Prediction of the atmospheric boundary layer in wind power plants by proper selection of the main air parameters

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Abstract. Romania, based on UE reports has a high wind potential, representing more than 14,000 MW. The main scope of the paper is to estimate the distribution of the horizontal component of wind velocity in the vertical direction and its influence on wind turbines efficiency. The selected domain for analysis is located in the Southeast part of Romania until an altitude of 600 m. Firstly is presented the impact of the boundary layer’s separation in the vertical wind distribution. The database of the main measured parameters is realized with two masts of 80 m high, situated at 20 km distance each other, during for 24 months. Firstly are presented theoretical aspects allowing estimation of the vertical Boundary Layer separation influence on the wind distribution. An altimetry model for the selected area, based on approximations of the soil roughness is calibrated. There are established the necessary corrections for average and variable roughness. Secondary parameters as the air density, pressure, and temperature, also have an essential role in the proper functioning of the wind turbines. The numerical results allow establishing a long-term prediction of the vertical air distribution. The paper ends with conclusions and references.

1. Introduction

Nowadays, utilization of renewable resources became a public interest for entire community. Since Romania is part of EU, its objectives are represented by the: energy saving policies, assuring an increase of the produced energy by renewable resources, and establish a new strategy in avoiding the waste of energy. Romania with a high wind potential in Eastern Europe, has a generated energy of 23,000 GWh/year [1], with an estimated potential by the wind resource of 14,000 MW. Due to the newly introduced legislation corresponding to the renewable implementation in the energetic domain and development of the wind power farms starting 2010, each year was developed new capacities. Today the installed capacity in wind power farms is around 3050 MW. Between April 2009 and December 2010, Romania added 440 MW/year to its installed wind capacity, meaning each day a new position of 2.5 MW [2], [3]. In January 2017 were registered 3025 MW produced by wind resource, representing more than 24% from the total energy.

Generally, a significant objective for the European Union is to develop new goals of generating energy from renewable, mainly from water, wind, solar, waves, and biomass. For this task, some arguments may be mentioned:

- The primary objective remains to decrease the Carbon Dioxide (CO₂) emissions, based on intensive utilization of renewable resources.
Due to the actual political situation, it is necessary to reduce as much as possible the import, for the natural gas and oil, improving in this way the security of energy. Each day, the renewable energy sources are economically competitive compared to the conventional ones for medium to long term.

- An increase in the share of renewable resources in the energetic balance maintains sustainability.

The annual average wind intensity is 7.2 m/s in southern Moldavia. The territory relatively flat and, the low-density population represents the main advantage of these areas, allowing installation of a large number of wind power farms.

2. Effect of the boundary layer separation on the vertical wind distribution

In the wind farms structure and wind turbines selection, the vertical distribution of the horizontal wind component has an important role. Necessary estimation of the characteristics for a selected area associated with the registered atmospheric data is the main base for a future projected wind farm.

Distribution of the wind velocity in the Atmospheric Boundary Layer-ABL is characterized by a variation from almost zero at the soil level to value, depending on the soil roughness and the characteristics of the local area. Baklanov defined the central zones in the vertical distribution of the ABL [4], considering that the altitude affects mainly the air characteristics. The most important in the ABL separation remains the soil roughness, determined by the presence of different obstacles, Fig. 1-a, near the cities, small localities, and agricultural lands. They have a significant influence on the roughness coefficient, responsible for air distribution and separation.

From the flow movement equation near the solid surfaces, due to the roughness, in boundary layer appears an inverse flow, Fig. 1-b. In the ABL, the force created by the horizontal component of the air distribution is partially equilibrated by the Coriolis force. As a consequence, an immediate effect determines a regeneration of the air energy, having as a principal effect the diminishing of the boundary layer thickness [5].

Figure 1. a – The zones defined for the ABL development; b - Flow separation at the surface layer.

Some zones are structured to establish the computational domain:
- A central zone of the field where the buildings are modeled separately;
- An upstream current estimated based on the environmental measurements
- The downstream region where the parameters are implemented implicitly. Its shape is generally considered outside the calculation domain and is modeled considering only their effect on the airflow distribution, as direct roughness or as wall functions for the bottom of the field.

All these functions substitute the roughness of the real obstacles, with a similar effect on the flow separation and turbulence. For CFD modeling, [6], [7] the upper side of the domain is assumed with an average value of roughness, with consequence on the internal boundary layer separation. It is not simulated at the beginning of the inlet zone.

In the center of the computational domain, the obstacles are modeled explicitly with a supplementary model of roughness, considering the surfaces themselves, as an example the turbine’s mast, the surfaces between them, hills, etc. In the present paper, some corrections for the wall
functions complete the calculations. To model the free level roughness some previous estimations of the roughness dimensions were made. The air displacement is considered mainly uniform and horizontal (only this component is useful for the wind applications).

The governing equations, in conservative form, for a rotating flow are:

\[ \frac{\partial u}{\partial x} = 0 \]

\[ \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{1}{Re} \left( -v \delta_j + u \delta_2 \right) = -\nabla p + \frac{1}{Re} \Delta u \]  

(1)

Where the Reynolds number, \( Re = \frac{U_g \delta_E}{v} \), Rossby number \( Ro = \frac{U_g}{f \delta_E} \) are defined in terms of Ekman depth \( \delta_E = \sqrt{2v/f} \), and \( f = 2\Omega \), where \( \Omega \) is the wind rotation rate. The velocity distribution follows the Ekman spiral being assumed as one dimensional, uniform flow. The equations for the boundary layer of the wind become straight isobars with barotropic currents:

\[ f(U_g - U) = \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} \]

\[ -f(V_g - V) = \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} \]  

(2)

Dividing equations (2) by \( f \) have been obtained the equations for the ABL. The components of the wind velocities are scheduled in Fig. 2-a. For the \( k-\varepsilon \) turbulent model is assumed the vertical distribution of the average estimated speed \( U \), in the boundary layer. The vertical dimension of the computational domain is selected smaller than the ABL. By considering constant, the shear stress was obtained a simplification of the velocity profiles. Then, the wind velocity distribution became:

\[ U_y = \frac{U_{ABL}^*}{k} \ln \frac{y + y_0}{y_0} \]  

(3)

\[ k(y) = \frac{U_{ABL}^{y2}}{\sqrt{C_\mu}} \]  

(4)

\[ \varepsilon(y) = \frac{U_{ABL}^{y3}}{k(y + y_0)} \]  

(5)

Here \( y \) is the vertical coordinate, with \( C_\mu \) the constant of the standard \( k-\varepsilon \) model. Equations (3-5) represent the analytical solution with the \( k-\varepsilon \) model. The results should be almost the same with the registered data if \( C_\mu \) is selected suitably. The logarithmic law (3) corresponds only for the bottom ABL making until 10\% and could be extended until 20\% with additional corrections. It is necessary to estimate if the Coriolis friction factor and the pressure variation are the main factors of the wind movement outside the domain. In this situation it was observed that the Coriolis force loses its effect at the layer’s surface, compared with the soil roughness. In these conditions are affected the isobars, the incidence angle of the wind at the soil level, and finally the vertical velocity distribution. For a proper estimation of the coefficient selection, a comparison with the experimental registered data is made.

3. The Altimetry model

The ground level affects the wind distribution at altitudes until 100 m. An excessive roughness will slow the wind intensity. Near the ground surface, due to the earth’s rotation, the air velocity is slightly modified from the course of the geostrophic movement.

A relative plane area characterizes the analyzed domain, having 440 m width from the Siret river course, being surrounded by medium hills oriented SW-NE. Erosions due to the wind’s intensity
fragment the soil. The nearest zones are used mainly for agricultural purpose, being without localities around. The landform mentioned assures a relatively constant direction of the wind. Fig. 2-b presents the analyzed area, with the map’s contour for modeling.

The law wall determined for smooth surfaces estimates the tangential velocity near the wall, noted \( u^* \) as being a wall function of the friction velocity. This value for the soil level may differ from the \( u^*_{ABL} \). In these conditions, the domain has three separate fields, with different characteristics: the laminar layer near the surface, the buffer layer, and finally the turbulent layer.

Into the laminar layer is adopted the logarithmic laminar law, considered for altitude under 5 m. The second one, the buffer layer is assumed between 30 m – 200 m, and from 200 m to 1000 m, the boundary layer is assumed as fully turbulent developed. The logarithmic law for rough surfaces may be modified based on measured and registered data, which allows creating of a statistic database. By assuming the altimetry model of the field as in Fig. 2-b was calculated the roughness model Fig 2-c.

During the local registrations made for a long time, we may say that the ground roughness influences the laminar airflow at a considerable distance of the measuring mast because they have 70 m high. In time, based on registrations from the winter, the analyzed zone was extended at 180 km².

In Table 1 is presented the roughness values \( z_0 \) (m) and the surface coefficient, estimated as in the equation (6). The distance 10 m is the standard height for the natural fields or buildings.

\[
K = \left[ \frac{k}{\ln(10/z_0)} \right]^2
\]  

(6)

| Type of Surface                     | \( z_0 \) | \( 10^3\text{K} \) |
|-------------------------------------|----------|-------------------|
| Ground \( U(10) < 1.5 \text{ m/s} \) | 0.0003   | 0.7               |
| Ground for \( U(10) > 15 \text{ m/s} \) | 0.5      | 2.6               |
| Smooth sand                         | 0.01...0.1 | 1.2...1.9        |
| Land (0.01 m)                       | 0.1...1   | 1.9...3.4        |
| Very Small buildings, bushes       | 1...4     | 3.4...5.2        |
| Small buildings, trees              | 2...3     | 4.1...4.7        |
| Buildings, high trees               | 4...10    | 5.2...7.6        |
| Very high buildings, small hills    | 90...100  | 28...30          |
| Rough soil, random obstacles        | 20...40   | 10.5...15.4      |
| Storm                               | 35...45   | 14.2...16.6      |

The value of roughness depends on the \( K \) value. For the actual situation are considered, only three regimes, often observed:
- Aerodynamic laminar, with small disturbances, considered smooth, in calm days, when \( K < 2.25 \)
- A domain of transition, in summer days, or cold winter, when \( 2.25 \leq K < 90 \)
- Entirely rough, in days with strong winds, \( K \geq 90 \)

During the days with strong wind, the airflow over a rough terrain became entirely turbulent mainly due to the encountered obstacles. The flow is perturbed so much that the laminar sub-layer became insignificant. In this case, the movement became independent of the air viscosity. That was the solution adopted for modeling the airflow at the domain boundaries, downstream and upstream. In the central part of the domain, the flow over the encountered obstacles is included in the analyzed field. Small roughness was not explicitly modeled. A general law distribution for the velocity was adopted:
\[
\frac{U}{U^*} = \frac{1}{K} \ln \frac{U^* y}{v \cdot k_0} + 8.5 \tag{7}
\]

Relation (7) is necessary for CFD modeling. Based on previous observation was determined the map of roughness, used for modeling with Fluent 6.1. Equation (7) is modified considering the factor \(1+C_3K_0\) representing the roughness modification, \(U_r = (r_w / \rho)^{1/2}\) the ground velocity, and \(E\) an empirical constant \(E \approx 9.793\).

\[
\frac{U \cdot U^*}{U^2_r} = \frac{1}{K} \ln \frac{E \cdot U^* y}{v(1+C_3K_0)} \tag{8}
\]

For the center zone of the atmospheric boundary layer is assumed turbulent kinetic energy. In the vertical domain of the wind, usually are defined classes of roughness, where are evaluated the air conditions such a large zone. Based on general observations, roughness class between 3- 4 is considered for surfaces with separated high buildings, trees or masts of monitoring, while usually, a soil surface with agricultural lands or forests, has a roughness in class 0. In Table 2 are mentioned partially the velocities registered in November 2017 with one mast implemented into the monitored area, up to a height of 150 m, at roughness from 0.0 to 4.0.

**Table 2.** Velocity variation due to roughness - Rgh, L- Length (m), H- High (m).

| Rgh | 0 | 0.5 | 1 | 1.5 | 2 | 3 | 4 |
|-----|---|-----|---|-----|---|---|---|
| L/H | 0.0002 | 0.002 | 0.03 | 0.06 | 0.1 | 0.4 | 1.6 |
| 150 | 25,76 | 24,15 | 22,1 | 21,4 | 20,75 | 18,91 | 16,54 |
| 140 | 25,54 | 24 | 21,9 | 21,2 | 20,56 | 18,69 | 16,29 |
| 20 | 21,84 | 19,74 | 16,8 | 16 | 15,03 | 12,48 | 9,2 |
| 10 | 20,53 | 18,23 | 15 | 14,1 | 13,07 | 10,27 | 6,68 |

4. Numerical model

Even if the computational ABL domain has only one border physically represented by the ground level, the computational domains must have borders in all directions. For complete the calculation are determined the others three unphysical borders. The upper boundary is assumed flat. The inlet boundary is determined based on the velocity estimation and the turbulence conditions. The outlet boundary is considered as outflow estimated with Neumann condition, considering the normal pressure gradients zero.

In the selected area, based on the hill’s direction the wind is oriented SW-NE. The numerical results confirm the situation registered in terrain for the vertical wind velocity distribution. The estimation of the ABL distribution with CFD codes is necessary for evaluation as more accurate as possible of the wind potential, likely to be used in further energetic developments. The presented method is more precisely even if there are some difficulties in the modeling and estimation of the correct variations induced by the different type of roughness. It is analyzed only the horizontal homogeneity, correlated with the ground roughness, by modifying the wall functions. The model was tested for the selected area. Fig. 3-a presents the curve of the time duration for velocity at three levels from the ground and in Fig. 3-b the Weibull frequency diagram at the level of 60 m.

Because the wind generates the turbine's movement, the flow behind them has perturbations, caused by the rotor and masts themselves. These perturbations must be considered in the estimation of wind farm efficiency. In these conditions, a significant role is represented by a proper distribution of the wind turbines in the wind power farms. It is generally accepted as the main rule that the distance between the turbines to be \((5-9)D\), where \(D\) is the diameter of the rotor, in the prevailing wind direction and between \((3-5)D\) in the perpendicular direction.
5. Conclusions

Romania has favorable wind resources, which creates a real interest in new power plants. In 2007 has begun a program of estimation for the favorable zones with energetic potential, by installing environmental masts with average heights of 60-80 meters. At the beginning of 2017, the investments in wind power plants have exceeded 5 billion euros. Presently, more than 15% of the produced energy in Romania is based on wind energy, higher than the EU average value of 10.5%.

The analyzed wind farm is in the southern part of Moldavia and will have 25 MW installed as a first stage, followed by another two phases, each one with the same capacity.

In the present paper was estimated the vertical distribution of the horizontal component of wind velocity, from the ground level to the altitude of 150 m – 200 m. The elevation was set in conformity with the nacelle's height of the wind turbines from the wind farm. The commonly used methods in estimating the vertical wind distribution, useful in energetic applications have now errors until 18%.

Even if there is only one physical border imposed for the ABL, the presented method is more accurate but with some difficulties in the numerical modeling. There are necessary supplementary estimations, related to the correct induced variations by the different type of roughness. Another essential aspect refers to the dependence of the results by a corresponding selection of the grid's spacing, in both vertical and the flow directions. A grid more refine allows better results but assumes more significant computational effort.

The CFD modeling of the horizontal homogeneous ABL considers different roughness values being necessary for both upstream and downstream zones of the computational domain. The wake effect induced by each turbine on all others influences the wind distribution and affects the proper functioning of the entire wind power farm. A significant objective of estimation the ABL with CFD codes is necessary for modeling new wind power farms, based on new wind turbines of high dimensions and efficiency.

The obtained numerical results were compared with the measured and registered data for more than 24 months. The vertical distribution of wind velocity confirms the theoretically calculated distribution. The difference between them is smaller than 3%.

Another problem appears when these large wind power farms are confronted with huge storms as it was in winter 2014. In these situations, the correct estimation of the roughness and the perturbations induced by the ground became essential.

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