small-Scale Vertical Axis Wind Turbine

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Abstract:- Wind in urban areas is extremely complex due to their location in the lower planetary boundary layer, irregular arrangement of buildings and enhanced surface roughness. Vertical axis wind turbines (VAWTs) are used in extracting energy within this environment. However, there is a huge knowledge gap as far as the effect of turbulence on the aerodynamic performance of VAWTs operating in non-uniform wind regimes are concerned. This study used an experimental method to investigate the effect of free stream turbulence intensity on the aerodynamic performance of a VAWT under non-uniform flow operating conditions in a wind tunnel environment. A small-scale Darrieus type VAWT was developed and tested. A wedge mechanism to generate non-uniform conditions was created and the effect of the generated turbulence intensity on the aerodynamic performance of the turbine investigated. The VAWT was subjected to free-stream wind speeds ranging from 5 m/s to 10 m/s at different tip speed ratios. Torque and power coefficients were systematically analysed and an evaluation was made of how they varied at uniform and non-uniform flow. Results reveal that non-uniform turbulent wind impacted the aerodynamic performance of the turbine with higher power coefficients being observed at lower wind speeds and improved self-starting ability in the presence of turbulence.

Keywords:- *Wind Tunnel; VAWT; Turbulence; Power Coefficient; Torque Coefficient.*

I. INTRODUCTION

For the longest time, the world has relied on burning of fossil fuels which is a non-renewable source of energy. These sources are dwindling and are expected to be depleted within the next century [1]. Equally, burning of fossil fuels leads to the release of greenhouse gases (GHGs) which have largely contributed to global warming and the resultant climate change [2]. This generation has seen some of the most dangerous and life threatening effects of climate change. It is important that as the world plans for its sustainable future, research and funding is directed towards finding sustainable alternative sources of energy [3].

In response to the need for utilizing other sources of energy, recent focus has been directed to renewable energy sources. Fuel sources including biofuel, geothermal power, hydropower, solar and wind energy provide the best alternative to the finite fossil fuels [4]. These five sources are readily available, environment friendly, infinite and relatively cheaper with [5] Wind energy source has increasingly been utilized since it is free, clean and readily available. Flowing ambient wind has an associated kinetic energy [1]. Wind turbines will convert this kinetic energy into mechanical power through the rotation of turbines [5]. Traditionally, this mechanical power has been used in tasks like grain grinding or to pump water through the operations of a wind mill. The turbine blades capture the power in the wind by rotating and turning the shaft inside the nacelle [1]. The shaft spins a generator which converts this mechanical power by way of gears into electricity making it available for grid use and powering homes and businesses [1,5].

Harnessing of wind energy is done both at small-scale and large-scale. On large-scale, a number of large wind turbines are used in a wind farm [5]. The power produced from individual turbines is connected to the others and added to the grid. Small-scale wind energy production utilizes small-scale wind turbines that can be used for powering single homes and light industries [4]. Urban environment constitutes the largest consumers of energy world over. In this environment, microgeneration of power presents an opportunity of developing renewable energy sources, conducting research, resource efficiency and furthering technological innovation [4]. Energy harvesting through wind turbines is an option that has been exploited and could yet be considered even further.

Wind energy is harnessed through wind turbines. Kinetic energy in the moving wind is converted to mechanical energy by the turbine blades then further to electrical energy through electromagnetic induction in the generators. Classification of turbines is made considering the orientation of their rotational axis as either horizontal axis or vertical axis wind turbines [6]. HAWT have been researched for a long time and are the major type of turbine today utilized for energy production. HAWTs are viewed as being more efficient than VAWTs besides the possibility of problems arising from dynamic and static loads in cases of very large applications [7]. However, research has shown that there is potential in the VAWT technology and a lot of attention has now been directed to this sector [8]. These turbines have distinctive features that make them suitable and attractive for applications especially in environments with complex flow patterns like urban areas. Further, VAWTs are simple to construct, they are located near the ground, have low noise due to low tip speed ratios, do not have many movable parts thus low maintenance costs and respond to wind from all directions thus no need for a yaw mechanism [7,9,10].

Turbulent behaviour of wind has ingrained complexities that would significantly affect the power production characteristics of turbines. Such complexities would mostly affect small wind turbines that are usually located at lower surfaces surrounded by or close to buildings, tree canopies among other obstacles [11,12]. According to Wekesa *et al*. [8]; literature describing how the wind turbulence affects a turbine's performance is scarce and further studies should be conducted. The existing power curves fail to account for this effect of turbulence on the energy produced by small wind turbines [12]. These curves just present a statistical average of power versus the wind speeds without much consideration for the variance of the respective data [10,12]. Effectively, we miss the information about the impact of free-stream turbulence on energy production by small wind turbines.

The study by Lubitz [12] investigated the effect of ambient turbulence levels on wind turbine energy production. The study concluded that ambient turbulence intensity affected energy production with different trends observed as wind speeds were varied. The output data from the study was analysed and comparison with other studies done. In the studies by Sunderland *et al*. [13], Kooiman and Tullis [14], Pagnini *et al*. [7] and Turk and Emeis [15], the data was divided into smaller sections then the variance used to find the turbulence intensity of each part was elucidated by Wekesa *et al*. [8] (see Eqs. 10 and 11). The power output increased for turbulence levels below 14%, with varying trends observed for higher turbulence levels [12]. Lubitz [12] concluded that the turbine power production was affected by ambient turbulence levels, although the effect varied at different wind speeds. Noticeably, these tests were performed in an open atmospheric environment, which meant that they could not control or vary the intensity of the turbulence under investigation [12].

Kooiman and Tullis [14] researched on how wind velocity and fluctuating wind directions affect the power production characteristics of a VAWT. The wind turbine was tested on an urban rooftop. They observed that power production varied with changing wind velocity but not much change observed by variations in the direction of wind. This behaviour on the urban tested turbine was then compared to results from the same turbine that was performed in a wind tunnel with low turbulence (of *Ti* less than 2%) as a benchmark for the performance. They reported a marginal reduction in turbine's performance from the smooth flow values for *Ti* less than 15% and almost a linear reduction with increasing turbulence intensity for *Ti* greater than 15% [10,14].

Smith [16] described performance curves and annual energy production for seven different wind turbines subjected to different turbulence intensities. The study reported that the turbines' annual energy production varied from 9% to 32% over the range of turbulence intensities that were used. The energy produced by most turbines was low in both cases of very low and very high turbulence intensities, apart from one that showed increased annual energy production with increasing turbulence levels.

It was observed by Majtaba *et al*. [10] a similar methodology was used in the mentioned works to characterize how turbulence affected power production; and that they all largely depend on the sample size selected. He further suggests that changing the size of the sample may result to different observations. There is no agreement by different studies on how turbulences affects wind turbine power productions with different studies reporting different trends. Different conditions such as different flow types and varying amounts of unsteady wind and wind shear studied by different researchers could be the cause of these different conclusions.

Wekesa *et al*. [8] reported an experimental method characterizing the performance and aerodynamics of a rotor subjected to turbulent flow operating conditions. They created a small-scale Savonius turbine and tested it in a wind tunnel. They reported higher power production by wedge generated turbulent flow as compared to that observed under uniform flow. Wind speeds above 7 m/s resulted to drastic reduction in power produced under turbulence. The study also showed a dual influence of turbulence intensity on the small wind turbines. Presence of turbulence inflow increased the kinetic energy available to small wind turbines at low wind speeds and also tended to increase efficiency at wind speeds near furling speed. It was also noted that the self-starting ability of the VAWT was improved on introducing an external turbulent inflow. This was attributed to the reduction of the relative velocity between approaching wind and rotor at low tip speed ratios, which resulted in a lower moment that decays rapidly as the turbine started rotating [8].

It can be seen from literature that most of the recent research had been done in open wind environments where the free-stream turbulence characteristics could not be controlled much. The effect of turbulence is highly dependent on the sample size in some cases since the same methodology is used to characterize the effect. Lubitz [12] observed that small wind turbines interact with wind through a complex process that is highly dependent on the characteristics of the wind turbine. There exists a knowledge gap on the aerodynamic characteristics of small-scale Darrieus-type wind turbine in turbulent environments. There is need to investigate the behaviour of this type of turbines for application in urban environments.

This paper, therefore, investigates the effect of free-stream turbulence intensity on the aerodynamic performance of a small-scale Darrieus-type VAWT in a wind tunnel environment. Turbulent wind was generated using elliptic wedge generators in a wind tunnel since there existed no turbulence mechanism, except for the wind tunnel testing facility at the Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. The turbulence intensity levels were matched with prevailing wind behaviour of urban environments for target sites in Kenya.

II. MATERIALS AND METHODS

A. The Wind Tunnel Facility

The wind tunnel used was an open-circuit suction device with an axial fan located at the outlet. It is set in the Fluid Engineering laboratory, Mechanical Department at the Jomo Kenyatta University of Agriculture and Technology. The tunnel has a total length of 4.6 m with the inlet section measuring 1.2 m by 1.2 m. It includes a 0.66 m long centralized test section with inlet section 0.44 m by 0.44 m. The inlet is fitted with an array of honeycomb mesh to straighten the wind flow. There is a short settling section after the mesh that allows turbulence and non-uniformities to dissipate then the wind is accelerated by a contraction cone through at a ratio of 7.4:1 into the inlet section of the working section. The working section is fitted with transparent Perspex glass with respective holes created to allow for the insertion of the rotor and measurement instrumentation. The Jomo Kenyatta University of Agriculture and Technology's wind tunnel facility is as shown in Figure 1.

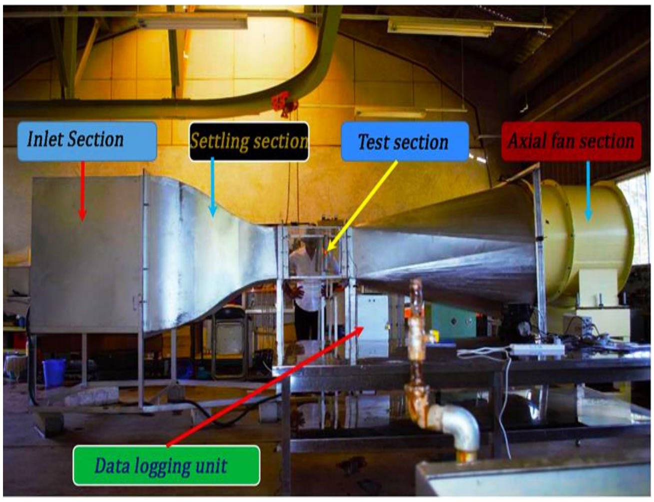

Fig 1:- Jomo Kenyatta University of Agriculture and Technology's Wind Tunnel Facility

The tunnel suction fan was controlled via a variable frequency drive (VFD) that allowed precise setting of the fan speed in 0.01 Hz resolution with a maximum speed of about 50 Hz which theoretically would results to tunnel speeds of about 20 m/s. For this experiment the frequency was restricted to about 36 Hz resulting to wind speeds of about 10 m/s; due to structural safety and also to control/reduce the aerodynamic forces generated on the rotor. Measurements were made with wind speeds ranging from 5 m/s to 10 m/s specifically choosing free-stream velocities of 5 m/s, 7 m/s, 8 m/s, 9 m/s and 10 m/s.

At the entrance of the test section, turbulence-generating wedge mechanism was used to generate the required turbulence. This consisted three elliptical wedges, 0.4 m high, positioned 0.05 m apart across the 0.44 m width inlet section at a distance of 0.5 m away from the rotor which was positioned on the downstream section of the working section as shown in Figure 2. Tests were first conducted for uniform conditions and then repeated under non-uniform turbulent flow conditions by introducing the wedge-turbulence generating mechanism then the two compared.

Fig 2:- Wedge-Turbulence Generating Mechanism

B. VAWT Rotor Model

The experiment used a straight-bladed, three blade Darrieus VAWT as shown in Figure 3. The rotor is 0.3 m high with a diameter of 0.3 m thus an aspect ratio, AR=1. A central shaft of diameter 0.01 m onto which the blades are attached, runs through the bottom to top walls of the test section. The rotor is positioned at the centre but 0.5 m downstream along the 0.66 m long test section. Three NACA 0022 symmetrical blades are attached to the central shaft by light aluminum spokes at ¼ and ¾ blade length positions. The symmetric profile is used because it is relatively thick, giving improved performance. Furthermore, increasing thickness makes the blade more resistant to bending and becomes easier to fix.

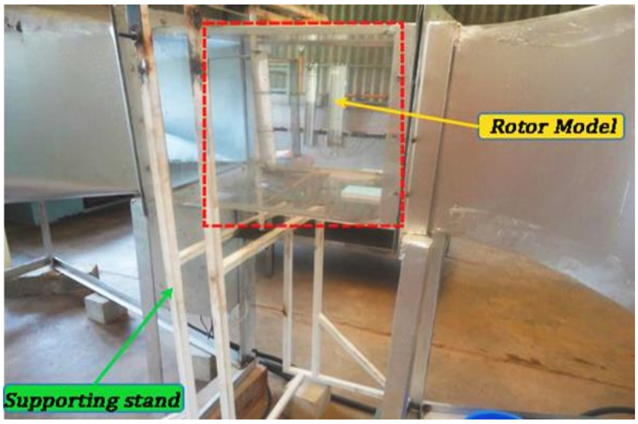

Fig 3:- The Darrieus VAWT Rotor Model in a Wind Tunnel Test Section

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C. Instrumentation and Measurement Procedures

The free-stream reference wind velocity was measured and set using a Pitot-static pressure tube shown in Figure 4 at the start of each test. We positioned the Pitot-tube at different heights spanning the test section to determine the wind profile. The Pitot-tube records the difference in static and total pressure through a differential-pressure transducer by application of Bernoulli's equation (see Eqs. 1-3). The output signal from the transducer is connected to a National Instruments Data Acquisition Card (NI USB-6008, 8 inputs, 12 kS/s, multifunction I/O) then through a USB cable to a LabVIEW program code on the computer. The LabVIEW program was coded to allow the velocity recorded after different time intervals as desired.

The Bernoulli's equation is simplified as [5]:

$$(P_s) + \left(\rho \times \frac{V^2}{2}\right) = (P_t) \qquad (1)$$

$$\left(P_s + \rho \times \frac{V^2}{2}\right) = P_t\,; \qquad (2)$$

Hence velocity;

$$V^2 = \frac{(P_t - P_s)}{\rho}\,. \qquad (3)$$

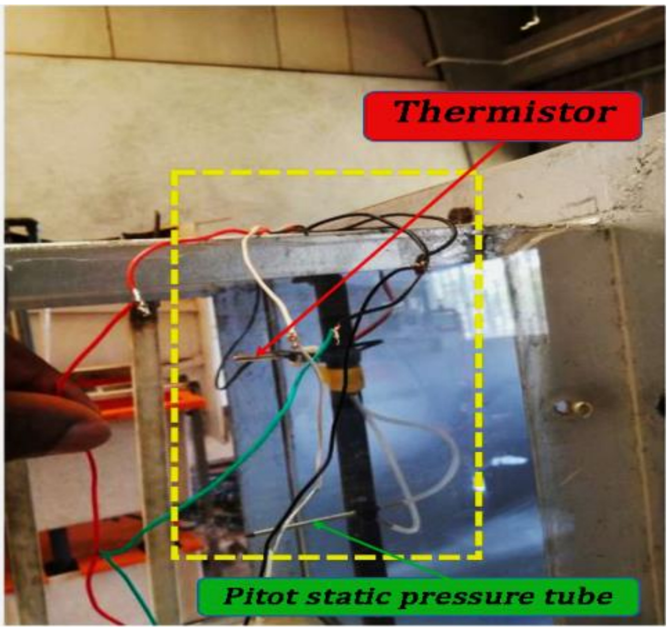

Fig 4:- Pitot and Thermistor Measurement Assembly

Observe in Figure 5, that the torque was measured directly using a torque detector model SS-500 with a torque range 0 Nm to 50 Nm and the value indicated on a torque meter model ONO SOKKI TS-2800. The rotor shaft was coupled directly to the torque detector which was then connected to the torque meter. Rotational velocity was also obtained from the transducer which was fitted with MP-981 magnetic detector with maximum rotational velocity of 6000 rpm.

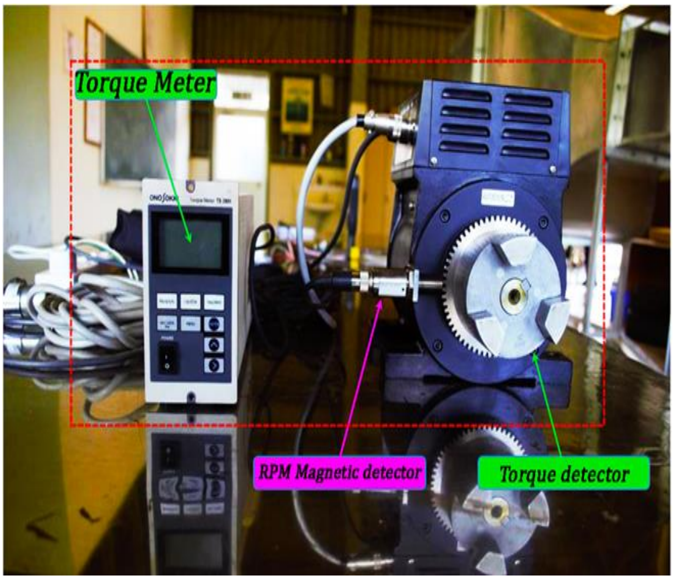

Fig 5:- Drive Side of the Torque Detector Model SS-500

To quantify the aerodynamic performance of the wind turbines, dimensionless performance parameters Torque coefficient C_m and Power coefficient C_P are expressed as functions of tip speed ratio. Their definitions are as follows [5,8]:

$$C_m = \frac{T}{\frac{1}{2}\rho A R U_\infty^2}\,; \qquad (4)$$

$$C_P = \frac{P_{blade}}{P_{wind}} = \frac{T}{\frac{1}{2}\rho A U_\infty^2 R_{rotor}} \frac{\omega R_{rotor}}{U_\infty} = C_m \times \lambda\,; \qquad (5)$$

whereas;

$$\lambda = \frac{\omega R_{rotor}}{U_\infty} = \frac{2\pi N}{60} \frac{R_{rotor}}{U_\infty}\,; \qquad (6)$$

Where T is the torque, ρ is the air density, U_∞ is the free-stream wind speed, R_{rotor} is the radius of the rotor, P_{blade} is the power produced by the rotor blades, P_{wind} is the power available in the wind, ω is the rotational speed, and *N* is the rotational speed per minute (rpm).

Power coefficient, C_P is the actual power produced by the wind turbine expressed as a ratio of the actual wind power flowing into the rotor at a given wind speed. This was used to measure the overall efficiency of the rotor. The power coefficient was tabulated for different wind speeds so that the study could estimate the electric power output. Power extractable from the wind can be calculated as [22, 23, 24, 25, 26]:

$$P_{available} = \frac{1}{2}\rho A U^3 C_P\,. \qquad (7)$$

The wind rotor was not able to self-start in some configurations like is the case with most VAWTs thus a self-starting mechanism was employed. An electrical motor and electrical clutch are used with the clutch disengaging immediately a desired rotational velocity is achieved. It is effectively observed that the self-starting ability is improved in the case of turbulent non-uniform wind such that the rotor does not need as much help as in the case of uniform flow (see section 4). This is consistent with literature studies made by [8,17,18].

III. WIND VELOCITY AND TURBULENCE INTENSITY PROFILES

The Pitot-static pressure probe was positioned at different heights within the wind tunnel test section and wind velocity measured at time intervals of 10 seconds in the absence of the rotor model. This data is used to determine the wind velocity and turbulence intensity profiles. Mathematical models are also employed to determine vertical wind shear for turbines due to high costs and time constraints. In the atmospheric boundary layer; log-law and power law are the common mathematical models used to approximate the wind velocity profiles. The logarithmic wind profile equation is expressed as [5,22, 23]:

$$\bar{u}(z) = \frac{u}{k}\ln\left[\frac{z}{z_o}\right] \quad (8)$$

Where; μ is the mean wind speed, z is the velocity above the ground, $\bar{u}$ is the shear velocity (m/s), k is the Von Karmans's constant (k=0.40) and z_o is the surface roughness length (m). Observe in Eq. (8) that in the boundary layer, depending on the surface roughness and atmospheric stability, the velocity of wind will increase logarithmically with an increase in height.

For neutral stability conditions (adiabatic conditions) the stability term drops out. Power law is thus used to find the velocity profile in cases of neutral stability. This study used the power law according to [5,22, 23]:

$$\frac{\mu(z)}{\mu_{ref}} = \left[\frac{z}{z_{ref}}\right]^{\alpha} \quad (9)$$

where; $\mu(z)$ is the wind speed at height z, μ_{ref} is the reference wind speed at height z_{ref} and α is the power law exponent that depends on the surface roughness and atmospheric stability. Power law is preferred in this study over log-law because it is simple and gives a better fit for data that covers higher height range and wind conditions [8,19]. Wind speeds and direction fluctuate in the atmospheric boundary layer due to turbulence and these two factors contribute largely when siting a turbine and designing turbine blades to be more efficient in power production [20].

In this paper, a pitot-static pressure probe was positioned in the middle of an empty tunnel test section to determine the reference wind speed. Three more measuring positions were spanned by the probe below and above the reference level. Turbulence intensity is a common metric used to explain turbulent effects since it is a description that gives statistical properties of this particular behaviour of wind [13]. The following formula was used to determine the turbulence intensity of the wind tunnel in the absence of the wind turbine rotor [8]:

$$Ti\ (\%) = \frac{\mu_{rms}}{\bar{u}} \times 100 \quad (10)$$

Where $\bar{u}$ is the time averaged value of the stream-wise velocity signal and μ_{rms} is the root mean square of the velocity fluctuations in the stream-wise direction and calculated from [8]:

$$\mu_{rms} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(u_i - \bar{u})^2} \quad (11)$$

Where; n is the sample number in velocity signals and u_i is the stream-wise velocity component for individual velocity signal.

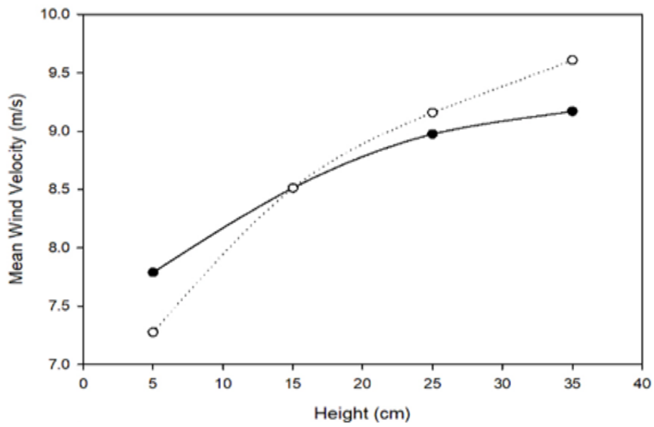

Fig 6:- Wind Velocity Profile of the Test Section

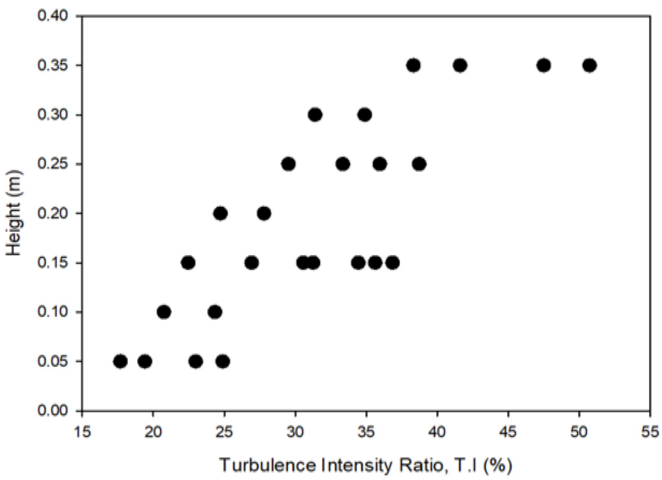

Fig 7:- Turbulence Intensity Profile of the Test Section

Figures 6 and 7 shows the mean wind velocity profile and the turbulence intensity profile, respectively, for the wind tunnel. The wind velocity profile is indeed a match with the desired urban area of study with a theoretical power law index of 0.1429 [22, 23]. The wind velocity in the tunnel test section is seen to be lower at the height of 0.05 m for the surface and equally starts to reduce at height 0.35 m which is closer to the upper Perspex enclosing. This is attributable to the surface friction occurring between the wind and the surface in this case the Perspex enclosing the test section; and also the high density of air at low surfaces

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which require more wind kinetic energy to move as compared to less dense wind in the middle. Turbulence intensity is shown to be fluctuating between 17.69% and 50.74%. Irregular and manmade obstructions, in this case the wedges, retard the flow of air and fluctuation in wind velocity. Turbulence intensity quantifies the level of turbulence in the wind. This range of fluctuation shows the random behaviour of wind about a mean speed giving us an idea of how the VAWT rotor power performance behaves under a non-uniform turbulent flow.

IV. RESULTS AND DISCUSSION

Analysis is made for the performance of VAWTs in both uniform and non-uniform turbulent conditions and the two results compared to investigate the aerodynamic performance of the turbine. Following published work in [7,8,10,12] as well as results from this study, it is observed that the Darrieus VAWT model is not able to self-start even under considerably high wind speeds. A start up mechanism consisting of an electronic motor and clutch is used to start the turbine accounting for the negative C_P band at lower tip speed ratio.

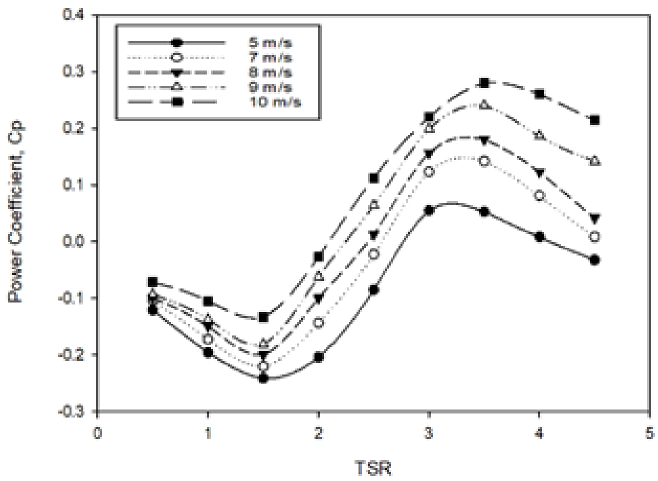

Fig 8:- C_P Distribution as A Function of TSR under Uniform Conditions.

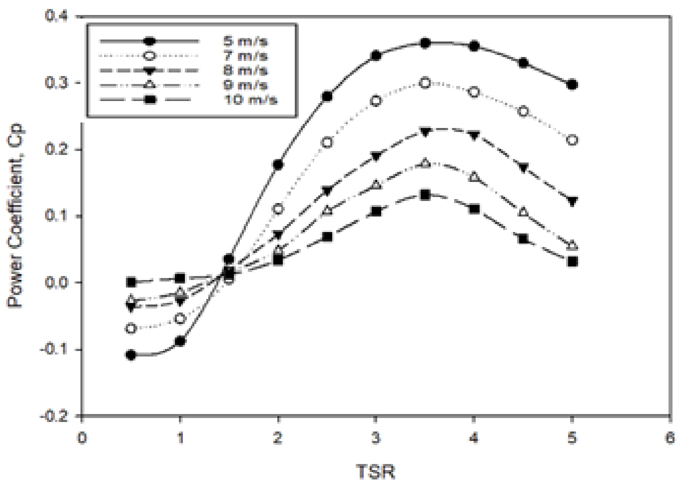

Fig 9:- C_P Distribution as a Function of TSR for Non-Uniform Turbulent Flow.

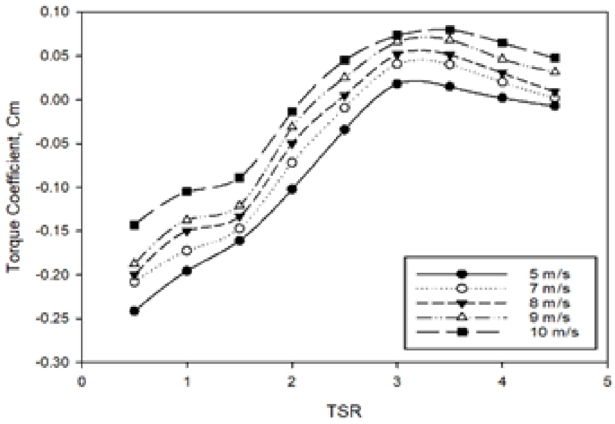

Fig 10:- Torque Coefficient Distribution for Uniform Flow.

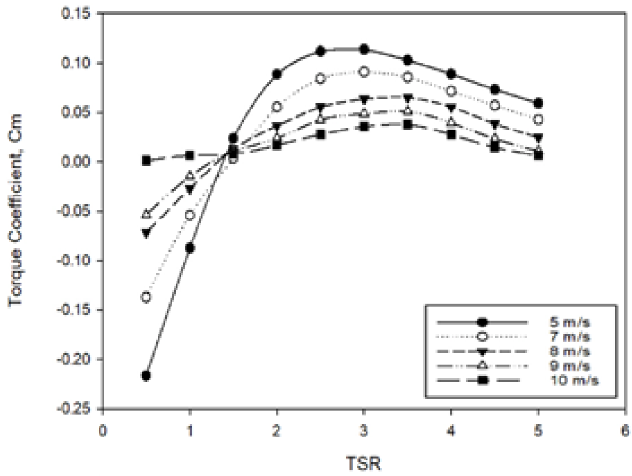

Fig 11:- Torque Coefficient Distribution for Non-Uniform Turbulent Flow.

Observe in Figures 8-11 that, the Power coefficient and Torque coefficient are expressed as functions of tip speed ratio. Figure 8 shows that for the uniform flow, C_P distribution power curve continues to increase with increasing free-stream velocity throughout the range of TSR under study. The power curve increases up to an optimum $C_P = 0.2822$ at uniform wind speeds of 10 m/s. Figure 9 on the other hand shows fluctuations on the curve with both increase and decrease in power performance recorded at low and high wind speeds respectively. Under non-uniform turbulent conditions, the optimum power is observed at $C_P = 0.36$ at flow wind speeds of 5 m/s. In both cases, the maximum C_P range is obtained at λ ranging between 3.5 and 4. These values thus give the optimum range of C_P for which maximum power is extracted from the wind turbine for both uniform and non-uniform turbulent conditions.

The power curves for both uniform and non-uniform turbulent flow reveal the inability of the rotor to self-start. The power curves plummet to a negative C_P band area when the rotor starts up from rest and keeps increasing through the λ range. This is consistent with studies by Danao *et al.* [18] and Kirke [21] that also observed the difficult of the rotor to self-start. An electronic motor and clutch powers the rotor in this band and power is in return spent to start the rotor to a steady sustainable speed. As can be seen in Figure 9, the rotor is capable of self-starting at high wind speeds for non-uniform turbulent flow. At 10 m/s the rotor was able to self-start. This could be attributed to the high wind speeds and the turbulence effects that are able to overcome the resistive torque present.

While the power from the VAWT rotor increases with increasing wind speeds for uniform flow, there is generally more power produced at lower wind speeds for non-uniform turbulent flow. The value of the power coefficient is generally lower for uniform flow as compared to non-uniform turbulent flow. Figures 8-11 shows that for the experimental VAWT rotor under investigation, turbulence increases the power performance. Non-uniform turbulent conditions resulted to more power performance at low wind speeds and reduced self-starting speeds. The turbine attains stable speeds and motor detached at λ=1.5-2 for non-uniform turbulent flow and λ=2–2.5 for uniform flow. This clearly exhibits the improved self-starting characteristics under non-uniform turbulent conditions as compared to uniform conditions.

Power coefficient distribution increased drastically at low wind speeds of 5 m/s and 7 m/s for the non-uniform turbulent flow. Despite the general trend of increasing C_P distribution in the non-uniform flow, it is revealed that at 8 m/s the rise is not as drastic as it was in the previous cases. As the wind speeds increase to 9 m/s and 10 m/s the C_P distribution keeps reducing. This reduction in power coefficient at high wind speeds in the non-uniform conditions suggests that the VAWT rotor experiences furling at that point. The experimental rotor design starts experiencing furling at wind speeds of about 8 m/s. Despite the rotor rotating under very high wind speeds, detrimental effects are observed that reduce the power performance of the wind turbine rotor.

Further analysis is done for torque coefficient distribution. There is a notable increase in the torque coefficient in the presence of turbulence at lower wind speeds as compared to the uniform flow. Observe in Figure 10 that, the torque coefficients take maximum peaks of 0.0182, 0.0410 and 0.0522 at wind velocities of 5 m/s, 7 m/s and 8 m/s respectively for uniform flow. Noticeably, for non-uniform turbulent flow, the value for torque coefficient increases to peak at 0.1137, 0.0911 and 0.651 at wind speeds of 5 m/s, 7 m/s and 8 m/s respectively (Figure 11). However, torque coefficient reveals a substantial decrease at higher wind speeds in the case of non-uniform turbulent flow. The torque coefficient drops from 0.0686 and 0.0800 at 9 m/s and 10 m/s for uniform flow to 0.0510 and 0.0357 for 9 m/s and 10 m/s for non-uniform turbulent flow, respectively.

The torque coefficient distribution curves (Figures 10 and 11) reveal that power coefficient is reduced for uniform flow compared to non-uniform turbulent flow at wind speeds of 5 m/s, 7 m/s and 8 m/s. However, for wind speeds 9 m/s and 10 m/s there is reduced torque coefficient in the non-uniform turbulent flow compared to the uniform flow. This suggests that this is the operating range for the turbine above the cut-in speed and below the turbines cut-out speed referred to as the furling. At 9 m/s and 10 m/s there is reduced power performance for non-uniform turbulent conditions, a clear suggestion that furling will be reached faster in non-uniform flow than in the uniform flow. As a result, the VAWT rotor under study operates best in the range 5 m/s to 8 m/s.

Maximum peak *CP* and C_m are plotted as functions of wind speeds to further explain the trends for uniform and non-uniform turbulent flows as seen in Figures 12 and 13. Power and torque coefficients increase with increasing wind speeds for uniform flow while the highest values for non-uniform flow are observed at the lower wind speeds. The VAWT rotor is seen to operate at its maximum for non-uniform turbulent flow in the wind speed range from 5 m/s to 8 m/s. Beyond these velocities both power coefficient and torque coefficient reduce drastically. This is because the VAWT rotor has approached furling speeds; and the gusty wind within this regime accelerates furling hence reduced power performance. It is also revealed that at wind speeds of 5 m/s to 8 m/s there is more power harnessed in turbulent conditions as compared to uniform flow. However, at 9 m/s and 10 m/s more power is produced by the uniform flow. This means that for uniform flow, the VAWT rotor rated speed is delayed before reaching furling speed.

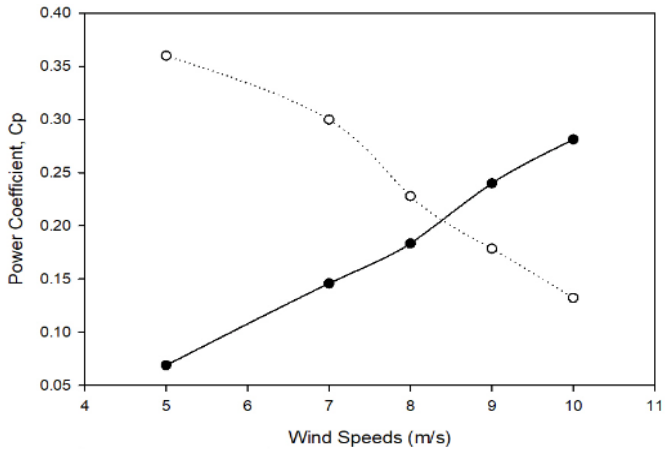

Fig 12:- Power Coefficient as A Function of Wind Speed for Uniform and Non-Uniform Flow

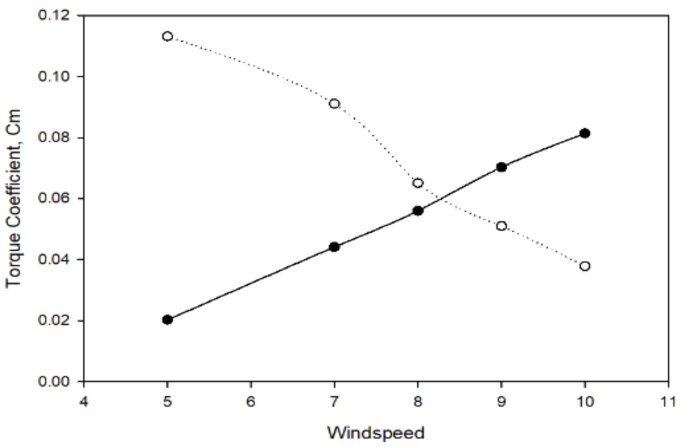

Fig 13:- Torque Coefficient as a Function of Wind Speed for Uniform and Non-Uniform Flow.

The study findings reported are in agreement with literature investigation by Wekesa *et al.* [8] where a small-scale Savonius turbine rotor was adopted for the wind tunnel tests. It was also reported that the power performance by wedge-generated turbulent flow was slightly higher than that produced by uniform flow, though drastic reduction was evident at wind speeds above 7 m/s. The present study reveals that the presence of non-uniform turbulence flow increases the kinetic energy available to small-scale wind turbines at low wind speeds and tends to increase efficiency at wind speeds near furling speed. It is also noted that the self-starting ability of the VAWT rotor is improved on introducing an external turbulent inflow. This is attributed to the reduction of the relative velocity between approaching wind and rotor at low tip speed ratios, resulting into a lower moment that decays rapidly as the turbine started rotating.

V. CONCLUSION

The research developed in this paper involved development of a mechanism to generate a non-uniform turbulent flow within a wind a tunnel. This included development of a Darrieus-type VAWT rotor within the laboratory to measure the VAWT rotor wind performance for both uniform and non-uniform turbulent wind conditions. Non-uniform wind conditions resulted to more power generation at wind speeds above cut-in and below furling speeds.

Equally, non-uniform wind flow resulted into improved self-starting ability by reducing the self-starting speed of the rotor. The rotor was able to start at lower TSR as compared to the case in uniform conditions. This was attributable to the rapid decay in the lower moment when the rotor starts rotating as a result of reduction of the relative velocity between free-stream wind and the VAWT rotor. It was also observed that at high free-stream speeds the rotor was able to self-start under non-uniform conditions. Uniform flow revealed higher power performance at increased wind speeds indicating a delay before reaching furling speeds, above 9 m/s. As a result, the VAWT rotor under study would operate best at rated wind speeds ranging from 5 m/s to 8 m/s.

Although the methodology developed in this paper including similar effects observed in the wind tunnel are transferable to full-scale VAWT rotors, the results may suffer from scaling effects. This is due to the fact that atmospheric turbulence is different from wind tunnel generated turbulence. Therefore, we recommend that future experimental investigations could be carried out to calculate the scaling effects on wind tunnel to investigate if the results are comparable to those from larger wind turbines. However, the results from the study will hopefully, be of importance to wind energy technology stakeholders and industrial aerodynamics applications that requires designs for wind turbines, reflecting urban turbulent environment.

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