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Article

Impacts of wind turbine characteristics on wake turbulence

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Abstract: The enhanced wake turbulence generated by wind turbine has remarkable effects on the power generation and fatigue loads of wind farm and the environment. The paper investigates the mechanism of the impacts of the wind turbine characteristics on the wake turbulence, to provide new knowledge on the design of wind turbine to wind turbine manufacturing factories. A novel wake turbulence coefficient is developed to quantify the ratio of the generated turbulence kinetic energy to the captured wind energy, and is derived as the function of wind turbine characteristics. This wake turbulence coefficient model is explored under optimal conditions. Results show that the wake turbulence coefficient decreases sharply with the increasing power coefficient of wind turbine. The larger the power coefficient is, the smaller the decrease of wake turbulence coefficient. Therefore, it is an effective way to reduce the enhanced wake turbulence through increasing the power coefficient, especially when the power coefficient is small. The wake turbulence intensity is the strongest around the hub of rotor and the weakest around the tip of rotor. It is therefore important to design the structure of the hub of rotor to reduce the enhanced wake turbulence.

Keywords: wind energy; turbulence; turbulence kinetic energy; renewable energy; sustainable

1. Introduction

Wind energy is one of the promising renewable energies to deal with the dual challenges of energy security and climate change [1]. The installation of wind turbine shows unprecedented growth globally. The global annual installed wind capacity increases by 198 % from 2010 to 2023 [2]. The operation of wind turbine will generate wake turbulence which has remarkable effects on both power generation and fatigue loads of wind farm. The enhanced wake turbulence increases the damaging loads on downstream turbines [3], lowering the total power output of wind farm. It is observed that the power losses are up to 40% in downstream turbines in large arrays due to the wakes from upstream turbines [4]. Moreover, the enhanced wake turbulence levels will accelerate fatigue of turbine components, increase maintenance frequency and shorten the operational lifetime [5–7]. It is, therefore, of great importance to investigate the enhanced wake turbulence, to minimize the damage on wind farm and to accelerate the development of industrial wind farm.

Wind turbine wakes and wake turbulence have been studies extensively in the past years. Kumer et al. [8] investigated the characterization of wake turbulence under different stability conditions and the effect of blade pitch on wake turbulence intensity using LiDAR Doppler Beam Swing. Carbajo Fuertes et al. [9] constructed a measurement setup based on two nacelle-mounted LiDARs to measure the wake characterization including the longitudinal turbulence intensity and the length of the near wake, and explored the relationships between them. Shin and Ko [10] used nacelle-mounted LiDAR to measure and analyze the wind turbine wake effects by distance. In addition to experiments, the numerical studies are also conducted to understand the wake turbulence. Wu and Porté-Agel [11] performed the large-eddy simulations to investigate the atmospheric turbulence effects on wind turbine wakes and found that the higher turbulence levels in the incoming flow led to the larger maximum wake turbulence levels. Yang et al. [12] developed a large-eddy simulation framework to simulate turbulence flow over wind turbines and wind farms in complex terrain, and found that the turbulence in inflow had a profound effect on the wake recovery, the turbine-induced turbulence in the wake and the power produced by various turbines in the wind farm. Sørensen et al. [13] developed an actuator line technique and combined it with large eddy simulations to investigate the spatial development of wake turbulence. Wu et al. [14] used large-eddy simulation to capture fine-scale details of turbulence wind flows and interactions with wind turbines to study wind turbine. All these studies are devoted to understand the characterization and development of wakes and wake turbulence. However, little efforts have been devoted to investigate the mechanism of the impacts of wind turbine characteristics on wake turbulence. For wind turbine manufacturing factories, it is of great importance to understand how the wind turbine characteristics influence the wake turbulence, so that they can design the wind turbine on demand. The paper will develop this new knowledge.

In this paper, a wake turbulence coefficient will first be defined, and then its relationship to the wind turbine characteristics will be derived. This wake turbulence coefficient model is explored and results are provided and discussed. Finally, some conclusions will be drawn.

2. Methods

2.1. Mathematical model

When air flows through the wind turbine, some part of air kinetic energy will be captured by wind turbine and finally be converted into electricity. Some part of air kinetic energy will be converted into turbulence kinetic energy (TKE), resulting in the increase of turbulence intensity in the wake. For the x,y,z-Cartesian coordinate system depicted by **Figure 1** where y axis is perpendicular to the page with positive direction towards the page, the air kinetic energy for the grid box of x,y,z-Cartesian coordinate can be expressed as

$$E_{air,ijk} = \frac{1}{2}\rho_{ijk}\Delta x_{ijk}\Delta y_{ijk}\Delta z_{ijk}|\vec{v}_{ijk}|^2 \tag{1}$$

where the grid indices i, j, k correspond to the Cartesian coordinate directions x, y, z. ρ is the air density. $\Delta x, \Delta y, \Delta z$ are the grid size in the x, y, z directions, respectively. $\vec{v}$ is velocity.

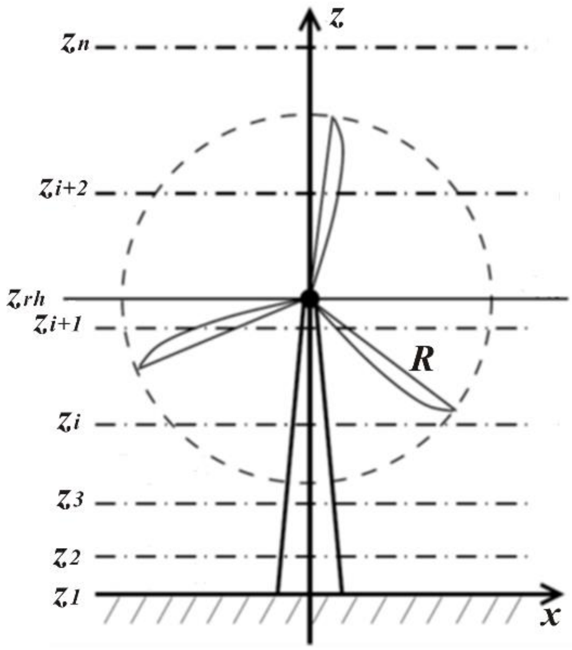

Figure 1. x,y,z-coordinate system for wind turbine adapted from Blahak et al. [15]. The y axis is perpendicular to the page and is towards the page.

The captured wind energy can be expressed as

$$E_{p,ijk} = \frac{1}{2} C_p \vec{v}_{ijk} . \vec{n} A_{ijk} \Delta t |\vec{v}_{ijk}|^2 \tag{2}$$

where A_{ijk} is the cross-sectional rotor area of one wind turbine within the grid cell i, j, k. $\vec{n}$ is the unit vector tangent to A_{ijk}. Δt is the time increment. C_p is the power coefficient.

The cross-sectional rotor area A_{ijk} can be calculated as

$$A_{ijk} = \int_{z_a}^{z_b} \int_{-\sqrt{R^2-(z-z_{rh})^2}}^{\sqrt{R^2-(z-z_{rh})^2}} dxdz = \int_{z_a}^{z_b} 2\sqrt{R^2-(z-z_{rh})^2} dz \tag{3}$$

The turbulence can be regarded as the fluctuation around average velocity of air, described as

$$\vec{v}_{ijk} = \bar{v}_{ijk} + v''_{ijk} \tag{4}$$

where $\bar{v}_{ijk}$ is the average velocity. The average of turbulence v''_{ijk} is zero. That is, $\bar{v}''_{ijk} = 0$.

Accordingly, the turbulence kinetic energy can be expressed as

$$TKE_{air,ijk} = \frac{1}{2} \rho_{ijk} \vec{v}_{ijk} . \vec{n} A_{ijk} \Delta t |\vec{v}''_{ijk}|^2 \tag{5}$$

According to the conservation of energy, it yields

$$\frac{\partial E_{air,ijk}}{\partial t} - \frac{\partial TKE_{air,ijk}}{\partial t} = \frac{\partial E_{p,ijk}}{\partial t} \tag{6}$$

Assuming that the generated turbulence kinetic energy is proportional to the captured wind energy, then it yields

$$TKE_{air,ijk} = \eta E_{p,ijk} \tag{7}$$

η is called wake turbulence coefficient.

Substituting the above equation to Equation (6), it yields

$$\frac{\partial E_{air,ijk}}{\partial t} = (1+\eta)\frac{\partial E_{p,ijk}}{\partial t}$$

Substituting Equations (1) and (2) to the above equation, it yields

$$\frac{\partial |\vec{v_{ijk}}|}{\partial t} = \frac{1}{2}(1+\eta)N_t^{ij}C_p|\vec{v_{ijk}}|^2\frac{A_{ijk}}{\Delta z_{ijk}} \tag{8}$$

where N_t^{ij} is the density of wind turbine for grid box.

In order to investigate the wake turbulence, it is important to derive η. The η is

$$\eta = \frac{TEK}{E} \tag{9}$$

The η can be derived using blade element momentum theory with wake rotation. For an actuator disk of blade with a radius r and a thickness dr, the power dP generated at the actuator disk is [16]

$$dP = \frac{1}{2}\rho\pi R^2|\vec{v}|^3\left[\frac{8}{\lambda^2}a'(1-\alpha)\lambda_r^3 d\lambda_r\right] \tag{10}$$

where λ is the tip speed ratio and λ_r is the local speed ratio.

The local speed ratio λ_r can be expressed as

$$\lambda_r = \frac{\lambda r}{R} \tag{11}$$

where R is the radius of blade.

The total power P generated by blades is

$$P = \int dP = \int_0^{\lambda}\frac{1}{2}\rho\pi R^2|\vec{v}|^3\left[\frac{8}{\lambda^2}a'(1-\alpha)\lambda_r^3 d\lambda_r\right] \tag{12}$$

Assuming that the turbulence velocity results from only the rotational angular velocity, then it yields

$$\vec{v_r^{``}} = wr \tag{13}$$

where w is the angular velocity.

Then the generated turbulence kinetic energy $dTEK$ at the actuator disk is

$$dTEK = \frac{1}{2}\rho 2\pi r dr|\vec{v}|t(wr)^2 = \frac{1}{2}2\rho\pi R^2|\vec{v}|tw^2\frac{R^2}{\lambda^4}\lambda_r^3 d\lambda_r \tag{14}$$

The total generated turbulence kinetic energy *TEK* is

$$TEK = \int dTEK = \int_0^{\lambda}\frac{1}{2}2\rho\pi R^2 t|\vec{v}|w^2\frac{R^2}{\lambda^4}\lambda_r^3 d\lambda_r \tag{15}$$

Substituting the generated power *dp* at the actuator disk and the generated turbulence kinetic energy *dTEK* into Equation (9), it can get the η_r at the actuator disk as

$$\eta_r = \frac{dTEK}{tdP} = \frac{\frac{1}{2} 2\rho\pi R^2 |\vec{v}| t w^2 \frac{R^2}{\lambda^4} \lambda_r^3 d\lambda_r}{t \frac{1}{2} \rho\pi R^2 |\vec{v}|^3 \left[\frac{8}{\lambda^2} a'(1-\alpha)\lambda_r^3 d\lambda_r\right]} = \frac{w^2 R^2}{|\vec{v}|^2 4a'(1-\alpha)\lambda^2} = \frac{w^2}{4a'(1-\alpha)\Omega^2} \quad (16)$$

Substituting the total power *P* and the total generated turbulence kinetic energy *TEK* into Equation (9), it can get the average η_{ave} as

$$\eta_{ave} = \frac{TEK}{tP} = \frac{\int_0^\lambda \frac{1}{2} 2\rho\pi R^2 t |\vec{v}| w^2 \frac{R^2}{\lambda^4} \lambda_r^3 d\lambda_r}{t \int_0^\lambda \frac{1}{2} \rho\pi R^2 |\vec{v}|^3 \left[\frac{8}{\lambda^2} a'(1-\alpha)\lambda_r^3 d\lambda_r\right]} = \frac{2R^2}{|\vec{v}|^2 \lambda^4 C_p} \int_0^\lambda w^2 \lambda_r^3 d\lambda_r \quad (17)$$

where C_p is the power coefficient and

$$C_p = \frac{8}{\lambda^2} \int_0^\lambda a'(1-\alpha)\lambda_r^3 d\lambda_r$$

The angular velocity *w* can be obtained through

$$w = 2\Omega a' \quad (18)$$

where Ω is the angular velocity of the wind turbine rotor and a' is the angular induction factor.

Substituting Equation (18) into Equations (16) and (17), it can get

$$\eta_r = \frac{a'}{1-\alpha} \quad (19)$$

$$\eta_{ave} = \frac{8}{\lambda^2 C_p} \int_0^\lambda (a')^2 \lambda_r^3 d\lambda_r \quad (20)$$

These two equations are the general equations for η_r and η_{ave}, indicating that the wake turbulence coefficient η_r at the actuator disk is the function of the angular induction factor a' and the axial induction factor α, and the average wake turbulence coefficient η_{ave} is the function of the angular induction factor a', the power coefficient C_p and the tip speed ratio λ.

2.2. Model under optimization operation

The Equations (19) and (20) are the general models for wake turbulence coefficients η_r and η_{ave}. We aim at deriving the model for wake turbulence coefficients η_r and η_{ave} under optimization operation, since most wind energy systems are operated towards optimization. Under optimal conditions, the following equations hold [16]

$$C_{p,max} = \frac{8}{729\lambda^2} \{\frac{64}{5} x^5 + 72x^4 + 124x^3 + 38x^2 - 63x - 12[\ln(x)] - 4x^{-1}\}_{x=(1-3a_2)}^{x=0.25} \quad (21)$$

$$\lambda^2 = (1-a_2)(1-4a_2)^2/(1-3a_2) \quad (22)$$

$$\lambda_r^2 = \frac{(1-a)(4\alpha-1)^2}{(1-3a)} \tag{23}$$

$$a' = \frac{1-3a}{4a-1} \tag{24}$$

Substituting the above four equations into η_r and η_{ave}, it can get

$$\eta_r = \frac{1-3a}{(1-\alpha)(4a-1)} \tag{25}$$

$$\begin{aligned}
\eta_{ave} &= \frac{4}{\lambda^2 C_p}\int_0^{\lambda}(a')^2\lambda_r^2 d\lambda_r^2 = \frac{4}{\lambda^2 C_p}\int_{0.25}^{a_2}\left(\frac{1-3a}{4a-1}\right)^2\frac{(1-a)(4\alpha-1)^2}{(1-3a)}d\frac{(1-a)(4\alpha-1)^2}{(1-3a)} \\
&= \frac{4}{\lambda^2 C_p}\int_{0.25}^{a_2}\frac{6(1-a)(4a-1)(2\alpha-1)^2}{(1-3a)}da \\
&= \frac{8}{81\lambda^2 C_p}\int_{0.25}^{1-3a_2}(16x^3+44x^2+24x-1-\frac{2}{x})dx \\
&= \frac{8}{81\lambda^2 C_p}(4x^4-\frac{44}{3}x^3+12x^2-x-2lnx)_{x=0.25}^{x=1-3a_2}
\end{aligned} \tag{26}$$

Therefore, given C_p, R, and r, η_r can be calculated using Equations (11), (21), (23) and (25). That is, η_r is the function of C_p, R, and r under optimization operation. Similarly, given C_p, η_{ave} can be calculated using Equations (21), (22) and (26). In other words, η_{ave} is the function of C_p under optimization operation.

3. Results

In this section, the paper demonstrates the impacts of the characteristics of wind turbine on the wake turbulence under optimal conditions, to show the usefulness of the developed model. This exploration is based on the wind turbine Vestas V164-8.0 because of the data availability. The Vestas V164-8.0 is a production of Vestas Wind Systems A/S, and has three blades. The rated power of Vestas V164-8.0 is 8 MW at the rated wind speed of 13m/s. The cut-in wind speed of Vestas V164-8.0 is 4 m/s and the cut-out wind speed is 25m/s. **Table 1** documents the parameters of Vestas V164-8.0. As literature [16] has provided the data related to the optimal power coefficient and the corresponding tip speed ratio, the data is used here for reference. That is, the optimal power coefficients of 0.289, 0.416, 0.477,0.511,0.533,0.57,0.581, and 0.585 are used.

Table 1. Parameters of Vestas V164-8.0.

Item	**Value**
Diameter of wind turbine	164.0 m
Hight of wind turbine	106 m
Δz	1m
N_t	1

Figure 2 shows the relationship between the wake turbulence coefficient η_r and the power coefficient C_p of wind turbine under optimal conditions. For the specified ratio of selected rotor radius r to blade radius R, r/R, the wake turbulence coefficient η_r decreases with the increasing power coefficient C_p. The larger the power coefficient C_p is, the smaller the wake turbulence coefficient η_r. The decrease of wake turbulence coefficient η_r shows nonlinear relationship with the increasing power coefficient C_p. The wake turbulence coefficient η_r shows sharp decrease for the small power coefficient C_p, whilst it shows relatively small decrease for the large power coefficient C_p. The wake turbulence coefficient η_r quantifies the ratio of the generated turbulence kinetic energy to the captured wind energy. When the power coefficient increases, it means the captured wind energy increase. Given the fixed air kinetic energy, the generated turbulence kinetic energy will consequently decrease in terms of the conservation of energy. Therefore, the relationship between η_r and C_p (**Figure 2**) follows the conservation of energy. It, in turn, proves to some degree the rationality of the derived function $\eta_r = f(C_p, R, r)$.

In addition, it can be seen from **Figure 2** that for the specified power coefficient C_p, the smaller the r/R is, the larger the wake turbulence coefficient η_r. Because the r/R reflects ratio of selected rotor radius r to blade radius R, this finding implies that given power coefficient of wind turbine, the generated turbulence kinetic energy is the biggest around the hub of rotor, and decreases from hub to outer. In other words, the wake turbulence intensity is the strongest around the hub of rotor and then decreases from hub to outer.

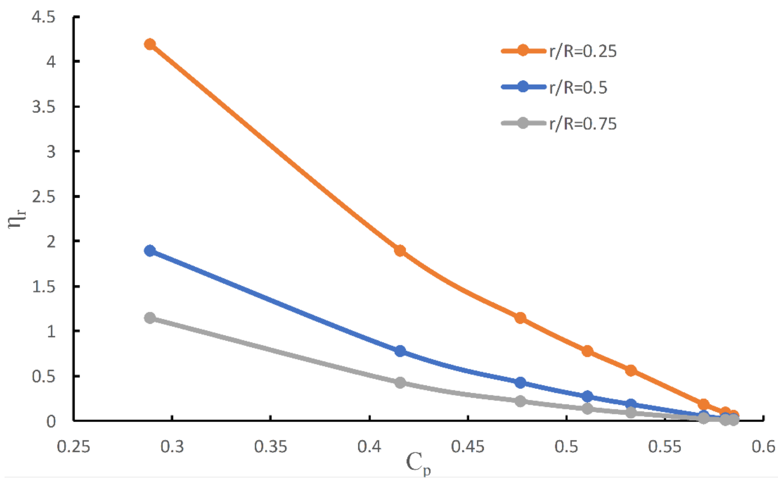

Figure 2. The relationship between the wake turbulence coefficient η_r and the power coefficient C_p of wind turbine under optimal conditions.

Figure 3 shows the distribution of the wake turbulence coefficient η_r around r/R under optimal conditions. The wake turbulence coefficient η_r decreases with the increasing r/R, implying that the wake turbulence intensity is the strongest around the hub of rotor and is the weakest around the tip of rotor. The decrease of wake turbulence coefficient η_r shows different pattern with the increasing r/R. The wake turbulence coefficient η_r has remarkable decrease for the small r/R, whereas it has relatively small decrease for the large *r*/*R*, indicating that the decrease of wake turbulence intensity is nonlinear from the hub of rotor to the tip of rotor.

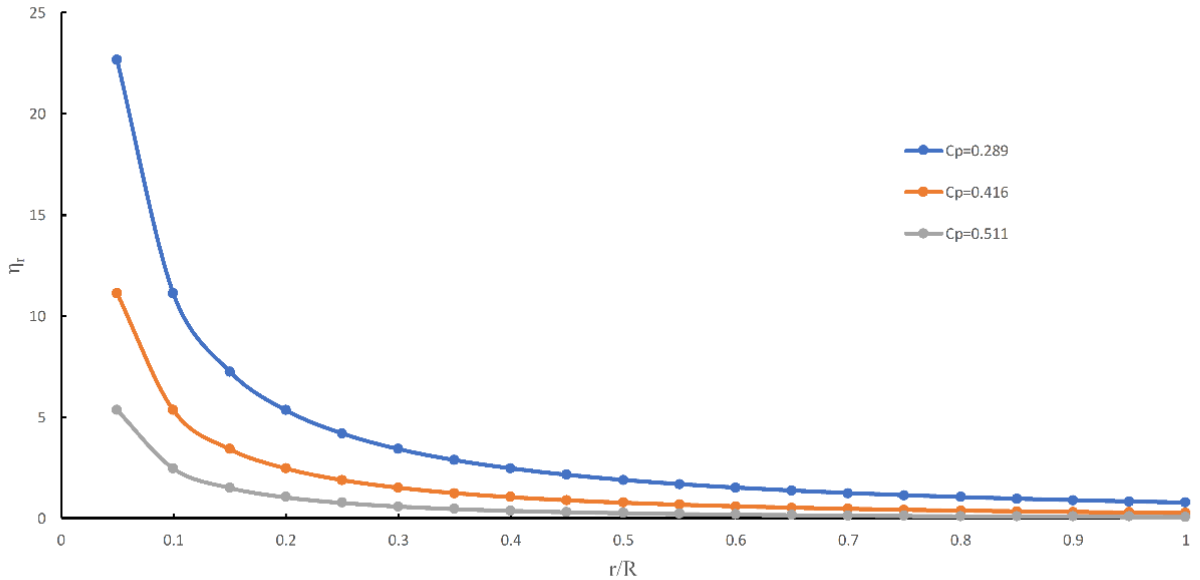

Figure 3. The distribution of the wake turbulence coefficient η_r around r/R under optimal conditions.

Figure 4 shows the relationship between the average wake turbulence coefficient η_{ave} and the power coefficient C_p of wind turbine under optimal conditions. The average wake turbulence coefficient η_{ave} decreases with the increasing power coefficient C_p, implying that the wake turbulence intensity decreases with the increasing power coefficient C_p. The decrease of the average wake turbulence coefficient η_{ave} shows nonlinear relationship with the increasing power coefficient C_p. The average wake turbulence coefficient η_{ave} is large for small power coefficient C_p, whilst it is small for large power coefficient C_p. The argument to the relationship between η_r and C_p (**Figure 2**) can be applied to here for the relationship between the average wake turbulence coefficient η_{ave} and the power coefficient C_p, and this verifies to some degree the rationality of the derived function of the average wake turbulence coefficient η_{ave}.

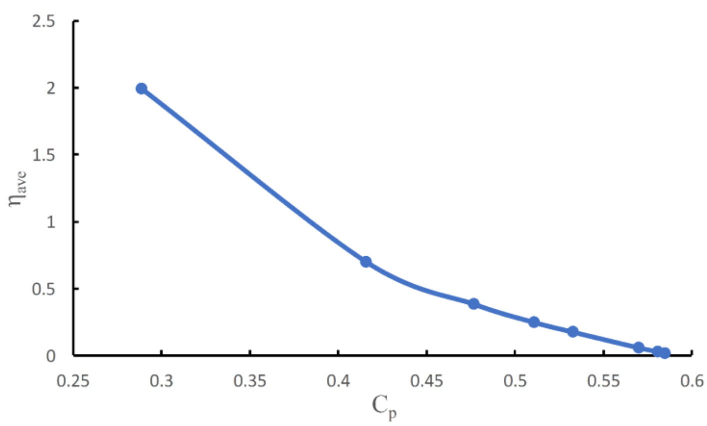

Figure 4. the relationship between the average wake turbulence coefficient η_{ave} and the power coefficient C_p of wind turbine under optimal conditions.

As it connects the atmospheric circulation, the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$, also called the momentum tendency, is interesting. **Figure 5** shows the relationship between the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$ and the power coefficient C_p for both the average wake turbulence coefficient η_{ave} and the wake turbulence coefficient η_r under optimal conditions. Totally, the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$ decreases with the increasing power coefficient C_p, for the the average wake turbulence coefficient η_{ave} and for the wake turbulence coefficient η_r. The decrease of the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$ becomes pronounced with the small power coefficient C_p. Given the power coefficient C_p, the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$ decreased with the increasing r/R. The smaller the r/R is, the larger the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$, implying that given power coefficient of wind turbine, the wind speed will have the biggest change around the hub of rotor, and decreases from hub to outer. This finding has informative implication for the design of materials for wind turbine, suggesting that the hub needs better materials than the blade.

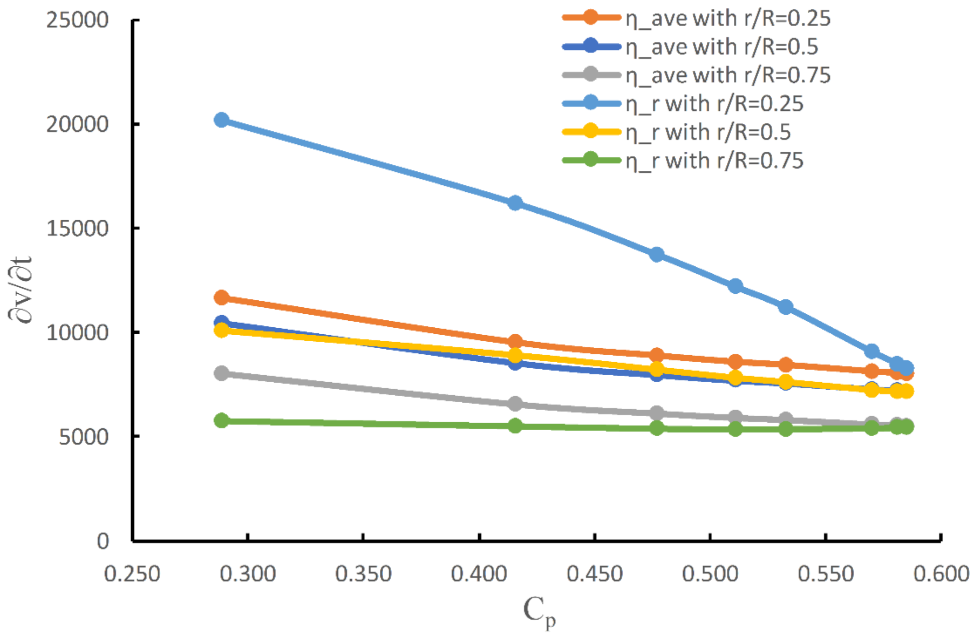

Figure 5. the relationship between the rate of change of wind speed $\frac{\partial|\overrightarrow{v_{ijk}}|}{\partial t}$ and the power coefficient C_p under optimal conditions.

4. Discussion

Wind energy has already been recognized as one of the promising renewable energies to displace fossil fuel. However, the wind turbine will have some negative impacts on the environment [17–20]. Consequently, some strategies are still necessary to mitigate the negative environmental impacts for the sustainable wind energy. When the air flows through the wind turbine, the turbulence downstream will be enhanced. The enhanced wake turbulence increases the damaging loads on downstream wind turbines [3,21] and results in warm effect on land surface [1,22]. It is therefore of great importance to understand the mechanism of the impacts of the wind turbine characteristics on the enhanced wake turbulence. Previous studies have set the generated turbulence kinetic energy to a constant [23]. Here the wake turbulence coefficient is developed to quantify the ratio of the generated turbulence kinetic energy to the captured wind energy, and is derived as the function of characteristics of wind turbine (i.e., the angular induction factor a', the axial induction factor α, the power coefficient C_p, and the tip speed ratio λ). Under optimal condition, it is the function of the power coefficient C_p, and the radius of blade R. This provides informative implications for wind manufacturing companies and wind farm owners.

When deriving the wake turbulence coefficient, it is assumed that the generated turbulence is in the form of rotational vortices. This assumption is consistent with the finding revealed by Mulinazzi and Zheng [24]. The turbulence can sustain strength and distance for several miles before fully dissipating [3], while having different characteristics in terms of the distance to the wind turbine. The turbulence can be measured using LiDAR [8,9,25] and other sensors.

The wind turbine is not always operated in optimal conditions to get the rated power coefficient. As a consequence, the control system on a wind turbine can be added to seek the highest operation efficiency that maximizes the power coefficient. It has two main control strategies: the blade pitch control and the generator torque control. One of the recent developments in wind turbine control is the Model Predictive Control (MPC). The MPC is a multivariable control strategy which considers both torque and pitch as control inputs. Henriksen et al. [26] presented a constraint-handling MPC which can be able to handle both hard and soft constraints on not only the actuators but also other components of the wind turbine and can operate in both partial and full load operation. Bottasso et al. [27] envisaged two MPC controllers: Receding Horizon Control (RHC) and a predictive Linear-Quadratic Regulator (LQR).

The enhanced wake turbulent generated from the upstream turbine in a wind farm is found having significant impact on the fatigue loads of downstream turbines [28,29], resulting in the high cost of energy and the increased pay-back time. Results here show that the enhanced wake turbulence has strong nonlinear relationship to the power coefficient of wind turbine. Therefore, it is an effective way to reduce the enhanced wake turbulence through increasing the power coefficient, especially when the power coefficient is small. Results also show that the wake turbulence intensity is the strongest around the hub of rotor. As a consequence, it is important to design the structure of the hub of rotor to reduce the enhanced wake turbulence.

5. Conclusions

Wind energy can enrich the energy portfolio. The paper investigates the mechanism of the impacts of the wind turbine characteristics on the wake turbulence, to provide new knowledge to the wind turbine manufacturing factories to design more sustainable wind turbine and accelerate the development of industrial wind farm. A novel wake turbulence coefficient is developed to quantify the ratio of the generated turbulence kinetic energy to the captured wind energy, and is derived as the function of wind turbine characteristics.

A demonstration use of the novel wake turbulence coefficient model is conducted to explore the impacts of the characteristics of wind turbine on the wake turbulence under optimal conditions. Results show that the wake turbulence coefficient decreases sharply with the increasing power coefficient of wind turbine. Therefore, it is an effective way to reduce the enhanced wake turbulence through increasing the power coefficient. The wake turbulence intensity is the strongest around the hub of rotor and is the weakest around the tip of rotor. It has remarkable decrease around the hub of rotor and has relatively small decrease around the tip of rotor. It is therefore important to design the structure of the hub of rotor to reduce the enhanced wake turbulence.

Results further show that the rate of change of wind speed shows negative nonlinear relationship to the power coefficient of wind turbine. The decrease of the rate of change of wind speed becomes pronounced with the small power coefficient. The rate of change of wind speed is one of important variables in atmospheric research, such as the weather prediction, and can be fed into numerical atmospheric model to investigate the environmental impacts of the deployment of wind turbines. This information can contribute to the development of sustainable wind turbine, to mitigate the environmental impacts of wind turbine.

The developed mechanism of the impacts of the wind turbine characteristics on the wake turbulence can be integrated into a large-eddy simulation to investigate the spatial distribution of wake turbulence and the evolution of wake which plays an important role in the power output and lifetime of wind farm.

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