Short Term Scientific Mission report

AIR FLOW SIMULATION IN URBAN AREA: FOCUS ON WALL FUNCTION MODELLING

COST ACTION TU1304

Wind Energy Technology Reconsideration to enhance the concept of smart cities

WINERCOST

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1. Background

1.1 Participant of the Short Term Scientific Mission STSM

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1.2 Host Institution / person

Dr. Ashvinkumar Chaudhari, Center of Computational Engineering and Integrated Design (CEID), Lappeenranta University of Technology, Finland.

1.3 STSM period

The mission started on the 23th November2015 and ended on the 04th December 2015.

1.4 Missions

A STSM at the CEID center in Lappeenranta University of Technology (LUT) was a great opportunity to benefit from experience and share techniques developed by Dr. Ashvinkumar Chaudary, a post-doc researcher at the CEID center who is also serving as a MC member in COST action TU 1304. Dr. Ashvinkumar Chaudhari has intensively worked with Large Eddy Simulations (LES), a technique that we also would like to apply to our project. During his PhD at the CEID center, he simulated atmospheric flows over realistic and complex terrains using OpenFOAM. The software OpenFOAM provides a wallfunction model which is based on the logarithmic law of a smooth wall which is not realistic for complex terrains and urban areas. This STSM was an opportunity to learn about a new rough wall-function that has been implemented and validated by Dr Ashvinkumar Chaudari.

During these two weeks visiting period, we proceeded with the following steps:

- LES in a channel using smooth & rough wall functions
- Compared two solvers
- Canopy model implementation

2. Simulations

In this STSM, we have been using the finite-volume method based open-source C++ code OpenFOAM [1]. All the simulations are carried with large eddy simulations (LES) combined with a one-eddy viscosity sub-grid scale model proposed by Yoshizawa [2].
We focus on flows with high Reynolds numbers using a frictional Reynolds number of 20000. The frictional Reynolds number Re_τ is defined as:

$$Re_\tau = \frac{u_\tau \delta}{\nu} \quad (1)$$

where u_τ is the frictional velocity, δ the boundary layer depth and ν the kinematic viscosity.

2.1 Wall-functions

This part focus on wall-function used in high Reynolds number flows. As it is impossible to use a fine enough computational mesh that resolves all the local roughness elements on the ground, one way is to model their effect on the flow by using a wall-function.
To describe the turbulent wall-bounded flows, the mean velocity profiles normalized over a smooth surface can be described as:

$$U^+ = \frac{u_\tau}{\kappa} \ln \frac{z . u_\tau}{\nu} + C \quad (2)$$

where κ=0.41 is the Von Karman constant, C=5.5 is the constant for a smooth wall, U^+ the non-dimensional mean velocity and z^+ is the non-dimensional vertical height defined as:

$$U^+ = \frac{U}{u_\tau} \quad (3)$$

$$z^+ = \frac{u_\tau z}{\nu} \quad (4)$$

The software OpenFOAM provides a wall-function model which is based on the logarithmic law of a smooth function called *nuSgsUSpaldingWallFunction* and based on the Spalding's model [3]:

$$z^+ = U^+ + \frac{1}{E} \left(e^{\kappa U^+} - 1 - \kappa U^+ - \frac{1}{2} (\kappa U^+)^2 - \frac{1}{6} (\kappa U^+)^3\right) \quad (5)$$

where E= 9.1 is a constant value,

The wall surface in Atmospheric flows is not smooth but consists of roughness elements. Thus the *nuSgsUSpaldingWallFunction* function should not be used for flow over complex terrains. Instead of that, a logarithmic law of a rough wall depending on the aerodynamic roughness-lenght z_0 should be used. In the present STSM, we use the wall-function called *ABLRoughWallFunction* (see Chaudhari [4]) based on the following equation:

$$U^+ = \frac{u_\tau}{\kappa} \ln \frac{z}{z_0} \quad (6)$$

where z_0 is the ground roughness length and C=5.5 is the constant for a smooth wall.
A simulation is carried out in a channel of size 4m × 2m ×1 m in the streamwise (x), spanwise (y) and vertical (z) directions, respectively. A 80×40×50 Cartesian mesh in the x, y and z directions is used for this calculation. The non dimensional wall distance z^+ is around 400 and a roughness length z_0 of 0.001m is used.
The flow is driven by an uniform pressure gradient aligned with the streamwise direction, and periodicity is applied in both horizontal directions while no-slip condition is used at the bottom face.
Figure 1 shows the results of the *ABLRoughWallFunction* function as green dots. The blue and red lines represent the analytical log-law of a smooth (eq 2) and rough wall (eq 6), respectively. From Figure 1, it can be observed that the LES simulation reproduces well the logarithmic velocity profile of a rough surface.

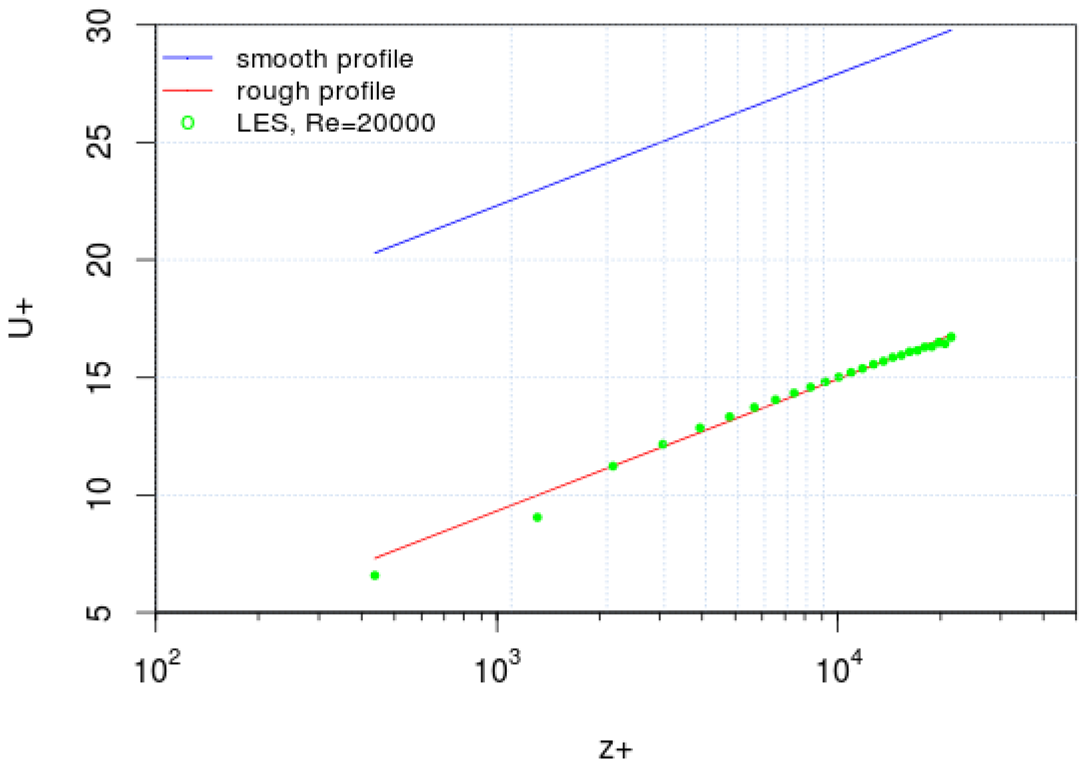

Figure 1. LES mean velocity profile obtained using the *ABLRoughWallFunction* function

2.2 Solver

Two different solvers were compared: the *rk4projectionFoam* solver recently implemented by Vuorinen [5] and *pisoFoam*, the OpenFOAM transient solver for incompressible flow.
The solver *rk4projectionFoam* uses a fourth order Runge-Kutta scheme for time integration with a low-dissipative projection method for the Navier Stokes equations (see Vuorinen [5]

for details). The solver *pisoFoam* uses the standard PISO pressure correction method to solve the continuity and momentum equation, see Issa [6].
A simulation using the same case as previously (channel of 4m × 2m ×1 m) is conducted. Figure 2 shows the results from the two solvers, the results from the *pisoFoam* and *rk4projectionFoam* solvers are represented by yellow and green dots, respectively. The two solvers provide almost the same results with a slight improvement for the *rk4projectionFoam* solver (green dots).
During this STSM, we also compared computational times and we found interesting results. Indeed, the *rk4projectionFoam* solver was 1.7 times slower than the *pisoFoam* solver which is not in accordance with the work of Vuorinen [5] . We couldn't find the reason. The use of different hardware may be one of the reason. For this STMS, calculations were run on the bwGRID cluster of Tübingen (Intel Xeon E5440).

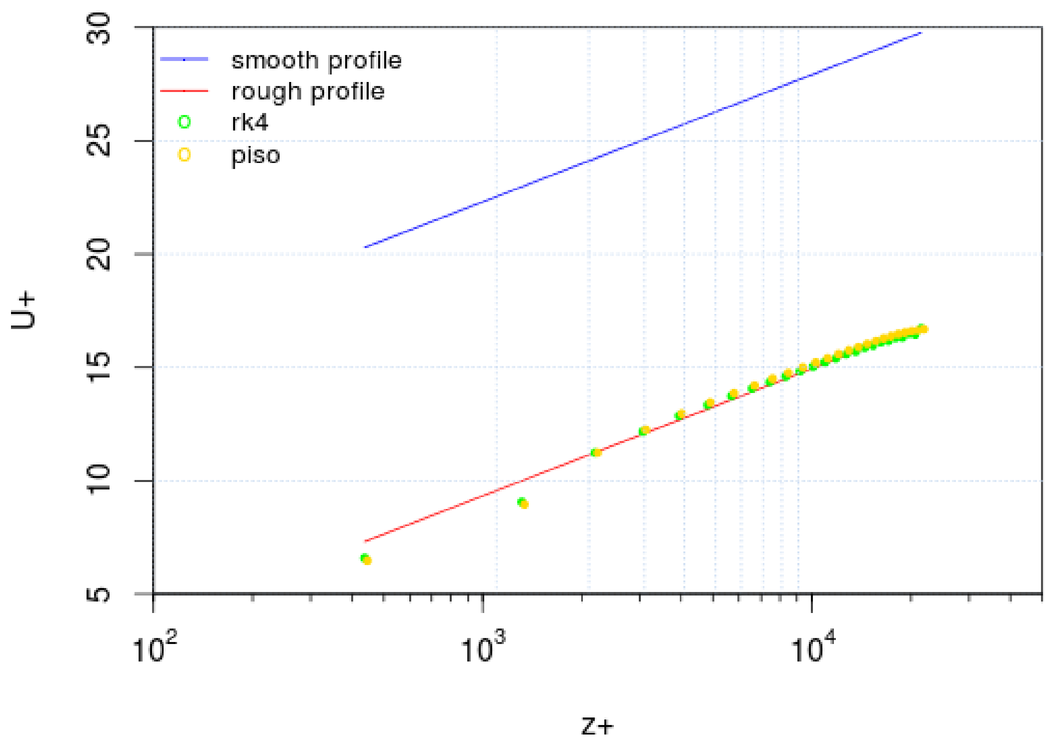

Figure 2. LES mean velocity profiles obtained using the *rk4projectionFoam* and *pisoFoam* solvers

2.3 Canopy Model

In studies on wind environment around buildings, rough surface is generally taken into account by the mean of roughness parameters. However wall-functions may not be sufficient to model the influence of vegetation as the use of roughness parameters provides no information of the turbulence structure within the canopy vegetation. Indeed vegetation form a windbreak and reduce the downstream wind speed. The vegetation drag can be accounted by introducing sink terms. To do so, a canopy model based on the work of Liu [7] where they represent the vegetation by a leaf area density (LAD) profile, which varies with height can be used. This method adds in the incompressible filtered Navier-Stokes equations an additional drag force D_i in the x_i direction generated due to vegetation in the following way:

$$D_i = - C_d \times LAD(z) \times V \times U_i \tag{7}$$

where C_d is a constant drag coefficient, V is the mean wind speed, U_i the local velocity and LAD the leaf area density at height z. The implementation in OpenFOAM is validated with the work of Shaw [8]. It consists of carrying out simulations over homogeneous forest canopies in a neutral atmosphere. The computational domain is 192m×96m×60m with a 20 meters tall homogeneous forest and a 2 meters grid resolution.
Figure 3 shows vertical profile of horizontally averaged longitudinal velocity. The velocity profile is in a good agreement with the original ones presented by Shaw [8].

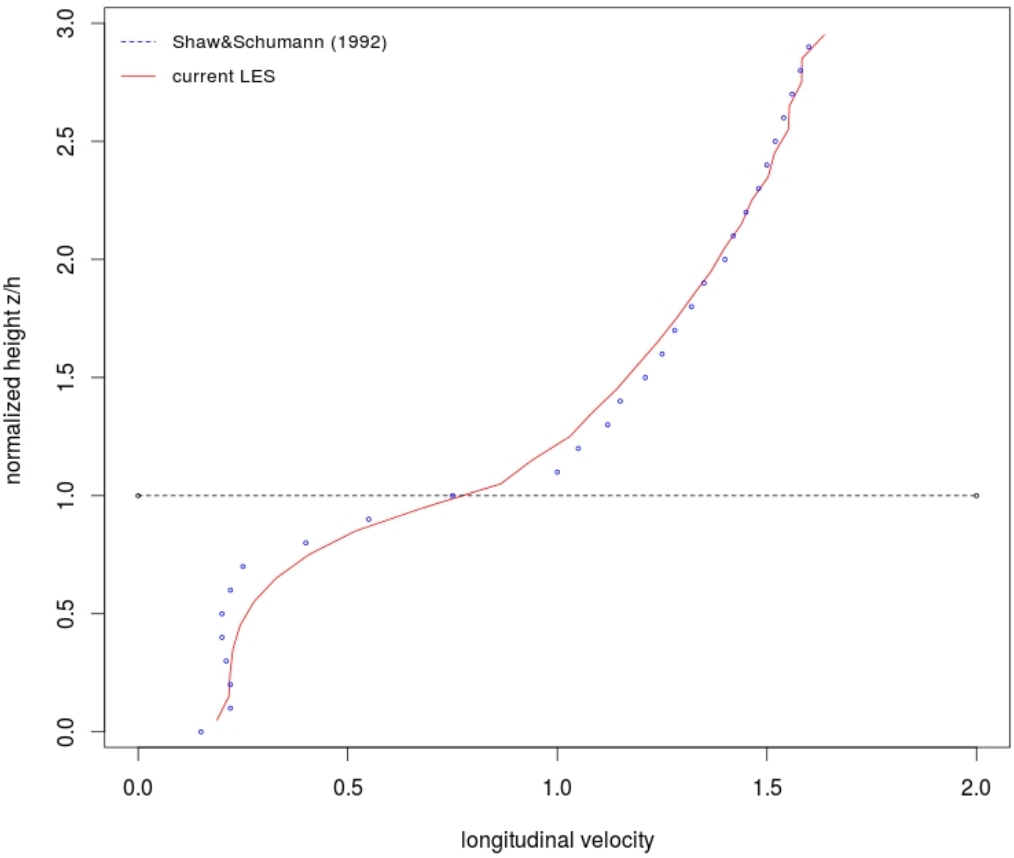

Figure 3. Validation of the canopy model against the field observations of Shaw [7]. Comparison between simulated (lines) and observed (symbols) vertical profiles of the longitudinal velocity.

3. Acknowledgements

The author would like to thank Dr. Ashvin Chaudhari from Center of Computational Engineering and Integrated Design (CEID) for his hospitality and help during this STMS.

4. References

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