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On the Horizontal Homogeneity of the Atmospheric Boundary Layer Profile in CFD Simulations

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Abstract: One of the main factors affecting the consistency of Computational Fluid Dynamics (CFD) simulation results is the horizontal homogeneity of the atmospheric boundary layer (ABL) profile, which is correctly reproducing the ABL profile and maintaining the profile throughout the streamwise direction of the computational domain for different flow variables. This paper is part of a research arguing that different commercial CFD codes, despite using the same simulation variables, can yield different results for achieving a horizontally homogeneous ABL profile. This paper aims to assess the performance of the commercial CFD code ANSYS Fluent, in achieving a horizontally homogeneous ABL profile.Since CFD is embedded with errors and uncertainties, best practice guidelines for using CFD is extracted from literature and used as a start point for the CFD simulations. Results show that FLUENT is able to achieve a horizontally homogenous atmospheric boundary layer profile using a set of simulations variables. To put the results in context, it is recommended that the obtained horizontally homogenous atmospheric boundary layer profile from more than one commercial code is implemented in studying wind flow around a surface mounted cube in a turbulent channel flow and comparing the obtained results with in-situ measurements and wind tunnels test results. This would demonstrate the effect of obtaining a horizontally homogenous atmospheric boundary layer profile on the consistency of the results of CFD simulations of wind flow around bluff bodies.

Keywords: CFD, fluent, horizontal homogeneity, atmospheric boundary layer (ABL) profile.

1 Introduction

Numerical simulations methods including Computational Fluid Dynamics (CFD) is one of the main assessment tools for urban physics [1]. CFD simulations have many applications such as investigating air pollutant dispersion within the built environment[2], assessing wind potential for wind turbines [3,4] and their integration within the built environment [5], assessment of cross-ventilation of buildings [6], pedestrian-level wind speed for wind comfort assessment [7], in addition to the potential of accurately predicting urban microclimate [8]. Thus, CFD simulation can be used as a tool for informed decision making in urban design applications [9].However, CFD simulations are embedded with errors and uncertainties. Thus, best practice guidelines should be consulted before running CFD simulations [10]. In addition, validation studies are required to give confidence in the obtained results. Validation studies can be carried out by comparing the obtained CFD simulation results by in-situ measurements and wind tunnels tests results. One of the main factors affecting the consistency of CFD simulations is the horizontal homogeneity of the atmospheric boundary layer (ABL) profile throughout the computational domain which means that there no streamwise gradients in the flow variables in the flow direction from the inlet boundary throughout the domain to the outlet boundary [11]. It is evident that simulating a horizontally homogenous ABL profile is difficult and requires careful consideration of the boundary conditions [3,4,12,13]. This paper aims to achieve the requirement of the horizontal homogeneity of the ABL profile so that it would be used with confidence in other CFD simulations. This work is part of a research investigating the consistency of different commercial CFD codes namely; FLUENT and CFX in achieving the horizontal homogeneity of the ABL profile, then using the obtained ABL profiles from both codes as the inlet profile for studying wind flow around a surface-mounted cube in a turbulent channel flow, then comparing the results to assess the accuracy of both codes in predicting the flow around the cube. However, this paper focuses on the

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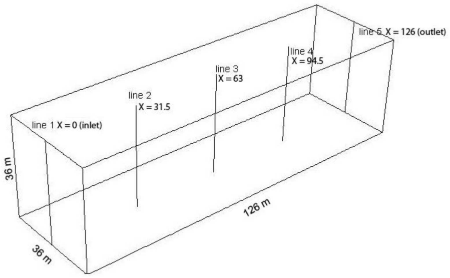


Fig. 1: Computational domain dimensions and positions of lines 1, 2, 3, 4 and 5

results from the commercial CFD code FLUENT in achieving a horizontal homogenous ABL profile.

2 Flow problem setting

Richards and Norris [14] and Yang et al. [15] asserted the importance of correctly reproducing the atmospheric boundary layer (ABL) profile in CFD simulations in addition to maintaining the profile throughout the stream wise direction of the computational domain. Richards and Hoxey [16] also stated that all simulation variables, especially the boundary conditions should be adjusted to produce a horizontally homogenous boundary layer flow in the absence of any obstructions. For achieving this, they suggested using the $k-\varepsilon$ turbulence model, and the inflow profile would be expressed in terms of velocity profile (u), turbulent kinetic energy (k) and its dissipation rate (ε) through the following equations:

$$u = \frac{u^*}{k}\ln(\frac{z+z_0}{z_0}). \tag{1}$$

$$k = \frac{u^{*^2}}{\sqrt{C_\mu}}. \tag{2}$$

$$\varepsilon = \frac{u^{*^3}}{k(z+z_0)}. \tag{3}$$

where u^* is the friction velocity, k is the von Karman constant, z_0 is the aerodynamic roughness length and C_μ is the turbulence model constant. In this work, modelling an equilibrium ABL profile in a 3D empty computational domain of dimensions $XxYxZ = 126mx36mx36m$ was carried out (see Figure 1). The mesh used is an equidistant structured mesh with spacing of 0.5m in X, Y and Z directions giving 1306368 hexahedral cells. It should be noted here that Hargreaves and Wright [11] and Yang et al. [15] asserted that the horizontal homogeneity of the ABL profile is independent of mesh resolution. The inlet boundary condition is specified using a user defined function (UDF) satisfying equations 1, 2 and 3 for the velocity (u), turbulent kinetic energy (k) and turbulent dissipation rate (ε) respectively as mentioned in Richards and Hoxey [16].

The bottom boundary condition is specified as a rough wall and standard wall functions are used, the roughness height (k_s) and roughness constant (C_s) were determined according to the relationship between k_s, C_s and z_0 derived by Blocken et al. [17] satisfying equation 4. In addition, a wall shear stress of 0.58Pa is assigned for the bottom boundary satisfying equation 5 for the shear stress (τ_w). According to Blocken et al. [17], specifying a wall shear stress at the bottom of the computational domain associated with the ABL profiles satisfying equations 1, 2 and 3 would result in a good homogeneity for both wind speed and turbulence profiles. The top and side boundary conditions are specified as symmetry while the outlet boundary condition is specified as pressure outlet.

$$k_s = \frac{9.793z_0}{C_s}. \tag{4}$$

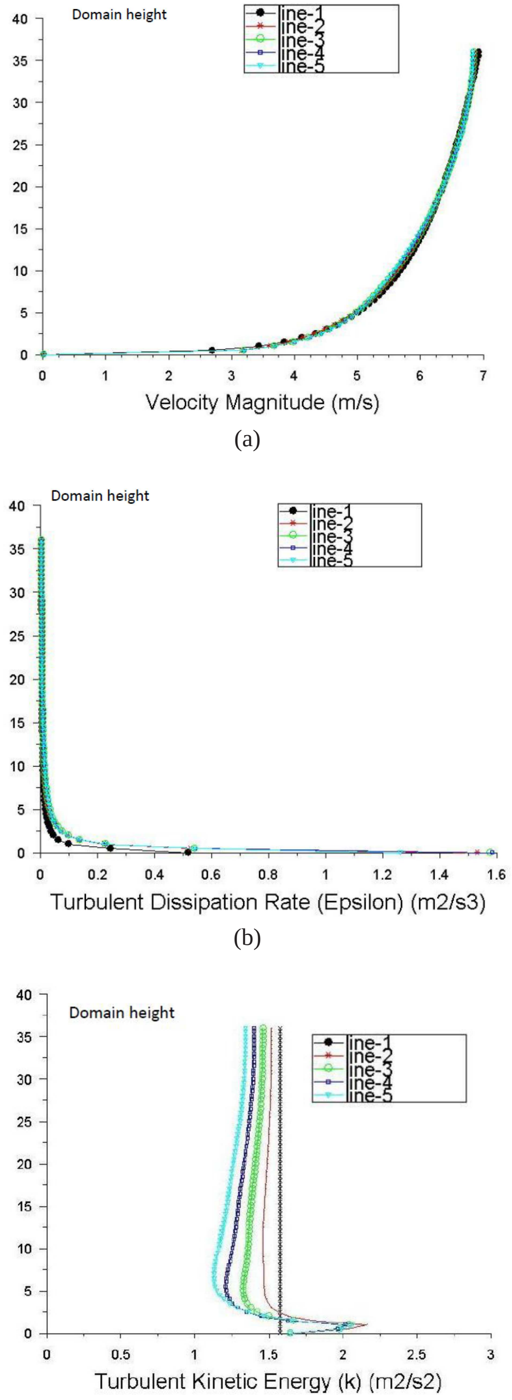
$$\tau_w = \rho u^{*^2}. \tag{5}$$

The realizable $k-\varepsilon$ turbulence model is used for the closure of the transport equations. The simple algorithm scheme is used for the pressure-velocity coupling. Pressure interpolation is second order and second-order discretisation schemes are used for both the convection and the viscous terms of the governing equations.

3 Results

The solution is initialised by the values of the inlet boundary conditions. The chosen convergence criterion is specified so that the residuals decrease to 10-6 for all the equations. The solution is initialized with the values at the inlet boundary condition and it converges after 499 iterations and velocity, turbulent dissipation rate (TDR) and turbulent kinetic energy (TKE) are plotted along five equidistant vertical lines in the streamwise direction of the domain (X= 0, 31.5, 63, 94.5 and 126m) (see Figure 1).

Horizontal homogeneity of the ABL means that the plots

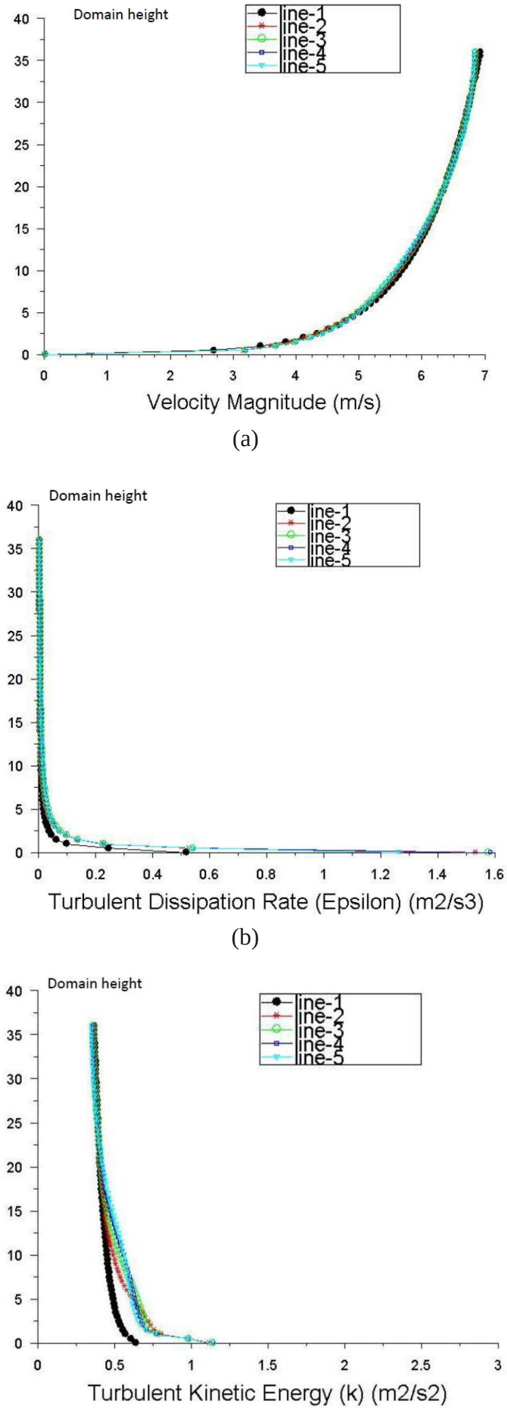


(a)

(b)

(c)

Fig. 2: Horizontal homogeneity (top and middle) for velocity magnitude and turbulent dissipation rate. Turbulent kinetic energy (bottom): no horizontal homogeneity achieved along the streamwise direction of the computational domain



(a)

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Fig. 3: Horizontal homogeneity (top and middle) for velocity magnitude and turbulent dissipation rate. Turbulent kinetic energy (bottom) no horizontal homogeneity achieved along the streamwise direction of the computational domain

of velocity, TDR and TKE should coincide along lines 1, 2, 3, 4 and 5 (Figure 1). Horizontal homogeneity was achieved for both velocity and TDR. As for TKE, Figure 2 shows streamwise gradients in the vertical TKE profile which means that horizontal homogeneity was not achieved.

According to Yang et al. [15], the measures taken by Blocken et al. [17] improved the level of horizontal homogeneity to some extent. However, Yang et al. [15] argued that better results can be achieved if the mean velocity profile is represented by the logarithmic law (Equation 1), turbulent kinetic energy (k) and turbulent dissipation rate(ε) represented by equations 6 and 7 respectively.

$$k = \frac{{u^*}^2}{C_\mu}\sqrt{C_1 \ln\left(\frac{z+z_0}{z_0}\right)+C_2}. \tag{6}$$

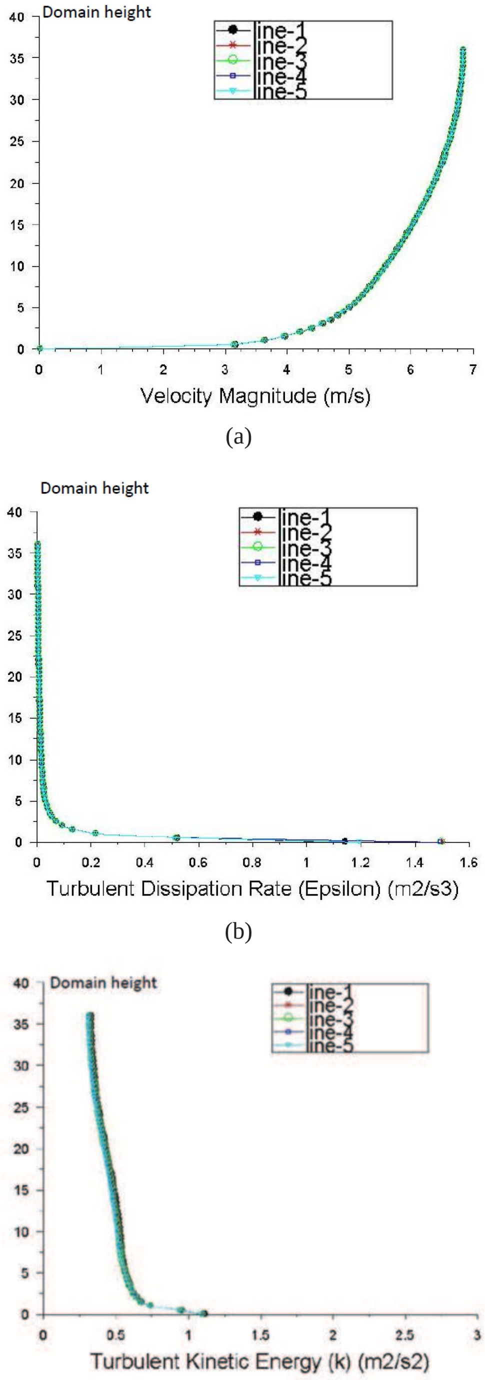
$$\varepsilon = \frac{{u^*}^3}{k(z+z_0)}\sqrt{C_1 \ln\left(\frac{z+z_0}{z_0}\right)+C_2}. \tag{7}$$

where C_1 and C_2 are constants obtained from fitted curve of the k profile from wind tunnel tests and equal to -0.17 and 1.62 respectively. All other simulation parameters are the same as those in Blocken et al. [17] except that the ground boundary condition is set as a non-slip wall with roughness height equal to 0.4m and roughness constant equal to 0.75 satisfying equation 4. The solution converges after 687 iterations. Both the velocity and TDR showed very good homogeneity in the streamwise direction of the domain, as for the TKE the results are improved largely. However, small streamwise gradients in the vertical TKE profile are noticed near the ground (Figure 3).

According to Blocken et al. [17] and Hargreaves and Wright [11], these near ground streamwise gradients can be eliminated if the outlet profile of a similar simulation in a longer domain (10000m and 5000m respectively) is used as the inlet profile of the same domain. However, for limited computational power available, simulation is run for the same domain but with double the length in the streamwise direction leading to a domain of dimensions 252m x 36m x 36m. When comparing the results with the results from the previous two simulations, it is noticed that horizontal homogeneity for velocity, TDR and TKE profiles are achieved throughout the computational domain (Figure 4).

4 Discussion and Conclusion

The horizontal homogeneity of the atmospheric boundary layer profile plays an important role in the consistency of the results of CFD simulations. Different CFD codes might yield different results for a horizontally homogenous atmospheric boundary layer profile. Thus, this paper has presented the results of achieving a horizontally homogeneous atmospheric boundary layer



(a)

(b)

(c)

Fig. 4: Horizontal homogeneity (top to bottom) for velocity magnitude, turbulent dissipation rate and turbulent kinetic energy along the streamwise direction of the computational domain

profile using the commercial CFD code FLUENT. After using different equations describing the velocity magnitude, turbulent dissipation rate and turbulent kinetic energy as the inlet profile, horizontally homogenous atmospheric boundary layer is achieved using the commercial CFD code FLUENT. The main factor affecting achieving a horizontally homogenous atmospheric boundary layer profile is to let the flow travel a long distance in the domain and use the outlet profile as the inlet profile. For assessing the effect of the obtained atmospheric boundary layer profiles from different commercial CFD codes, it is recommended to use the obtained atmospheric boundary layer profiles from two different CFD codes as the inlet profile for studying wind flow around a surface-mounted cube in a turbulent channel flow and compare the obtained results with in-situ measurements and wind tunnel tests which is an ongoing research by the author and will be published in further publications.

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