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Large-eddy Simulation of Turbulent Flow in an Idealized Street Canyon

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ABSTRACT

The use of CFD as a research tool has been adopted successfully in many ways to predict the turbulent flow nature and pollutant dispersion properties in urban environment. Apart from the advance advantages offer by this method, some problems can be arising on respect to accurate prediction of data and uncertainties of assumption that are made in numerical modeling. Therefore, validation and generic sensitivity analyses are important to provide guidance for the execution and evaluation of the CFD studies. This study performs a series of Large-eddy simulations (LESs) to investigate the flow field within and above a two-dimensional idealized street canyon. Simulations were conducted for various domain sizes with a unity aspect ratio i.e. street width to building height ratio. Three computational domains were 2H x H x 6H (streamwise (x), spanwise (y) and vertical (z) directions), 6H x H x 6H and 10H x H x 6H define as Case 1, Case 2 and Case 3 respectively. The results were validated against experimental data obtained in wind tunnel studies. The mean velocities for each run cases estimated by LES are in good agreement with those obtained by wind-tunnel experiments. However, profiles of the Reynold shear stress as well as standard deviation for the streamwise and vertical velocity components show large discrepancies at all measured locations for each cases at building height. Apparently, it was indicating that increasing the domain size does not fully rectify the under predicted turbulent statics in the street canyons. This is most likely due to coherent structures that have developed above a canyon cannot properly simulated in a small domain size as designated without any consideration of other compromise parameters such as grid resolution.

Keywords:
Street canyon; Large-eddy Simulation (LES); wind-tunnel; turbulence

1. Introduction

Due to emergence of the rapid urbanization and industrialization throughout the world, deterioration of outdoor air quality in cities become one of the most serious environmental

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problems. It was found that the largest sources of urban air pollution in town and cities primarily comes from vehicular emissions such as the road traffic that continues to grow annually and thus further complicates urban air pollution as describe by Yazid *et al.,* [1]. The term "street canyon" have been defined as a restricted space with surrounding buildings along both sides of the urban street and become one of the typical element of urban area. It constitutes the basic geometric unit of the labyrinth confining the urban canopy layer of the city center. The most important features of street canyon are the wind-induced flow patterns, such as air recirculation which dominated by micro-scale meteorological processes [2]. It was found that the most pronounced effects of the human activities under this circumstance are natural ventilation and dispersion of air pollutants issues which is could lead to various adverse health problem towards urban resident if being expose in long-term exposure.

Urban air quality within the street canyon are inherently complex due to a wide range of physical phenomena interactions and how strongly it dependent on many aspects of meteorology, wind engineering and environmental science aspects [3-5]. The poor understanding of the unsteady and intermittent wind field inside the canyon has been consider as one of the major obstacles that causes the build engineer not sufficiently able to minimize and avoid the creation of inhospitable environment within the urban area.

Thus, due to impact of continuing urbanization, the study of flow structures and pollutant dispersion has become popular and still consider as active research until nowadays. There are many various methods have been taken to cater with this situation, these include field measurements, wind tunnel experiment, operational modeling techniques and Computer Fluid Dynamics (CFD). Each of the methods has their own impact towards research study, but due to rapid development of advanced computer technology, CFD has become one of main tool that being use to explore the flow and pollutant dispersion problem issue. According to Zhong *et al.,* [6], CFD are able to provide a complete view of distribution of flow and pollutant fields at high-resolution in both time and space, which other methods could not tackle this matter. The most comprehensive applications of CFD have been base on Reynolds averaged Navier-Stokes (RANS) equations and large-eddy simulation (LES). RANS has been used to predict the flow and pollutant dispersion within street canyons at the earlier of studies. Several previous RANs of street canyon flow have been reported; [7-15].

While RANS models have provided many insights into the characteristics of flow and dispersion in urban street canyons, large-eddy simulation (LES) has recently gained popularity in street-canyon studies [16]. Michioka *et al.,* [17] stated that previous studies have implemented LES method for the transport of a pollutant that emitted from a line source along the centerline of ideal street canyons with different building-height to street-width that term as aspect ratios (AR). Study by Yazid *et al.,* [18] indicate that the LES performs better than RANS to reproduce the wind flow structure at different thermal intensities as well at different locations of heated wall. Meanwhile, in some cases, study by Li *et al.,* [19] have used LES to investigate the effect of surface heating on the airflow and pollutant dispersion in urban street canyons instead of isothermal condition. In addition, Mohamad *et al.,* [20] in his study investigate the effect of the overhang length on the flow field regime in idealized street canyon using LES model analysis.

Many studies have shown that the CFD method approach is capable of reproducing the qualitative features of airflow and pollutant distributions in urban street canyon cases particularly [21]. However, apart from the advance advantages of CFD offer as compared to others methods, the accuracy and reliability of it has been considering vitally important since an accurate prediction of these properties can be challenging due to complex nature of turbulence modelling. According to Meroney [22], the continued of verification and validation should be taking into account at almost every level of CFD modelling. Franke *et al.,* [23] have classified two types of errors and being recognized as critical aspects; physical modelling base on turbulence models and the applied boundary conditions, while the other govern by numerical simulation such as computational domain size, grid design and numerical iteration algorithm.

The verification and validation of numerical modelling is design to reduce programming error while sensitivity analysis found can be used to provide additional information relevant to uncertainty estimation. Yazid *et al.,* [24] mentioned in his study that the aim to conduct the sensitivity analysis is to check on how different parameters affect the wind flow and pollutant dispersion in an idealized street canyon. Therefore, in the case of the present study, the nature of turbulent flow through the idealized urban street environment are investigate first in order to deepen the understanding of the relation between the accuracy of air flow regime data with respect to various computational domain sizes. Large-eddy simulation (LES) was adopted for the study for simulated the unsteady flow fluctuation in the canyon.

2. Methodology

2.1 Governing Equations

The continuity and momentum equations for steady incompressible are given as follows

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial \bar{U}_j \bar{U}_i}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{U}_i}{\partial x_j}\right) - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where the overbar denotes the filtered value, U_i is the velocity vector and *P* is the pressure, μ is the fluid kinematic viscosity. τ_{ij} represents the subgrid-scale (SGS) Reynolds stress. These terms were modeled using standard Smagorinsky model. All the simulations were carried out using the open-source CFD code OpenFOAM v2.3.1.

2.2 Simulation Domain

The computational domain adopted in the simulation is shown in Figure 1. It is consisting of one idealize 2D street canyon with a unity aspect ratio (building height and the street width, H/W). The height of the building is H=0.12. The height of the domain was set to 6H as proposed by Frankee *et al.,* [25] and the spanwise domain length was kept at H.

Table 1 lists the computational conditions and Figure 2 shows a schematic diagram of the computational domain where L_x, L_y and L_z denote the streamwise, spanwise and vertical domain length, respectively. Three runs are implemented to check the influence of domain size on the turbulence statistics. The computational domains are 2H x H x 6H (Case 1), 6H x H x 6H (Case 2) and 10H x H x 6H (Case 3) in streamwise (x), spanwise (y) and vertical (z) directions. The domain consists of several arrangement of rectangular arrays (surface roughness) set on the lower surface at equal intervals of H, and the number street canyon is one for Case 1, three for the Case 2 and five for the Case 3. The numbers of LES grid points defined as $N_x \times N_y \times N_z$ used here are listed in Table 1.

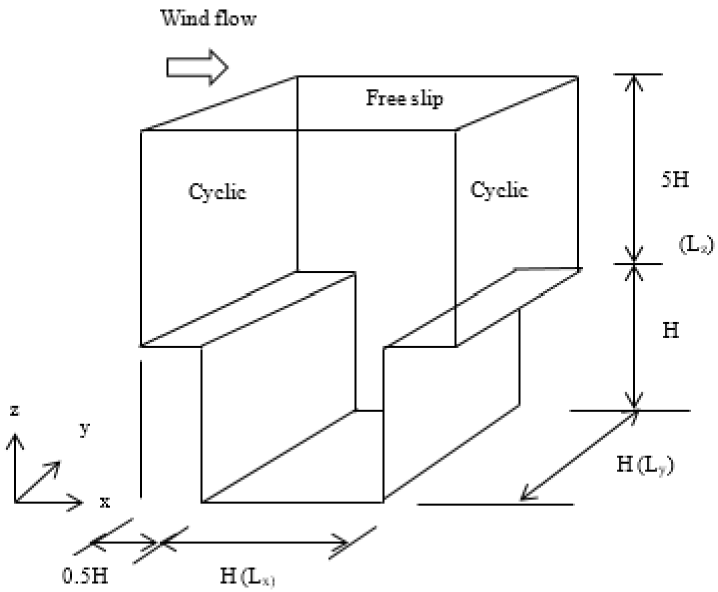

Fig. 1. Schematic of the computational domain adopted in this study

The domain was discretized into a uniformly structured mesh with a grid size of H/16. The origin of the coordinate axis is located at the central lower surface of the street canyon. A constant flow was driven by a pressure gradient across the free surface layer (above the canyon) is imposed in the x-direction to maintained the atmospheric flow bulk velocity of 2 m/s. Periodic boundary or cyclic boundary conditions were employed in the streamwise and spanwise directions to simulate infinitely repeated street canyons at regular interval. In addition, this pressure force is perpendicular to the street axis where it representing the worst-case scenario for dispersion of pollutant within a street canyon. Non-slip boundary conditions were applied on the lower walls and building surfaces, and free slip boundary conditions were imposed on the velocity components at the top boundary, where the velocity normal to the boundary equals zero and the gradient of velocity parallel to wall should be zero.

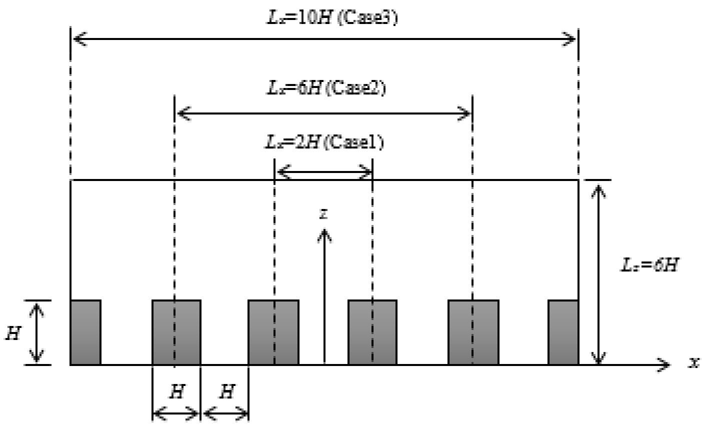

Fig. 2. Configuration of simulated urban street canyon for Case 1, Case 2 and Case 3

Table 1
Computational domain and total grids

	Case1	Case2	Case3
L_x/H	2	6	10
L_y/H	1	1	1
L_z/H	6	6	6
N_x	32	96	160
N_y	16	16	16
N_z	96	96	96

3. Results
3.1 Model Validation

Figures 3, 4, and 5 show the vertical distributions of mean streamwise velocity, the Reynold shear stress and standard deviations of streamwise velocity fluctuations at *x* = 0H, which is located at the center of the upstream building in the canyon. The mean values are indicate using < >, height z is normalized by the block height, H and the velocity statistics are normalized by the reference velocity, U_{ref} at a height 2H. The data obtained from the previous wind tunnel experiment by Michioka *et al.,* [17] are also included for a comparison purpose. The mean velocity profiles derived from the present LES show generally good agreement with the wind tunnel results as shown in Figure 3. The two plots are qualitatively almost identical for z/H < 1.0 but seems underestimated for the current LES slope at z/H > 1.0 which is above the roof.

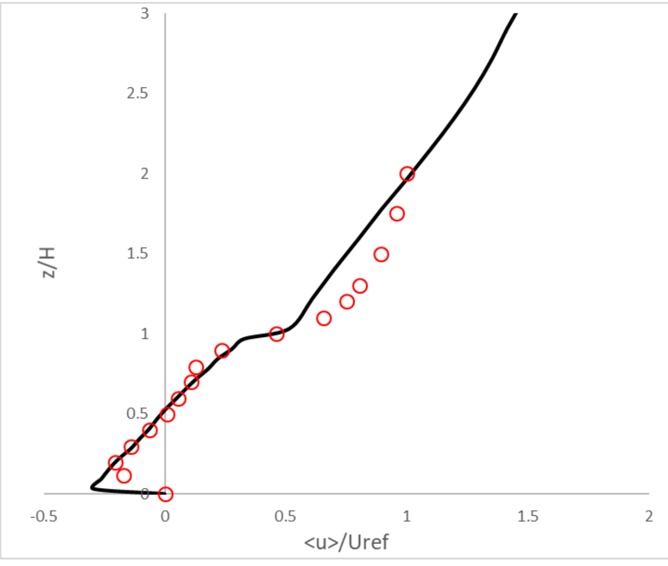

Fig. 3. Vertical distribution of u for the LES case with different domain sizes at x=0H. The solid line refers to the present simulation result, where black color line ; Case 1 and the open circles refer to the data of the wind tunnel experiment by Michioka *et al.,* [17]

The current LES is steep as comparing with the wind tunnel data resulted from the vertical momentum transport by turbulent motions (Reynold shear stress) is underestimated, as shown in Figure 4. Considering the finding pointed out by Kanda *et al.,* [26] that mentioned about the coherent structures that have developed above a canyon cannot be properly simulated in a small domain, it is acceptable the current LES properly reproduces the mean flow field within and above the street canyon.

On the other hand, the streamwise standard deviations σu at the x = 0 derived from the LES are much smaller than those of the wind tunnel experiment, as seen in Figure 5. This behavior is equivalent to a typical two-dimensional street canyon from previous study that represent the small computational domain, which includes only one street canyon. The underestimation of the standard deviation value in the current LES likely due to the fact that the development of the instantaneous turbulent structure is restricted by the streamwise domain size, as pointed by Kanda *et al.,* [26]. Nevertheless, apart from discrepancy, the shapes of the LES profiles are qualitatively similar to those obtained by the wind tunnel.

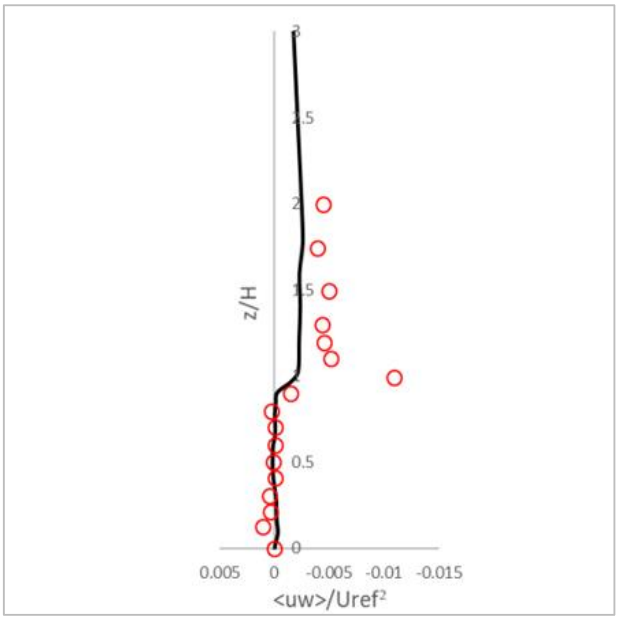

Fig. 4. Vertical distribution of the Reynolds shear stress at x=0H. Symbols as in Figure 3

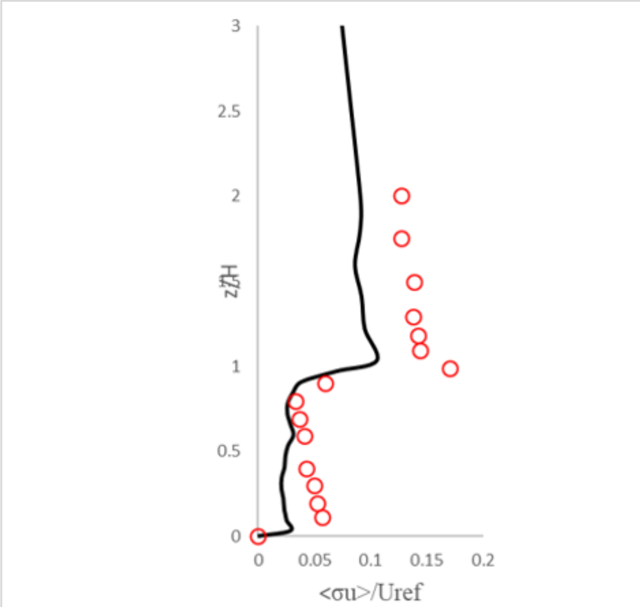

Fig. 5. Vertical distribution of the r.m.s values of the streamwise velocity fluctuations at x=0H. Symbols as in Figure 3

3.2 Spatially Averaged Profiles of Turbulent Statistics

Figures 6, 7, 8 and 9 show the vertical distributions of the spatially averaged mean streamwise velocity, standard deviations of streamwise and vertical velocities fluctuations and the Reynold shear stress. The LES results shown here (Figure 6) are derived from the whole domain size based on the averaging procedure in the spanwise direction. It is obvious that the profiles pattern for the all cases of domain size have almost matching profiles below and above the street canyon regardless the size of the domain.

The LES predicts the reversed flow in the lower part signifies the rotating primary vortex that present in the canyon. Meanwhile, the streamwise flow in the upper part of the canyon show a clear kink across the rooftop, indicating a shear layer at that level. The profiles of velocity gradient become smoother across the rooftop for all the cases of simulation domain due to the friction effect. This feature was also noted in the wind tunnel results of Michioka *et al.,* [17] where in general indicate the fully developed wind profiles obtained in the current LES result. However, apparently, based on the result, increasing the domain size does not fully rectify the under predicted mean vertical velocity in the street canyons.

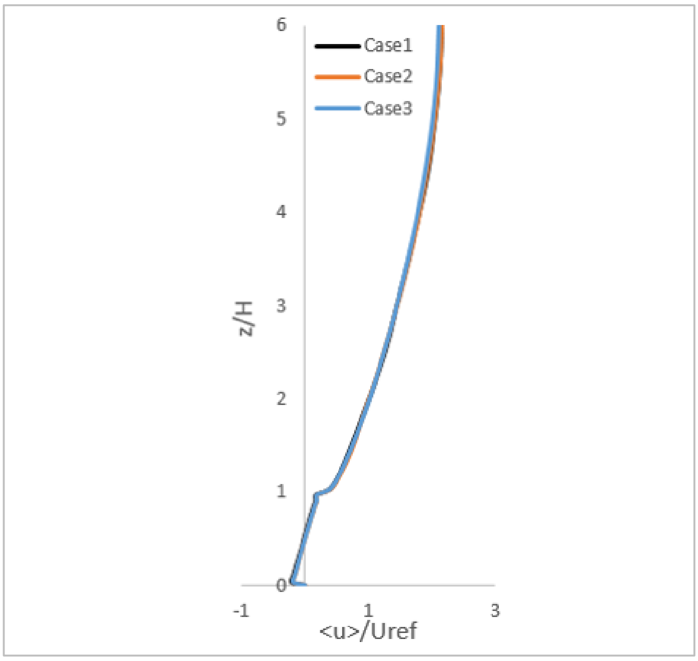

Fig. 6. Vertical distribution of spatially average streamwise mean velocities. The solid line refers to the present simulation result, where black color line : Case 1, orange color line : case 2 and blue color line : Case 3

With regard to the standard deviation of streamwise velocity, the results from the all three cases generally agree well with each other, with the peak can be observed at the roof height and the values decrease as the height increases (see Figure 7). The profiles of vertical velocity also have almost matching profile for all cases, except for the Case1 where only slightly decreasing of value have noticed at approximately 1.8H as comparing to Case 2 and Case 3 (see Figure 8). In general, both σu and σw have almost similar profile pattern and there is no significant changing in magnitude value are observed with respect to different size of domain use in current LES.

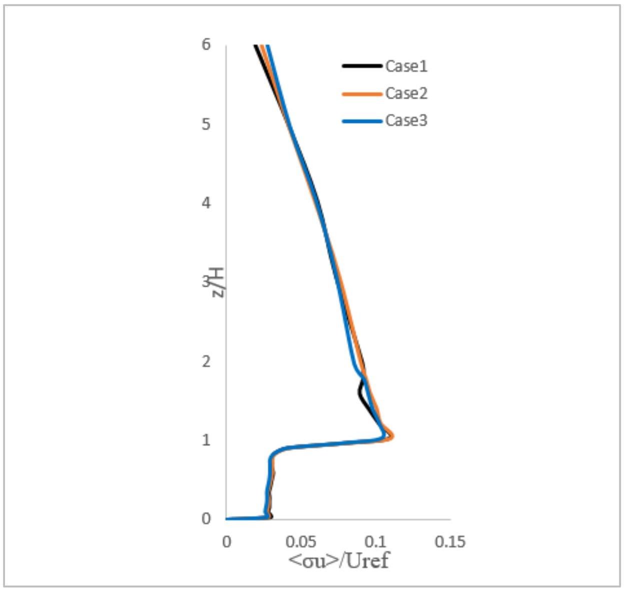

Fig. 7. Vertical distribution of spatially average standard deviation of streamwise velocity. Symbol as in Figure 6

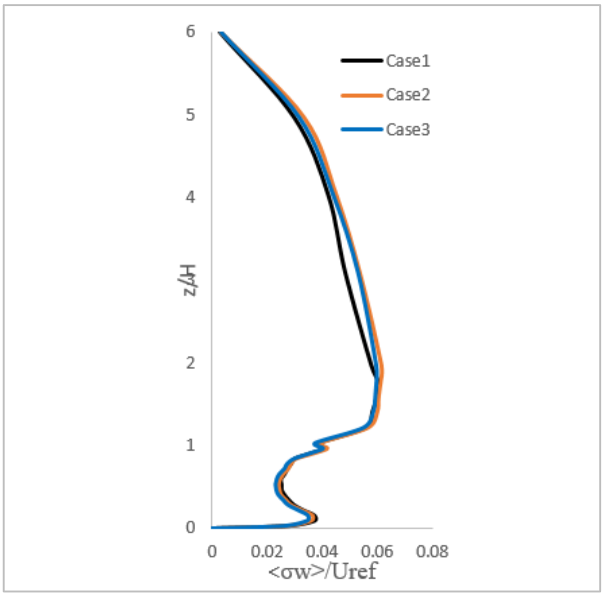

Fig. 8. Vertical distribution of spatially average standard deviation of vertical velocity. Symbol as in Figure 6

Under the present configuration, the typical well-known dogleg shape indicate a peak appears at the roof height, are not observed in the current LES for all the cases of simulation for Reynold stress profile (Figure 9).

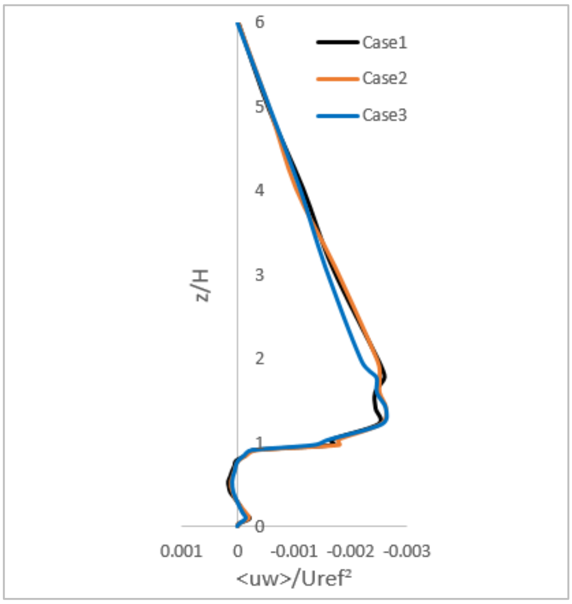

Fig. 9. Vertical distribution of spatially average Reynold shear stress. Symbol as in Figure 6

All the statistic for Case 1-3 have no significantly changing in respect to increasing and decreasing horizontal domain. This can be explained due to the current LES adopts a limited domain size due computational cost reasons. LES can simulate turbulent statistic accurately if the domain size is more than ten times of the canyon height as suggested by Kanda *et al.,* [26]. This is well explained the under predict of statistic data for the Case 1 and 2 since the streamwise domain size is clearly less than ten times the canyon height.

However, the discrepancy of the statistic does not significantly rectify while increasing the horizontal domain size up to 10H in Case 3. This is consistent with the finding suggested by Cui *et al.,* [27] that indicate the difference is attribute to the shallow vertical extent of the computational domain and the coarse roof-level mesh resolution. Xie and Castro [28] also suggested that a fine mesh is needed to simulate accurately the details of the shear above the canopy. Note that resolution of the current LES is 16/H (recall H is building height) for each cases and the underestimate of the turbulent statistic profile are simply might due to the lack of resolution use in this study.

4. Conclusions

Large-eddy simulation was conducted to investigate the flow field within and above a two-dimensional idealized street canyon. Simulations were conducted for three different size of domain with a unity aspect ratio i.e. street width to building height ratio. Comparing with wind tunnel result from previous study, the validation exercise demonstrated that the current LES model gives reliable mean velocity. In contrast, the profile of standard deviation of streamwise and the Reynold shear stress indicate some discrepancies resulted from the small domain use for the simulation case. It is because the coherent structures that have developed above a canyon cannot be properly simulated in a small domain.

The vertical profiles of mean wind, standard deviation of streamwise and vertical velocity and Reynold shear stress had similar profiles for all Case 1-3. Apparently, it was indicating that increasing the domain size does not fully rectify the under predicted turbulent statics in the street canyons. The study shows that the LES implemented in small computational domain size (which is less than ten times the canyon height) have a good agreement in velocity statistic, but contains some discrepancies in regards to Reynold shear stress and standard deviation. In addition, the cause which is also believed to be result of the insufficient of resolution use for LES that as well adopts a limited domain size. Therefore, a more detailed analysis is required to examine the correlation among domain size and mesh resolution.

References

[1] M. N. A. Mohd Yazid. "Large Eddy Simulations of Pollutant Dispersion in a Street Canyon." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 8, no. 1 (2015): 11-19.

[2] Afiq, W. M. Y., CS Nor Azwadi, and K. M. Saqr. "Effects of buildings aspect ratio, wind speed and wind direction on flow structure and pollutant dispersion in symmetric street canyons: a review." *Int J Mech Mater Eng* 7, no. 2 (2012): 158-165.

[3] Liu, Chun-Ho, and Colman CC Wong. "On the pollutant removal, dispersion, and entrainment over two-dimensional idealized street canyons." *Atmospheric research* 135 (2014): 128-142.

[4] Yazid, Afiq Witri Muhammad, Nor Azwadi Che Sidik, Salim Mohamed Salim, and Khalid M. Saqr. "A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies." *Simulation* 90, no. 8 (2014): 892-916.

[5] Lateb, M., Robert N. Meroney, M. Yataghene, H. Fellouah, F. Saleh, and M. C. Boufadel. "On the use of numerical modelling for near-field pollutant dispersion in urban environments− A review." *Environmental Pollution* 208 (2016): 271-283.

[6] Zhong, Jian, Xiao-Ming Cai, and William James Bloss. "Modelling the dispersion and transport of reactive pollutants in a deep urban street canyon: Using large-eddy simulation." *Environmental pollution* 200 (2015): 42-52.

[7] Baik, Jong-Jin, and Jae-Jin Kim. "A numerical study of flow and pollutant dispersion characteristics in urban street canyons." *Journal of applied meteorology* 38, no. 11 (1999): 1576-1589.

[8] Assimakopoulos, Vasiliki D., H. M. ApSimon, and N. Moussiopoulos. "A numerical study of atmospheric pollutant dispersion in different two-dimensional street canyon configurations." *Atmospheric Environment* 37, no. 29 (2003): 4037-4049.

[9] Lien, F. S., E. Yee, and Y. Cheng. "Simulation of mean flow and turbulence over a 2D building array using high-resolution CFD and a distributed drag force approach." *Journal of Wind Engineering and Industrial Aerodynamics* 92, no. 2 (2004): 117-158.

[10] Santiago, Jose Luis, Alberto Martilli, and Fernando Martín. "CFD simulation of airflow over a regular array of cubes. Part I: Three-dimensional simulation of the flow and validation with wind-tunnel measurements." *Boundary-layer meteorology* 122, no. 3 (2007): 609-634.

[11] Memon, Rizwan Ahmed, Dennis YC Leung, and Chun-Ho Liu. "Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons." *Building and Environment* 45, no. 1 (2010): 176-188.

[12] Hang, Jian, Yuguo Li, Mats Sandberg, Riccardo Buccolieri, and Silvana Di Sabatino. "The influence of building height variability on pollutant dispersion and pedestrian ventilation in idealized high-rise urban areas." *Building and Environment* 56 (2012): 346-360.

[13] Lin, Man, Jian Hang, Yuguo Li, Zhiwen Luo, and Mats Sandberg. "Quantitative ventilation assessments of idealized urban canopy layers with various urban layouts and the same building packing density." *Building and Environment* 79 (2014): 152-167.

[14] Ramponi, Rubina, Bert Blocken, B. Laura, and Wendy D. Janssen. "CFD simulation of outdoor ventilation of generic urban configurations with different urban densities and equal and unequal street widths." *Building and Environment* 92 (2015): 152-166.

[15] Mei, Shuo-Jun, Zhiwen Luo, Fu-Yun Zhao, and Han-Qing Wang. "Street canyon ventilation and airborne pollutant dispersion: 2-D versus 3-D CFD simulations." *Sustainable Cities and Society* 50 (2019): 101700.

[16] Lin, Man, Jian Hang, Yuguo Li, Zhiwen Luo, and Mats Sandberg. "Quantitative ventilation assessments of idealized urban canopy layers with various urban layouts and the same building packing density." *Building and Environment* 79 (2014): 152-167.

[17] Michioka, Takenobu, Ayumu Sato, Hiroshi Takimoto, and Manabu Kanda. "Large-eddy simulation for the mechanism of pollutant removal from a two-dimensional street canyon." *Boundary-layer meteorology* 138, no. 2 (2011): 195-213.
[18] A. W. M. Yazid, S. M. Salim, and S. Mansor. "Numerical Simulation of Thermal Atmospheric Conditions in an Idealized Street Canyon: Comparison Between RANS and LES." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 1, no. 1 (2014): 19-27.
[19] Li, Xian-Xiang, Rex E. Britter, Tieh Yong Koh, Leslie K. Norford, Chun-Ho Liu, Dara Entekhabi, and Dennis YC Leung. "Large-eddy simulation of flow and pollutant transport in urban street canyons with ground heating." *Boundary-layer meteorology* 137, no. 2 (2010): 187-204.
[20] Mohamad, Mohd Faizal, Aya Hagishima, Naoki Ikegaya, Jun Tanimoto, and Abd Rahman Omar. "Aerodynamic effect of overhang on a turbulent flow field within a two-dimensional street canyon." *Engineering Sciences Reports, Kyushu University* 37, no. 1 (2015): 1-7.
[21] Huang, Yuandong, Xiaonan Hu, and Ningbin Zeng. "Impact of wedge-shaped roofs on airflow and pollutant dispersion inside urban street canyons." *Building and Environment* 44, no. 12 (2009): 2335-2347.
[22] Meroney, R. N. "Wind tunnel and numerical simulation of pollution dispersion: a hybrid approach." *Paper for Invited Lecture at the Croucher Advanced Study Institute, Hong Kong University of Science and Technology* (2004): 6-10.
[23] Franke, Jorg, Antti Hellsten, K. Heinke Schlunzen, and Bertrand Carissimo. "The COST 732 Best Practice Guideline for CFD simulation of flows in the urban environment: a summary." *International Journal of Environment and Pollution* 44, no. 1-4 (2011): 419-427.
[24] Yazid, A. W., Azwadi Muhammad, S. Mohamed Salim, and S. Mansor. "Preliminary Study on the Wind Flow and Pollutant Dispersion in an Idealized Street Canyon." *Journal of Advanced Research Design* 1, no. 1 (2014): 1-17.
[25] Franke, Jorg, Antti Hellsten, Heinke Schlunzen, and Bertrand Carissimo. "The COST Action 732: Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment." *University of Hamburg, Hamburg, Germany* (2007).
[26] Kanda, Manabu, Ryo Moriwaki, and Fumi Kasamatsu. "Large-eddy simulation of turbulent organized structures within and above explicitly resolved cube arrays." *Boundary-Layer Meteorology* 112, no. 2 (2004): 343-368.
[27] Cui, Zhiqiang, Xiaoming Cai, and Chris J. Baker. "Large-eddy simulation of turbulent flow in a street canyon." *Quarterly Journal of the Royal Meteorological Society* 130, no. 599 (2004): 1373-1394.
[28] Xie, Zhengtong, and Ian P. Castro. "LES and RANS for turbulent flow over arrays of wall-mounted obstacles." *Flow, Turbulence and Combustion* 76, no. 3 (2006): 291.