

ON WIND VELOCITY PROFILES OVER URBAN AREA

Klara Bezpalcova¹, Zbynek Janour², Viktor M. M. Prior³, Cecilia Soriano⁴ and Michal Strizik⁵

¹ Charles University, Dept. of Meteorology and Env. Protection, Prague, CR

² Institute of Thermomechanics, Prague, CR

³ Portuguese Meteorological Institute, Lisboa, Portugal

⁴ Universitat Politècnica de Catalunya (UPC). Barcelona, SPAIN

⁵ LIDAR s. r. o. Prague, CR

INTRODUCTION

The basic parameters that should be concerned for air pollution studies are wind and temperature profiles. There have been numerous investigations into atmospheric boundary layer carried out, but relatively few of them were carried out in urban areas in contrast to the fact that the most direct impacts of air pollution are felt in cities. The continuous increase of vehicular traffic within densely populated cities adds further pressure on a deteriorating urban air quality in many towns. Therefore, in recent years, boundary-layer meteorologists' attention has been directed towards problems of surface/inertial layer. Velocity and temperature profiles over urban areas above this layer are of interest to designers of structures, buildings in towns, meteorologists etc.

This topic is still considered very complex. Only a few engineering or micrometeorological rules are general enough to be exported from one city to another. The aim of this contribution is to find a simple "universal" mean velocity profile for the core of the urban atmospheric boundary layer (UABL). Obviously the horizontally homogeneous atmospheric boundary layer belongs to the simplest cases. This layer is a theoretical case of the atmospheric boundary layer (ABL) with conditions, which in reality are never satisfied simultaneously. In analogy to Wippermann (1973)-ABL can be defined as a *Planetary Boundary Layer (PBL)*, if:

- The boundary-layer flow is turbulent,
- The mean flow and the turbulence properties are stationary,
- The mean flow and the turbulence properties are horizontally homogeneous.

ROSSBY SIMILARITY

The simplest model of UABL consists in considering that the flow over an urban area is similar to the flow over a rough surface, with a given, large, roughness length z_0 and a defined surface heat flux. In this way we shall model the UABL as the PBL over a rough surface.

Let us non-dimensionalize the equations by using the friction velocity u^* and the internal scale height of the PBL $H = \kappa u^* / f$, where κ is von Kármán constant and f denotes the Coriolis parameter. The equations of motion in tangent-plane co-ordinates with the Boussinesq assumption on eddy viscosity can be transformed into following form:

$$\frac{d^2 X}{dZ^2} + \frac{Y}{K_m} - \lambda_x = 0 \quad (1)$$

$$\frac{d^2 Y}{dZ^2} - \frac{X}{K_m} + \lambda_y = 0 \quad (2)$$

$$K_m = K_m(Z, \mu) \quad (3)$$

With following boundary conditions:

$$Z \rightarrow \infty : \quad X \rightarrow K_{m\infty} \lambda_x \quad (4)$$

$$Y \rightarrow K_{m\infty} \lambda_{yy} \quad (5)$$

$$K_m \rightarrow K_{m\infty} \quad (6)$$

$$Z = Z_0 : \quad X = X_0 = 1 \quad (7)$$

$$Y = Y_0 = 0 \quad (8)$$

$$K_m = K_{m0} = Z_0 \quad (9)$$

Here are: $Z=z/H$, $K_m=K/(H^2 f)$, $U=U/u^*$, $V=V/u^*$, $X=\tau_x/(\rho u^{*2})$, $Y=\tau_y/(\rho u^{*2})$, $\lambda_x=dU_g/dZ$, $\lambda_y=dV_g/dZ$ and μ is a stability parameter.

The set of equations (1) – (3) and boundary conditions (4) – (9) depends on three internal parameters - λ_x , λ_y , μ . The lower boundary conditions depend on nondimensional roughness length:

$$Z_0=1/(\kappa c_g Ro_0) \quad (10)$$

with

$$Ro_0 = \frac{|V_{g0}|}{fz_0} \quad \text{and} \quad c_g = \frac{u^*}{|V_{g0}|} \quad (11)$$

Here the surface Rossby-number depends on a non-dimensional combination of the external parameters $|V_{g0}|$, f and z_0 . If Z_0 would be zero ($Ro_0 \rightarrow \infty$) and eddy viscosity should satisfy the condition

$$\frac{\partial K_m}{\partial (Ro_0)} = 0 \quad (12)$$

the system would be independent of Ro_0 , i. e. the profiles $X(Z)$, $Y(Z)$ and $K_m(Z)$ must be independent on Ro_0 . This is called Rossby similarity and the profiles $X(Z, \lambda_x, \lambda_y, \mu)$, $Y(Z, \lambda_x, \lambda_y, \mu)$, $K_m(Z, \lambda_x, \lambda_y, \mu)$ and the dimensionless velocity defect components $\kappa(U-U_{g0})/u^*$, $\kappa(V-V_{g0})/u^*$ are universal. However the roughness length Z_0 is different from zero and the Rossby similarity is not existent in the low layer, which has the depth Z_b in the order of the roughness length and it should be related to the blending height¹.

To assess this depth Wipermann (1972) mixing length hypothesis has been used and numerical solution for varying roughness length Z_0 and for different thermal stratification has been performed – see Janour, Benes(2001). The example of the nondimensional Reynolds stress profiles for different roughness length Z_0 is shown on Figure 1.

¹ height over the ground at which the ground inhomogeneity is not perceived, over which the various IBLs merge into a layer having an horizontally homogeneous structure

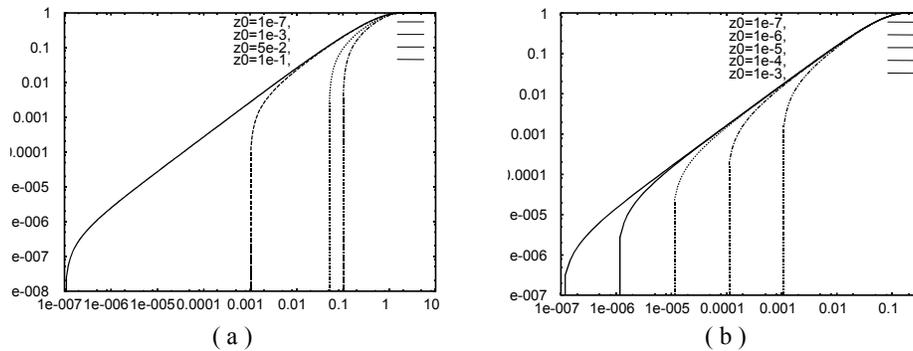


Figure 1. Plot of function $1 - \tau / \rho u_*^2$ for a) unstable, b) extremely stable stratification.

All determined profiles coincide in the upper part, which means that the Rossby similarity exists there. The profiles are splitted in the lower part – the Rossby similarity is not existent. It can be assessed that the height Z_b , where the Rossby similarity exists, is roughly

$$Z_b \approx 10Z_{0,\max} \tag{13}$$

The CFD code Fluent with “k- ϵ ” model of turbulence was used to assess the influence of the roughness length too – see Kozubkova, Drabkova (2002). The nondimensional velocity defect stress for different roughness length Z_0 (indifferent stratification) is demonstrated on Figure 2 demonstrating the qualitative similar results.

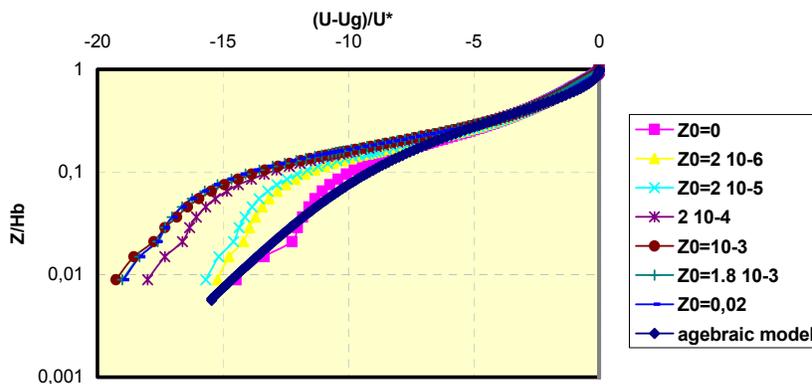


Figure 2. Wind defect profiles for different roughness lengths.

Let us define the depth Z_b corresponding to boundary layer thickness δ as that distance for which difference of velocity defect for rough surface with Z_0 and for smooth surface is less than $n\%$. The estimation of the blending height from CFD data are plotted in Figure 3.

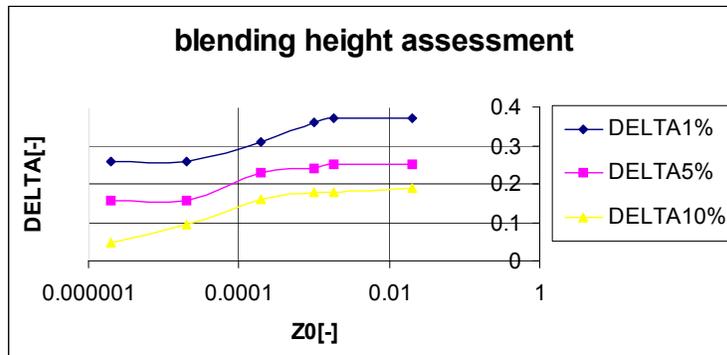


Figure 3. Blending height Z_b assessment.

COMPARISON WITH EXPERIMENTS

There have been relatively few available experiments performed in urban areas to test the above-introduced urban velocity profile:

- Jones et al. (1970) used a captive balloon to carry measurement instruments for wind and other meteorological magnitudes above Liverpool urban area. The boundary layer depth and the dependence of power-law index on stratification had been assessed;
- Dobbins (1976) selected data from low-level soundings over Cambridge, U. S. A. and determined the data on the basis of an “Ekman-like” variation of the wind vector with altitude;
- radiosounding launched by SERVEI DE METEOROLOGIA DE CATALUNYA (Catalan Meteorological Service) in Barcelona;
- radiosounding launched by INSTITUTO de METEOROLOGIA (Portugal hydrometeorological institute) in Lisboa, Évora and Neves Corvo;
- SODAR (and LIDAR) measurements for wind (and concentrations) above Prague for COST 715 project by LIDAR s. r. o., CR.

Examples of preliminary comparisons of our simulation with above-mentioned results are presented on Figures 4 and 5 for indifferent stratification.

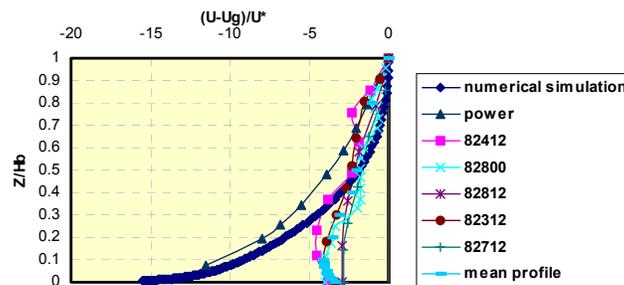


Figure 4 Comparison of velocity defect profiles inside the UABL simulation with radiosounding launched in Barcelona.

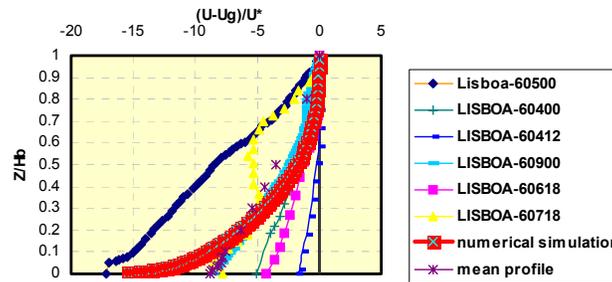


Figure 5. Comparison of velocity defect profile inside the UABL simulation with radiosounding launched in Lisboa.

CONCLUSIONS

The horizontally homogeneous atmospheric boundary layer over rough surface with a large, roughness length z_0 has been investigated to model the simplest cases of the UABL over flat plain. The Rossby similarity has been demonstrated for the core of the urban atmospheric boundary layer (UABL). It means that the profiles $X(Z, \lambda_x, \lambda_y, \mu)$, $Y(Z, \lambda_x, \lambda_y, \mu)$, $K_m(Z, \lambda_x, \lambda_y, \mu)$ and velocity defect components $\kappa(U-U_{g0})/u^*$, $\kappa(V-V_{g0})/u^*$ are universal and independent on surface characteristics for $Z > Z_B$. It can be concluded that the Rossby similarity cannot be used for non-dimensional components of the velocity. The conclusion is in contrast to Rafailidis (1997) results that concluded from wind tunnel simulations that the wind above an urban fetch is influenced by the presence of the buildings only within 3 combined building heights above ground. The altitude of the Rossby similarity lower limit corresponding to the blending height was estimated.

Comparisons of our simulation with empirical results pointed out complexity of the topic, e. g.: scattered radiosounding mean velocity defect profiles (averaging time $T \sim 1$ minute) are compared with the simulated ones ($T \sim 15$ minutes). Artificial mean profile determined from the data sets seems to be more suitable for comparison - see Figure 5; influence of topography is more important across the Barcelona Internal-Sub-Layer - see Figure 4.

REFERENCES

- Dobbins R. A., 1977: Observations of the Barotropic Ekman Layer over an Urban Terrain, *Boundary_layer Meteorology* 11, 39 – 54.
- Janour Z., Benes M., 2001: Numerical simulation of the Planetary-Boundary-Layer Equations, *Workshop on Urban Boundary Layer Parametrisations*, Zürich.
- Jones P. M., de Larringa M. A. B., Wilson C. B., 1971: The Urban Wind Velocity Profile”, *Atmospheric Environment* 5, 89 – 102.
- Kozubkova M., Drabkova S., 2002: Influence of the wall roughness on the wind profile and concentration of pollutants in the atmosphere, *Seminar Topical problems of fluid mechanics 2002*, pp. 49-52.
- Wippermann F., 1972: Empirical Formulae for the Universal Functions $M_m(\mu)$ and $N(\mu)$ in the Resistance Law for Barotropic and Diabatic Planetary Boundary Layer, *Beitrag zur Physik der Atmosphäre*, 45, 305-311.
- Wippermann F.: 1973: The Planetary Boundary Layer of the Atmosphere, *Deutscher Wetterdienst*.