

NUMERICAL EVALUATION OF THE THERMALLY STRATIFIED ATMOSPHERIC WIND TUNNEL

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Abstract: *The atmospheric boundary layer (ABL) flow occurs due the interaction between earth surface and atmosphere and it is usually under thermally stratification. However, the atmospheric wind tunnels need appropriate devices, such as spires and cubical roughness elements, at the entrance of the test section to create atmospheric characteristics. These structures simulate the atmospheric boundary layer far from tunnel inlet. Another ABL feature is the temperature difference for height variation. Hence, the atmospheric fluid stratification will be done with bottom surface heating. In order to study different thermal heating configurations and the boundary layer profile effects under different spires set configuration, a mathematical model will be done and simulated using Openfoam software. This computational tool is a free open source Computational Fluid Dynamics (CFD) software widely used among researchers across the world. For this problem, the momentum equation and energy equation are coupled and they need to be solved together using the software. The final result will be the analysis of the velocity profile and temperature distribution within the wind tunnel flow.*

Keywords: *Atmospheric boundary layer, Turbulent flow, Heat transfer and Computational fluid dynamics*

1. INTRODUCTION

The atmospheric boundary layer (ABL) is the atmosphere region directly affected by the Earth's surface. The ABL height is variable and depends on the particular geomorphology region, the surface roughness and stratification environment. It may extend a few hundred meters to the radial distance of approximately 1 km above the Earth's surface. The study of the atmospheric boundary layer wind tunnel plays an important role in many engineering applications. Usually, the ABL flow simulation in wind tunnels is applied to environmental studies and the investigation of the basic phenomena occurring in micro-meteorological atmosphere processes (Petersen, 2013). Furthermore, these researches help to solve problems of practical engineering interest, such as the pollutants dispersion in complex terrain or urban areas, which buildings produce different flow patterns. Wind tunnels are experimental facilities designed to simulate the air flow conditions. Similar studies can be performed in real environmental conditions. After a wind tunnel is built, it is necessary to evaluate the flow characteristics and analyse the flow patterns for which it was constructed (Al-Nehari *et al.*, 2010).

Wind tunnel experimental studies are the main knowledge sources for investigations that require an ABL profile. Recent techniques and facilities are continually developed with extensive research related to environmental and aerodynamics architectural structures issues (Cermak, 1995; Cermak *et al.*, 1995; Abbaspour and Shojaee, 2009). To determine the effects of flow in high buildings, bridges and other structures is an important step in the structural design process (ASCE, 2005). In addition, the simulation of ABL profile has key role in transport modelling and pollutants dispersion in the environment (Abdullah *et al.*, 2007; Kho *et al.*, 2007).

A series of experimental evaluations were conducted in the development of the ABL wind tunnel (Counihan, 1969, 1973; Cook, 1973; Irwin, 1981). The simulated characteristics of the boundary layers are consistent with the interpretation of measurements in real scale. In addition, studies of thermal stratification also has attracted scientific interest (Mahrt, 1999; Ohya, 2001; Pieterse and Harms, 2013; Mahrt, 2014). In this context, the use of spires in wind tunnels input for ABL simulation has become a common technique in experimental procedures of turbulent flows in external environments (Cermak, 1995; Cermak *et al.*, 1995; Garg *et al.*, 1997). Nevertheless, new techniques of observation and analysis are necessary to advance the comprehension of the atmospheric boundary layer (Mahrt, 2014).

Numerical simulations have been widely implemented as a comparison source of the phenomena associated with atmospheric boundary layer. The computational results show an overall good agreement with experimental data (Ferreira *et al.*, 1995). The study of flow on hills can show good agreement between the numerical results and computational (Athanasiadou and Castro, 2001). Finally, numerical studies also help to obtain a preliminary understanding of the development of the boundary layer, reduces the tunnel operating time and cost during the actual testing stage. Lastly, the experimental results show good agreement with the numerical predictions (Shojaee *et al.*, 2014).

The current paper is the initial numerical simulations of thermally stratified boundary layer of Inmetro's atmospheric wind tunnel. The thermally and hydrodynamic boundary layer will be analysed. In order to study different thermal heating configurations and the boundary layer profile effects under different spires set configuration, a mathematical model will be done and simulated using Openfoam software. For this problem, the momentum equation and energy equation are coupled and they need to be solved together. The final result will be the analysis of the velocity profile and temperature

distribution within the wind tunnel flow.

2. MATHEMATICAL FORMULATION

The proposed problem in this work is the air flow through three spires which the geometry can be seen on figure 1. The spires have a length of 0.0922276m, width of 0.015m, height of 0.609649m and the distance between the center of them is 0.25m. The tip of the spires were designed to be round, with a diameter curvature of 10% of the spire length, in order to improve numerical convergence.

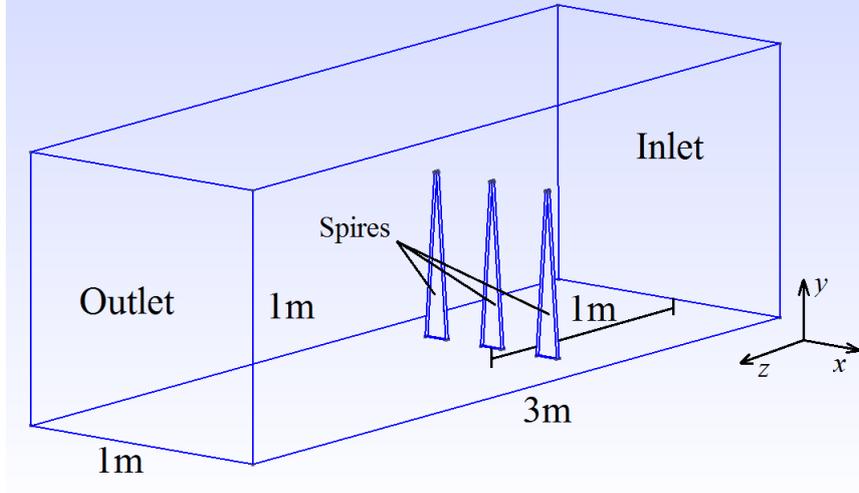


Figure 1: Proposed problem geometry

For the simulation of the stratified air flow of the proposed problem, one needs to solve the coupled momentum, mass and energy equation, which are given by the following system:

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \mu \nabla^2 \mathbf{v} - \rho g \hat{e}_y \quad (1)$$

$$\nabla \cdot \mathbf{v} = 0 \quad (2)$$

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = k \nabla^2 T \quad (3)$$

where μ is the fluid dynamic viscosity, ρ is the fluid density, k is the fluid conductivity, c_p is the specific heat at constant pressure and g is the gravitational acceleration, and all of these parameters are considered constant. The simplification of negligible viscous dissipation was implemented on equation (3).

The boundary conditions for the velocity, pressure and temperature of the problem are showed in the following expressions:

- Side and upper walls:

$$\mathbf{n} \cdot \nabla p = 0 \quad (4)$$

$$\mathbf{v} = \mathbf{0} \quad (5)$$

$$\mathbf{n} \cdot \nabla T = 0 \quad (6)$$

- Bottom wall:

$$\mathbf{n} \cdot \nabla p = 0 \quad (7)$$

$$\mathbf{v} = \mathbf{0} \quad (8)$$

$$\frac{\partial T}{\partial y} = -\frac{q_0}{k} \quad (9)$$

- Inlet section:

$$\mathbf{n} \cdot \nabla p = 0 \quad (10)$$

$$\mathbf{v} = \hat{e}_z \quad (11)$$

$$T = T_{\text{in}} \quad (12)$$

- Outlet section:

$$p = 0 \quad (13)$$

$$\mathbf{n} \cdot \nabla \mathbf{v} = \mathbf{0} \quad (14)$$

$$T = T_{\text{out}} = T_{\text{in}} + \frac{3q_o}{\rho c_p} \quad (15)$$

where \mathbf{n} is the boundary orthonormal vector and $\mathbf{0}$ is the null vector.

In order to solve the turbulent flow, the k-epsilon turbulence model is utilized, which is the most common model used in computational fluid dynamics to simulate mean flow characteristics for turbulent flow conditions. It gives a general description of the flow by means of two transport equations.

3. RESULTS AND DISCUSSIONS

The spires are first designed to obtain required atmospheric boundary layer similarity within the test section of the Inmetro's Wind Tunnel using the design methodology described in [Shojaee et al. \(2014\)](#). Subsequently, a computational analysis of the designed inlet configurations is performed using CFD to have a preliminary understanding of how well the inlet configurations could simulate the desired boundary layer conditions within the test section. The design goal is to obtain a boundary layer characteristic after 4 m from inlet.

As an initial attempt, we selected a model building height of 0.6 m and a wind tunnel speed of 1 m/s for spire configuration presented in figure 1. The computational analysis of the wind tunnel test section is performed with the spires elements using the free CFD software OpenFoam. Results of the computational simulations are obtained by solving RANS equations using $\kappa - \epsilon$ turbulence model without energy equation, with standard pressure, second order momentum, turbulent kinetic energy and turbulent dissipation rate computations.

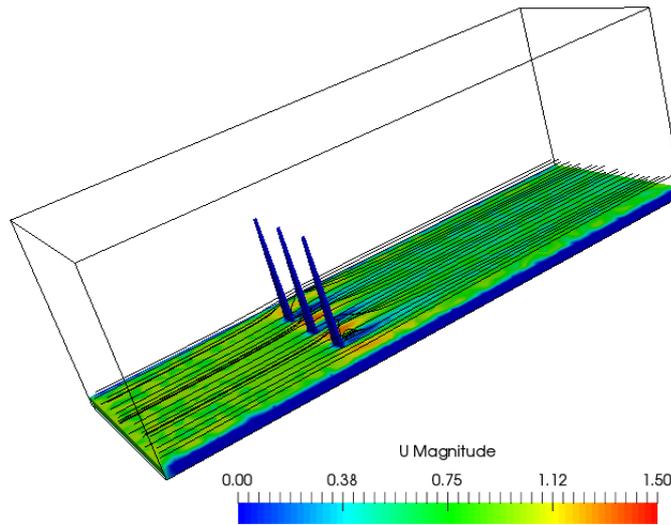


Figura 2: Streamwise direction velocity development.

Figure 2 and 3 show the numerical results for the atmospheric boundary layer development. Figure 2 shows the velocity magnitude contours and streamlines. Figure 3 presents the velocity magnitude contours downstream of the spires on cross sections. The effects of the spires and the roughness elements are clearly visible in both figures. The individual wakes of the spires are identifiable up to about 2 m downstream of the test section entrance. These wakes as well as the disturbances created by the spires elements start to mix out and create a thick boundary layer near the wall as one moves downstream.

Figure 4 presents velocity profile in different positions in downstream direction. The figure 4 left shows the mean velocity profile of boundary layer in the tunnel center line. As can be seen the wake region provided by the spires create a boundary layer thickness about 0.5m. The figure 4 right show the spanwise velocity profile.

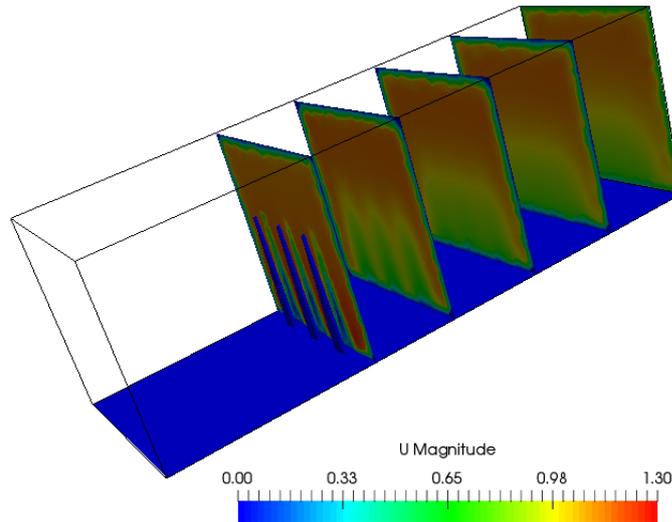


Figura 3: Streamwise flow field mean velocity.

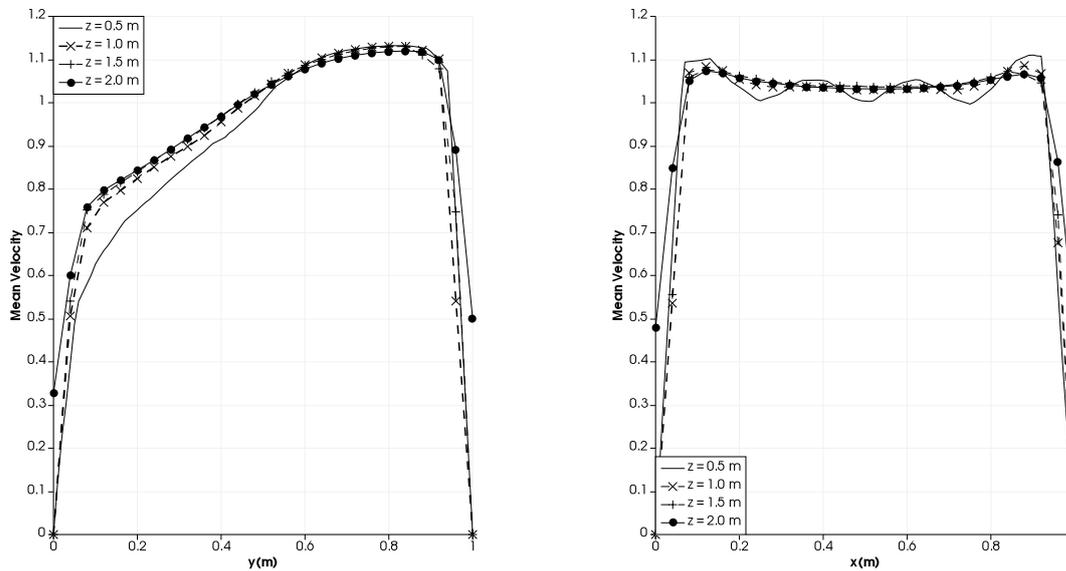


Figura 4: Mean velocity profile for different streamwise position.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

- Abbaspour, M. and Shojaee, M., 2009. "Innovative approach to design a new national low speed wind tunnel". *International Journal of Environmental Science & Technology*, Vol. 6, No. 1, pp. 23–34.
- Abdullah, L.C., Wong, L.L., Saari, M., Salmiaton, A. and Rashid, M.S.A., 2007. "Particulate matter dispersion and haze occurrence potential studies at a local palm oil mill". *International Journal of Environmental Science & Technology*, Vol. 4, No. 2, pp. 271–278.
- Al-Nehari, H.A., Abdel-Rahman, A.K., Shafey, H.M. and Nassib, A.E., 2010. "Characterization of a low-speed wind tunnel simulating urban atmospheres". *Journal of Engineering Sciences*, Vol. 38, No. 32, pp. 509–532.
- ASCE, 2005. *Minimum design loads for buildings and other structures*, Vol. 7. Amer Society of Civil Engineers.
- Athanassiadou, M. and Castro, I.P., 2001. "Neutral flow over a series of rough hills: a laboratory experiment". *Boundary-layer meteorology*, Vol. 101, No. 1, pp. 1–30.
- Cermak, J.E., 1995. "Progress in physical modeling for wind engineering". *Journal of wind engineering and industrial aerodynamics*, Vol. 54, pp. 439–455.
- Cermak, J.E., Cochran, L.S. and Leflier, R.D., 1995. "Wind-tunnel modelling of the atmospheric surface layer". *Journal of wind engineering and industrial aerodynamics*, Vol. 54, pp. 505–513.

- Cook, N., 1973. "On simulating the lower third of the urban adiabatic boundary layer in a wind tunnel". *Atmospheric Environment* (1967), Vol. 7, No. 7, pp. 691–705.
- Counihan, J., 1969. "An improved method of simulating an atmospheric boundary layer in a wind tunnel". *Atmospheric Environment* (1967), Vol. 3, No. 2, pp. 197–214.
- Counihan, J., 1973. "Simulation of an adiabatic urban boundary layer in a wind tunnel". *Atmospheric Environment* (1967), Vol. 7, No. 7, pp. 673–689.
- Ferreira, A., Lopes, A., Viegas, D. and Sousa, A., 1995. "Experimental and numerical simulation of flow around two-dimensional hills". *Journal of wind engineering and industrial aerodynamics*, Vol. 54, pp. 173–181.
- Garg, R., Lou, J. and Kasperski, M., 1997. "Some features of modeling spectral characteristics of flow in boundary layer wind tunnels". *Journal of wind engineering and industrial aerodynamics*, Vol. 72, pp. 1–12.
- Irwin, H., 1981. "The design of spires for wind simulation". *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 7, No. 3, pp. 361–366.
- Kho, W.L.F., Sentian, J., Radojevic, M., Tan, C.L., Law, P.L. and Halipah, S., 2007. "Computer simulated versus observed no2 and so2 emitted from elevated point source complex". *International Journal of Environmental Science & Technology*, Vol. 4, No. 2, pp. 215–222.
- Mahrt, L., 2014. "Stably stratified atmospheric boundary layers". *Annual Review of Fluid Mechanics*, Vol. 46, pp. 23–45.
- Mahrt, L., 1999. "Stratified atmospheric boundary layers". *Boundary-Layer Meteorology*, Vol. 90, No. 3, pp. 375–396.
- Ohya, Y., 2001. "Wind-tunnel study of atmospheric stable boundary layers over a rough surface". *Boundary-Layer Meteorology*, Vol. 98, No. 1, pp. 57–82.
- Petersen, G., 2013. *Wind tunnel modelling of atmospheric boundary layer flow over hills*. Ph.D. thesis, Hamburg University.
- Pieterse, J.E. and Harms, T., 2013. "Cfd investigation of the atmospheric boundary layer under different thermal stability conditions". *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 121, pp. 82–97.
- Shojaee, S.M.N., Uzol, O. and Kurç, Ö., 2014. "Atmospheric boundary layer simulation in a short wind tunnel". *International Journal of Environmental Science and Technology*, Vol. 11, No. 1, pp. 59–68.

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