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Implicit rule for the application of the 2-parameters RANS turbulence models to solve flow problems around wind turbine rotor profiles

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ABSTRACT

Appropriate wind farm layout design depends on the accurate prediction of flow characteristics around turbine's rotor, especially as it affects downstream turbines. The complexities of the flow characteristics as a result of the wake deficit affects prediction accuracy. Thus, the importance of selecting an appropriate turbulence model to resolve the flow dynamics of the wake deficit cannot be overemphasized. There are several numerical turbulence models and selecting one that converges to the flow characteristics is inevitable for accurate performance prediction. Most practices usually based the choice of model on previous studies' methodologies and results without the essence of application. While selecting the best performing model is usually not straightforward, it is however hinged on knowledge of the capabilities to resolve eddies. This is the focus of this study. Various studies were analysed alongside their turbulence resolution techniques with special consideration given to the Reynolds-Averaged Navier Stokes methodology and the two equation transport models of k-ε and k-ω turbulence models. The study showcased and determined the rule of engagement for the application of the eddy viscosity model of the type of the k-ε and k-ω turbulence models to resolve the closure problem associated with flow analysis. The shortcomings of each model were analysed and the comparative advantage of each was showcased alongside the combinatorial shear stress transport k-ω model.

1. Introduction

The development of wind power technology have come a long way. The progression in technology enhancements has been through the last two to four decades. This growth in technology improvements range from design optimization for noise emission reduction (Göçmen and Özerdem, 2012), aeroacoustics and aerodynamic performance (Zhang et al., 2018), optimisation under stochastic processes Keshavarzzadeha et al. (2019), increase in hub heights for enhanced optimal generation, increase in generation capacity, determination of number of blades for optimum power production, to startup capacity improvement (Ajayi et al., 2019). Others include optimization of blade shape with Gurney flap (Amini et al., 2015), taper modification (Kaya and Elfarra, 2019), and winglets (Khalafallah et al., 2019). Many other studies also focused on the dynamics of turbine siting (Sathyaith et al., 2016), resource assessments (Riahy and Abedi, 2008), modelling for pre-assessment study (Ajayi et al., 2012), and mapping and econometrics of wind power generation (Ajayi et al., 2016), among others. On control technologies for effective performance, Jeong et al. (2013) and Li et al. (2016) studied the effects of yawed conditions, Zhou et al. (2017) considered the connection between Mach number and rotor flow dynamics, Melo et al. (2018) worked on the lifting line methodology for wake alignment, and Wang et al. (2018) considered the effects of the various positions of a control mechanism on flow dynamics. Whereas Archer and Vasel-Be-Hagh (2019) looked into the impact of wake steering via yaw control, Hao et al. (2019) studied the effect of adaptive flap on flow control, and Pasquale et al. (2019) focused on flow control through plasma actuators. Various other studies also considered wind turbine condition monitoring, wind turbine clustering and wind farm layout design Niayifar and Porté-Agel (2015), turbine wakes using different wake models like those of Shakoor et al. (2016), and Li et al. (2018), experimental wake investigation by Dou et al. (2019), wake effect under yawed conditions (Lee and Lee, 2019), and the influence of boundary layer on wake dynamics (Sedaghatizadeh et al., 2019). Different studies also highlighted the importance of the aerodynamics of the rotor blades. Such studies include those of Sedaghat et al. (2014), Tahani et al. (2017)

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and Kaya et al. (2018). The main purpose of these technology improvements is to have an optimum increase in the size of energy harvestable from an installed wind turbine at reduced cost per kW power generation. The wind power industry have leveraged development on the ability to design and analyze wind turbine performance for effective utilization and power generation.

Employing a cluster of wind turbines in a wind farm setup requires adequate layout design. This is because the rotor shape and attached flows are very essential parameters to the performance of the wind turbines. Various studies have focused on the parametric and geometric analyses, as well as the flow dynamics around the wind turbine blades, and how they affect wind turbines/farm performance. The impact of the atmospheric boundary layer on the flow dynamics is of major essence and have direct effect on energy harvest and the material integrity of the rotor systems, especially at the downstream regions. Not until recently, the majority of the investigations around wind turbines are on the augmentation of power coefficient and aerodynamic performance. Studies on wake characteristics were scanty.

Adequate knowledge of flow characteristics, especially in the turbine's wake, is important for prediction of power generation from a wind farm. The ability to analyze and solve the flow problems around the turbine rotor system is very essential for appropriate wind farm layout design. Flow past a turbine introduces a phenomenon called wake deficit. Wake deficit is associated with velocity reduction, flow deviation, and turbulence, thereby introducing complexities to its analysis, and place the burden of assessment of wind turbine/farm performance on the accuracy of flow analysis. The accurate prediction of wake recovery is essential to wind farm design and energy harvest. Researches have shown that the choice of a right turbulence model significantly influence the outcome of the analysis. Selecting the best performing model is usually not straightforward at the beginning (Richmond et al., 2019). This is because it is not always enough to base the choice of turbulence model on previous studies' results, it is also worthwhile to understand the essence of application before selection. This is the focus of this paper. It aimed to review various studies on the subject and collated the very important information that guides the choice of turbulence models. Although there are different numerical approaches to resolve the turbulence flow characteristics, this paper focused on the Reynolds-Averaged Navier Stokes (RANS) methodology and the two equation transport models of k-ε and k-ω turbulence models. The basic objective is to showcase and determine the rule of engagement for the application of the eddy viscosity model of the type of the k-ε and k-ω turbulence models to resolve the closure problem associated with flow analysis based on the RANS technique.

The paper is organized to capture the review of recent developments in wind turbine research, concepts and analysis of flows around turbine rotors, and advances and applications of wake models, with particular focus on the application of the 2-parameter RANS methodology.

2. Review on recent wind turbine research developments

Despite all of the technological advancements in wind turbine systems, research efforts related to blade shape optimization, turbine wakes, and aerodynamics of the rotor blades are still ongoing and dominating most recent research activities. This is because, the shape of the blade is one of the most important factors that affect turbine performance, and its aerodynamics influence its behaviour in a stream of air. For example, Cheng et al. (2018) carried out a comparative study to assess the effect of blade optimization on the performance of a semi-submersible Darrieus rotor vertical axis wind turbine (VAWT). The focus was to evaluate the influence of the radial orientation, rotor height and length, and blade chord length on the augmentation of the annual power generation. The results indicate that optimization improved the annual power production by 11.3%. Li et al. (2018) studied the effects of change in blade pitch and chord length on the average power coefficient from an H-rotor VAWT. The focus was to develop a real-time optimal pitch control in a complete azimuth regime and to test the effect of blade pitch optimization on power generation. The outcome demonstrates that the optimization led to improvement in the average power coefficient. Chan et al. (2018) and Ramadan et al. (2018) carried out the performance enhancement of a Savonius wind turbine by optimizing the blade shape.

Mohamed et al. (2019) numerically studied the effect of blade shapes on the aerodynamic efficiency of three-blade Darrieus VAWT. Several airfoils were analyzed and the performance variations noted. Storti et al. (2019) modified the airflow around the aerodynamics of a Savonius wind turbine by designing and installing deflector plates. Also, Keshavarzzadeh *et al.* (2019) carried out the shape optimization of a horizontal axis wind turbine (HAWT) rotor blade under uncertainty conditions of wind speeds in time and space, and structural material properties. It also studied the influence of blade shape optimization via twist angle distribution along the span and employed a computational technique based on the aerodynamic parameter analysis of the blade element method. It utilized the reduced order model of the blade structure and wind load alongside design sensitivity analysis to integrate the aerodynamic blade element method with the uncertainty conditions of blade structure and wind load. A non-intrusive polynomial chaos expansion was used to analyze the structural stability and coefficient of power. Kavari et al. (2019) investigated the effect of wind shear on the aerodynamic performance and power coefficient of a HAWT. It employed the blade element momentum theory and incorporated the power law wind shear estimation model. The results demonstrated that changes in wind shear profile affects the aerodynamic coefficients of lift and thrust, along the blade span, and also impact on the efficiency of power generation. In the same vein, Saleem and Kim (2019) investigated the effect of the blade tip clearance on the aerodynamic performance of the newly developed buoyant airborne wind turbine that is of the non-crosswind type fly-gen system. The focus was to study both the impact of the blade geometry modification on the power performance and the airflow structure in the wake at the downstream section of the turbine.

In other studies, Fatehi et al. (2019) carried out the aerodynamic performance improvement via the cavity shape optimization approach. The cavity shape optimization was employed as a passive means of augmenting the airfoil performance. The cavity was created on the suction side of the airfoil along the chord length. Its purpose was to modify the wind circulation and improve the flow around the blade profile, thereby increasing the lift-to-drag ratio. Sessarego et al. (2020) demonstrated that blade curvatures have a slight advantage over straight blade shape in terms of average power production and mean thrust. Lee and Kwon (2020) studied the aerodynamic shape optimization and performance improvement of a wind turbine by modifying the blades' section contours. Sedighi et al. (2020) studied the effect of blade shape modification by creating dimples on the surface of the blade of a small HAWT. The influence of the dimpled-surface blade, blade pitch angle, and wind speed on the performance of the turbine were then numerically investigated. Also, the impact of radius, quantity, and location of dimples on the aerodynamic efficiency of the turbine were considered alongside the power generation, torque, thrust, and flow separation. The results showed that blade shape modification via dimpled-surfaces can affect the turbine's performance by increasing the torque and power generation. Salimipour and Yazdani (2020) carried out a study on the effect of a moving surface on the aerodynamic performance improvement of an offshore HAWT blade. The moving surface was employed as a flow control mechanism and made a part of the airfoil surface. Li et al. (2020) on the other hand, investigated the performance improvement of a straight-blade VAWT with wind gathering devices attached to both ends of the airfoil. The study also considered the impact of the wind gathering device parameters like the ratio of radii, inlet and outlet angles. Baghdadi et al. (2020) carried out a novel dynamic shape modification and optimization of a VAWT. It used the approach of blade morphing as a function of the tip speed ratio and azimuth angle in order to maximize the moment at the turbine's axis and improve the power generation. Mohamed et al. (2020) created a slot on the airfoil employed in a VAWT and used it to improve torque and power coefficient at low tip speed ratio. The effect of the slot parameters such as angle of inclination, location and dimension were investigated alongside the turbine performance and startup characteristics. The outcome indicates that the slot brought about generation at lower optimum tip speed ratio, and higher torque at lower rotational speed. The results further showed that the slot impacted on the airflow by delaying the flow separation at higher angles of attack.

Based on the aforementioned studies and some other studies, it is clear that airfoil or blade modifications are carried out for the purpose of having a better performing and optimum power generating wind turbine at low production cost. This invariably is predicated on the fact that the blade's aerodynamicity is a major criterion that governs the turbine's behaviour and improves the lift-to-drag ratio. Hence, the airflow characteristics around the blade, upstream and downstream, is of utmost concern. As a result, flow separation, reattachment, and control principles are essential to turbine performance, turbine clustering in wind farm design, and turbulence analysis. In line with this, various technologies have been developed. These include the use of flaps (by Bianchini et al. (2019), Huanga et al. (2019), and Zhang et al. (2019)), flanged-diffuser systems (by Khamlaj and Rumpfkeil (2018), and Siavash et al. (2020)), airfoil concavity (Ma et al., 2019), and wind lenses (by Clements and Chowdhury (2019), and Dessoky et al. (2019)), among others, to improve flow regimes, upstream and downstream, for the purpose of augmenting the aerodynamic efficiency and also enhance flow characteristics.

3. Concept and analysis of the flow around wind turbine rotors

The flow around a wind turbine rotor system is complex and at times difficult to analyze due to its peculiar characteristics. This is due to the fact that when wind flows through and around a wind turbine rotor system, an aerodynamic wake region is produced at the downstream section of the turbine. This wake region is characterized by reduction in flow speed and associated increase in downstream area, pressure drop between the upstream high and downstream low pressures, vorticity of the wake field due to blade tip vortices, and increased turbulence. This wake effect has implications on the performance of wind turbines and the magnitude of power generation, most especially when several turbines are clustered in wind farms. This gives the reason for the concept of near wake, for generation from a single turbine system, and far wake, for generation from turbines in the downstream sections such as in wind farms.

The deviations in the wind flow between the upstream and downstream and its impact on the performance of turbines vis-à-vis the turbulence characteristics at the turbine's downstream have been the subject of researches. This is because, the wake effect brings about a reduction in the available power in the downstream wind turbine systems. Thus, the increased turbulence, according to Lundquist and Bariteau (2015), is very important to how wakes are formed, how they combine in wind farms and how they dissipate downstream. Suffice then to say that the energy available to downstream wind turbines depend on the characteristics of turbulence dissipation. It is worthy of note that the flow characteristics of the far wake profiles are principally influenced by surrounding atmospheric field and not by the turbine's parametric characteristics, unlike the near wakes. This link to the fact that appropriate understanding and evaluation of wake formation, propagation, and dissipation are important to wind farm design and assessment of power generation.

The knowledge of turbulence dissipation and wake erosion is necessary to understand the behaviour and performance of a turbine or clusters of turbines in a wind farm and how the turbines communicate with each other through their flow interactions. This is given the fact that the primary purpose of wake models is the prediction of velocity deficit, with the focus of such studies and analyses on turbine wakes with a bid to control or deflect the wake from the turbine rotor while employing different associated models. For instance, Ishihara and Qian (2018) employed the Gaussian-based analytical wake model to predict the mean velocity and turbulence intensity distribution in the wake regions of downwind turbines. Ge et al. (2019) on the other hand, extended the Gaussian-based model to employ a two dimensional wake model with self-similar Gaussian shape of velocity deficit in which an expansion rate is associated with the physical wake boundary. Cheng et al. (2019) based the analysis of the turbine wakes on the Monin-Obukhov similarity theory and employed the roughness and Monin-Obukhov lengths as the input parameters. The resulting model follows a Gaussian-like function and includes the effect of atmospheric stability. It establishes the relationship between lateral turbulence intensity and wake expansion rate. Qian and Ishihara (2019) employed a new Gaussian-based analytical wake model of modified delayed detached eddy simulation to investigate the wake characteristics over escarpment. It considered the effects of terrain and surface roughness on wind speed, direction, and turbulence intensity. Due to the nature of travel dynamics of wakes, there is a need for accurate prediction taking cognizance of its meanderings. As a result, Braunbehrens and Segalini (2019) introduced a statistical model to evaluate and account for the wake meandering at the turbines' downstream section. The model is based on the Lagrangian particle dispersion.

In another study, Ti et al. (2020) employed a methodology of the machine learning approach in which the artificial neural network (ANN) model, based on the back propagation algorithm, was designed and developed to analyze wake flows and turbulence intensity accurately. It incorporated the actuator disk model with rotation (ADM-R) into the Reynolds-Averaged-Navier Stokes (RANS) simulation coupled with modified k-ε turbulence model as a means to train, test and validate the ANN model. The upstream flow speed and turbulence intensity were used as input and the downstream turbulence kinetic energy and velocity deficit were the output. Kabir et al. (2020) used the genetic programming technique to evaluate and analyze the wake velocity and turbulence intensity for both the uniform and atmospheric boundary layer flows.

On the other hand, Fu et al. (2019) studied the impact of roll and pitch motions at different frequencies and amplitudes on the turbine power output and wake characteristics of a floating offshore wind turbine model. It found that the turbine's motions significantly alter the wake at the turbine symmetry, while the rolling caused a reduction in momentum deficit. Motions not more than 10° enabled increased power production. Lei et al. (2019) studied the effect of pitch and surge motions of the floating structure platform on the wake characteristics of an offshore VAWT. Lee and Lee (2019), on the other hand, considered the impact of the floating platform's six degree-of-freedom motion on the distortion of the wake structure of a floating offshore wind turbine. It showed that the platform motion caused a periodic deformation of the wake structure and breakdown of the helical wake vortices. Abraham et al. (2019) demonstrated how the flow fields around the turbine nacelle and tower impacts upon the near wake of a wind turbine. It accounted for the velocity fields around and behind the rotor structure and showed that there is an accelerated flow region around the nacelle and a velocity deficit behind the tower. Dou et al. (2019) also demonstrated the influence of pitch angle, tip speed ratio and yaw angle on the far wake evolution of a wind turbine. Archer and Vasel-Be-Hagh (2019) investigated the influence of yaw angle variations on the wake structure and power production of wind turbine-clustered farm. It demonstrated that positive yaw angle control leads to increase in power production. Wang et al. (2019) carried out the flow investigation of the impact of turbine wake on the downstream turbines with different control strategies. The approach was to alter and observe the influence of the yaw and tilt angles on power generation. It employed the actuator line method. The study found that the wake deviation strategy can optimize offshore wind farms and demonstrated that yaw control is preferable with better impact on generation than the tilt angle control strategy. Additionally, Abraham and Hong (2020) investigated the dynamic wake modulation by considering the wake motion with wake expansion and deflection and how the wake modulations affect wake recovery.

Going by the highlighted studies and several other studies, it is clear that the optimum production from a cluster of wind turbines is dependent on the wind farm layout design and ultimately on the accurate analysis of the flow around turbine rotors. More importantly, proper wind farm layout design is predicated on accurate modelling and characterization of turbine wakes and turbulence intensity. This is because the operation of upstream turbines and its airflow dynamics significantly affect the downstream turbine installations and impacts on their performance, production capacity, and lifespan due to the associated wake effect. Also, the downstream turbines are affected by the atmospheric boundary layer of the downstream zone. Thus, the essence of proper wake characterization and evaluation is due to its essentialities to the development of appropriate control strategy and wind farm design and management for optimal production and protection of downstream turbine life (Kumer et al., 2017). Based on this, many studies that have evaluated and assessed the wake effects have employed various methodologies to characterize and understudy the formation, propagation, and dissipation of turbine wakes. The methodologies varies from field experiments, wind tunnel testing, to development and application of various models. While field experiments remain the best form of approach to understand the theory and principle of real life turbine-wake dynamics, it is limited by the difficulty posed as a result of the turbine size and measurement instrumentation. In line with this, wind tunnel testing and measurements have been used to mimic field experiments. This also is limited due to its inability to capture the full signatures of atmospheric boundary layers and its impact on wake propagation and dissipation vis-à-vis wake steering dynamics and large rotor-airflow interaction. As a result, several studies have focused on employing wake models.

4. Advances and application of wake models

Wake induced turbulence impacts on the structural integrity of downwind turbines. Modelling the turbulence in wind turbine wakes is necessary to understand the effects of turbulence intensity on the fatigue loading of downwind turbines. In essence, adequate knowledge of wind turbine wakes is important towards the augmentation of turbine performances. Due to the complexities of flow scales and the interaction through atmospheric boundary layer, wake flows can be solved via the simulation of models. These models are developed basically to analyze the velocity deficit in the turbine downstream section. Based on this, the model expression that properly mimics wake propagation dynamics is one that is suitable.

Wake propagation can be simulated using appropriate models, especially the far wake models. Advances in wake modelling can be traced to the popular Jensen's model (Jensen, 1983) and its modification by Katic et al. (1986). The Jensen's model (equation (1)) assumed the velocity deficit to be of a top-hat profile shape and employed the momentum conservation theory. It expresses the wake velocity (U_w) as a linear function of the rotor diameter (d) and distance behind the turbine (x). Katic et al. (1986) extended the model to include the effects of topography, turbine's characteristics and wind direction. The model was improved with the influence of thrust (C_T) and wake decay (k_w) coefficients adequately captured.

$$U_w = U_\infty\left[1-\left(1-\left(\sqrt{1-C_T}\right)\right)\left(\frac{d}{d+2xk_w}\right)^2\right] \tag{1}$$

The wake diameter (d_w) can be evaluated from:

$$d_w = d + 2xk_w \tag{2}$$

where: U_∞ is the upstream flow velocity.

The expression of equation (1) is simple and easily employed to define the factor of velocity deficit caused by the wake effect of the turbine. It can also be used, at constant x and C_T, to understand the impact of turbulence dynamics, roughness, wind shear or hub-height effect, and atmospheric stability. Based on the Jensen's model, the value recommended for wake decay coefficient for offshore and onshore wind farms are 0.05 and 0.075 as utilized in Wind Atlas Analysis and Application Program (WAsP) (Shao et al., 2019). The model assumes a constant rotor speed within the wake and expands radially at the rate of (xk_w).

The extension was based on a major issue about the Jensen's model, which is the fact that it applies to near wake and of a single turbine. For that, the wake structure is dependent on the periodic swirling vortices and does not consider the ambient turbulence intensity. Based on some of these shortcomings, Katic et al. (1986) further modified Jensen's model by assuming the wake to be turbulent and neglects the near wake effect. It captured the turbine's behaviour to changes in thrust coefficient when the turbine is regulated by stall or pitch control and considered the ground interaction of the wake. It also ensured the model cater for the in-wake velocity deficit of any turbine, n, within a wind farm, by recognizing the superimposition of the local wakes within the wind farm, to estimate the velocity deficit of the nth turbine (δ_n) as shown in Göçmen et al. (2016) and Peña et al. (2016):

$$\delta_n = \sqrt{\sum_{i=1}^{n}\delta_i^2} \tag{3}$$

The velocity deficit of the turbine is defined from equation (1) as:

$$\delta_n = 1 - \frac{U_{wn}}{U_\infty} = \frac{U_\infty - U_{wn}}{U_\infty} \text{ and } \delta_i = 1 - \frac{U_{wi}}{U_\infty} = \frac{U_\infty - U_{wi}}{U_\infty} \tag{4}$$

Equations (3) and (4) can be used to estimate the resultant effect of interacting wakes with the assumption that the energy deficit of the superimposed wakes is equivalent to the sum total of the energy deficit of individual wake at the downstream location.

4.1. Frandsen wake model

Frandsen et al. (2006) developed an analytical model to evaluate the velocity deficit in turbine wakes of small and large wind farms. The model is similar to Jensen's in the assumption of a top-hat wake velocity profile, but applied the momentum and mass conservation theories and further assumed self-similarity and axis-symmetry of flow to develop the wake model. In addition, the model development focused on even row distribution of offshore wind turbines. The model expression for the velocity deficit can be expressed as given by Frandsen et al. (2006) and Brusca et al. (2018):

$$U_W = U_\infty\left(\frac{1}{2}\pm\frac{1}{2}\sqrt{1-2\frac{AC_T}{A_W}}\right) \tag{5}$$

where: A is the rotor swept area, and A_W is the wake area.

The wake diameter (D_W) at any distance downstream (x) is given as:

$$D_W = D\left(\beta^{\frac{k}{2}} + \alpha s\right)^{\frac{1}{k}} \tag{6}$$

where: D is the wind turbine rotor diameter, β is the wake expansion coefficient, k and α are constants such that k is assumed to be 2, for square rotor shape or 3 going by the analysis of Schlichting. α is related to the thrust coefficient and determined experimentally. It is set as 0.5 by Barthelmie et al. (2006), s is the relative distance downstream, simply referred to as turbine spacing and it is given as:

$$s = \frac{x}{D} \tag{7}$$

The initial wake diameter ($D_{initial}$) is evaluated from:

$$D_{initial} = D(\beta)^{\frac{1}{2}} \quad (8)$$

The expression for the wake expansion coefficient is:

$$\beta = \frac{1 + (1 - C_T)^{\frac{1}{2}}}{2(1 - C_T)^{\frac{1}{2}}} \quad (9)$$

4.2. The Larsen's model

The Larsen (2009) is a model that was first developed by Larsen in 1988 and modified in 2008. It is a little more complex than Jensen's and Frandsen models, and denotes a Gaussian velocity deficit profile instead of the top-hat shaped profile assumed by Jensen and Frandsen et al. (2006). Larsen applied the mixing length theory to represent the turbulence closure and assumed axis-symmetric wake deficit and fluid incompressibility. The model is based on boundary layer equation and ignores the effect of wind shear and pressure gradient. The modification to the earlier model (of 1988) recognizes the distinction between the near and far wakes by considering a wind farm arrangement instead of the single turbine of the earlier, thereby making provisions for multiple wake phenomenon. Also, additional boundary condition was considered with the first defined at the rotor plane and the other at a downstream distance of 9.6 multiplied by rotor diameter. The Larson's model for wake velocity deficit and wake radius (R_W) are represented as:

$$U_\infty - U_W = \frac{U_\infty}{9}\left(C_T A(x + x_o)^{-2}\right)^{\frac{1}{3}}\left[r^{\frac{3}{2}}\left(3C_1^2 C_T A(x + x_o)\right)^{-\frac{1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3C_1^2\right)^{-\frac{1}{5}}\right]^2 \quad (10)$$

where: U_∞ is the upstream flow velocity, A is the rotor swept area, C_T is the thrust coefficient, x is the distance downstream, and x_o is the wind turbine rotor position.

$$R_W = \left(\frac{105C_1^2}{2\pi}\right)^{\frac{1}{5}}\left(C_T A(x + x_o)\right)^{\frac{1}{3}} \quad (11)$$

The non-dimensional Prandtl mixing length (C_1) is given as:

$$C_1 = \left(\frac{D_{eff}}{2}\right)^{\frac{5}{2}}\left(\frac{105}{2\pi}\right)^{-\frac{1}{2}}\left(C_T A x_o\right)^{-\frac{5}{6}} \quad (12)$$

The effective diameter (D_{eff}) is expressed in terms of the rotor diameter (D) as:

$$D_{eff} = D\left(\frac{1 + \sqrt{1 - C_T}}{2\sqrt{1 - C_T}}\right)^{\frac{1}{2}} \quad (13)$$

The wind turbine rotor position (x_o) is expressed in terms of the wake radius, at a distance of 9.6 rotor diameter (i.e. 9.6D), and effective diameter as:

$$x_o = \frac{9.6D}{\left(\frac{2R_{9.6D}}{D_{eff}}\right)^3 - 1} \quad (14)$$

$$R_{9.6D} = a_1 e^{\left(a_2 C_T^2 + a_3 C_T + a_4\right)(b_1 I_a + 1)D} \quad (15)$$

where: I_a is the atmospheric turbulence intensity, the constants a_1, a_2, a_3, a_4, b_1 are given in [76].

4.3. Ishihara model

Ishihara et al. (2020) developed the wake model simply described here as the Ishihara model. It considered that the velocity deficit profile is Gaussian shaped. While the model ignores the wind shear effect within the atmospheric boundary layer, it includes the rotor wake turbulence effect and recognized the ambient turbulence intensity. The model development employed the momentum conservation equation for axial-symmetric flow and relate the ambient turbulence with thrust coefficient. The model is expressed as (Ishihara et al., 2020):

$$\frac{U_\infty - U_W}{U_\infty} = \frac{\sqrt{C_T}}{32}\left(\frac{1.666}{0.27}\right)^2\left(\frac{x}{D}\right)^{-p} exp\left(-\left(\frac{R_W}{b}\right)^2\right) \quad (16)$$

where: D is the rotor diameter, R_W is the wake radius, x is the distance downstream, and b is a parameter defined by equation (17).

$$b = \frac{0.27C_T^{\frac{1}{4}}}{0.833}D^{\left(\frac{2-p}{2}\right)} x^{\frac{p}{2}} \quad (17)$$

$$P = 6(I_a + I_W) \quad (18)$$

where: I_a is the ambient turbulence intensity, and I_W is the rotor wake turbulence intensity.

$$I_W = 0.004\frac{C_T}{max(I_a, 0.003)}\left[1 - exp\left(-\left(\frac{x}{5D}\right)^2\right)\right] \quad (19)$$

Ishihara and Qian (2018) extended the Ishihara model to capture the effect of ambient turbulence intensity and thrust coefficient. The new model is capable of predicting the mean velocity deficit and added turbulence intensity in both the near and far wake regions. The Ishihara and Qian (2018) model is more accurate than the Katic et al. (1986) model and the Frandsen et al. (2006) wake model. The model expressions and development procedures are highlighted and discussed in Ishihara and Qian (2018).

Going by the highlighted models, it is clear that all of the four models and their modifications are analytical and kinematics. While Jensen, its modification by Katic et al. (1986)] and Frandsen models are one dimensional with top-hat shaped profiles, Larsen and Ishihara models are two dimensional with Gaussian shaped velocity profiles. A major limitation of the Jensen and Frandsen models is the choice of the top-hat shape of the wake velocity profile. The shape assumption leads to under prediction of the velocity deficit at the wake centre. It is worthwhile to note that wake models are divided into two broad types of kinematics and field models. While the kinematics models are typically analytical with lower computational requirement, they are less accurate than the field models. The field models, on the other hand, captures the full flow dynamics and are based on the solution of the kind of RANS equations (Lopez et al., 2019). In line with this, understanding the aerodynamics induced wake flow is based on three theories of momentum conservation, vortex, and computational fluid dynamics (CFD). Based on this, conventional numerical approaches for wake analysis are hinged on three methods of Blade Element Momentum (BEM), Vortex Wake method (VWM), and CFD. The BEM and VWM are fast analysis methods due to their low computational requirements, but the BEM is not accurate for wake and flow field analysis and the VWM is limited, in many cases, for the analysis of small vortex. CFD on the other hand is expensive due to its computing resources, but very accurate for analysis and prediction of blade aerodynamics, wake and flow field modelling and analyses, and captures the dynamics of atmospheric boundary layer on the flow characteristics downstream of a turbine system. Many recent studies have focused on the application of CFD for the understanding of wake phenomenon and its dynamics.

Further to this, CFD methodology as an approach to flow turbulence modelling and resolution is sufficiently accurate, flexible in application, and capable of capturing the flow structure dynamics. The CFD approach of analysis can be used to determine complex flow structures with different turbulence models. With the accuracy of the CFD methodology not in doubt, the issue lies with the choice of the turbulence model that adequately mimics the flow structure dynamics. Hence, different numerical turbulence models exist. These includes the Large Eddy Simulation (LES), Embedded LES, Detached Eddy Simulation (DES), Delayed DES, standard k-ε, Re-Normalization Group (RNG) k-ε, standard k-ω, Shear Stress Transport (SST) k-ω, Reynolds-Averaged

Navier Stokes (RANS), and Unsteady-RANS, to mention a few. The complexity of flow turbulence modelling is based on the fact that it is nonlinear with spatial and temporal scales that depend on the flow field, flow geometry and boundary conditions. Based on this, apart from the methods highlighted, the Direct Numerical Solution (DNS) is one in which the CFD solution is used to resolve all the scales (small and large) by solving the Navier Stokes equations. The DNS method does not require the application of turbulence models, making it a precision based approach. Its limitation is in its maximum applicable Reynolds number and high computational cost. The DNS is not suitable for practical and design applications.

To overcome the challenge of large (or increasing) Reynolds number, the LES is a suitable approach. The LES is a method that is close in accuracy to DNS. Its methodology is to differentiate eddies into large and small scales. While the large-scale eddies are resolved, the small-scale eddies are modelled. This is because the large-scale eddies are flow geometry and direction dependent, whereas the small eddies are dissipative and approximately isotropic. Despite the accuracy of the LES, computational resources as a result of the attached wall boundary layer at high Reynolds number is a limitation. Due to this, the LES method is divided into the wall-modelled and wall-resolved large eddy simulations. The wall-modelled LES rely on wall functions around the near wall region and it is computationally less costly but also with lower accuracy compared to the wall-resolved LES. Based on this, several researches have applied the LES methodology to analyze the flow around wind turbine rotor blades. For instance, Wang et al. (2018) employed the LES method to study the unsteady aerodynamic efficiency of blunt wind turbine airfoils. Posa (2019) carried out the LES of coupled configurations of a VAWT for two different tip speed ratios. It employed an immersed boundary technique, and focused on the wake interactions between coupled turbines, while also demonstrating the blockade effects on downstream momentum flux. Also, Ichenial and Elhajjaji (2019) used the methodology of LES to study the wake effects in a neutral-turbulent boundary layer. Qian and Ishihara (2019) on the other hand engaged the modified delayed detached eddy simulation to numerically study the turbine wakes over complex terrain for different wind directions. The simulation focused on determining the effects of escarpment and surface roughness on wind speeds, directions, and turbulence intensity. In another study, Qian et al. (2020) demonstrated that the LES coupled with actuator line method (ALM-LES) is suitable for prediction of rotor performance with minimal error for single turbine flow dynamics. Recent studies, such as Onel and Tuncer (2021), and Posa and Broglia (2021) also demonstrated the capacity of LES methodology for investigation and characterization of turbine wakes and wake recovery. Stival et al. (2022) analysed the wake deficit phenomenon of two turbines using LES with immersed boundary method under a structured mesh. Nakhchi et al. (2022) employed the ALM-LES to develop a novel hybrid wake control strategy for power augmentation in a wind farm setup. It particularly investigated the combined effects of variation in yaw and tilt angles on power production and wake flows. The results demonstrated that controlling both the yaw and tilt angles improved the turbine performance. The study also reported larger upward and sideward wake deflections than that of yaw or title angle control. Wang et al. (2022) engaged the ALM-LES together with the proper orthogonal decomposition method to investigate the flow characteristics around a wind turbine and to determine the power coefficient and wake length. Li et al. (2022) engaged the ALM-LES with rotation to demonstrate the influence of the combinatorial impact of ground roughness or terrain factor and atmospheric stratification on the wake characteristics of wind turbines. In the same vein, Duan et al. (2022) used an improved delayed detached eddy simulation to analyse the wake flow structure of a floating horizontal axis wind turbine under the platform's surge motion condition.

RANS is an averaging method of approach. Its methodology is to model all the scales (small and large) and derive conservation equations that gives approximate solutions of mean flow quantities. RANS gives closely related solutions with less computational resource requirements. Several studies have employed the RANS methodology for flow analysis. Based on this, the related conservation equations that connects the pressure-velocity relations are the continuity and momentum equations of (20) and (21) (Versteeg and Malalasekera, 2007).

$$\frac{\partial \overline{U_i}}{\partial x_i} = 0 \tag{20}$$

$$\frac{\partial \overline{U_i}}{\partial t} + \overline{U_j}\frac{\partial \overline{U_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 \overline{U_i}}{\partial {x_j}^2} + \frac{\partial}{\partial x_j}\left(-\overline{u_i u_j}\right) \tag{21}$$

The first term on the left hand side of equation (21) differentiates the RANS steady-state from the unsteady RANS (URANS). While equation (21) can simply represent for URANS, the steady-state RANS is devoid of the first term, i.e. for steady state RANS:

$$\frac{\partial \overline{U_i}}{\partial t} = 0 \tag{22}$$

where: $\overline{U_i}$, $\overline{U_j}$ are the mean velocities, $\overline{u_i}$, $\overline{u_j}$ are the fluctuating velocities, $\overline{p}$ is mean pressure, ρ is density, t is time, and x_i, x_j are the directions.

Equation (21) introduces a closure problem and require solving by applying the Boussineq hypothesis which states that the Reynolds stresses can be expressed in terms of mean velocity gradients and eddy viscosity (μ_t) as:

$$-\overline{u_i u_j} = \frac{\mu_t}{\rho}\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \tag{23}$$

where δ_{ij} is the kronecker delta and k is the turbulence kinetic energy.

Solving equation (21) with equation (23) gives the simplified equation (24):

$$\frac{\partial \overline{U_i}}{\partial t} + \overline{U_j}\frac{\partial \overline{U_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{(\mu + \mu_t)}{\rho}\frac{\partial^2 \overline{U_i}}{\partial {x_j}^2} + T \tag{24}$$

Solving equation (24) further require using the eddy viscosity model with the desired number of transport equations. In line with this, this study focused on the two equation models of the k-ε and k-ω turbulence models. The k stands for the turbulence kinetic energy, the ε is the rate of dissipation of turbulence kinetic energy, and the ω is the specific rate of dissipation of turbulence kinetic energy. Turbulence kinetic energy (k) and its associated eddy dissipation rate are two parameters that can aid the classification and analysis of mean turbulent flow conditions. The knowledge of the turbulence kinetic energy gives understanding to how the turbulent scales are produced and propagated, while the eddy dissipation rate enables the understanding of the rate at which energy cascades from large to small eddies. Wake models can be resolved through proper and accurate analysis as a contribution from functions of these parameters.

4.4. The k-ε turbulence models

The k-ε turbulence models are made up of two transport equations that gives the rate of change of the turbulence kinetic energy (k) and dissipation rate (ε) as a function of the combination of transport by convection and diffusion, and the rate of production and decay of k and ε. The standard k-ε model equations, written in the conservation form, is given as (Versteeg and Malalasekera, 2007):

$$\mathrm{k}: \rho\left(\frac{\partial k}{\partial t} + U\frac{\partial k}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t S_{ij}^2 - \rho\varepsilon \tag{25}$$

$$\varepsilon: \rho\left(\frac{\partial \varepsilon}{\partial t} + U\frac{\partial \varepsilon}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + 2C_{1\varepsilon}\frac{\varepsilon}{k}\mu_t S_{ij}^2 - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{26}$$

where: μ_t is the eddy viscosity given as

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{27}$$

S_{ij} is related to the rate of deformation of the fluid element in a turbulent flow, given as:

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) + \frac{1}{2}\left(\frac{\partial u_i^{/}}{\partial x_j} + \frac{\partial u_j^{/}}{\partial x_i}\right) \tag{28}$$

where: U and $u^{/}$ are the mean and fluctuating component of the flow velocity.

The equations (25)–(27) throws up five unknown constants whose approximate values were arrived at through series of curve fittings for several turbulent flows. These constants are assigned the values (Versteeg and Malalasekera, 2007):

$C_\mu = 0.09$; $\sigma_k = 1.00$; $\sigma_\varepsilon = 1.30$; $C_{1\varepsilon} = 1.44$; and $C_{2\varepsilon} = 1.92$

According to Jones and Launder (1972), additional terms must be added to equations (25) and (26) in order to account for situations of the flow within the viscous layer, close to the wall. The first term on the right hand sides of equations (25) and (26), with the introduction of the dynamic viscosity, becomes:

$$\frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \text{ and } \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right]$$

Despite the attempt to ensure that the equations of the k-ε model can predict accurately, there is still limitations to its accuracy and applicability at the wall. This may be due to the fact that the model equations are elliptical and the k and ε are isentropic. Adapting the flow model to curved surfaces (or boundaries), such as of wind turbine rotor blades, and atmospheric boundaries adjacent to a moving wall may cause inaccurate prediction. As a result, wall functions are usually employed to reduce complications and computational issues around boundary layer problems.

Based on this, several studies have employed the k-ε model equations to analyze the wake effect of wind turbine rotor system. For instance, Tian et al. (2018) investigated the influence of inflow boundary conditions for the simulations of atmospheric boundary layer and wake flow. It employed the RANS k-ε turbulence model and used various modifications through the measurement and determination of certain parameters that are related to the physical characteristics of turbulence. In order to predict the wake velocity deficit, the ε-equation was modified with an additional source term. The outcome demonstrated that with appropriate modifications, the k-ε model can be used to simulate homogenous atmospheric boundary layer with required inlet boundary conditions. While the modified model predicted the far wake reasonably, it overestimated the near wake. Yagmur et al. (2020) employed different turbulence models to analyze the flow around a semi-circular cylinder and showed that apart from the RNG k-ε model, the standard k-ε model, and other tested models reported similar flow characteristics that aligns with that of the experiment. In same vein, El Kasmi and Masson (2008) used an extended standard k-ε turbulence model to analyze the flow around a HAWT rotor system, while Anil Kumar et al. (2018) employed the standard k-ε model to analyze the flow separation over NACA 23024 airfoil.

Li et al. (2020) numerically studied the aerodynamic characteristics of a straight-bladed VAWT enhanced with curved wind-gathering device at both ends of the blades. It used the RNG k-ε model to predict the flow around the rotor system. Saad et al. (2020) carried out a study on the aerodynamic performance assessment of twisted-bladed Savonius VAWTs. The analyses were based on flow field characteristics of pressure field and streamlines. Four different turbulence models which include standard k-ε, realizable k-ε, RNG k-ε and SST k-ω turbulence models were used with experimental measurements to determine the best numerical model. The outcome showed that the SST k-ω comparatively gave the best results. Kabir and Ng (2019) investigated the effect of atmospheric boundary layers with no-slip boundary conditions on the wake characteristics of a HAWT. Three dimensional Unsteady RANS with k-ε turbulence closure model were used for the numerical analysis. The simulation was based on the assumption that the atmospheric boundary layer is considerably higher than the computational domain and the shear stress at each boundary layer height is constant. Also, the Coriolis effect was assumed negligible. Moghadassian and Sharma (2020) used the k-ε turbulence closure model to solve the Reynolds stress tensor of the incompressible RANS equations employed to analyse the flow around a row of in-line wind turbines. Steiner et al. (2022) noted the shortcomings of the RANS methodology and developed a new technique that hybridised the time-averaged LES with RANS k-ε turbulence model. The new method, known as the data-driven RANS closure, was then used to evaluate wake flow under neutral atmospheric conditions, similitude of a wind tunnel space. The accuracy of the model/method to real life situation is yet to be demonstrated. It is worthwhile to note that in comparative studies where RANS k-ε turbulence based model results were compared with experimental results, discrepancies are usually noted almost all the time. Based on these discrepancies, methods of improving the model's accuracy have been proposed (see Han et al. (2020) for example).

These efforts notwithstanding, the model is limited in the capacity to accurately predict and analyze flow separation, flows with high vorticity, and no-slip wall conditions. It is equally not very adequate for near wake flows, and high stream-wise variable changes. For example, in flows that are subjected to large deformation rates, the transport equation of the dissipation rate (i.e. equation (26)) becomes a source of inaccuracy. That is why the RNG k-ε model's ε-equation includes a strain-dependent correction term in the constant $C_{1\varepsilon}$, to take care of the shortcoming of the standard k-ε equations (especially the ε-equation). When consideration is given to flows with high stream-wise variable changes or large deformation rates, the RNG k-ε model is better in terms of performance. Also, it is worthwhile to note that in the presence of adverse pressure gradients, as may be obtained in curved shear layers, the k-ε model results in over-prediction of the turbulence shear stress. This situation may lead to suppression of flow separation on curved walls. Nonetheless, the model is very good for the analysis and prediction of fully developed flows, in the fully turbulence region, such as obtained in far wake, downstream. Based on this, Tian et al. (2021) used the RNG k-ε model combined with the actuator disk model to predict the flow over complex/hilly terrain with regions of flow separation. It employed the first order upwind scheme to interpolate the k and ε, while the second order scheme was used to solve the face pressure and also resolve the spatial discretisation of momentum. The results of the method was compared with those obtained from the Jensen wake model. The outcome showed that the Jensen model exhibited marked errors associated with its shortcomings while the accuracy of the study's methodology was demonstrated.

4.5. The k-ω turbulence models

A major highlight of the limitation of the k-ε turbulence models is its inaccuracy at predicting flow structures near the wall, no-slip wall condition, and near wake flows. The near wall turbulence limitation further exacerbate its inability to correctly predict flow separation and reattachment at the wake of a turbine rotor system. Analysis of the impact of the transport equations shows that the errors are usually associated with the ε – equation. This is because the ε has a local extrema close to the wall. To resolve the shortcomings, Wilcox (2008) developed the k-ω turbulence models.

Just like the expression for the k-ε turbulence models, the k-ω turbulence models are also made up of two transport equations that gives the rate of change of the turbulence kinetic energy (k) and specific dissipation rate (ω) as a function of the combination of transport by convection and diffusion and the rate of production and decay of k and ω. The standard k- ω model equations, written in the conservation form, is given as (Wilcox, 2008):

$$k:\rho\left(\frac{\partial k}{\partial t}+\frac{\partial(u_j k)}{\partial x_j}\right)=\rho\left(\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta^* k\omega\right)+\frac{\partial}{\partial x_j}\left[\left(\mu+\sigma_k\rho\frac{k}{\omega}\right)\frac{\partial k}{\partial x_j}\right] \quad (29)$$

$$\omega:\rho\left(\frac{\partial \omega}{\partial t}+\frac{\partial(u_j \omega)}{\partial x_j}\right)=\rho\left(\alpha\frac{\omega}{k}\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta\omega^2\right)+\sigma_d\frac{\rho}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}+\frac{\partial}{\partial x_j}\left[\left(\mu+\sigma_\omega\rho\frac{k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right] \quad (30)$$

The Reynolds stress is computed with the Boussinesq equation as:

$$\tau_{ij}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\rho k\delta_{ij} \quad (31)$$

where: β^*, σ_k, α, β, σ_d, and σ_ω are constants described as closure coefficients, whose values are available in Wilcox (2008).

Worthy of note is the presence of the dynamic viscosity, μ, in the transport equations (29) and (30). This aids the k-ω models to effectively account for flows within the viscous region, close to the wall. In addition, the model employed a no-slip wall condition for velocity and the turbulence kinetic energy. This property of the k-ω turbulence models makes it a better predictor of near wake flow analysis.

Based on the foregoing, employing the k-ω turbulence models to solve the closure problems of RANS equations, the methodology has some advantages over the standard k-ε variants. Some of the advantages include the fact that it suitably analyze flows around curved surfaces, especially strong curvature flows with characteristic adverse pressure gradient. Also, it is a more accurate predictor for flow separation and reattachment, and adequate for no-slip wall conditions. The model is devoid of damping function and permits fixed boundary conditions. One additional advantage of the model is its ability to accurately predict the mean flow profile and the wall skin function. This is because at regions very close to the wall, the molecular viscosity is much larger than the eddy viscosity and the mean flow profile is independent of the turbulence asymptote. In the analyses of flows around wind turbine rotor/blades systems, the k-ω turbulence models can be used for wake flow regions that is within a length of up to 3D (rotor diameter) to 4D downstream. Beyond this length, especially in the region of fully developed flows, where turbulence phenomenon dominates, the model is strongly sensitive and thus the accuracy of k-ω models is limited. For this, the standard k-ε models suffices. In line with the advantages, and considering the disadvantages, few studies have employed the k-ω models to analyze flows around wind turbine rotor/blade systems. For example, Bouras et al. (2018 and 2019) capitalized on the advantage of the k-ω models to accurately predict flows near the wall, and then slightly modified the ω-equation of the turbulence model for proper prediction at the far wake region for zero streamwise gradient condition in neutral atmospheric flows. The outcome demonstrated that the modified k-ω models gave better agreement with experimental data at both the near and far wake regions of two different tested turbines. The modification is in the addition of a source term to the ω-equation, thereby making the turbulence kinetic energy, k, a function of dissipation, limiting its production. Without this modification before application, it is worthwhile to note that the presence of a high level of turbulence in the k-ω models ensures quick wake recovery. This leads to inaccurate prediction at both the mid and far wake regions.

4.6. The shear stress transport (SST) k-ω models

The SST k-ω models were developed to resolve the challenges associated with the standard variants of the k-ω and k-ε models. The SST k-ω models considered the effectiveness of the k-ω turbulence models side by side the k-ε models and combined the superior qualities of the two models. It employed the k-ω models for the analysis of the inner boundary layer through the viscous layer to regions closer to the wall and used the k-ε models at the far wake region of fully developed turbulence, free stream, flow. It is very good for the prediction of flow at adverse pressure regions. It does not require damping functions and it is insensitive to free stream turbulence associated with far wake region. The SST k-ω models, written in the conservation form, is given as (Menter, 1994):

$$k:\rho\left(\frac{\partial k}{\partial t}+\frac{\partial(u_j k)}{\partial x_j}\right)=\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta^*\rho k\omega+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right] \quad (32)$$

$$\omega:\rho\left(\frac{\partial \omega}{\partial t}+\frac{\partial(u_j \omega)}{\partial x_j}\right)=\rho\left(\frac{\gamma}{\mu_t}\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta\omega^2\right)+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_j}\right]+2(1-F_1)\sigma_{\omega 2}\frac{\rho}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \quad (33)$$

$$\tau_{ij}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)-\frac{2}{3}\rho k\delta_{ij} \quad (34)$$

The eddy viscosity is defined as:

$$\mu_t=\frac{\rho a_1 k}{max(a_1\omega,\Omega F_2)} \quad (35)$$

The closure coefficients and the associated variables are given in Menter (1994).

In line with the aforementioned, several studies employed the SST k-ω models to analyze flows around wind turbine rotor systems. For instance, Rocha et al. (2014) employed experimental data to calibrate the SST k-ω turbulence based numerical model in order to analyze the turbulence intensity and characteristic length based on β* parameter. The results showed that the numerical results of power performance agreed with experimental measurements from a 3-bladed fixed tip-speed ratio for NACA 0012 profile of a small HAWT. In the same vein, Rocha et al. (2016) extended the calibration of the SST k-ω models to a range of tip-speed ratio for drag effects. Richmond et al. (2019) investigated the influence of different turbulence models on the accuracy of predicting the wind flow dynamics in a wind farm, lined with 25 turbine systems, at a range of wind speeds and directions. The study implemented the actuator disk model for the numerical framework and resolve the closure problems of the Navier Stokes equations with two different variants of the RANS turbulence models of standard k-ε models and the SST k-ω models. The results were evaluated in terms of wake deficit, and then compared with actual measurements. The outcome shows that, in the region between the direct wakes of two turbines upstream, the k-ε models show good agreement with actual data, while it underpredicts at the near wake regions. Saad et al. (2020) used a 3-dimensional, incompressible URANS with SST k-ω turbulence models to analyze the flow field characteristics around twisted-bladed Savonius VAWTs. The study demonstrated the influence of geometrical variables on the aerodynamic performance of the turbines and assessed the pressure fields around the blades.

In addition, Fertahi et al. (2018) used the URANS with SST k-ω turbulence models to characterize the hydrodynamic performance of a nested coupled hybrid Savonius-Darrieus VAWT. The results showed that the SST k-ω models is adequate for predicting the flow characteristics and performance of the hybrid turbine. Also, Qasemi and Azadani (2020) used the 3-dimensional URANS with SST k-ω turbulence models to characterize the velocity deficit and analyze the power performance of a straight blade VAWT augmented with flat plate deflector. Karimian and Abdolahifar (2020) numerically studied the flow field and performance of a VAWT using a 3-dimensional RANS coupled with SST k-ω turbulence models. Sedighi et al. (2020) employed the incompressible RANS with SST k-ω models to characterize the flow around the blades of a HAWT installed with dimples on blades. The turbulence models was adequate for predicting and analyzing the flow separation and reattachment around the blade. Bai et al. (2019) numerically studied the flow around a VAWT placed in a confined long channel using a 2-dimensional RANS with SST k-ω models. The numerical model employed enabled the easy prediction and analysis of pressure distribution, vorticity, and wakes around the blades. Rezaeiha and Micallef (2021) investigated the wake interaction of two tandem floating offshore wind turbines and the impact of the upstream turbine platform's surge motion on the fixed downstream turbine using the URANS with SST k-ω turbulence models coupled with ADM. Also, Kamal et al. (2023) used the steady RANS with SST k-ω turbulence models to investigate the performance of a novel Archimedes spiral horizontal axis wind turbine. The impact of the blade shape and the pitch to diameter ratio was considered among others. The outcome shows that the simulation results matched closely with those of the experimental. Ye et al. (2023) employed the steady RANS with SST k-ω turbulence models and LES to determine the aerodynamic performance and noise of airfoils with serrated gurney flap. The flow characteristics around the airfoils and wake vortex structure were analysed adequately. Most notably, Rezaeiha et al. (2019) carried out a comparative analysis of 7-eddy viscosity turbulence models for fluid dynamics modelling of VAWTs. The turbulence models investigated are the Spalart-Allmaras, RNG k-ε, realizable k-ε, SST k-ω, SST k-ω with an additional intermittent transition model (SSTI), k-k_l-ω, and the transition SST (TSST) k-ω models. The outcome demonstrated that the SST based models (i.e. SST k-ω, SSTI, and TSST) showed good agreement with experimental measurements and most accurate. The report further stated that within the transition zone, the SSTI and TSST are the most accurate because they can account for the transition from laminar to turbulence flows on the blade surface. Going by the outcome of Rezaeiha et al. (2019) and also that of Troldborg *el at.* (2022), it is worthwhile to consider the SST k-ω turbulence models as the model of choice for simulation using RANS based (i.e. steady state and unsteady state) approaches.

5. Conclusion

The study considered the impact of flow dynamics on the performance of a turbine rotor and how it affects power production from a cluster of wind turbines in a farm. Some recent studies were reviewed and the influence of various parameters on the efficiency of the turbines were highlighted. Such parameters include blade shape and curvatures, wind shear, blade tip clearance, surface dimples, attached wind gathering devices and airflow structures around the turbine rotors. It was noted that despite the effects of blade shape and its associated modifications, the influence of airflow characteristics around the turbines, especially the flow separation and reattachment is vital to turbine performance, wind farm's layout design and turbulence structure. Most important, is the fact that the peculiar characteristics of flow around turbine rotor systems makes it complex and sometimes difficult to analyse without the right model (Chen et al., 2022). The turbulence generated at the downstream of the turbine brings a necessary implication to the formation, combination, and dissipation of the wakes. The airflow characteristics at the far wakes are critically affected by surrounding atmospheric boundary layer, making the appropriate understanding and assessment of wake formation, propagation, and dissipation an important tool for accurate prediction of turbine performance.

Based on the aforementioned, this paper focused on the review of very recent studies on flow dynamics around wind turbines. Consideration was given to the advantages of making a good decision on the choice of turbulence model and its impact on the accuracy of prediction. Amongst the different numerical approaches to analysing and resolving the turbulence flow scales, the paper specifically highlighted the application of the Reynolds-Averaged Navier Stokes methodology and the two equation transport models. The rule of engagement for the application of the models were demonstrated. Also, the uniqueness of employing the turbulence models individually and their differences were highlighted. The implication of using the Shear Stress Transport turbulence models was explored and discussed.

Credit author statement

Dr. Oluseyi O. Ajayi conceptualized, and designed the project. Dr. Oluseyi O. Ajayi and Logan Unser carried out the analyses. Dr. Oluseyi O. Ajayi wrote the first draft of the paper. Dr. Joseph O. Ojo supervised the entire research process.

Declaration of competing interest

The authors wish to state categorically that there is no conflict of interest.

Data availability

No data was used for the research described in the article.

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