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Analytical models for concentrator and diffuser augmented wind turbines: A review

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Abstract

Energy from wind is envisaged as one of the second largest inexhaustible and clean green energy resource around the world. It has the potential of replacing fossil fuel based energy, which has high carbon dioxide emissions contributing to global warming. In addition, wind energy can provide power in remote areas which are not connected to the national electricity grids. In wind energy technology, wind turbines convert wind energy to electricity. However, most commercially available wind turbines are made for wind speeds greater than 5m/s, therefore fail to operate in areas with low wind speeds. Innovative ways of improving the wind power output include the use of concentrators and diffusers. Although there are notable experimental and computational fluid dynamics researches on concentrator – diffuser augmented wind turbines (CDAWTs), attempts to develop analytical to semi-empirical models are extremely scarce. Only analytical models for diffuser augmented wind turbines (DAWTs) dominate in literature. In this work, a comprehensive review of previously developed analytical models is presented. The information will assist researchers to comprehend current research efforts and to discover the knowledge gaps so as to develop accurate analytical models that incorporate CDAWTs structure. In this review, existing analytical models fail the validity tests due to their underlying assumptions which give incomplete explanations of the major flow phenomena. Once all these issues are considered, an analytical model that predicts accurately the power output of CDAWTs can be developed. This will be a step in the right direction in designing and constructng the CDAWTs for commercialization.

Keywords: Wind turbines, low wind speed, power augmentation, diffuser, concentrator, analytical model.

1. Introduction

The use of renewable sources of energy such as wind, solar, biofuels has increased [1]. Inarguably, the use of renewable energy sources is a panacea to meet the demand of clean energy.Therefore, the use of renewable energy particulary wind in the case of this paper is a probable avenue of meeting the energy needs of an increasing population and a way of improving the people's standards of living and economic productivity [1]. Incontrovertibly, the use of non-renewable energy from fossils is still rampant worldwide. The disadvantage of using energy derived from burning fuels is that it emits greenhouse gases such as carbon dioxide which are detrimental to the environment and has greater influence to global climate change [2, 3].

The wind resource is currently contributing around 3.7 % of the world electricity needs and in 2050 the International Energy Agency (IEA) expects wind power to contribute around 15% to 18% to the world electricity consumption [4]. The increase in wind energy use is likely to reduce carbon dioxide (CO_2) emissions by approximately 6.3 gigatonnes (Gt) per annum. Undeniably, alternating from fossil fuels to wind energy is significant in mitigating the effects of climate change [5]. The use of wind energy is gaining prominence as indicated by an increase in global cumulative installed wind capacity from 539,6 GW in 2017 to 594,4 GW in 2019 [4]. It is anticipated that it will supply 817 GW worldwide by 2021 [6].

Despite the inextricable positive impacts between the use of wind energy and reduction in carbon

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dioxide emmissions, the inefficiency of some of the devices which turn wind energy to electricity is still a challenge for example, of all the wind which a wind turbine receives, only 40% of the energy is converted into electricity. The aim of this paper is to come up with efficient ways of capturing wind energy so that we are able to meet our energy needs [6].The loophole of wind energy is that it is impossible to store wind energy mechanically before using it. As a result, the use of wind energy is solely determined by its availability [7, 8]. It is critical to note that lower wind speed results in lower wind turbine efficiency, for instance, in low wind speed areas the efficiency of a wind turbine is approximately 10-20% [9]. Overall, while the use of wind energy is gaining prominence worldwide, the challenge is that most parts of the world experience low wind speeds of approximately 4 m/s for about 330 days of the year [10, 11]. Most wind turbines are manufactured to operate in areas with relatively high wind speeds above 5 m/s. Considering the fact that most parts of the world receive low wind speeds, use of wind turbines that require high wind speed will be a mismatch and will not perform efficiently [10].

Concentrators, blades design modification, diffusers,vortex and augumentation tip vanes are some of the ways of enhancing the performance of wind turbines [11]. Researchers have noted that the wind energy output per unit time of a wind turbine is directly related to the wind velocity cubed, therefore a small change to the velocity of the wind flowing towards the wind turbine rotor plane leads to greater increase in the power output [12].The use of wind turbines encased by structures such as concentrators and diffusers amplify wind speed at rotor plane [13]. This is caused by alterations of fluid dynamic nature in the rotor plane [14]. As a result, the wind power generation will begin at lower wind speeds less than 3 m/s and increasing more potential sites for wind power [15].

An ordinary wind turbine encased with a shroud/diffuser is widely referred to as Diffuser-augmented wind turbine (DAWTs) [8]. In DAWTs the purpose of the diffuser is to generate separation regions behind it. Low pressure regions create a suction effect and the advantage of this is that they draw a lot of wind through the wind turbine rotor than an open wind turbine without the diffuser [15, 16]. It has been pointed out by researchers that DAWTs are more efficient than an open wind turbine because of the diffuser that causes the pressure to decrease behind the turbine [17]. Furthermore, DAWTs have an advantage of the small tip speed losses and small rotor diameter as well as being less yaw sensitive than HAWTs [17]. On the other hand, a Concentrator Augmented Wind Turbines (CAWTs) is an alternative option for wind power augmentation [9]. If a nozzle / concentrator is placed around a wind turbine to capture wind into a big cross sectional area and pass it to the turbine rotor through a smaller exit area of the concentrator, a lot of wind power will be generated beyond Betz limit [10, 17, 18]. A combination of a concentrator and diffuser has a greater power output than a diffuser or a concentrator [12, 19]. It is therefore necessary to consider it in this current study.

This paper provides a review of analytical models of concentrators and diffusers augmentation systems. The main goal is to establish research gaps as well as research breakthroughs made so far, so that the analytical models can be extended to a combination of a concentrator and diffuser structure. Analytical models that adequately predict the power production of wind turbines are required so as to produce energy in areas of low wind speed using concentrators and diffusers.

2. History of Analytical Models

Analytical models have been studied and established for almost ninety years. The rationale behind studying analytical models was to predict the power which a wind turbine can produce. Initially most theoretical models were used to predict power output of bare wind turbines. On the other hand, wind turbine augmentation started more than 50 years ago [20]. There has been much progress in predicting the power output of shrouded / ducted wind turbines, however, validating the mathematical models is still a challenge. The models have different results emanating from their underlying assumptions [21, 22].

The first theory of the diffuser augmented wind turbine was done by Bertz in 1929. However, the theory had two misleading assumptions which were proved to be wrong later. Firstly it was assumed that the surrounding atmospheric pressure was equal to the statistic pressure at the DAWT's exit plane.

Secondly he was of the view that if the exit to the throat area ratio is small, there will be a small disk velocity ratio. He concluded from his findings based on wrong assumptions that diffusers were not commercially viable. Most researchers at that time could not see the reason to carry on with the idea of ducted wind turbines so it was abandoned and resuscitated in the 1950s [23].

The Japanese researcher Sanuki in 1950 did experiments of shrouded wind turbines and obtained an interesting gain in power output of up to 88% relative to Bertz limit of 59,3%. On the other hand, Iwasaki in 1953 discovered a 30% increase in power when the wind turbine was encased using cylindrical structure of constant radius [7]. In 1956, two British researchers Lilley and Rainbird were the first to publish literature on ducted wind turbines [24].They derived their models using potential flow methods and the momentum theory [25]. Lilley and Rainbird asserted that the power augmentation from a shroud was a result of a decrease of blade tip losses as well as an increment in axial velocity. They also identified the diffuser exit pressure and the inlet contraction ratios as the main design parameters. These two design parameters were in turn affected by diffuser exit area ratio, the external shape of the duct as well as internal frictional losses.

From 1962 to 1963 Professor Kogan carried some experimental research on ducted wind turbines, however availability of cheap and abundant oil halted the research [26]. The research on ducted wind turbines resurfaced again due to the oil crisis in 1973 as a result of the Yom kipper War between Arabs and Israel [9, 27]. This resulted in countries investing more in alternative energy sources. In 1974 Igra, a former student of Professor Kogan at Ben-Gurion University began to conduct experiments on ducted wind turbines and almost at the same time a leading researcher Foreman with others at Grumman aerospace research Centre did a number of experiments on ducted wind turbines [25]. Although these efforts made a clear promising path ahead of future research, the conclusions from these experiments varied significantly. Igra noted sub- atmospheric pressures produce a suction and which cause high mass flow [28]. He also emphasized that the exit pressure must be as low as possible and the area ratio to be made big [28].

In spite of Lilley and Rainbird's assumption that the exit area of the diffuser makes it impossible to increase power, Foreman's experiments achieved an increase in power four times more than the power produced by a bare wind turbine. The fact that previous research contributed to the development of analytical models cannot go unacknowledged. However, the gap is that the previous research did not provide a clear and complete description of the major flow concepts in ducted wind turbines. In 1979, a conference was held on wind energy innovative systems [8, 29]. At the conference, the ducted wind turbines became a topical issue and the consensus which was reached was to shelve the idea of power augmentation since the cost of production of a shroud was deemed expensive [16]. The concept of power augmentation was also described as fascinating at the conference, however, the disappearance of DAWTs from research agendas was magnified after the conference.

Recent events of climate change and the need to make the world green has led to more research outputs on power augmentation and a drive towards commercializing the idea of shrouded wind turbines again. Researchers have noted that the power augmentation concept can be improved if the physics of fluid flow is well comprehended [30]. Review work in this paper focuses mainly on theoretical studies which might be combined with experimental results.

3. Analysis of Analytical Models

In 1976, Gilbert studied radial velocity distribution along the rotor plane in contrast with current research which ignores the radial velocity gradient for simplicity [31]. Gilbert made an effort to obtain optimum geometry of the duct as well as the appropriate spot for rotor inside the duct. In 1981, Fletcher through his analytical model attempted to study the flow characteristics of shrouded turbines by taking into account wake rotational effects [32, 33]. Fletcher also mentioned a notion shared by many researchers that the performance of a shrouded turbine depends mainly on the diffuser's efficiency and its exit pressure [34]. However, Fletcher ignored the effects of the thrust due to the diffuser as well as far wake velocity [32]. In 1983, Dick in his analytical model expressed the coefficient of power output in the form of a product of three coefficients namely energy increase, mass concentration and extraction [35].

In 2000, Hansen through his one dimensional analytical model for a ducted turbine found that Betz limit was surpassed by a ratio corresponding to the increase in mass influx through the rotor when the diffuser is added to a turbine [36]. The augmentation cannot approach the relative speed- up for a simple diffuser at a zero thrust. The reason is that the ratio between the mass influx through a DAWTs and mass influx through an open wind turbine decreases when the thrust coefficient is increased [22, 37, 38].

In 2007, Van Bussel strived to develop mathematical model for DAWTs based on energy conservation laws [39]. In trying to make his model to have a close resemblance to the momentum theory for traditional bare wind turbine, he assumed that viscous wake mixing was not present behind the diffuser. However he asserted that the negative back pressure effects must be considered [38]. More so, he claimed that for a physical diffuser just downstream, the velocity would be equal to the mean of the far upstream and downstream velocities. This is only true for short diffusers because it can accommodate similar conditions for induction factor as in bare wind turbine, at the end of the diffuser exit plane [40]. Van Bussel indicated that an increase in mass flow would result in an increase in power coefficient. The mass flow increase is achieved in two ways either by back pressure decrease at exit or by increasing the diffuser exit area ratio [41].

Among the main findings he made was that the value of the decrease in pressure over the rotor was equal to 8/9 and similar to one obtained for traditional bare wind turbines. In addition, it was found that specific energy extraction was identical in both DAWTs and open wind turbines and power augmentation values of 2.5 times high, would be obtained with remarkable backpressure [16, 38, 42]. Van Bussel noted that power augmentation obtained experimentally will always be less than the one calculated theoretically from analytical model due to flow separation in the duct wall, as illustrated in Fig.1.

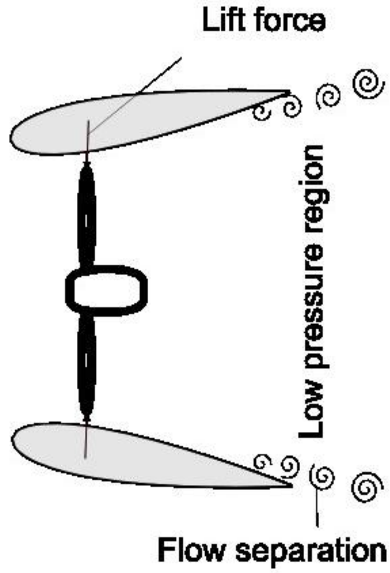

Fig. 1. Shrouded wind turbine depicting flow separation along the duct inner walls [43].

In 2008, Jamieson presented a changed version of the actuator disc momentum theory similar to Van Bussel's model [43]. In Jamieson's theory, the diffuser is decoupled from the whole system [44]. The diffuser is only considered by making an assumption of an induction factor at zero thrust [43–45]. The thrust on the shroud and the wind turbine rotor are assumed to be independent. Due to the exclusion of the axial force interaction between the shroud and wind flow, momentum conservation over the whole control volume is ignored [46]. This is not feasible because the performance of the diffuser depends on the thrust exerted by the rotating blades [37].

From his theory, Jamieson derived the power coefficient C_{pr} in Equation 1 and the maximum power coefficient C_{pmaxr} value in Equation 2 using wind turbine rotor swept area.

$$C_{pr} = \frac{4(a_{dr} - a_o)(1 - a_{dr})^2}{(1 - a_o)^2} \tag{1}$$

where a_o and a_{dr} are the axial induction factors for empty diffuser and the DAWTs respectively.

$$C_{pmaxr} = \frac{9}{8}(1 - a_{max}) = \frac{16}{27}(1 - a_o), \quad a_{max} = \frac{1 + 2a_o}{3} \tag{2}$$

where a_o is the axial induction factor for empty diffuser, a_{max} is axial induction factor which maximize the power coefficient C_{pr} and $1 - a_{max}$ is considered to be area ratio of upstream source to the wind turbine rotor plane.

Equation 2 depicts that the maximum power coefficient C_{pmaxr} depends on a_o . Jamieson found that the thrust coefficient which matched with maximum energy of a DAWTs was equal to 8/9 which was also in agreement with Van Bussel and Werle and Presz's results [44, 46]. Although Jamieson and Van Bussel's models provide useful alternative to standard Actuator disc model for the shrouded case, the models fail to find the physical parameters on which the performance of the duct depends on.In 2008,Werle and Presz developed a unified analytical model. This model was totally different from other models put forward before because the effect of the diffuser was included through an axial force acting as a force vector to incoming flow. In the model, the total thrust T_{thrust} is a summation of the force exerted on the diffuser $F_{diffuser}$ and the force exerted on rotor blades F_{rotor} as shown in Equation 3 [37].

$$T_{thrust} = F_{rotor} + F_{diffuser} \tag{3}$$

The power obtained from this model was given by:

$$P = \frac{1}{2}\rho A_r v_\infty^3 (4a(1-a)^2(1 + C_{Tdiffuser}) \tag{4}$$

where ρ is density of air, A_r area covered by the rotor, v_∞ upstream velocity, a is axial induction factor and $C_{Tdiffuser}$ is the thrust coefficient for the diffuser.

From Equation 4, in the absence of the diffuser, the thrust coefficient for the diffuser $C_{Tdiffuser}$ will be equal to zero. In this case, the obtained power from this model will be the same as for open wind turbine. At an induction factor of 1/3 the maximum power is obtained and yields similar results of the thrust coefficient of 8/9 obtained by Jamieson. Using their model Werle and Presz found that shrouded wind turbines had greater ability of extracting a lot of wind power than an open wind turbine [10].

The maximum power extracted by a DAWTs is only determined by non-dimensional shroud force coefficient as indicated by Equation 5.

$$Cs = \frac{F_d}{T_r} \tag{5}$$

where F_d is the axial force on the duct and T_r is the thrust of the rotor [47].

The main limitation of Werle and Presz model is that the influence of both the rotor and duct on each other is ignored. Therefore, an incorrect linear relationship between the axial force due the duct and the rotor on the fluid is implicitly assumed [38, 48]. Konijn noted that the theory breaks down and becomes invalid if disc loading coefficient is two. He concluded that it is not necessarily true that the thrust of the rotor is proportional to axial force as assumed by Werle and Presz in their model.

Bontempo and Manna [49] applied a nonlinear model which was semi-theoretical to study aerodynamic performance of DAWTs [48]. The non-linear approach took into consideration the wake rotational effects and velocity alterations in the radial direction as well as rotor-duct interactions [30]. The results obtained from the model depicted that more wind power is extracted due to an increased mass influx entering through a shrouded turbine than a bare turbine with a similar rotor load [48].The model was considered good and successful because it was simplified, robust and had low computational cost. It is important to note that, numerous further improvements of the model by Bontempo and Manna in 2014 has been done [49, 50].

In 2018, Vaz and Wood [22] developed a mathematical model for DAWTs by extending the blade element model. Thrust and diffuser efficiency were the two additions in the model. It was concluded from their analysis that as diffuser efficiency increases both the thrust and the power also increases [51].

In 2019, Siavash et al [31] developed a mathematical model of a shrouded wind turbine. They derived analytical relations and used them to find power coefficients. They also interpreted the analytical relations graphically. It was also emphasized that it would be impossible to manufacture a duct with duct exit area ratio β =0.1, and efficiency of the duct η_d =0.1, hence the need to calculate the duct performance using parameters that are mathematically valid within acceptable range. It is envisaged that any duct designed correctly cannot give a coefficient of power (Cp) =1, for a wind turbine but Cp =0,93, can be achieved. Siavash et al [31]'s model focused mainly on two features. Firstly they pointed out that velocity decrease ratio found within the wake area of shrouded wind turbine and open bare wind turbine were different, therefore $\mu = 1 - 2a \neq \frac{1}{3}$. Secondly, a pressure drop factor was included in the equation of Bernoulli due to duct wastes.

The model replaced the following Equation 6 with Equation 7 [31]

$$V_w = \left(1-2a\right) V_\infty \text{ where } a = \frac{1-V_r}{V_\infty} \tag{6}$$

where, V_w is far wake velocity and V_∞ is upstream velocity, V_r is velocity of rotor plane and a is the induction factor. Equation 6 is for open bare wind turbine.

$$\mu = \frac{V_w}{V_\infty} \tag{7}$$

where, μ depends on γ, β and η_d. γ is ratio of velocity through the diffuser to velocity far upstream (velocity speed-up ratio), β is the ratio between the inlet area and outlet area of diffuser and η_d is the efficiency of the duct. The model replaces Equation 6 with Equation 7 because an analytical solution does not exist that depicts that the far wake velocity for shrouded turbine is equal to that of open wind turbine. In addition the axial induction factor for bare wind turbines in Equation 6 was not used [31].

The power derived from the model is given by:

$$P = \frac{1}{2}\rho A_r v_\infty^3 \gamma \left[\left(1-\mu^2\right) - \gamma^2\left(1-\beta^2\right)\left(1-\eta_d\right)\right] \tag{8}$$

where ρ is the density, A_r area covered by the rotor, v_∞ is upstream velocity, μ is turbine Speed reduction factor, γ is ratio of velocity through the diffuser to velocity far upstream (velocity speed-up ratio), β is the ratio between the inlet area and outlet area of diffuser and η_d is the efficiency of the duct.

The model also outlined that the best value for the speed-up ratio is approximately 1.6 and this number is mainly affected by energy absorbed by the rotor and duct. The results obtained by Siavash et al [31] differed from Palmer et al ‘s results. The difference was due to the underlying assumptions in their models about the capture area. Palmer et al [16] assumed that between the area where the wind is captured and the area of the shroud, mass conservation law must apply. In contrast, Siavash et al [31] did not use the same assumption as Palmer but instead proposed a certain parameter which represents the percentage of capture area’s available energy. Palmer et al [16] predicted a power augmentation of ratio of 2,7 with a power coefficient of approximately 1.6. Siavash et al [31] in their work proved that a high speed up ratio of γ =2,7, is required for this value of 1.6 to be achieved and it is practically not possible [16]. It is important to note that Siavash et al [31] ‘s model can be extended to a concentrator - diffuser augmented wind turbine. However, the total physical estimation of the total maximum power coefficient needs further analysis to improve it.

In 2017 Khamlaj and Rumpfkeil [52] developed a one- dimensional theory for ducted wind turbines including a nozzle and diffuser. They modified the theory for DAWTs developed by Foreman and Lawn previously so that they could incorporate the effect of the nozzle section. The nozzle section was combined to the DAWTs section and a new structure was formed called NDAWT where N is the nozzle section. The structure is depicted in Fig. 2.

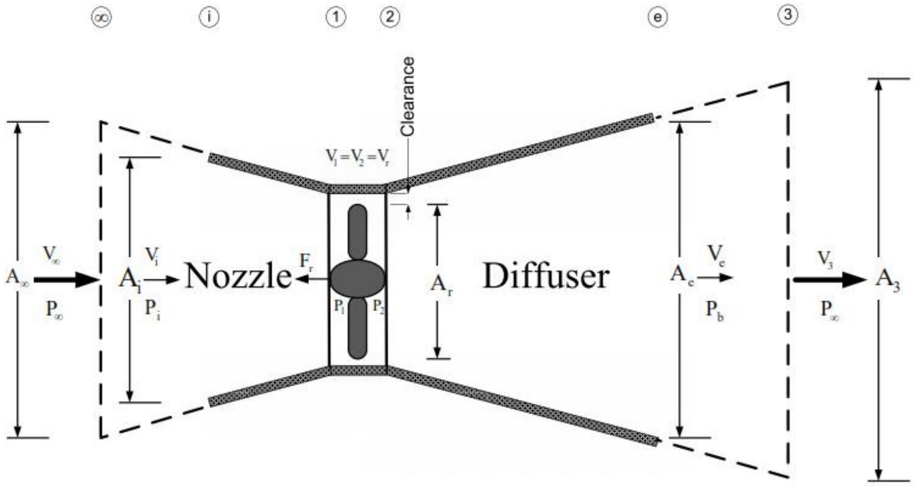

Fig. 2. Shows the structure of NDAWT [52]

Khamlaj and Rumpfkeil [52] through his model observed the same results as Vaz and Wood that as diffuser flow efficiency increases the power is also increased. They also noted interesting results that NDAWT geometry had a 12% increase in the power output and 15% decrease in back pressure coefficient compared to DAWTs geometry. The results agrees with many experimental and computational fluid dynamics modeling results carried out so far by researchers on NDAWT that its power augmentation is greater than DAWTs or bare wind turbines [12, 19]. The mathematical model gives a good foundation for initial design of NDAWT structure. An optimized NDAWT must be prioritized during designing stage focusing on decreasing back pressure at the exit even using flanges or brims [52].

The coefficient of the power output for the NDAWT is given by:

$$\frac{c_{pnd}}{\eta_t} = C_t V_r = \psi \left[\frac{1 - c_{pb}}{\psi + \eta_n + \lambda_n{}^2 \left(1 - \eta_n\right) - \eta_d \left(1 - \lambda_d{}^2\right)} \right]^{1.5} \tag{9}$$

where c_{pnd} is the coefficient of the power output of the NDAWT, c_{pb} is back pressure coefficient , η_t is the turbine efficiency, C_t is coefficient of thrust for turbine, V_r is velocity speed-up ratio, ψ is loading coefficient, η_n is nozzle efficiency, λ_n is area ratio of the nozzle, η_d is efficiency of the diffuser and λ_d is area ratio of the diffuser [52].

Using Equation 9 , Khamlaj and Rumpfkeil [52] asserted that power increase is achievable only when exit area ratio for both the diffuser λ_d and the nozzle λ_n are small and this must be coupled by high diffuser and nozzle efficiencies as well as a very big negative back pressure coefficient Cpb. In addition, it was noted that Equation 9 can be reduced to match the traditional Betz results by eliminating diffuser and nozzle's effects. This is done by equating $\eta_n = \eta_d = 1$, and $\lambda_n = \lambda_d = 1$, and using $C_{pb} = 1/3$. It is important to note that Equation 9 is semi-empirical as also pointed out by Khamlaj and Rumpfkeil [52] therefore, a lot of its performance weakness emanates from the coefficients that are supposed to be empirically determined. This is aggravated by the unavailability of NDAWT data to use to determine the coefficients such as, c_{pb} , η_n and η_d .

Although the model borrowed ideas from Foreman and Lawn, it was supposed to take into consideration the wake rotational effects and non-uniformity of velocity flow along the blade radii as well as the rotor-duct interactions [53].The incorporated theory of Lawn becomes invalid for big values of diffuser exit area ratio if back flow cannot be ignored and also if there is no continuous air flowing inside. In reality these conditions exist.As a result, Lawn made assumptions to avoid them. It may be suggested that by using the Lawn theory which had these shortcomings to develop their mathematical model, Khamlaj and Rumpfkeil brought in limitations in their model. In addition, Bernoulli equations used for bare wind turbines cannot be applied in nozzle-diffuser structure without modification. As noted before, a semi-empirical model has serious flaws since empirically determined coefficients will lead to calculations that are invalid and in most cases with no analytical solutions hence unable to provide physical interpretation. The positioning of the rotor in the nozzle-diffuser structure is the key to the performance of the rotor hence the model must be able to indicate that particular position mathematically rather than through trial and error method [6]. The model has to take into consideration how the nozzle and the diffuser are joined together to allow the extension structure to have an effect to the physics of flow of the wind inside the structure.

4. Conclusion

The findings indicated that the analytical models developed so far are mainly for diffusers. Attempts to develop analytical models on shrouded structures with both nozzle and diffuser to author's knowledge begun with a semi-empirical model pioneered by Khamlaj and Rumpfkeil in 2017. The challenges in predicting correctly the power output of wind turbines is a result of incorrect assumptions of the developed theoretical models hence the need to put much focus on them. Most developed models are semi-empirical and this has led to incorrect coefficients to be determined using wind tunnel experiments or computational fluid dynamics modeling results mainly for diffusers. The controlled conditions in a wind tunnel and the underlying assumptions in many computational fluid dynamics programs contribute to semi-theoretical models that have led to poor prediction of the power output leading to closure of projects. In addition, the validation of the models using CFD results or experimental data results obtained in different environments or set up maybe misleading and lacking data to validate analytical models.

It can be concluded that CDAWTs are experimentally regarded as an alternative possible route to consider with lots of potential of producing electrical energy in areas with low wind speeds. It is therefore necessary to focus more on developing analytical models that would correctly predict the power output. Over the years, a lot of effort and emphasis has been on the diffusers, but the issue of increasing the power output to reach commercialization stage using diffusers only is still a challenge.

Conflict of Interest

The authors declare no conflict of interest.

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