CFD wind turbines wake effects by using UDF

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Abstract. The numerical simulation of wind turbine generators was carried out to investigate the relationship between wake expansion and distance of two wind turbine generators in a row. The commercial software ANSYS Fluent was used to perform the Computational Fluid Dynamics (CFD), and further, the standard \( k-\varepsilon \) turbulence modeling has been adopted to solve the steady-state, 3D Reynolds Averaged Navier-Stokes (RANS) equations. Results of near and far wake regions are analyzed. In fact, due to the squeezing effect of the wind turbine generators on the surrounding air, it is found that there is an acceleration area nearby the wind turbine rotors. The arrangement distance of wind turbine generators in a row is analyzed. The results show that as the arrangement distance of the wind turbine generators increases, the average wind speed and the wind power density in the acceleration area decrease. This conclusion has guiding significance for the arrangement of wind turbines in wind farms.

1. Introduction
There exist the wake effects and their interaction when operating the wind turbine generators. The rotors extract the wind energy from the wind through them. As a result, there occurs a velocity deficit with increasing levels of turbulence downstream. The wake effect can cause total power losses up to 30% [1]. If the wind turbine generators downstream were affected by the wake effect, it would cause power losses and unexpected loads from the turbulence fluctuations. Hence, it is essential to study the wind flow in the wind farm. Our study aims to optimize wind farms' layout and reach the maximum wind energy power in a limited area. Improving the working condition of wind turbine generators downstream is an effective method to reduce failures. In this study, we used the Ansys CFD-Fluent to simulate two wind turbine generators' influence in a row. Using the Fluent UDF [2], the atmospheric boundary layer and the wind turbine generator models can be considered. The theory of this method is described in Sec.2. The numerical results are presented in Sec.3, and a summary is given in Sec.4.

2. Methodology
2.1. Statement of the problem
Under investigation, the physical problem is the wind flow near the wind turbine generators in a row under the wind field's controlled condition. The current study is focusing on wake expansion by changing the distance between wind turbine generators. The distance between two wind turbine generators (case 1: 3D₀, case 2: 4D₀, case 3: 5D₀, case 4: 6D₀) is being simulated (\( D₀ \) is the diameter of the wind turbine) (Table 1). UDF file can simulate the wind turbines in the wind farm by adding the source items.
Table 1. Cases of simulation.

| Cases | 2D \(\text{d}_{\text{downstream}}\) | 4D \(\text{d}_{\text{downstream}}\) |
|-------|-----------------|-----------------|
| No atmosphere | | |
| Case 1 | 3D \(\text{d}_{\text{WT}}\) | 3D \(\text{d}_{\text{WT}}\) |
| Case 2 | 4D \(\text{d}_{\text{WT}}\) | 4D \(\text{d}_{\text{WT}}\) |
| Case 3 | 5D \(\text{d}_{\text{WT}}\) | 5D \(\text{d}_{\text{WT}}\) |
| Case 4 | 6D \(\text{d}_{\text{WT}}\) | 6D \(\text{d}_{\text{WT}}\) |
| Atmosphere | | |
| Case 5 | 3D \(\text{d}_{\text{WT}}\) | 3D \(\text{d}_{\text{WT}}\) |
| Case 6 | 4D \(\text{d}_{\text{WT}}\) | 4D \(\text{d}_{\text{WT}}\) |
| Case 7 | 5D \(\text{d}_{\text{WT}}\) | 5D \(\text{d}_{\text{WT}}\) |
| Case 8 | 6D \(\text{d}_{\text{WT}}\) | 6D \(\text{d}_{\text{WT}}\) |

2.2. Governing equations

The governing equations solved of the flow field are the conservation of momentum equations [3]. The change rate of the fluid momentum in the microelement with respect to time is equal to the sum of the surface force and the volume force acting on the microelement by the outside. The formula is as follows:

\[
\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot \left( \rho \mathbf{V} \times \mathbf{V} \right) = -\nabla p + \nabla \cdot \mathbf{\tau} + S_M
\]  

(1)

Where \(\rho\) is the air density, \(\mathbf{V}\) is the fluid velocity vector, \(p\) is the pressure, \(\mathbf{\tau}\) is the shear stress tensor and \(S_M\) is a momentum source.

2.3. Turbulence modeling

In the turbulent kinetic energy \(k\) equation, based on the turbulent dissipation rate \(\varepsilon\) equation, it constitutes the \(k-\varepsilon\) equation model below [4]:

\[
\varepsilon = \frac{\mu}{\rho} \left( \frac{\partial u_i^l}{\partial x_k} \right) \left( \frac{\partial u_i^l}{\partial x_k} \right)
\]  

(2)

The turbulent viscosity \(\mu_t\) is expressed by \(k\) and \(\varepsilon\):

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}
\]  

(3)

In the equation, \(C_\mu\) is the empirical constant. Two unknown fundamentals \(k\) and \(\varepsilon\) are depicted in the transport equations below:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_B - \rho \varepsilon - Y_M + S_k
\]  

(4)

2.4. Wind turbine modeling

In the case of the actuator disk model, the wind turbine rotors are approximated as momentum sinks that represent the axial thrust force \(F\) [5]

\[
F = \rho S v (v_2 - v_1)
\]  

(5)

Where \(S\) is the surface area of the rotor disk, \(v\) is the velocity at the wind turbine rotors \((v = v_1 (1 - a))\), \(v_1\) is the velocity in front of the wind turbine rotors, \(v_2\) is the velocity behind the wind turbine rotors \((v_2 = (1 - 2a)v_1)\). The standard actuator disk model is implemented in ANSYS Fluent based on the induction factor \(a\). Felix Braunheim [7] found that the range of induction factor \(a\) is from 0 to 0.5. In our study, the induction factor \(a\) is set to 0.3.

2.5. Assessment criterion

To assess the potential capacity of the wind farm, wind power density is imported as shown in the equation below [4]:

\[
E = \frac{1}{2} m v^2 = \frac{1}{2} \rho F v tv^2 = \frac{1}{2} \rho A t v^3
\]  

(6)

Where \(A\) is the projected area.
Wind power is used to describe the capacity of air to do work in unit time, which is defined as follows [5]:

\[ W = \frac{1}{2} \rho F v^3 \]  

(7)

2.6. Atmosphere

The height of wind turbine rotors is usually more than one hundred meters nowadays. Nevertheless, it is still under the influence of the atmospheric boundary layer. The atmospheric boundary layer is considered. An essential characteristic of the wind flow is wind speed. Because it determines how much energy a wind turbine generator can produce and how big the loads are. The wind speed decreases at a lower height because the roughness of the ground slows it down.

Power law approximation [8] is imported into this article. It is an empirical approach to represent the vertical profile of the wind speed. It concludes the uniform expression of wind speed profile based on the international standards of ASCE7, AS1170.2, NBC, RLB-AIJ and Eurocode.

\[ V = V_{ref} \times b \times \left( \frac{Z}{10} \right)^a \]  

(8)

\( V_{ref} \) is the wind speed in the height of 10 m. \( a \) and \( b \) are the relative parameters of the velocity profile. According to Table 2 [9], \( a \) is equal to 0.11, \( b \) is equal to 0.8.

Table 2. The velocity profile standard parameters.

| Topography | ASCE7 | AS1170.2(filled) | NBC | RLB-AIJ | Eurocode(filled) |
|------------|-------|-----------------|-----|---------|-----------------|
|            | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) | \( a \) | \( b \) |
| C\textsuperscript{a} | 1.00  | 0.11 | 0.65 | 0.15 | 1.04 | 0.07 | 0.58 | 0.16 | 1.00 | 0.14 | 0.79 | 0.20 | 1.00 | 0.16 |
| D\textsuperscript{b} | 1.09  | 0.09 | 0.80 | 0.11 | 1.18 | 0.04 | 0.69 | 0.13 | 1.00 | 0.15 | 1.17 | 0.12 |

\textsuperscript{a} C: Open areas with scattered obstacles
\textsuperscript{b} D: Flat, barrier-free areas can be approximated as sea or desert

3. CFD simulation

3.1. Computational domain

The computational domains were designed to match the wind farm dimensions (Figure 1, Table 3). The height of the wind farm is set to 500 m.

![Figure 1. The wind farm layout of the wind turbine positioning.](image)

Table 3. The wind farm dimensions.

| Variable | Dim |
|----------|-----|
| A        | 1000 m |
| C        | 3D_{b}, 4D_{b}, 5D_{b}, 6D_{b} |
| H        | 200 m  |
| E        | 200 m  |
| F        | 1000 m |
3.2. Grids
The Mechanical Model utility of ANSYS Workbench was used to generate a hexahedral computational mesh of 4800k cells (Figure 2). The global hexahedral mesh element is set to 5 mm.

![Figure 2. Computational domain grids.](image)

3.3. Boundary conditions
All the simulations have been performed in the commercial software CFD platform ANSYS, using the steady-state, incompressible solver which is based on the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm.

The boundary conditions that were used are summarized in Table 4.

**Table 4. Air-flow boundary conditions.**

| location      | No atmosphere       | Atmosphere                      |
|---------------|----------------------|---------------------------------|
| Inlet         | \( u = 10 \text{ m/s} \) | \( u = x_{velocity} \) (From UDF) |
| Outlet        | Amp. Pressure \( P_o \) | Amp. Pressure \( P_o \)         |
| Wall side     | Specified Shear = 0  | Specified Shear = 0             |
| Upper wall    | Specified Shear = 0  | Specified Shear = 0             |
| Lower wall    | No-slip              | No-slip                         |

4. Results and discussion
For the cases under investigation, the wake expansion's qualitative and quantitative results are given below (Figure 3). Eight cases have been tested using the standard \( k-\varepsilon \) turbulence models. Results showed different wake expansions for each case.

![Figure 3. Wind farm diagram, (a) wake velocity profiles simulated for different positions downstream, (b) wind farm scheme.](image)

4.1. Predictions of the axial velocity and wind power density contours
This section highlights the results for the changes in distance between two wind turbine generators in a row to study the relationship between velocity and distance. The differences can be observed qualitatively and quantitatively by observing the velocity and velocity charts' contours.
Velocity distribution and wind power density distribution along horizontal planes behind the upstream wind turbine rotors were extracted. Moreover, wake profiles and wind power density profiles along horizontal lines behind the upstream wind turbine rotors and at the elevation of the center of the turbine hub were also extracted. The horizontal planes P1, P2, and the horizontal axis L1 and L2 are positioned at 2D₀ and 4D₀ downstream of the wind turbine rotors.

Figure 4 shows the velocity distribution in different cases. With the distance between two wind turbines increasing, the global velocity decreased. However, these changes are negligible. The acceleration overlap begins to split. The results show a symmetrical velocity profile at the middle of two wind turbine rotors. The minimum velocity occurs at the axial direction behind the wind turbine rotors.

Nonetheless, the average velocity is higher than the velocity without wind turbine rotors, which can infer wind turbine rotors can increase the surrounding air's velocity. Likewise, there is stratified velocity distribution after taking the atmospheric boundary layer into account. The velocity profile at the 2D₀ downstream horizontal line is similar to the profile without the atmospheric boundary layer.

The velocity distribution at the 4D₀ downstream is similar to the velocity distribution at the 2D₀ downstream. A comparison of the acceleration area at 2D₀ and at 4D₀, shown in Figure 5, shows a larger velocity distribution area at 4D₀ downstream. Figure 6 plotted the wind power density distribution at 2D₀ downstream to observe the wind energy distribution intuitively. These contours are similar to the contours of velocity because the wind power density is proportional to the wind velocity cubed. The minimum wind power density occurred at the axial direction behind the wind turbine rotors. The maximum wind power density occurred in the middle of wind turbine rotors. The wind power density below the wind turbine rotors is also low.

Table 5 shows the average velocity in different cases. With the distance between two wind turbines increasing, average velocity decreased. When the distance is 3D₀, the velocity increment rate is the largest (5.229%). When the distance is 6D₀, the velocity increment rate is the most insignificant (3.01422%). Besides, the global velocity is lower than it is without the atmospheric boundary layer.

Figure 4. Wake velocity profiles simulated for different positions at 2D₀ downstream, (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) horizontal wake velocity profiles without atmosphere, (f) case 5, (g) case 6, (h) case 7, (i) case 8, (j) horizontal wake velocity profiles with atmosphere.
Figure 5. Wake velocity distribution at 4D₀ downstream, (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) the velocity distribution without atmosphere, (f) case 5, (g) case 6, (h) case 7, (i) case 8, (j) the velocity distribution with atmosphere.

Table 5. Average velocity in different cases.

| Distance | 3D₀   | 4D₀   | 5D₀   | 6D₀   |
|----------|-------|-------|-------|-------|
| No atmosphere | 10.5229 | 10.433 | 10.3578 | 10.3014 |
| Rate of increase | 5.229% | 4.3303% | 3.5784% | 3.01422% |
| atmosphere | 10.4791 | 10.3948 | 10.3249 | 10.2724 |
| Rate of increase | 4.79053% | 3.94825% | 3.2494% | 2.7235% |

Table 6. Wind power density in cases.

| Distance | 3D₀   | 4D₀   | 5D₀   | 6D₀   |
|----------|-------|-------|-------|-------|
| No atmosphere | 754.463 | 735.293 | 719.51 | 707.817 |
| Rate of increase | 16.6997% | 13.7344% | 11.2931% | 9.4844% |
| Atmosphere | 745.067 | 727.245 | 712.675 | 701.841 |
| Rate of increase | 15.2463% | 12.4895% | 10.2359% | 8.56006% |
Figure 6. Wind power density distribution at 2D₀ downstream, (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) the wind power density distribution without atmosphere, (f) case 5, (g) case 6, (h) case 7, (i) case 8, (j) the wind power density distribution with atmosphere.

Figure 7. Wind power density distribution at 4D₀ downstream, (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) the wind power density distribution without atmosphere, (f) case 5, (g) case 6, (h) case 7, (i) case 8, (j) the wind power density distribution with atmosphere.
Figure 7 shows the wind power density distribution at 4D₀ downstream. The wind power density distribution is similar to the wind power density distribution at 2D₀ downstream. The acceleration area is more significant than it is at 2D₀ downstream.

Table 6, Figure 5, 6, and 7 show that the wind power density decreases as the distance between two wind turbines increases. Additionally, the wind power density peaks when the distance of two wind turbine rotors is 3D₀ with a growth rate of 16.6997% and is the least when the distance of two wind turbine rotors is 6D₀ with a growth rate of 9.4844%. The global wind power density is lower than it is without the atmospheric boundary layer.

5. Conclusion
The wake expansion of upstream wind turbines was investigated. This study used the commercial software ANSYS Fluent, the actuator disk model with the incompressible, and the steady-state solver. A comparison was made against simulation data at two downstream positions over horizontal lines at hub height and planes. To a certain extent, with the distance between two wind turbines increasing, average velocity and wind power density decrease.

The highest average velocity and wind power density were depicted when the distance of two wind turbine rotors is 3D₀. The maximum velocity and power density occur at the middle of wind turbine generators and 2D₀ downstream. The minimum velocity and power density have occurred at the axial direction of wind turbine generators and 4D₀ downstream.

By analyzing the wake expansion of multiple wind turbines, rationally arranging the wind turbines' location, putting them in a better working condition (the area with considerable wind speed and large wind power density) has significant significance for improving the utilization rate of wind energy.

Base on the above analysis, we have come out with another wind turbine generator distribution, as shown in figure 3(b). We suggest putting the powerful wind turbine generators in the acceleration area. It may improve the work condition of wind turbine generators.

Acknowledgments
This work was supported by the National Key Research and Development Program of China (2018YFB1502900).

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