THEORETICAL ASPECTS AND NUMERICAL MODELLING FOR LONG TERM PREDICTION OF ABL AND WIND DISTRIBUTION IN POWER FARM

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Abstract: The paper is structured in seven parts, the last for few conclusions and finally some references. It is based on concrete measurements and observation during around 2 years. First is presented an introduction of the actual situation. In part two are mentioned the methods and hypotheses in evaluation of wind velocity distribution in boundary layers for atmospheric air, taking into account the roughness of ground surfaces. It is mentioned a concrete area, south part of Moldova. In third part is presented a solution for the geodetic model and finally are selected the altimetry solution. In chapter four is determined the influence of air density, temperature and pressure on wind turbine functioning. In the next chapters are presented the numerical model with special boundary conditions, taking into account different value of roughness and finally the obtained results. It is also estimated velocity variation during day-night. Finally is presented the vertical distribution of horizontal wind velocity for a wind farm, obviously important due the power of turbine (around 3 MW each one). Some conclusions and references are also mentioned.

Keywords: wind farm, inverse flow, efficiency, altimetry model, geodetic model, ABL-Atmospheric Boundary Layer, ground roughness, BL-boundary layer

1. INTRODUCTION

The main objective of the present paper is to determine the vertical distribution of horizontal wind velocity, into a concrete area, till altitude of 200m. To realise the numerical model was considered as initial conditions the registration in the nearest 5 meteorological stations, in the last 50 years. It must be mentioned that, in these cases the data are determined at 20m altitude to ground level. In area of wind farm are implemented 2 masts for environmental monitoring having around 80m in high; 24 months were registered all essentials data. . Based on them was recalibrated and correlated the initial conditions for numerical modelling.

First was estimated the efficiency of wind farm taking into account the influence of ground roughness on the boundary layer separation and established the necessary corrections. As first step was considered a medium roughness for selected area, and as second step were made corrections in direct correlation with concrete terrain and neighbourhood buildings. There was also considered the influence of air density, pressure and temperature.

The power of wind farm is 20MW then it’s obviously necessary to determine the energetic potential in medium and long term. The method used to estimate the wind distribution is absolutely necessary because position of each turbine on the field has influence to all others, taking into account the wake effect, Fig.1.

Fig. 1. Schematic representation of wake effect for wind turbine

In Fig.1 is presented the wake effect [4] for turbines placed in line. In projected wind farm, the turbines are placed into a network, established by numerical modelling. The wake effect must be minimized in this case taking into account that the wake effect of ABL has greater influence.

Finally, based on concrete roughness of the terrain, registered data and ABL equations solved for an area of 110 km^2, considered relevant for the wind farm was determined with CFD the vertical distribution of horizontal wind velocity for all directions. The obtained results confirm the main direction NE-SW, favourable for the placement of wind farm.

2. INFLUENCE OF BOUNDARY LAYER SEPARATION FOR AIR VELOCITY

The ABL is characterised by a variation from almost zero at ground level to an average value, depending the altitude. Into ABL [1] the altitude has effect on air characteristics. Generally into the flow on different surfaces in boundary layer appears an inverse flow, due to gradient pressure distribution, Fig. 2.

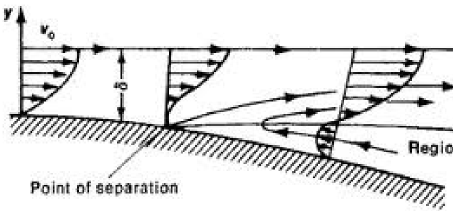

Fig. 2. Schematic representation of inverse flow in boundary layer near body surface

In ABL, because the force generated by horizontal gradient of pressure is only partial equilibrated by the Coriolis force, appears a regeneration of the fluid energy, meaning velocity, having as main and immediate effect a reduction of the thickness of the boundary layer.

The main importance into the ABL separation remains the ground roughness, [2]. In Fig.3 is presented the influence on ABL variation for different conditions of ground: urban, suburban and plane. They have a direct influence on roughness coefficient.

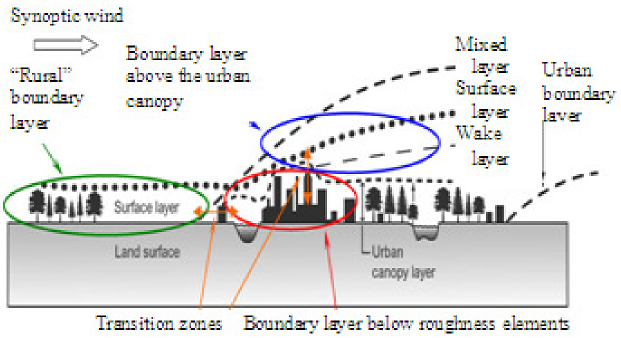

Fig. 3. Schematic representation of ABL influenced by ground surface

For selecting the computational domain may be defined three different regions, as illustrated in Fig.3:

1-central region of the domain where the actual obstacles (buildings, trees, stacks) are modelled explicitly with their geometrical shape;

2-the upstream current

3-the downstream region of the domain; the actual obstacles are modelled implicitly. Their geometry is not included in the domain but their effect on the flow can be modelled in terms of directly roughness, as different wall functions applied to the bottom of the domain. These wall functions replace the actual roughness obstacles but they should have the same overall effect on the flow as these obstacles

In CFD simulations, [5], [7] often the upstream part of the domain is assumed to be at medium roughness, implying that it's not simulated the development of an internal boundary layer starting from the inlet plane. In the centre of the computational domain, Fig.4, where the actual obstacles are modelled explicitly, additional roughness modelling is limited to the surfaces of the obstacles themselves (walls, roofs, hills, agricultural crops, etc.) and the surfaces between these obstacles. In present paper it is done with corrections to the wall functions. The roughness of these surfaces is expressed in terms of the roughness height.

The velocity distribution follows the Ekman spiral, but generally it may be assumed as one dimensional and uniform flow.

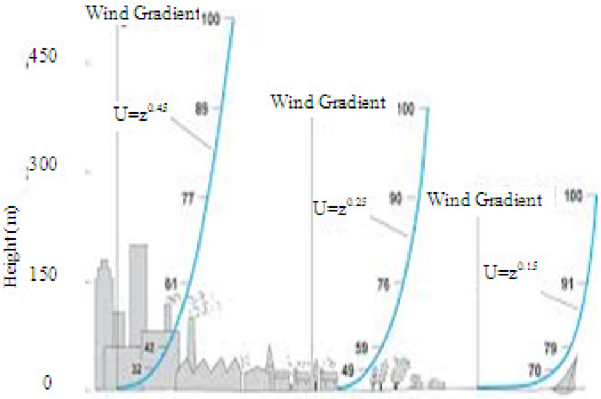

Fig. 4. Schematic representation of theoretical wind distribution

Considering the air movement as manly horizontal and uniform, the boundary layer equations for wind geostrophic (rectilinear isobars) the barotrophic currents became:

$$f\left(U_g - U\right) = \frac{1}{\rho}\frac{\partial \tau_x}{\partial z}$$
$$-f\left(V_g - V\right) = \frac{1}{\rho}\frac{\partial \tau_y}{\partial z} \qquad (1)$$

Where: U_g, V_g are the geostrophic wind components, U, V are the main wind velocities into BL domain, τ_x, τ_y are the tangential efforts, f the Coriolis parameter and ρ is the air density. By dividing with f Eq.(1) we obtain the flow motion equations for ABL. In Fig. 5 are presented the mentioned components of wind velocities.

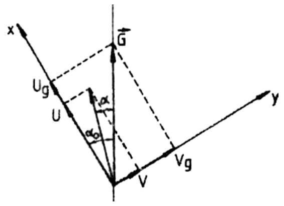

Fig. 5. Representation of wind components

For the k-ε model is proposed [1] a vertical profiles for the mean wind speed U, a turbulent kinetic energy k and turbulence dissipation rate ε in the ABL based on [2]. Generally the height of the computational domain is significantly lower than the ABL height. Then, these profiles usually are simplified by assuming a constant shear stress with height [3]. In these conditions, the velocity may be defined:

$$U_y = \frac{U^*_{ABL}}{k}\ln\frac{y+y_0}{y_0} \qquad (2)$$

$$k(y) = \frac{U^{*2}}{\sqrt{C_\mu}} \qquad (3)$$

$$\varepsilon(y) = \frac{U^{*3}_{ABL}}{k\left(y+y_0\right)} \qquad (4)$$

Where: y is the height co-ordinate, U^*_{ABL} the ABL friction velocity, κ the von Karman constant (≈ 0.40-0.42) and Cμ a model constant of the standard k-ε model. Eqs. (2-4) represent an analytical solution to the standard k-ε model, [6] if C_μ is chosen in proper conditions, correlated with registered data from local position.

The logarithmic law may be applied only for the lower ABL, representing till 10% form the entire ABL. It may be assumed that it may be extended till 20% from the ABL, but with supplementary corrections.

3. THE ALTIMETRY MODEL BASED ON DIFFERENT TYPE OF GROUND ROUGHNESS

The analysed area, south part of Moldova, is characterized by a relative plate area at 110m above the Black sea, surrounded by hills oriented NE-SW, with average slope. The slope is fragmented by rivers valleys; some of them characterized by erosions during floods. The interest area is manly used for agriculture. At 400m in the east part is present a hydropower lake. The relief mentioned assure a relative constant direction of wind. In Fig. 6 is presented the modelling map contour analized.

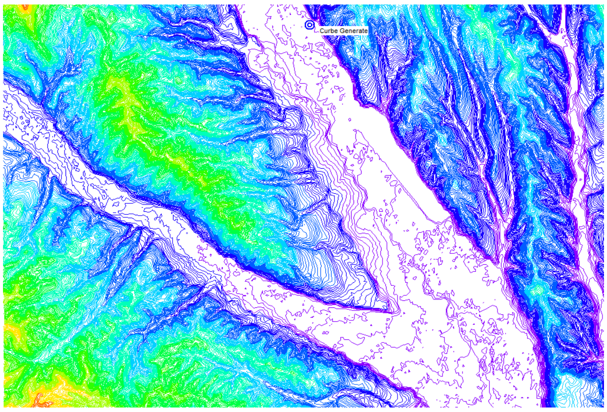

Fig. 6. Modelling of map area contour

The universal law of the wall for a smooth ground surface assumes the mean velocity tangential to the wall, u* as a wall-function friction velocity. Note that the u* at ground can be different from u^*_{ABL}.

The near-wall region consists in three main parts: the laminar layer, the buffer layer and the turbulent layer. The logarithmic laminar law is valid into the laminar layer, below about y+ =5m, the buffer layer for y+ =30 up to 200m. From 200m till 1000m the ABL is fully turbulent developed.

The modification of the logarithmic law for rough surfaces is mainly based on the extensive experiments and by registered data from the desired area. Based on the altimetry estimated model form Fig.6, was established the roughness model.

During local registration could be observed that the ground roughness influences the laminar flux of air flow till a large distance from the measuring masts. In accordance to local observations and registrations, the selected area, initial smaller was extended to a larger one, having around 110 km^2.

In next table are mentioned the roughness z_0 defined in m and the roughness surface coefficient, defined as it was used in relation (5); 10m is considered the standard reference high for different types of natural surfaces or buildings.

$$K = \left[k / \ln(10 / z_0)\right]^2 \tag{5}$$

Table 1. Roughness for different type of ground obstacles

Type of Surface	Z_0	$10^3 \cdot K$
Lake level U(10) = 1,5 m/s	0,0003	0,7
Lake level U(10) > 15 m/s	0,5	2,6
Sand	0,01...0,1	1,2...1,9
Mown grass (0.01m)	0,1...1	1,9...3,4
Small steppe grass	1...4	3,4...5,2
Uncultivated field	2...3	4,1...4,7
High grass	4...10	5,2...7,6
Forest (medium high of threes 15m, density one three at 10m, surface 12m^2	90... 100	28...30
Suburbs of villages	20...40	10,5...15,4
Suburbs of cities	35...45	14,2... 16,6

The roughness function takes different forms depending on the K value. Three regimes are mainly distinguished:

- aerodynamically smooth $K < 2.25$
- transitional $2.25 \le K < 90$
- fully rough $K \ge 90$).

The ABL flow over rough terrain is classified as fully rough due the roughness obstacles; they are so large that the laminar sub-layer is eliminated then the flow is considered to be independent of the air viscosity. This is the case for flow in the upstream and downstream part of the computational domain.

It's not necessarily to be imposed for the flow over the explicitly modelled surfaces with a small-scale roughness from the central part of the domain. In this case the velocity distribution may be determined:

$$\frac{U}{U^*} = \frac{1}{K} \ln \frac{U^* y}{\nu \cdot k_0^*} + 8.5 \tag{6}$$

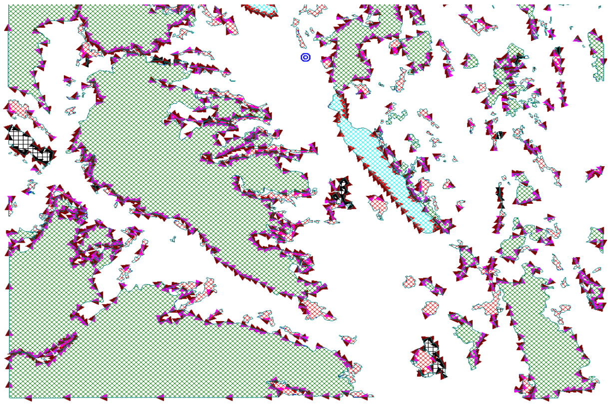

Fig. 7. The roughness of the selected area

The relation (6) was used in CFD modelling. With specified mentions was established the roughness map, Fig.7, used, in further modelling.

For modelling with Fluent 6.1 Eq.(6) must be transformed, where the factor $1{+}C_S K_0$ represents the roughness modification, E is an empirical constant E ≈ 9.793 and $U_\tau = (\tau_w / \rho)^{1/2}$ is the ground velocity.

$$\frac{U\cdot U^{*}}{U_{\tau}^{2}}=\frac{1}{K}\ln\frac{E\cdot U^{*}y}{\nu\left(1+C_{s}K_{o}\right)} \qquad (7)$$

The turbulent kinetic energy is assumed in the centre zone of ABL.

4. INFLUENCE OF AIR DENSITY, COMPRESSIBILITY AND TEMPERATURE

The correct function of the wind turbine blades is directly dependent by air mass characteristics. Of course, at high values of velocity may be produced more energy; then a real estimation of wind velocity is obviously necessary in determination of the farm efficiency.

Conceptually, it is useful to admit the airflow within the BL as consisting of three components: the mean wind, waves and turbulence. Turbulence occurs because of the shear in the mean wind distribution, temperature stratification, air density and pressure which can enhance or suppress turbulence.

Waves often occur in the nocturnal BL, where the stable stratification supports gravity waves.

The flow of air over hills is one supplementary source of waves and density modification.

Turbulence promotes rapid mixing; wave motions do not. Turbulence is the source of complications appearing in modelling and measuring the BL. Generally must be considered the nature of turbulence, how it affects the wind turbine functioning, taking into account the possibilities of modelling.

Then, it must be considered the influence of:

- Air density which depends on humidity, air pressure. In essence, the equation for the density of moist air is:

$$\rho=\frac{p\cdot M}{ZRT}\left[1-H\left(1-\frac{M_{v}}{M_{a}}\right)\right] \qquad (8)$$

where p- the pressure, T- thermodynamic temperature, H- air humidity, M_a the molar mass of dry air, and M_v- molar mass of water vapour, R the molar gas constant, and Z the compressibility factor.

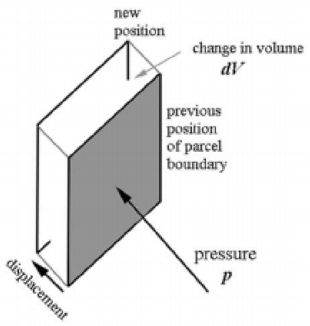

Fig. 8 Influence of air compressibility on wind displacement

- Air compressibility determine slope of air wave, Fig.8, due pressure variation

The equation describing this phenomenon may be finally expressed:

$$\frac{p}{\rho}\frac{d\rho}{dz}=C_{v}\frac{dT}{dz} \qquad (9)$$

Where dρ is density variation over a change dz in elevation; it must be accompanied by a change dT in temperature. The sign indicates that ρ and T vary in the same direction. With increasing altitude, it is known that density decreases dρ/dz< 0 and so temperature dT/dz < 0.

We have three fluid properties: pressure p, density ρ and absolute temperature T, linked by the hydrostatic balance, the equation of state and conservation of energy. This forms a 3-by-3 system of equations.

- Air temperature; we are directly interested in the variation of temperature with height in order to determine correlation with the compressibility effect.

The potential temperature, θ represents an adjusted value, which minimize the compressibility effect and pressure. It is often used in numerical modelling and calibrations. In Fig.9 are presented the calculated variations during Day-Night. It may be observed considerable differences.

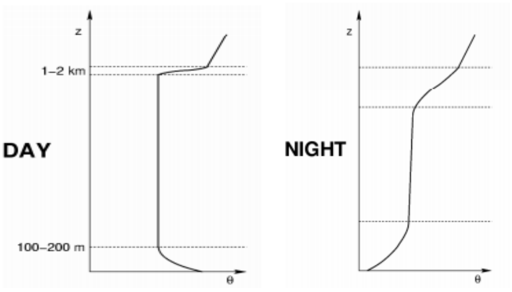

Fig. 9 Potential temperature variations

To calculate the potential temperature it is necessary to establish the dependence of pressure, in concordance with z level.

$$\frac{1}{\theta}\frac{d\theta}{dz}=\frac{1}{T}\frac{dT}{dz}-\frac{R}{C_{p}\cdot p}\frac{dp}{dz} \qquad (10)$$

When:

- $d\theta/dz < 0$, the potential temperature decreases upward; the air atmospheric is top heavy and unstable

- $d\theta/dz = 0$, the potential temperature is vertically uniform; the atmospheric air is neutral

- $d\theta/dz > 0$, the atmospheric air is stably stratified

Due the presence of the neighbouring hills most of the registered data, allow correct wind estimation.

The higher resolution of map provides a slightly higher altitude at the summit of the hill; a less smoothed topography could lead to different numerical results.

5. NUMERICAL MODELLING

There are some difficulties in simulating the horizontally homogeneous ABL flow in the upstream part of the computational domain, because the flow changes rapidly in the upstream region. A particular observation was the considerable acceleration of the flow near the ground.

Using the k-ε model and the standard wall functions without consider a variation of roughness as in [6] reported an unwanted change in the profiles of mean wind speed and especially a supplementary turbulent kinetic energy, responsible for some of the discrepancies found between the CFD simulations and the corresponding wind measurements.

A similar problem for turbulent kinetic energy was reported [7] who used the k-ε model in CFX-4.1.

The unintended differences between the inlet profiles and incident profiles can be solved with success of CFD simulations. The results respond immediately at current situation; even a minor change of the incident wind flow profiles cause significant changes in energy production.

That was also underlined the important influence of the shape of vertical incident wind flow profiles on the simulation results of flow around turbines and buildings.

Basic requirements for ABL flow simulation

In almost all CFD simulations in the lower part of the ABL, an accurate description of the flow near the ground surface is required. In such cases, the ground roughness must be directly expressed as k_S in the flow equations. In present paper were always made corrections for different values of roughness.

Four requirements should be simultaneously satisfied, as presented [7], [8]:

- The high mesh resolution in the vertical direction close to the bottom of the computational domain must be for the first cell < 1 m and for the others up to the high of the bulb turbine of wind farm, not higher then 5m.
- A horizontally homogeneous ABL flow in the upstream and downstream region of the domain
- A distance y_P from the centre point P of the ground, as adjacent cell, bottom of domain that is larger than the physical roughness height k_S of the terrain $y_P > k_S$
- It must be known the relationship between the ground roughness height k_s and the corresponding aerodynamic roughness length y_0.

The numerical calculations have been performed for the selected domain of 110 km^2, having average value 12km^2 long and 9 km^2 wide. For altitude the calculations were made till 200m, based on measured values till 70m.

A non-uniform grid was selected for horizontal and vertical distribution. The geometric characteristics of the used grids are summarized in Table 2.

Table 2. Characteristics of used grids element

Height of the domain	L_y	200 m
Length in long of the domain	L_x	12 km^2
Length in wide of the domain	$L_{x'}$	9 km^2
Length of cell stream-wise	Δx	20-40m
Length of cell cross stream-wise	Δy	variable

6. NUMERICAL RESULTS. VERTICAL WIND DISTRIBUTION

Physically the ABL domain has only one border, the terrain, but computational domains have to be bounded in all directions; other unphysical borders are introduced. As regards the other boundaries, the top of the domain is treated as plane, the inlet as velocity condition (that needs the assignment of velocity and turbulence).

The outlet is instead treated as outflow; all normal pressure gradients are imposed zero, being a Neumann condition [8].

First was determined the wind velocity variations during day and night, based on air properties, Fig. 10.

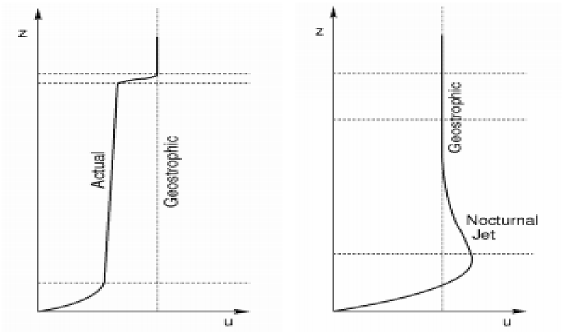

Fig. 10. Wind variation during a-Day, b-Night

The ABL is generally convective during daytime, when the sun shines and heats the ground surface, which in turns re-emits the radiation in the form of heating infrared rays in the lowest atmosphere from below.

The wind blows oriented in direction NE-SW, due to hills orientation, river channel and lake surface. Further are presented the obtained results only on two specified direction N-E and N-W, for comparison, in Table 3. The numerical results confirm the terrain situation.

Table 3. Numerical results

Height [m]	Direction N-E		Direction N-W	
	Velocity (m/s)	k	Velocity (m/s)	k
5	4.37	1.47	2.78	1.31
10	5.27	1.56	3.35	1.39
15	5.82	1.61	3.7	1.44
20	6.22	1.65	3.95	1.47
25	6.51	1.67	4.14	1.49
30	6.81	1.71	4.33	1.53
35	7.08	1.75	4.5	1.56
40	7.29	1.77	4.63	1.58
45	7.47	1.80	4.75	1.61
50	7.63	1.83	4.85	1.63
55	7.82	1.85	4.97	1.65
60	8.01	1.87	5.09	1.67
65	8.17	1.88	5.19	1.68
70	8.32	1.89	5.29	1.69
75	8.47	1.90	5.38	1.7
80	8.61	1.92	5.47	1.71
85	8.73	1.93	5.55	1.72
90	8.84	1.94	5.62	1.73
95	8.97	1.95	5.7	1.74
100	9.08	1.95	5.77	1.74
105	9.22	1.95	5.86	1.74
110	9.36	1.95	5.95	1.74
115	9.50	1.94	6.04	1.73
120	9.63	1.94	6.12	1.73
125	9.74	1.93	6.19	1.72
130	9.87	1.93	6.27	1.72
135	9.98	1.93	6.34	1.72
140	10.09	1.92	6.41	1.71
145	10.20	1.92	6.48	1.71
150	10.29	1.92	6.54	1.71
155	10.39	1.90	6.6	1.7
160	10.48	1.90	6.66	1.7
165	10.57	1.90	6.72	1.7
170	10.67	1.89	6.78	1.69
175	10.75	1.89	6.83	1.69
180	10.84	1.89	6.89	1.69
185	10.92	1.89	6.94	1.69
190	11.00	1.89	6.99	1.69
195	11.08	1.88	7.04	1.68
200	11.16	1.88	7.09	1.68

The main interest in investigating the ABL with CFD codes resides in the assessment of wind energy by more accurate numerical tools than commonly used.

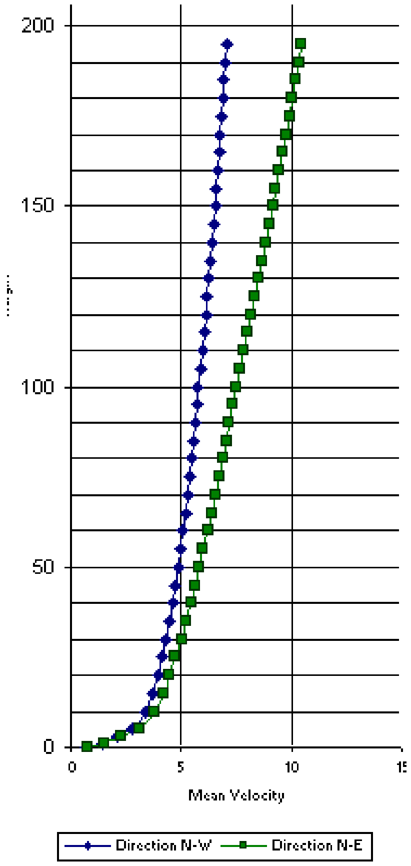

Fig. 11. Vertical repartition of wind velocity on 2 differential directions

Even if the terrain is the only one physical border certainly imposed, for the ABL, [9] it provides some difficulties in modelling connected to variations induced by different ground roughness.

This paper addresses mainly to the problem of horizontal homogeneity ABL of wind velocity, associated with variation of roughness, with correction of wall functions and modelled to a selected area. The reasons for the main difficulties encountered were clearly explained.

7. CONCLUSION

A grid refinement study has been conducted showing the strong dependence of the results on the correct selection of grid spacing both in the vertical direction and in the flow direction. It has been shown that finer grid determine better results but with a supplementary computational effort.

The simulation with CFD of the horizontally homogeneous ABL over a terrain with different value of roughness is often required in the upstream and the downstream region of the computational domain, due huge correlation into wake effect induced by each wind turbine and the efficiency of wind farm.

The term “horizontally homogeneous” refers to the absence of stream wise gradients in the vertical profiles of the mean wind speed and turbulence quantities, i.e. these profiles may be maintained in downstream distance. This type of flow occurs when the vertical mean wind speed and turbulence profiles are in equilibrium with the roughness characteristics of the ground surface.

The numerical modelling was based on local registered data during around 24 months, considered as initial conditions.

The obtained profiles of wind velocity, presented in chapter 6 are in conformity with the theoretical distribution mentioned into literature (chapter 2).

We may suggest that similar or maybe even more serious problems can be expected when more complex cases of ABL flow have to be simulated, e.g. the development of internal boundary layers (IBL) over terrains with highly roughness changes.

REFERENCES

[1]. Richards, P. J., Hoxey, R. P. - Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model. Journal of Wind EIA 46&47, 145-153, 1993

[2]. Radulescu V., - Teoria profilelor hidrodinamice izolate si in retea, Seria Hidraulica, Editura Bren, Bucuresti, ISBN 973-648-279-0, 2004

[3]. Harris, R.I., Deaves, D. M.,- The structure of strong winds. Engineering, Proc. of the CIRIA Conference, 12-13 November London 1980

[4]. Radulescu V., Seteanu I., - The Real Fluid Flow through Cascade Blades and Efficiency Estimation, International Conference "Hydropower into Next Century, Potential Opportunities Challenge", 279-284, Barcelona Spain, 1995

[5]. Mochida, A., Tominaga, Y., Murakami, S., Yoshie, R., Ishihara, T., Ooka, R., - Comparison of various k-ε models and DSM applied to flow around a high-rise building, Wind and Structures 5(2-4), 227-244, AIJ, 2002

[6]. Zhang, C., -Numerical prediction of turbulent recirculation flows with a k-ε model. Journal of Wind Engineering and Industrial Aerodynamics 51, 177-201, 1994.

[7]. Radulescu V., Seteanu I., -A "wall" Turbulent Flow Model for Turbo Machinery Impellers, Scientific Bulletin, UPB, Series D: Mechanical Engineering, Vol. 58-59, No.1-4, pag.103-108, , ISSN 1220-3041, 1996-1997

[8]. Franke, J., Frank, W., -Numerical simulation of the flow across an asymmetric street intersection, in Náprstek, J., Fischer, C. (Eds.), Proceedings of the 4EACWE, Prague, Czech Republic, 2005

[9]. Quinn, A.D., Wilson, M., Reynolds, A.M., Couling, S.B., Hoxey, R.P., -Modelling the dispersion of aerial pollutants from agricultural, an evaluation of CFD, Computers and Electronics in Agriculture 30, 219-235, 2001