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The effect of atmospheric boundary layer turbulence at a height of wind turbine installation

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☐ ABSTRACT ☐

The aim of this paper is to investigate the overlap between lower atmospheric boundary layer and real wind turbine wake which installed not far from ground surface, Here we adopted rotating actuator-disk model (RADM) as a complex model of 3D actuator-disk model, virtual blade modeling (VBM) and tip loss correction, in order to get more reliability and satisfied result.

Wind turbines have grown significantly in size over the last years and, it generally placed in an atmospheric boundary layer, then the assumption of uniform wind velocity cannot be valid.

The lower part of atmospheric boundary layer has a high level of turbulence intensity and great velocity gradients, then when wind turbine placed in these conditions, a high rate of fluctuation will occur subsequently power losses in wind farms, and change wake turbulence character which affects the flow-induced dynamic loads on downwind turbines.

Keyword: Actuator disk, Virtual Blade model, Tip Loss Correction, Large eddy simulation.

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تأثير اضطراب طبقة الغلاف الجوي السطحية في ارتفاع تنصيب العنفة الريحية

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ملخّص

يهدف هذا البحث إلى اكتشاف التمازج الحاصل بين اضطراب طبقة الغلاف الجوي السفلى والجريان خلف عنفة ريحية بإبعاد حقيقية على ارتفاع مناسب عن سطح الأرض، اعتمدت الدراسة نموذج القرص الفعال في الحالة الدورانية (RADM) كنموذج مختلط بين حالة القرص الفعال ثلاثي البعد 3D ، ونموذج الريشة الافتراضي VBM، وتم إدخال تصحيح ضياعات طرف الريشة TLC وذلك من اجل تقريب النموذج من الحالة الواقعية.

في الجزء السفلي من طبقة الغلاف الجوي السطحية ترتفع نسبة الاضطراب نتيجة عدة عوامل ، وتتدرج السرعة مع الارتفاع الشاقولي عن الأرض، ومع ازدياد أحجام العنفات الريحية مؤخراً و وازدياد قطر الدوار و بنتيجة وقوعها ضمن الجزء المضطرب من طبقة الغلاف الجوي أصبح لايمكن عد توزع السرعة منتظما على كامل الدوار.

إن تدرج السرعة على ارتفاع الدوار ونسبة الاضطراب المرتفعة في الجزء السفلي منه يؤدي إلى زيادة أحمال التعب على الريش وامتداد اضطراب اعقاب الجريان الى مسافات اكبر مما يزيد من الضياعات في المزرعة الريحية ويقلل من الطاقة السنوية المنتجة AEP.

الكلمات المفتاحية: القرص الفعال، نموذج الريشة الافتراضي، تصحيح ضياعات طرف الريشة، محاكاة الدوامات الضخمة.

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Introduction:

The effect of atmospheric boundary layer (ABL) turbulence on wind turbines wake, have become important issues in both the wind energy and the atmospheric science communities (e.g., Petersen et al., 1998; Vermeer et al., 2003; Baidya Roy et al., 2004). Accurate prediction of ABL flow and its interactions with wind turbines is of great importance for optimizing the design (turbine sitting) of wind energy projects. In particular, it can be used to maximize wind energy production and minimize fatigue loads in the evaluation of wind-farm layouts. Additionally, numerical simulations can provide valuable quantitative insight into the potential impacts of wind farms [17] on local meteorology. These are associated with the significant role of wind turbines in slowing down the wind and enhancing vertical mixing of momentum, heat, moisture and other scalars.

The turbulence parameterization constitutes the most critical part of turbulent flow simulations. It was realized early that direct numerical simulations (DNSs) are not possible for most engineering and environmental turbulent flows, such as the ABL. Thus, the Reynolds-averaged Navier-Stokes (RANS) approach was adopted in most previous studies of ABL flow through single wind turbines or wind farms (e.g., Xu and Sankar, 2000; Alinot and Masson, 2002; Sørensen et al., 2002; G´omez- Elvira et al., 2005; Tongchitpakdee et al., 2005; Sezer-Uzol and Long, 2006; Kasmi and Masson, 2008). However, as repeatedly reported in a variety of contexts (e.g., AGARD, 1998; Pope, 2000; Sagaut, 2006), RANS computes the mean flow and models the effect of the unsteady turbulent velocity fluctuations according to a variety of physical approximations. Consequently, RANS is too dependent on the characteristics of particular flows to be used as a method of general applicability.

Methodology and material :

1-actuator disk model :

The classical actuator disc model is based on conservation of mass, momentum and energy, and constitutes the main ingredient in the 1D momentum theory, as originally formulated by Rankine and Froude, and combining with classical BEM Technique by Glauert. In a numerical actuator disc model, the NS (or Euler) equations are typically solved by a second order accurate finite difference/volume scheme, as in a usual CFD computation. However, the geometry of the blades and the viscous flow around the blades are not resolved. Instead, the swept surface of the rotor is replaced by surface forces that act upon the incoming flow. The main limitation of the axisymmetric assumption is that the forces are distributed evenly along the actuator disc, hence the influence of the blades is taken as an integrated quantity in the azimuthal direction. To overcome this limitation, an extended 3D actuator disc model has been developed [13], and a hybrid models provided, thus the kinematics of the wake is determined by a full 3D NS simulation.

To obtain sufficient numerical results , Here In 3D actuator disc model the influence of the rotating blades on the flow field is included using tabulated airfoil data to represent the loading on each blade, and the tip vortices and their influence on the induced velocities in the rotor plane were submitted,

Then we adopted the hybrid models which comprise two modules, the first one is CFD solver to compute the velocity field around wind turbine rotor. And the second module uses based on the blade element method (BEM) to computes the pressure jump distribution and the attached flows around known aerodynamic airfoil performances, and also CFD computes the resulting rotor wake as [3], where this hybrid models used for various problems of interaction in propeller-body in fluids machinery.

2-Virtual Blade model VBM:

VBM is based on the Blade Element Theory (BET), the blade divided in a number of spanwise sections and the rotor performance is then calculated by summing the contribution of each section taking into account varying characteristics such as chord length, airfoil type, blade twist and pitch angle. The effect of each airfoil type is considered indirectly by using aerodynamic tables of lift and drag coefficient vs. angle of attack without the need of creating and meshing the actual rotor geometry [1].

These models implicitly the time-averaged effect of the rotor on the flow field using source terms in the momentum equations located in a disk volume fig (1).

It is more detailed approach than simply applying the actuator disk concept by means of a uniform pressure drop without the rotational effect in the wake.

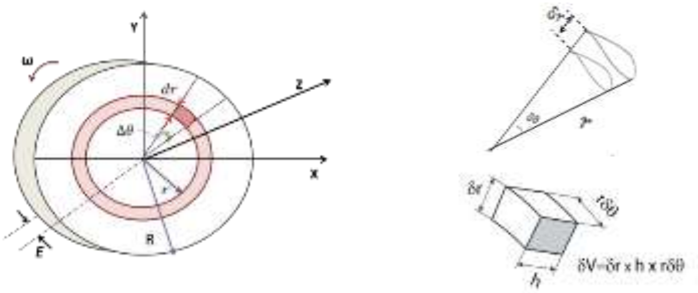


Fig (1) aerodynamic forces on blade element

For each of blade sections the local lift and drag coefficients (C_L and C_D) values are obtained from the look up table. The instantaneous rotor forces are calculated in the form [15].

$$f_{L,D} = C_{L,D}(\alpha, Re).c(r/R).\frac{W}{2} \tag{1}$$

Where W is the relative velocity 'seen' by the airfoil section calculated during the flow field solution, α is the angle of attack and c is the airfoil chord length.

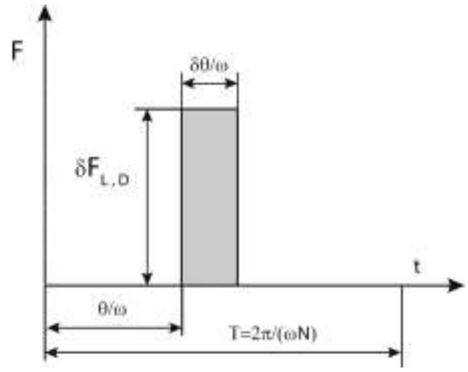
3-Numerical model:

The blade forces depend only on radius and do not vary azimuthally so they can be averaged spatially. Here contrarily the blade forces are averaged temporarily over one blade-passing period T:

$$T = \frac{2\pi}{N.\omega} \tag{2}$$

Here ω is the angular velocity and N is the number of blades. The actuator disk, with a radius R equal to the rotor radius, is presented in Fig (1) Let's calculate the averaged source terms intensity for an infinitesimal element situated at the radius r and the azimuth angle θ. This element corresponds to the sector, $\theta\delta$ and if the blade is assumed as a thin line, the staying time of the blade in this element will be $\delta t = \delta\theta/\omega$ Fig (2). During the time δt this element will be submitted to the blade element force $\delta F_{L,D}$. Therefore, during a blade passing period, the time averaged force can be calculated as:

$$\delta F_{m\,L,D} = \delta F_{L,D}\frac{\delta t}{T} = \delta F_{L,D}\frac{N\delta\theta}{2\pi} \tag{3}$$



Fig(2) Time diagram

Here, the force $\delta F_{L,D}$ which is applied on infinitesimal blade element with radial length of δr and chord of c, can be obtained by means of the blade element theory:

$$\delta F_{L,D} = \rho\frac{W^2}{2}C_{L,D}(\alpha)c(r)\delta r \tag{4}$$

In this formula, ρ is the air density, W is relative velocity and $C_{L,D}$ is the lift/drag coefficient of the blade section, Fig(3). The angle α is angle of attack, β is pitch angle and ϕ is the flow angle.

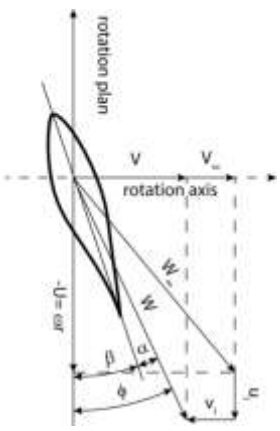


Fig (3) Velocity

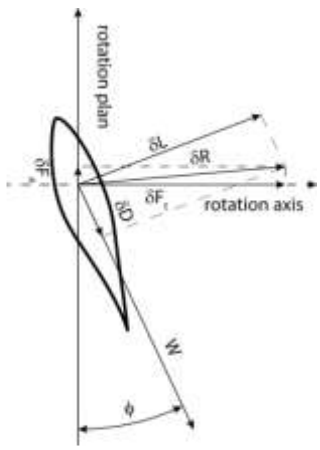


Fig (4) Aerodynamic forces

Replacement of the blade force in Eq. (3) by means of the force, represented by Eq. (4), permit to obtain the averaged blade force applied on the infinitesimal actuator surface element:

$$\delta F_{m\,L,D} = \rho\frac{W^2}{2}C_{L,D}(\alpha)c(r)\delta r\frac{N\delta\theta}{2\pi} \tag{5}$$

If the actuator disk has a thickness h, the volume of the considered infinitesimal element is $dV = \delta r * r\delta\theta * h$ .Therefore intensity of source terms is this element is:

$$f_{L,D} = \frac{\delta F_{m\,L,D}}{\delta V} = \rho\frac{W^2}{2}C_{L,D}(\alpha)c(r)\delta r\frac{N\delta\theta}{2\pi}\frac{1}{\delta r r\delta\theta h} \tag{6}$$

The simplification of Eq. (6) gives:

$$f_{L,D} = \rho \frac{W^2}{2} C_{L,D}(\alpha) c(r) \frac{N}{2\pi rh} \qquad (7)$$

Thus, the eq. (7) permits to calculate the source terms intensity for each cell of the actuator disk, depending on cell centre radius r_c. In Eq. (7) the relative velocity is calculated from the following relation:

$$W = \sqrt{(\omega r + u_i)^2 + V^2} \qquad (8)$$

Here ω is the angular velocity of the rotor disk, V is the axial velocity and u_i is the tangential velocity. The axial and tangential velocities should be obtained from CFD model during calculation, in the plane of actuator disk.

Source term is calculated as:

$$S_{u,cell} = \frac{F_{cell}}{V_{cell}} \qquad (9)$$

The source term is added into the conservation of momentum equation applied to the rotor region. Then, the conservation of mass and momentum equation are solved for the velocity and the pressure. This process is repeated until the solution converges.

4-Tip Loss Correction:

The tip loss correction for the wind turbines and propellers take into account finite aspect ratio of the blades the tangential momentum equation in the same way as in the axial momentum equation|.

A new tip correction was proposed in [11] where 2D force coefficients should include further the tip loss effects at the blade tip (corrected 2D force coefficients). This relation between uncorrected and corrected force coefficients was proposed as

$$C_a^r = F_1 C_a \qquad (10)$$

$$C_t^r = F_1\, C_t \qquad (11)$$

Where C_a^r and C_t^r are the force coefficients obtained directly by applying 2D airfoil data and the function F1 is:

$$F_1 = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-g\frac{N(R-r)}{2r\sin\varphi}\right)\right] \qquad (12)$$

Where N is the number of blades, R the rotor radius, r the local radius and The function **g** is: a coefficient which depends on number of blades, TSR and chord distribution, etc. For simplicity, the function is chosen to be only dependent of the variable $N\omega R/V_\infty$

$$g = \exp\left(-c_1\left(\frac{N\omega R}{V_\infty} - c_2\right)\right) \qquad (13)$$

Where two coefficients in the function are determined empirically using data at two different tip speed ratio.

In order to be consistent for cases of an infinite number of blades or infinite tip speed ratio, the function is shifted with a small value of 0.1. The final form is expressed as

$$g = \exp\left(-0{,}125\left({}^{N\omega R}/_{V_\infty} - 21\right)\right)$$

5-Atmospheric Boundary Layer :

The specific structure of ABL turbulence is generated by mechanical means through surface friction, wind shear, and convectively due to surface heating and buoyancy.

The atmospheric boundary layer generally classified in three types: stable, neutral and convective

The stable ABL results when the ground cools, and heat is transferred from the air to the ground, Neutral conditions only result when heat transfer is negligible. The unstable or convective boundary layer (CBL) is common when the ground is warmer than the air flow.

In convective boundary layer (CBL) the thermal stratification modifies the wind profiles of boundary-layer flows in the lowest part of it (10–15%) over a flat surface, the mean horizontal velocity is commonly described by a log profile [18]. It can be written as:

$$U(y) = \frac{u^*}{\kappa}\left[ln\left(\frac{y}{y_0}\right) - \psi_m\left(\frac{y}{L}\right)\right] \tag{14}$$

Where u∗: is the friction velocity, κ the Karman constant (≈0.40–0.42), y_0 is the Aerodynamic roughness length and ψ_m is a function of the dimensionless height y/L, The Obukhov length L is defined as:

$$L = \frac{-\bar{\theta}u^{*3}}{\kappa g\,\overline{(\acute{w}\acute{\theta})}_s} \tag{15}$$

θ: is the reference temperature, g is gravitational acceleration, and $\overline{(\acute{w}\acute{\theta})}_s$ is the surface kinematic heat flux.

CBL flow characteristics have important effects on the structure of wind-turbine wake flows[15], as reported in several studies[11],[2]. And its parameters determined depending on each zone and it changes from day to night and from season to another

6-Turbulence intensity:

Turbulence is the fluctuation in wind speed and it very much dependent on kind of terrain of the ground, then it must define the typical value of roughness length [14] as shown in Table (1)

High turbulence intensity level occurs at the shear layers immediately behind wind turbine rotor which caused by hub and root vortices as reported in wind-tunnel studies (Dobrev et al. 2008, Sherry et al. 2010), this turbulence intensity level associated with wind turbine hub altitude, and the atmospheric boundary layer type, where it increase in case of CBL than neutral ABL especially in lower elevations due to convective condition [18].

Table (1) Flat terrain categories

	Category	Condition at construction site and upwind region
Smooth	I	Open, no significant obstruction, sea, lake
↑	II	Open, few obstructions, grassland, agricultural field
	III	Suburban, wooded terrain, few tall buildings (4 to 9-story)
↓	IV	City, tall buildings (4 to 9-story)
Rough	V	City, heavy concentration of tall buildings (higher than 10-story)

We can define turbulence intensity I_y on flat terrain categories from [14] in Eq (16)

$$I_y = \begin{cases} 0.1\left(\frac{y}{y_G}\right)^{-\alpha-0.05} & y_b < y \le y_G \\ 0.1\left(\frac{y_b}{y_G}\right)^{-\alpha-0.05} & y \le y_b \end{cases} \quad (16)$$

Where
y (m): height above ground
y_b , y_G , α : parameters determining the exposure factor, defined in Table (2):

Table (2) Parameters determining I_y

Category	I	II	III	IV	V
y_b (m)	5	5	10	20	30
y_G (m)	250	350	450	550	650
α	0.1	0.15	0.2	0.27	0.35

7-Large eddy simulation LES

Large-eddy simulation (LES) is generally considered one of the highest accuracy turbulence models; it is a filtered solution of the continuity, Navier-Stokes, and heat equations (Porté-Agel, Yu-TingWu, HaoLu, Robert J. Conzemius 2011) as intermediate approach between (DNS)and (RANS), then it showed very good results in simulating atmospheric boundary layer turbulence.

In case of rotating actuator-disk model (RADM) with (BEM, VBM), the (LES) filtered heat equation for overlap wind turbine wake with (CBL)[14]:

$$\frac{\partial \tilde{u}_i}{\delta \tilde{x}_i} = 0 \quad (17)$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j\left(\frac{\partial \tilde{u}_i}{\partial \tilde{x}_j} - \frac{\partial \tilde{u}_j}{\partial \tilde{x}_i}\right) = -\frac{1}{\rho}\frac{\partial \tilde{p}^*}{\partial \tilde{x}_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu\frac{\partial^2 \tilde{u}_i}{\partial {x_j}^2} + \delta_{ij} g \frac{\tilde{\theta} - \langle\tilde{\theta}\rangle}{\theta_0} + f_c \varepsilon_{ijk}\tilde{u}_j - \frac{f_i}{\rho} + \mathcal{F}_i \quad (18)$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j\frac{\partial \tilde{\theta}}{\partial x_j} = \frac{\partial q_j}{\partial x_j} + \alpha\frac{\partial^2 \tilde{\theta}}{\partial {x_j}^2} \quad (19)$$

Where : $\tilde{\theta}$ potential temperature, θ_0 is the reference temperature, f_c Coriolis parameter, δ_{ij} is the Kronecker delta, ε_{ijk} the alternating unit tensor, $\partial\tilde{p}^*$ is the modified pressure, α is the thermal diffusivity of air, f_i is an immersed force (per unit volume), $\mathcal{F}_i$ is a forcing term.

Based on the Boussinesq approximation, both ρ and θ_0 in Eq (18) are assumed to be constant τ_{ij} and q_j are the SGS fluxes of momentum and heat, respectively are defined as

$$\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j \tag{20}$$

And

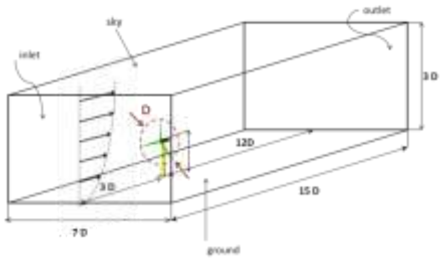
$$q_j = \widetilde{u_j \theta} - \tilde{u}_j \tilde{\theta} \tag{21}$$

This study focuses on modeling the impact of atmospheric boundary layer turbulence on wind turbine wake (rotating actuator disk model), for fairly low hub height .

8-Computational Conditions:

The wind turbine model that used for the present study is three-blade horizontal axial wind turbines (HAWTs) from VERITAS, each blade has 7 variant sections (aerofoil) along its chord.

The computational domain was determine as shown in Fig (5), to clarify the wake extension and its blending with turbulence atmospheric boundary layer, and the mesh grid have been developed very fine at rotor surrounding area and close to ground[8],



parameters	Dimension
R_{rotor}[m]	30
H_{hup}[m]	60
$d_{nacelle}$[m]	2
V_∞ at H_{hup} [m/s]	12.5

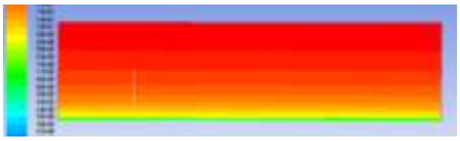
Fig (5) Computational domain parameters

The simulations was utilized the software FLUENT (14.5.7) based on finite volume methods (FVM). The incompressible, turbulent, non –axisymmetric, unsteady state flow was calculated using a pressure based approach. The solution algorithm is SIMPLE. The turbulence models utilized Large-eddy simulation (LES) with supgrid-scale model (WMLES) , and turbulence intensity for flat terrain define from eq (16). For the inlet boundary condition we type non-uniform flow velocity as eq (14),

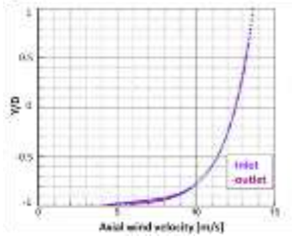
This research was done in fluid mechanics laboratory / Arts et Métiers Paris Tech/Paris, Franc 2014.

Results and discussion:

For empty computational domain with convective atmospheric boundary layer condition, LES turbulence model and flat terrain hypothetical, the velocity gradated in vertical direction Fig (6), and the velocity profile must be at the inlet smeller to outlet char(1)



Fig(6) velocity gradated in vertical direction



chart(1) Inlet - outlet velocity profile

The major factor which has significant effect in changing the upstream structure is turbulence intensity$\boldsymbol{I_y}$ [14], by making some calculations from eq (16) and table (1), (2). We can get chart (2) for flat terrain, and chart (3) for several categories, that illustrates a big turbulence intensity value near the ground.

In our study the wind turbine hub placed at height equal to 60 m, then for rotor diameter = 60m, the lower point of rotor disk will be at 30m height

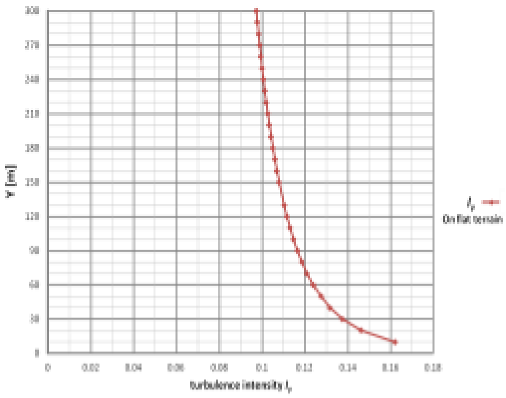


chart (2) turbulence intensity$I_y$for flat terrain

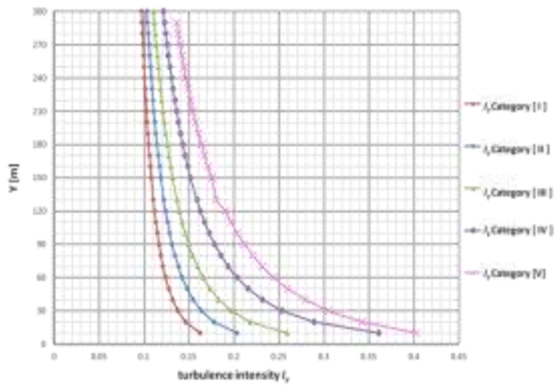


chart (3) turbulence intensity$I_y$for several categories

From chart (2) we can see that: ($I_{y=30} \approx 0.14$, $I_{y=90} \approx 0.115$).The big difference could be observed by considering the minimum turbulence intensity value for flat terrain is about $I_{ymin} \approx 0.10$, and maximum value is $I_{ymax} \approx 0.16$.

The induced tip blade vortex in lower part of rotor wake blended with this height level of turbulence intensity which case significantly deficit in velocity Fig (7), consequently fatigue loads increased, output power decreased and life time of wind turbine reduced , moreover the turbulent wake flow will extends for longer distances and affects on other turbines placement in wind farm

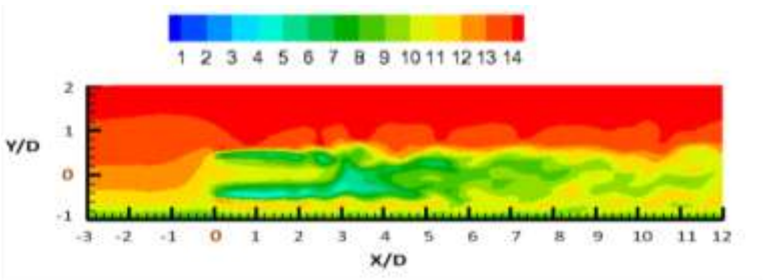


Fig (7) velocity counters in vertical plane passes in rotor center

A big difference noticed by comparing the wake flow velocity swings in two horizontal plane, the first one aligned to the bottom of rotor disk and the second aligned to the top of rotor disk as Fig (8), that demonstrate a considerable variation of turbulence levels.

The blades exposed to different velocity level during the rotation. Here in our study the free axial velocities at different levels, fig (9) are:

$V_{A\ (h=30\ m)} = 11.6$ m/s

$V_{O\ (h=60\ m)} = 12.5$ m/s

$V_{B\ (h=90\ m)} = 13.2$ m/s

The velocity graduation in a lower part of rotor disk is about 20% more than the higher part. These velocity variances increase with rotor diameter increases as modern wind turbine, and it takes a high values near the ground whereas high turbulence intensity.

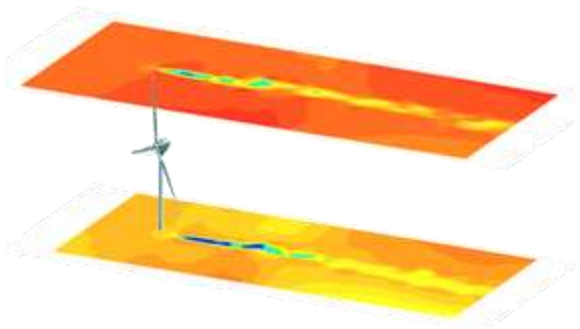


Fig (8) comparing wake flow velocity in two horizontal plane

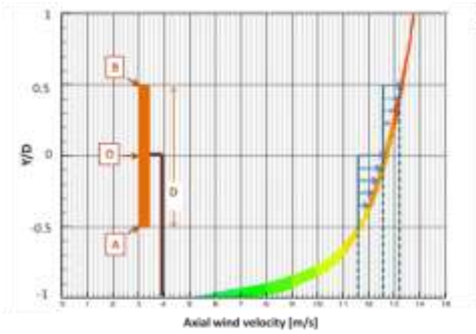


Fig (9) velocity levels at different heights

Then to install wind turbine in convective atmospheric boundary layer it must take into account the height over the ground as a function to the type of terrain which define the turbulence intensity level, in parallel with other conditions like durability and economic..etc, to avoid the adverse effects.

Conclusion:

We present in this study the effect of convective atmospheric boundary layers with Large-eddy simulations over a flat terrain, the (LES) model which demands a fine grid mesh in a computational domain near the ground surface, award a very good resolution to investigate the characteristic of wind-turbine wake and clarify the impact of high turbulence intensity value close to the ground.

The simulation results show the different turbulence intensity levels of the incoming flow lead to substantial differences in the spatial distribution of the mean velocity deficit.

Recommendation:

We look forward in future work to define the appropriate height to install wind turbine in parallel with other conditions, and to study the effect of tower presence on wake flow stability.

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