Orography analysis with respect to wind flow modelling. Wind tunnel modelling

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Wind farm energy production depends mainly on the strength of the wind at the wind turbine hub height. The wind shear distribution depends mainly on the orography of the terrain. When a flow passes close to a solid wall with a certain roughness a thin layer with different velocity distribution appears.

The numerical study of the velocity distribution is a complicated issue so in some cases it is necessary to be performed experimental studies. Based on the dimensional analysis methodology are presented the terms for leading the experimental study, and are described the respective limitations.

Key words: orography, open flow; wind tunnel, similarity modelling

Анализ на релефната грапавост на терен върху поведението на ветровия поток. Моделиране на течение в аеродинамичен канал

Кирил Мавров Ангел Терзиев

Енергопроизводството на вятърен парк основно зависи от силата на вятъра на височината на хъба на вятърната турбина. Разпределението на скоростта на вятъра по височина зависи основно от орографията на терена. При движението на въздушни маси върху терен с определена грапавост се формира слой, чиято структура най-вече зависи от посочената по-горе орография.

Численото изследване на скоростното разпределение не е лесна задача, поради което в някой от случаите се налага провеждането на експериментални изследвания. Посочени са условията при провеждане на такъв тип изследвания според метода на подобието, както и са описани съответните ограничения.

Ключови думи: orography, open flow; wind tunnel, similarity modelling

Introduction

When the fluid moves close to a solid surface, the molecules of the fluid near the solid surface attaches to the wall because of the prevailing adhesion forces. This leads to the formation of a layer near the surface with properties different from the main flow. The described above layer is called boundary layer as the velocity in the boundary layer changes from zero at the solid surface to a maximum in the main stream flow. As the boundary layer thickness become graters the velocity gradient become smaller and the respective shear stresses decreases. The set of points where the shear stresses are no longer enough to drag the slow fluid are called the external border of the boundary layer. If only the viscous forces was responsible for the boundary layer then the fluid would come at rest. In this case the boundary layer is called laminar boundary layer. Usually the shear stresses keep the fluid particles in a constant motion within the separate layers. If they are no longer able to hold them in the layers the fluid begins to rotate. In this case the boundary layer is called turbulent.

In the above lines when the wind flow passes near the Earth's surface it is affected by the friction with the terrain artefacts – flat ground, low vegetation, forests, cities, hills etc. In order to better understand wind power meteorology three categories of the topography effects should be studied.

Orography specifics and wind velocity profile modeling

Surface Roughness

The phenomenon of surface terrain effects near the ground is expressed as terrain roughness of the terrain. Those elements could be flora, urbanized areas, soil and water surfaces. The size of those terrain elements determine the roughness of the area. Roughness is parameterized by a simple length scale, the roughness length z_0 [20]

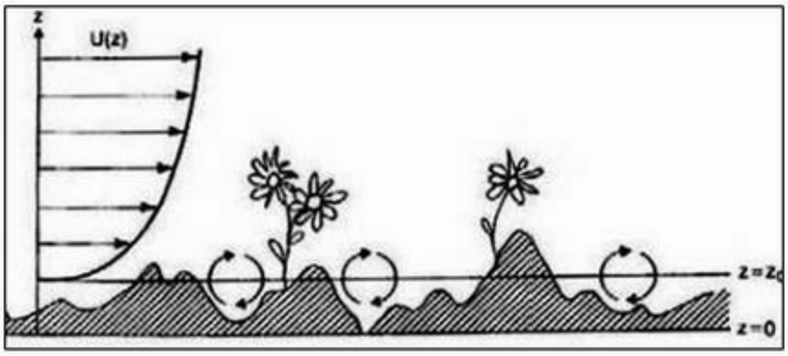

Figure 1 Roughness length [6]

Second category of local effects on wind flow is different kinds of obstacles, like buildings in urban area. A more general classification of obstacles can be defined depending on the porosity of the obstacles that can be examined from detailed maps.

Terrain Orography

The term orography can be described as difference in height. This allows the terrain to be classified in three general types: flat, hilly and mountainous.

Flat terrain could be described as the type of terrain that affects the wind flow only with its roughness.

Hilly terrain is described by the presence of slopes that are less steep than 0.3 [18]. Those slopes does not have significant effect over the wind speed. Hills, on the other hand, have a significant influence on the wind speed. Smooth and not too steep hill could accelerate the wind when it reaches the top of the hill. This energy increase is called hill impact.

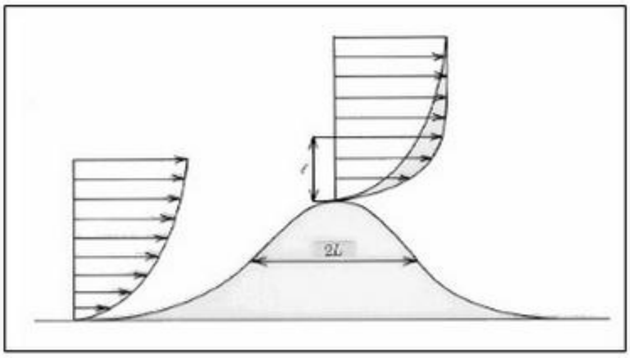

Figure 2 Speed up effect [21]

In more mountainous terrains, the steeper slopes often result in flow separation. Terrains with high mountains and steep hills are classified as complex terrains. There the prediction of the wind flow is hard and cannot be modelled by linear models.

The figure below shows the velocity profile in a forest canopy. Due to the internal boundary layer effect the logarithmic wind profile is affected by canopy layer.

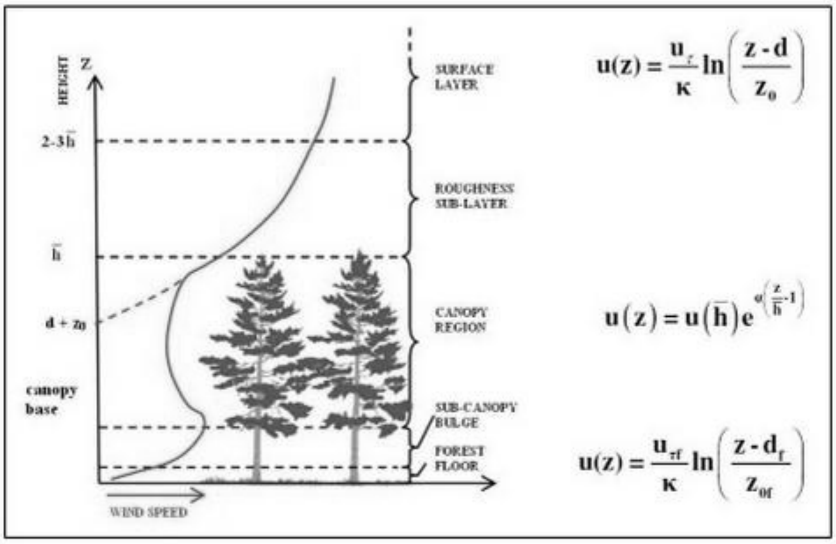

Figure 3 Flow inside and above forest canopy [5]

The urban heat island (UHI) is a phenomena caused by the larger warming of the air above the urban area with respect to the countryside. As discussed by Oke (1987) [17] various causes can be considered responsible for the heat island existence, and their relative role depend on the season, the geographic location and the city characteristics. In fair and near calm conditions the UHI generates a circulation that is characterized by the rise of warm air above the city and the convergence of surface winds from the countryside to the centre of the UHI. In non-stagnating weather conditions the UHI and the urban canopy modify the boundary layer characteristics giving rise to the Urban Boundary Layer (Fig. 4) and to a plume that is transported downwind outside of the city.

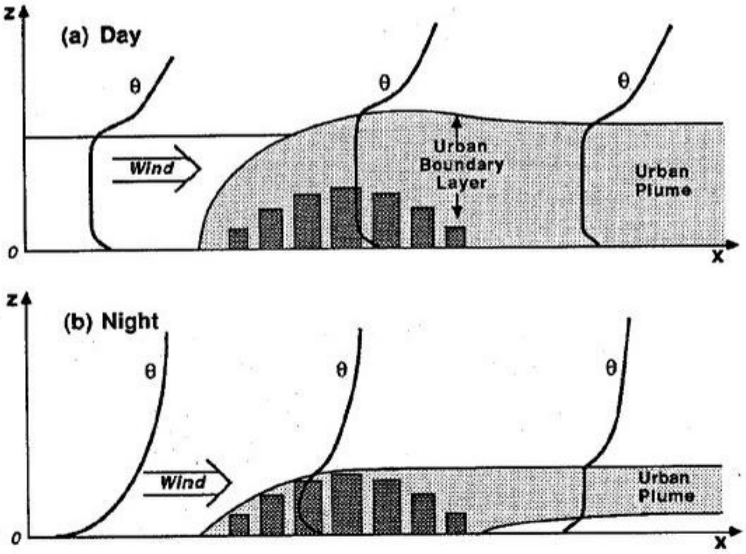

Figure 4 Sketch of the urban boundary layer and urban plume for a windy day (a), and night (b) (from Stull, 1988, p. 611, fig. 14.22).

Wind flow over a moderate slope could be classified as a flow over complex terrain, that has been subject of many studies in the last 20 years. Experimental studies have been performed both in real atmosphere and laboratories (e.g: Khurshudyan et al., 1981 [15]; Finnigan et al., 1990 [7]; Baskaran et al., 1987 [3], 1991 [4]; Frank et al., 1993 [8]; Walmsley and Taylor, 1996 [22]). Jackson and Hunt (1975) [14] and Hunt et al., (1988a [10], 1988b [11]) represent the most influential theoretical works relating to flow over low hills, in neutral and stable conditions, where the equations of motion can be linearized.

The definition of hilly terrain can be topography made by rows of hills and valleys. Over this kind of terrain, many of the flow characteristics introduced in the previous paragraphs can be retained as still valid, and, if the slope steepness is limited, the linear theory can be considered applicable.

Complex topography

The simplest way to define complex topography is the representation of a mountain. The terrain is made by systems of crests and valleys, which are characterized by steep slopes.

The characteristics of the wind systems depend on the geometry and orientation of the valley. The mountain winds can be roughly divided in two classes: slope winds and valley winds. The slope winds are produced by buoyancy forces induced by temperature differences between the air adjacent to the slope and the ambient air at the same height far from the slope (e.g. over the centre of the valley): slope winds blow up-slope during daytime and down-slope during night-time. This type of terrain and circulation spans a wide range of scales, from local to sub-synoptic scale. On this kind of topography simple assumptions are no more valid and the flow can be described only by extensive measurements and/or simulations employing models of proved capability [19].

The lowest region of the atmosphere, where the flow is affected by the surface friction, is known as the planetary or atmospheric boundary layer (ABL). As opposed to small-scale laboratory experiments, the flow in the ABL is significantly affected by the rotation of the earth. This phenomenon is known as the Coriolis force.

Mean velocity profiles

- Power law

The relation between wind speed and height is called the wind profile [23]. The wind speed increases with height. The increase in speed is in direct relation to the surface friction, which the wind flow is experiencing. Usually when the wind flows over a complex terrain the increase in speed is more significant.

Getting closer to the surface the friction increases. This leads to decrease in speed with decrease in height. This change of wind speed and wind direction is called wind shear. [23]

$$\frac{U(z_1)}{U(z_2)} = \left(\frac{z_1}{z_2}\right)^p, \tag{1}$$

where U (z_1) and U (z_2) are the wind speeds at heights (z_1) and (z_2); p is the power law exponent, which varies with height, surface roughness and stability; for this reason a more realistic expression for the wind speed as function of height z can be obtained using the logarithmic wind profile.

- Logarithmic law

The logarithmic law describes the vertical mean velocity profile in the main flow direction in a turbulent boundary layer.

The logarithmic law represents the flow over a uniform surface, and is strictly valid only for neutral stability. It is universal for smooth surfaces, and shifted downwards for rough surfaces. The logarithmic law can be written in two ways:

$$\frac{U}{u_*} = \frac{1}{k} ln\left(\frac{Z_z u_*}{v}\right) + C_0 - \frac{\Delta U}{u_*}, \tag{2}$$

$$\frac{U}{u_*} = \frac{1}{k} ln\left(\frac{Z_z}{z_0}\right), \tag{3}$$

where κ = 0.41 is von Karman's constant, z_0 is the roughness length, u_* the friction velocity, C_0 ≈5.2 and $\Delta U^+ = \Delta U/u_*$ is called the roughness function. $\Delta U^+ = 0$ for smooth surfaces. The roughness function increases for rougher surfaces, resulting in a downwards shift in the smooth logarithmic law. The roughness function for sand-grain roughness in a fully rough flow is given by (Raupach et al., 1991)

$$\Delta U^{+} = -8.5 + C_0 + \frac{1}{k} ln(k_s^{+})\,, \qquad (4)$$

Where $k_s^{+} = k_s\ u*/\nu$ and k_s is representative for the height of the roughness.

Depending on the roughness of the surface the zero level could be defined at different heights. The zero level is in practise found from wind measurements in the surface layer. It can be defined by $Z_z = z - d_0$, where z is the height above ground and Z_z is the height above the new zero level. d_0 is called displacement height, and is expected to be between 0 and the average height of the roughness elements, dependent on the density and shape of the elements. d_0 is typically 70−80 % of the height of large roughness elements like trees and houses. [19]

The table 1 below gives an overview of typical terrain types and corresponding roughness lengths.

Typical values of the roughness length z0 and the exponent in the power law α for various types of terrain (Counihan, 1975 [13]; Arya, 1988 [1]; Freris, 1990 [9])

Table 1

Type of terrain	z_0 [m]	α
Ice, mud flats	10^{-5} -3.10^{-5}	
Calm open sea	10^{-4}	
Sand, flat desert	2.10^{-4} – 10^{-3}	0.10
Off-sea wind in coastal areas	10^{-3}	
Snow surface	10^{-3} – 6.10^{-3}	
Fairy level grass plains	6.10^{-3} – 2.10^{-2}	
Farmlands	2.10^{-2}– 10^{-1}	0.19
Forest and woodland	10^{-1} – 1	
Suburb	1 - 2	
City	2 - 4	0.32

Wind tunnel modeling and analysis

Wind flow modelling specifics

Large wind farms are situated on the land with dimensions several kilometres. Accurate determination of the energy production of the wind farm is in a relation with proper determination of the wind flow over the terrain. The on-site measurements accomplished with tall towers and calibrated measuring equipment give information for the wind flow distribution near the measurement point. In order to be determined wind parameters at the hub height point of each wind turbine either must be carried out a series of on-site measurements or should be accomplished numerical study of the flow by using commercial software products. Running series of on-site measurements is very expensive procedure. Using CFD tool for analysis of the wind flow is also time consuming procedure because of the great size of the wind farm domain. The proper selection of the turbulent model during the numerical procedure is also important factor.

For a small or moderate wind farms with flat or not so complex orography is sometimes appropriate to be run tests in a wind tunnel in order to be determine the flow behaviour over the terrain. In this case a model of the terrain should be prepared using dimensional analysis approach.

The experimental data can be applied to a full-scale flow when the preliminary selected similarity parameters for the model and full scale object are equal. Such parameters can be obtained applying non-dimensionalizing procedure of the equations of motion of real fluids. Following dimensionless numbers relating to the open flows distribution are [2] (Table 2):

Dimensionless numbers applicable for open flows ([2]) **Table 2**

Type of dimensionless parameter	Expression	Force relation
Reynold number (Re)	$U.d/\nu$	Inertial/viscous
Froude number (Fr)	U^2/gl	Inertial/gravitational
Rossby number (Ro)	$\frac{U}{L}.\Omega$	Advective acceleration/Coriolis acceleration
Prandtl number (Pr)	$\frac{\nu}{a} = \frac{\nu\rho c_p}{\lambda}$	Viscous diffusive rate/thermal diffusion rate
Eckert number (Ec)	$\frac{U^2}{c^2\Delta T}$	

Boundary layer mdeling

In order to have a greater similarity a boundary layer modelling is needed. For a flat orography laminar boundary layer can be modelled easily. For a turbulent boundary layer additional terms have to be adopted. The most important from the modelling view point conditions that have to be considered are presented in Table 3 [2].

Dimensionless numbers applicable for boundary layer ([2]) **Table 3**

Type of dimensionless parameter	Expression	Nomenclature
Roughness Reynold number (Re*)	$U_*.z_0/\nu$	U_* - friction velocity; z_0 – roughness lenght
Jensen’s length scale criterion	δ/z_0	δ – thickness of the boundary layer

The other constrain is that the model should not cover more than 10-15% of the wind tunnel area cross section.

Experimental Equipment (Wind tunnel data)

The existing wind tunnel is from the closed type as the testing area is open type. The overall dimensions of the tunnel are approximately 6.5 m long and 3.5 m wide [12] (Figure 5). The work area, where the test object is situated, has the size: 1.5 m long and 0.85 m wide. The wind tunnel is supplied with air trough axial fan driven by an AC electric motor with adjustable rpm.

The speed of the motor shaft can be varied smoothly from 300 min^{-1} (output 13.6 kW) to 1550 min^{-1} (output 71.2 kW).

The generated jet is approximately rectangular with a height of 0.5 m and width 0.75 m. The length of the operational area is 1.5 m. The airflow velocity in the work can be precisely adjusted (via remote control of the speed of the motor) in the range between 6 m/s to 60 m/s.

Figure 5 Wind tunnel at dept. of "Hydroaerodynamics and hydraulic machines" [12]

The provided in [12] experimental study shows that when a small object obscuring 10-20% of the net cross area of the wind tunnel is tested a velocity drop in the amount of 10% can be expected. The data are provided in Figure 5.

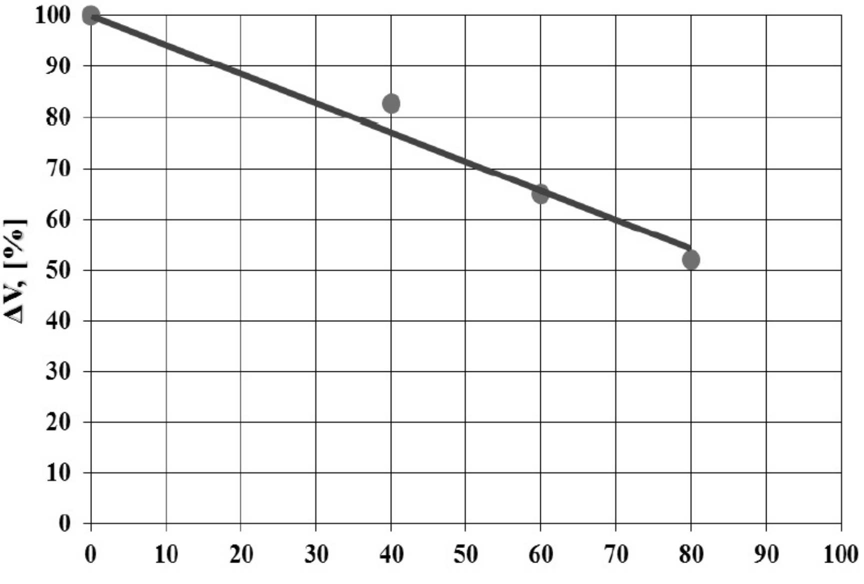

Figure 6 Velocity drop at different wind tunnel shading percentage [12]

Conclusion

Current work focuses on the methodologies for determination of the wind shear over different types of orography. It is pointed the usage of the discussed power and logarithmic law for different terrain types.

Some specifics concerning the wind flow modeling in wind tunnel are pointed. Dimensionless numbers relevant to wind flow and boundary layer modeling are presented and discussed. Some limitations during the process of experimental study that have to be considered are also discussed and analyzed.

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