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LES SENSITIVITY TO DOMAIN SIZE AND GRID RESOLUTION IN IDEALIZED URBAN STREET CANYON

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Abstract: A series of large-eddy simulations (LES) was performed to investigate the effects of computational domain size and grid resolution on flow prediction within an idealized urban street canyon. Three streamwise domain lengths were examined in combination with coarse, medium, and fine grid resolutions. The building height, H, was kept constant, and the canyon aspect ratio (street width to building height) was set to unity. Flow statistics were evaluated at the central canyon of each configuration and compared with available wind-tunnel data.The LES results indicate that the simulated mean velocity profiles agree well with experimental measurements for all cases. Both domain size and grid resolution exhibited minimal influence on the mean velocity components, suggesting that mean flow within a street canyon can be reliably predicted using a relatively small computational domain when combined with medium or fine grid resolutions. This offers a computationally efficient option for mean flow analysis. In contrast, turbulence statistics were found to be more sensitive to grid resolution than to domain size. Fine grid resolution significantly improved the prediction of velocity fluctuations and momentum transport, whereas smaller domains tended to produce less consistent turbulence results. Consequently, while small or medium domains may be suitable for mean flow assessment, they are not recommended for detailed turbulence analysis.Overall, this study highlights the importance of balancing domain size and grid resolution to obtain reliable LES results while minimizing computational cost, providing practical guidance for CFD–LES studies of urban street canyon flows.

Keywords: Computational Fluid Dynamic (CFD), Street Canyon, Turbulence flow, Large-eddy simulation (LES), Wind-tunnel, Computational parameters

ЧУВСТВИТЕЛЬНОСТЬ МЕТОДА КРУПНЫХ ВИХРЕЙ К РАЗМЕРУ РАСЧЁТНОЙ ОБЛАСТИ И РАЗРЕШЕНИЮ СЕТКИ В ИДЕАЛИЗИРОВАННОМ ГОРОДСКОМ УЛИЧНОМ КАНЬОНЕ

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Аннотация: Была выполнена серия расчетов с использованием метода моделирования крупных вихрей (LES) для исследования влияния размера расчетной области и разрешения сетки на прогнозирование течения в идеализированном городском уличном каньоне. Были рассмотрены три продольных размера области в сочетании с грубым, средним и мелким размером сетки. Высота зданий H сохранялась постоянной, а коэффициент формы каньона (отношение ширины улицы к высоте зданий) был принят равным единице. Статистические характеристики потока оценивались в центральном каньоне каждой конфигурации и сравнивались с доступными данными продувки в аэродинамической трубе. Результаты моделирования с помощью LES показывают, что рассчитанные профили средней скорости хорошо согласуются с экспериментальными измерениями для всех случаев. Как размер области, так и разрешение сетки оказали минимальное влияние на компоненты средней скорости, что позволяет предположить, что среднее течение внутри уличного каньона может быть надежно предсказано с использованием относительно небольшой расчетной области в сочетании со средним или мелким разрешением сетки. Это дает вычислительно эффективный вариант для анализа среднего течения. С другой стороны, было обнаружено, что турбулентные характеристики более чувствительны к разрешению сетки, чем к размеру области. Мелкое разрешение сетки значительно улучшает прогнозирование пульсаций скорости и переноса импульса, тогда как меньшие области, как правило, дают менее согласованные результаты по турбулентности. Следовательно, хотя малые или средние области могут быть пригодны для оценки среднего течения, они не рекомендуются для детального анализа турбулентности. В целом, данное исследование подчеркивает важность балансировки размера области и разрешения сетки для получения надежных результатов при использовании LES с учетом минимизации вычислительных затрат, предоставляя практические рекомендации для исследований CFD-LES течений в городских уличных каньонах.

Ключевые слова: вычислительная гидродинамика (CFD), уличный каньон, турбулентное течение, моделирование крупных вихрей (LES), аэродинамическая труба, расчетные параметры

INTRODUCTION

Urban areas are major contributors to air pollution due to dense human activities [1]. At the same time, the urban mobility landscape is undergoing rapid transformation as cities confront increasingly complex challenges related to transportation, sustainability, and urban development [2]. A substantial portion of this pollution originates from vehicular emissions trapped within street canyons, one of the most characteristic micro-environments of contemporary cities [3]. A street canyon is formed by rows of adjacent buildings flanking both sides of a roadway, creating a confined geometric unit within the urban canopy layer [4]. The airflow within these canyons is strongly influenced by wind-driven circulation patterns, which are governed by microscale meteorological processes. Understanding these flow behaviours is essential, as they directly affect pollutant dispersion, thermal comfort, and overall urban environmental quality as well as better energy-efficient construction implementation. [5-7].

The poor understanding of the unsteady and intermittent wind field inside the canyon has been considered as one of the major obstacles that cause the build engineer not sufficiently able to minimize and avoid the creation of an inhospitable environment within the urban area. Thus, the extensive investigation and particular guideline for the analysis of atmospheric processes in the street canyons should be continued as an active and growth research within this century [8].

The majority of the previous studies focus on a street with perpendicular background wind conditions, as this is the worst case situation for ventilation and pollutant removal [9-13]. On regards to street canyon geometries, Oke [9] reported the occurrence of three distinct flow regimes inside a street canyon at various aspect ratio threshold, namely isolated roughness flow, wake interference flow and skimming flow. The skimming flow was shown to be the most adverse effect for the ventilation and pollution removal while comparing with the three flow regimes profile. The normal velocity in the street canyon is often a significant degree lower than the free-stream velocity in the atmosphere in this flow regime. Thus, a wind vortex forms inside a street canyon when the mean wind direction is perpendicular to the street [10].

Furthermore, the pollutant concentrations are higher on the leeward side rather than the windward side due to flushes effect by the vortex flow pattern. Meanwhile, according to Meroney et al., [11], a constant rotating vortex has been generated within the urban canyon under perpendicular wind direction, limiting the ventilation process and trapping pollution inside the canyon. Vardoulakis et al. [12] further claimed that when the wind speed is greater than 1.5 to 2 m/s and the flow is perpendicular to the canyon, the free-stream velocity over the canyon in typical canyons results in the skimming flow, which is identifiable by the formation of a single vortex within the canyon. According to research conducted by Li et al. [13], the perpendicular inflow wind direction to the street had the worst effects on pollution transport in street canyons due to the formation of a recirculating vortex within an even street canyon and a significant shear layer at the roof level.

The fluid stream pattern inside the street canyons has govern the mechanism of passive and inert pollutant. Previous literature have looked on the characteristics of stream flow and mechanism pollutant dispersion in urban street canyons using field measurements, laboratory experiments, and CFD [13-18]. On-site measurement is a useful research method for demonstrating the real-world microclimate of a street canyon, such as the reduced wind speed and enhanced pollution levels. However, a number of factors influence this approach, including the continuously changing meteorological conditions [15]. Wind tunnels, on the other hand, have been widely employed in both industry and research for many years. Wind tunnels have been used to verify aerodynamic theories and facilitate the design of aircraft, as well as to build new aircraft, wind turbines, and other designs that included dynamic interaction with an airflow [16].

The field measurement and wind tunnel measurement have a distinct drawback since most of the data sampled only a one-point measurement [17]. In addition, due to the time and cost issues associated with in-field measurement and wind tunnel testing, CFD has become the primary tool used to explore and predict flow fields. CFD can provide a comprehensive data of the flow structure and pollutant distributions in temporal and spatial scale, whereas other methods are still lack of this criteria [18-19]. The three type of CFD methods that have been adopted and successfully used in urban street canyon environment are include Direct Numerical Model (DNS), Large Eddy Simulation (LES), and Reynolds-Averaged Navier-Stokes (NS) equations (RANS) modelling.

By resolving the full field of spatial and temporal scales of turbulence, the DNS technique directly simulates, computes, and solves the Navier-Stokes equation. This signifies that no turbulence model was used. As a result, DNS providing a high-fidelity resolution for fluid flow simulation and has frequently regarded as a numerical experiment. However, in term of computing resources, the DNS method acquires highly cost as compare to RANS and LES and thus not really used for industrial flow computations [20]. As a consequence, the most comprehensive applications of CFD is seen to be the RANS equations and the LES.

The RANS method, in general, is based on mean flow properties where the time-averaging of the Navier-Stokes equations has been applied. Due to its minimal computational resource requirements and reasonably computed accurate flow field, this method has been widely employed in engineering flow computations throughout the previous few decades [21]. Several previous studies used RANS for various flow conditions in street canyon have been reported; Mishra et al. [22] looked on the influence of street canyon configurations on the pollutant dispersion and ventilation performance with various aspect ratios and different street length. Lien [23] has been studied of the disrupted flow for buildings immersed in a neutrally stratified deep rough walled turbulent boundary-layer flow, Cheng et al. [24] focused on how street canyon geometry could affect the ventilation and pollutant removal process, Ai et al. [25] investigates the buildings located in long street canyon under a wind-caused single-sided natural ventilation and Cui et al. [26] looked on the impact of three type of envelope features on wind flow and pollution exposure to occupants within street canyon. However, the conventional *k*-model has an obvious flaw in terms of model correctness, despite the fact that most RANS models serve the most economical cost in terms of computational resources. One of the significant flaws in the model assessments is the concept of a steady-state solution that could be the major source of the inconsistencies.

Meanwhile, LES used the separated filtered in the transport equations where it permitted only bigger eddies to be resolved, in the meantime the smallest eddies are being modelled. [27]. The use of LES to accommodate the inadequacies of RANS has recently gained popularity. Due to its consistency and precision, the LES approach has been more superior than the RANS method [28].

A list of LES-based studies on flow structures and pollution related issues in street canyons that has been published; Alwi et al. [29] conducted the LES model to investigated the effect of various eave design on the modification of flow structure and turbulent characteristic for 2D semi-open street canyons. Meanwhile, Liu et al. [30] used model of street canyon for various aspect ratio to simulate the performance of air and pollutant exchange rate, Li et al. [31] further explored the pollutant dispersion process for deep canyons geometries, Mohamad et al. [32] looked on the mechanism of average and fluctuation for air flow for building with overhang and Munixta et al. [33] performed the evaluation of mean and turbulence structure flow under building geometry effect such as roof and façade aspect.

Base on literatures, it is noticed that CFD is one of the most widely used tools for studying such flow problems in an urban environment due to its ability to provides detailed information on the relevant flow variables under controlled conditions [34]. However, the accuracy and reliability of the data have found to have some skepticism issue involve while applying numerical modelling to problems associated with wind engineering [35-37]. Due of their limitations and errors, CFD models still require further improvement [37].

The fundamental objection to this issue, according to Franke et al. [38], is the approach's availability of various physical and numerical factors that can be freely chosen by the user. The physical modelling based on models of turbulence used and the type of boundary conditions are considering as one of sources of error in CFD results accuracy. Meanwhile, the second contribution is made by numerical simulation factors such as size of computational domain, design for grid resolution, and numerical iteration method. While CFD models have been widely used to examine atmospheric processes in street canyons, the need for adequate computational parameters is one of the most essential elements to determine predictive accuracy. The computational dimensions, as well as the grid design and quality, are some of the computational parameters that have a considerable impact on the predictability and accuracy of the flow field.

Liu and Barth [39] used an LES model to explore the flow and turbulence scalar transfer mechanism in a 3D-idealized street canyon. Before validating the results, a grid dependence analysis was performed to ensure grid solution accuracy. Cui et al. [40] investigated a turbulent structure flow within a three-dimensionally modelled street canyon. The comparison of grid resolution (fine and coarse only) and initial wind profile, as well as the variation of Smagorinsky constant for the LES model, was carried out for the purpose of accuracy and validation.

Cheng and Liu [41], on the other hand, used a two-dimensional idealized street canyon to evaluate the flow field and pollutant dispersion case using the LES model simulation. The study is motivated by the concept of the influence of computational domain size, which suggested that increasing the domain size would result in higher resolution data. Meanwhile, Michioka et al. [42] investigated the impact of the computational domain size on the flow field within the street canyon. The LES simulation analysis was used to predict the effects of the coherent structure on pollutant removal in general. Meanwhile, Dai et al. [43] show application of LES to realistic building problems and discuss setup/validation best practices that translate to street-canyon studies.

The accuracy performance of the CFD models was found to be affected by parameter characteristics such as computational domain and grid resolution in previous research. However, to the author's knowledge, no specific and rigorous examination of the effect and correlation for both parameters on the accuracy of flow statistics has been done. By knowing the proper approach for the selection of those computational setting is certainly useful to optimize the time and cost consumption for CFD simulation particularly for the LES model for instance [44].

Therefore, the motivation for the overall current study is to use the LES model as a tool to validate and statistically analyses in detail the correlation of the two computational parameters; computational domain and grid resolution towards the accuracy of the flow field within the idealized urban street canyon environment.

The LES method was chosen primarily because of its capacity to provide deeper insights into the mean flow and statistics of the resolved fluctuation, which were obviously appropriate for the study's goals. Finding should be expected to enrich the fundamental understanding and also increase the confidence in the used of CFD simulations.

METHODS

2.1 Governing Equations

By applying a filter operation, the flow equations that consists of the continuity (1), momentum and mass conservation equations (2) as follow is assumed to be isothermal and incompressible,

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

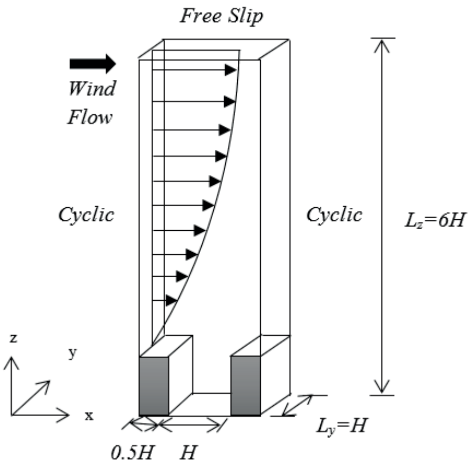
$$\frac{\partial \bar{u}_i}{\partial t}+\frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j}=-\frac{\partial \bar{P}}{\partial \bar{x}_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial \bar{u}_i}{\partial x_j}\right)-\frac{\partial \tau_{ij}}{\partial_j} \tag{2}$$

where the filtered value is indicated by the overbar, *u* is the velocity vector and *P* is the pressure and υ is the fluid kinematic viscosity. For this study, the sub-grid scale (SGS) stress was modelled by the standard Smagorinsky model with Smagorinsky’s constant Cs of 0.12 to reproduce the turbulent nature due to elements of roughness. The Reynolds number is defined as Re = *uH*/ν for this study (*H*= square block height) and all the terms are calculated and analyze by using an open-source software of OpenFOAM v2.3.1.

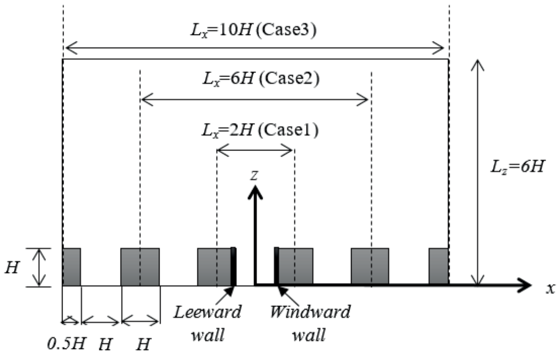
2.2 Simulation Domain

Three different computational domains are adopted in this study as shown in Fig. 1 (a and b). Each domain is characterised by the length in each direction in term of streamwise (*Lx*), spanwise (*Ly*) and vertical (*Lz*) directions. Case1 is defined as *2H x H x 6H* (one canyon: small), *6H x H x 6H* for Case2 (three canyons: medium) and *10H x H x 6H* for Case3 (five canyons: large) (see Table 1). Case1 with a grid size of *H/16* is used for validation with the wind tunnel experiment by Michioka [42] and Brown [45] as depicted in Fig. 1a.

To investigate the correlation of the domain size and grid resolution size, three runs are implemented (see Fig. 2, 3 and 4) for coarse (*H/8*), medium (*H/16*) and fine (*H/32*) resolution run where define as G8C, G16C and G32C, respectively. A uniform height (*H=0.12 m*) of square arrays are arranged at the bottom surface corresponds with the domain size. As the aspect ratio of all simulations is unity, the height of the domain was set to *6H* as proposed by Franke [46] and the spanwise domain length was kept at *H,* since the effects of the spanwise direction was not concerned in this study, which adopted the two-dimensional analysis.



(a)



(b)

Figure 1. Schematic of the computational domain adopted in this study (a) Case 1 for validation purpose (b) Configurations of simulated urban street canyon for Case 1, Case 2 and Case 3

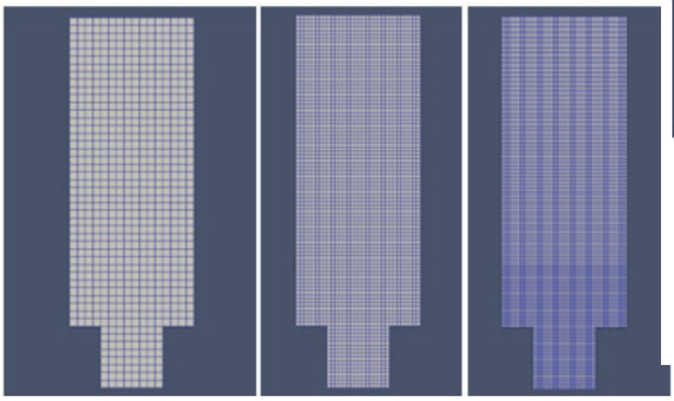


Figure 2. Diagrams of the Run Case 1 for Grid Size Resolution of H/8, H/16 and H/32

Table 1. Computational Domains and Total Grids

G8	Case 1	Case 2	Case 3
L_x/H	2	6	10
L_y/H	1	1	1
L_z/H	6	6	6
N_x	16	48	80
N_y	8	8	8
N_z	48	48	48
Number of cells	5632	45056	229376
G16			
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
Number of cells	16896	135168	688128
G32			
L_x/H	2	6	10
L_y/H	1	1	1
L_z/H	6	6	6
N_x	64	192	320
N_y	32	32	32
N_z	192	192	192
Number of cells	28160	225280	1146880

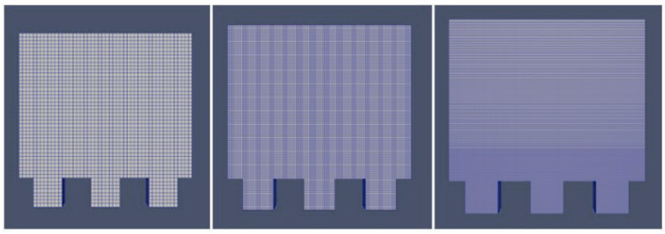


Figure 3. Diagrams of the Run Case 2 for Grid Size Resolution of H/8, H/16 and H/32

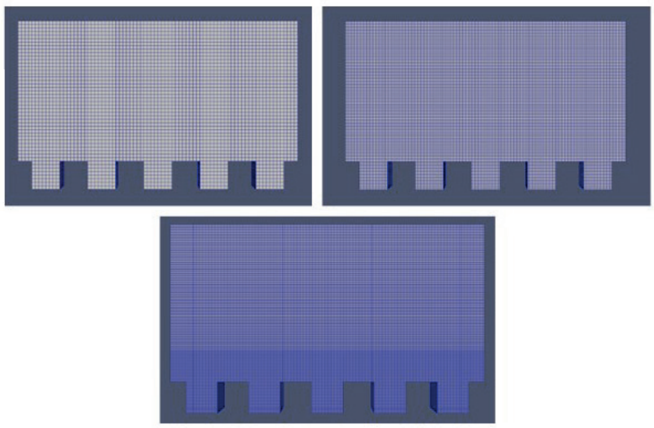


Figure 4. Diagrams of the Run Case 3 for Grid Size Resolution of H/8, H/16 and H/32

To simulate infinitely repeated street canyons cyclic boundary conditions are applied for both directions of streamwise and spanwise. The bottom surface and building surfaces are subjected to no-slip boundary conditions, while the velocity components at the top boundary are subjected to free-slip boundary conditions. This conditions allowed for the velocity normal to the boundary and the velocity gradient along the wall to be zero. The summary inflow boundary condition for the LES model is shown in Table 2.

Table 2.

LES Boundary Conditions

Boundary condition	Velocity (u)
Inlet	Cyclic
Outlet	Cyclic
Top	Slip
Bottom	Non-slip
Side Wall	Cyclic
Block	Non-slip

To keep the mean velocity over a cross-section at 2 m/s, an additional source term in the Navier-Stokes (NS) equations is used to drive the flow. The time step is set to 1.0 x 10^{-4} to ensure the mean Courant number is less than one. The sampling frequency of the data is 500Hz. For all cases of simulations for this study, the Reynolds number was in the range of 10000-12000, indicating that a fully developed turbulence flow was produced by using current LES model.

RESULTS AND DISCUSSION

3.1 Model Validation

As is well known, the validation process is required to determine the accuracy and dependability of the CFD simulation results. The degree to which a model accurately represents the real world from the perspective of the intended model uses can be defined through validation. One of the most effective approaches to get perfect practice with a CFD is to compare it to published or experimental data Oberkampf [47].

For this study, the dimensions of the building model and computational domain were chosen to compare the obtained results of this study with the experimental study results of Michioka [42] and Brown [45]. Michioka [42] performed the research in the Central Research Institute of Electric Power Industry's wind tunnel facility (CRIEPI) for two-dimensional street canyon model. The wind tunnel was built in a bigger test section (17.0 m x 3.0 m x 1.7 m) and consisted of a series of 25 evenly spaced bars. Meanwhile, Brown [45] carried out the experiment in the US Environmental Protection Agency's meteorological wind tunnel. An idealised street canyon with unity aspect ratio are made up of six identical canyons formed from seven identical square cross-section building components (0.15 m x 3.8 m x 0.15 m). The turbulent flow sample was taken at the sixth street canyon, which features fully developed wind profiles.

Fig.5 shows a vertical profile of the streamwise mean velocities of current LES at three vertical plane positions within a target street canyon together with the wind tunnel experiments. As mentioned before, the validation has been performed by using Case 1 (one street canyon). The current LES results agree well with the previous wind tunnel by Brown [45] and Michioka [42] particularly inside the canyon. At (z/H<1), the reversed flow is successfully reproduced at all measured positions. However, approximately at (z/H>1), the profile of mean vertical velocity for current LES is quite steep compared to the profile of wind-tunnel experiment by Michioka [42] and more obvious in Brown [45]. The difference may have resulted from the coarse roof-level mesh resolution near the roof level where strong wind shear is present as well as due to limited domain size as suggested by Cui [40] The current LES does not have a refined mesh structure near the building level and thus attribute to the insufficient numbers of small eddies within the LES system.

On the other hand, the current LES adopts a limited domain size that allows only those eddies whose sizes are smaller than half the canyon width (e.g. 0.12 m) to be developed where this is not the case in the wind tunnel experiments. The larger eddies whose sizes are larger than canyon width can be properly produced by the roughness elements and instability of flow in upstream locations resulted from the fact that those maximum eddies are confined by the dimension of the cross-section of the tunnel itself.

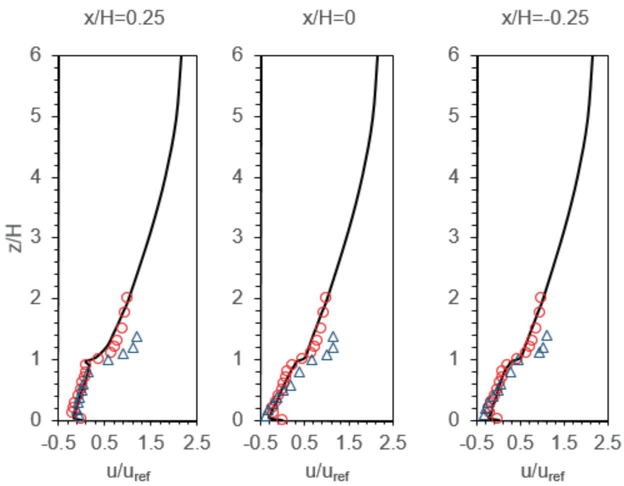


Figure 5. Vertical profiles of streamwise mean velocity at x/H=0.25, x/H=0 and x/H=-0.25 respectively. Current LES: solid line, Michioka et al., [42]: empty circle and Brown et al., [45]: empty triangular

Therefore, with the availability of these extra eddies, more intensive momentum transfer from the mean wind to inside the canyon could happen and thus developed a stronger primary vortex. Apart from the differences, considering the profiles of current LES become smoother across the building height as predicted in the wind-tunnel experiment, it is acceptable that the current LES reproduces the mean flow field inside and over the street canyon and the fully developed wind profiles have been sampled. It should be noted that the limited domain size has been selected for this study for economic reasons as well as due to limitations of computer resources.

3.2 Flow and Turbulent Statistic

This section analyzes the influence of two key computational parameters; domain size and grid resolution on the turbulent flow structure within the idealized street canyon. The subsequent discussion also examines the corresponding effects on momentum transport statistics. The LES results were obtained by decomposing instantaneous flow variables into mean and fluctuating components, as the mean values provide a more reliable representation of overall flow characteristics. Due to computational constraints, the analysis was conducted along the central plane of the domain, excluding variations in the spanwise (*y*) direction. Comparisons among cases were performed along five vertical lines within the canyon to assess velocity and turbulence distributions as shown in Fig. 6. To characterize the overall flow behavior, spatial and temporal averages of the flow field were evaluated in the *x–z* plane at the centerline (*y/H = 0*). Results are presented in statistical profiles for each grid resolution (C1G, C2G, C3G) and domain size (G8C, G16C, G32C).

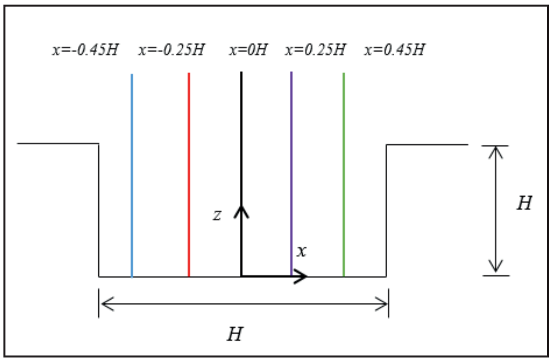


Figure 6. The Positions for Data Comparison where the Blue Line is x/H = −0.45, Red Line is x/H = -0.25, Black Line is x/H= 0, Purple Line is x/H = 0.25 and Green Line is x/H = 0.45

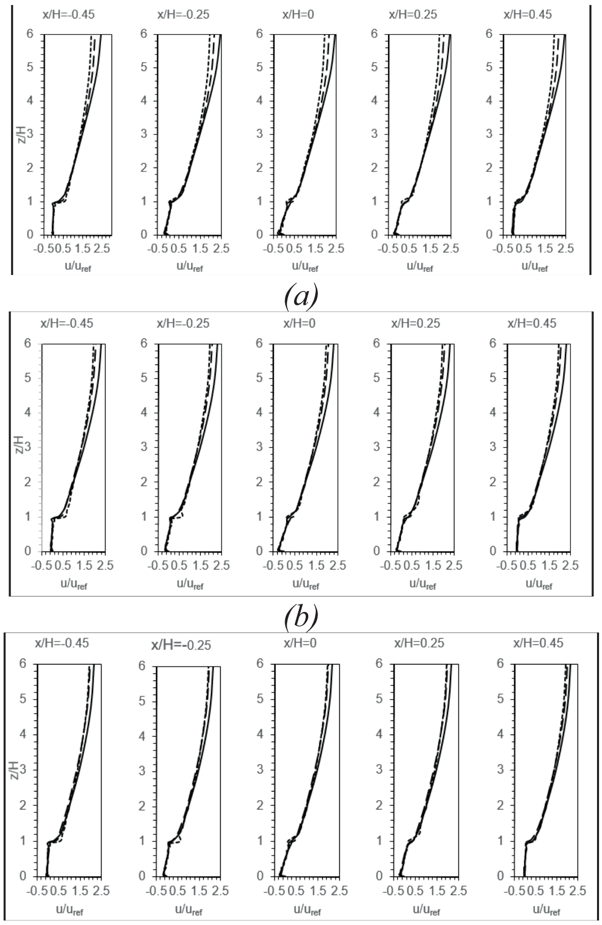
3.2.1 Mean Velocities Components

Fig. 8 and Fig. 9 presents the vertical distribution of the normalized streamwise velocity (*u*) and vertical velocity (w) at five positions within the target street canyon of unity aspect ratio. The first measurement point (x/H = –0.45) corresponds to the upstream wall on the leeward side, while the subsequent positions at x/H = –0.25, 0, 0.25, and 0.45 represent the leeward quarter line, canyon centerline, windward quarter line, and windward wall, respectively. The vertical coordinate (*z*) was normalized by the building height (*H*), and the velocity statistics were normalized by the reference velocity (u_{ref}) measured at z = 2H, where the flow field was relatively uniform and the wind speed remained nearly constant. The comparison includes all three computational domains—Case 1, Case 2, and Case 3—each simulated with coarse (G8C), medium (G16C), and fine (G32C) grid resolutions.

As shown in Fig. 8, all cases produced similar streamwise velocity (u) profiles. LES effectively captured the reversed flow region (z/H < 1.0), indicating the primary vortex, and the shear layer formation near the building height due to flow separation similar to previous studies by Cui et. al. [40], Michioka et. al. [42] and Liu & Wong [48]. Above the rooftop, the velocity gradients became smoother across all cases, reflecting frictional damping. Variations above the canyon (z/H > 2.5) were more pronounced for coarse grids, where the streamwise velocity gradient was noticeably steeper. At z/H = 5, the mean velocity differences between coarse and fine grids ranged from 8.5–10.3% (C1G), 2.9–11.2% (C2G), and 1.9–7.4% (C3G), confirming improved consistency with grid refinement.

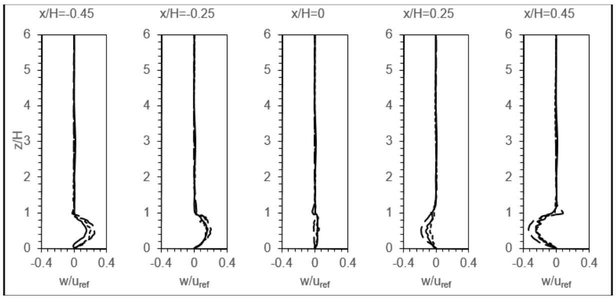
Fig. 9 shows the vertical velocity (w) distribution, where all cases exhibited comparable trends within the canyon (z/H < 1.0). The upward flow transported aged air outward, while the downward motion recirculated cleaner air toward the canyon core. However, coarse-resolution runs slightly underestimated w values, reflecting limited resolution accuracy. At z/H = 0.5, variations between coarse and fine grids ranged from 50.7–60.1% (C1G), 65.5–70.3% (C2G), and 31.7–46.8% (C3G). Overall, finer and medium grids produced smoother and more stable profiles compared with the coarse grid.

These findings highlight that LES performance strongly depends on grid resolution. The coarse grid failed to resolve the full range of large eddies responsible for momentum and scalar transport, leading to deviations in the velocity fields. Since LES resolves large, energy-containing structures while modeling smaller eddies via subgrid-scale closure, adequate grid density is essential. Hence, finer meshes (H/16 and H/32) yielded better prediction accuracy and more realistic flow representation within the street canyon [49].

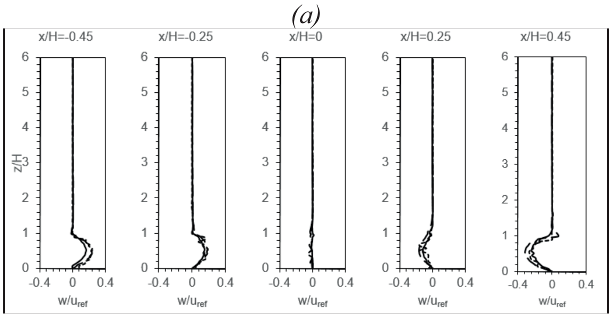


(c)

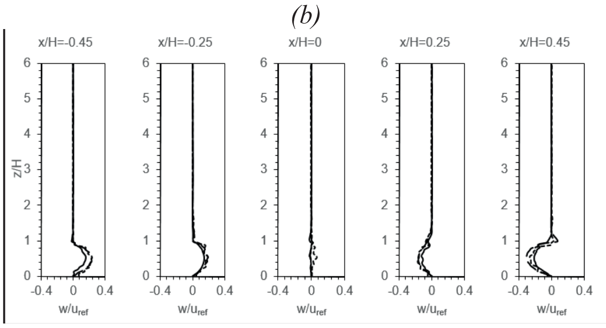
<u>Figure 8.</u> Vertical Profiles of the Mean Streamwise Velocity for All Cases of Domain Sizes; (a) Case1 (b) Case2 and (c) Case3 with Different Grid Resolution at x/H=-0.45, -0.25, 0, 0.25 and 0.45. The Square Dot Lines Refer to the: Grid 8 (Coarse), Dash Line: Grid 16 (Medium) and Solid Line: Grid 32 (Fine)



(a)



(b)



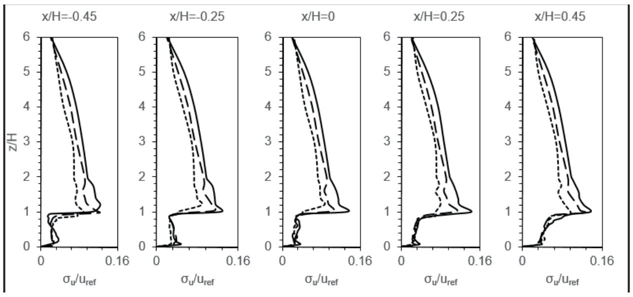
(c)

Figure 9. Vertical Profiles of the Mean Vertical Velocity for All Cases of Domain Sizes; (a) Case1 (b) Case2 and (c) Case3 with Different Grid Resolution at x/H=-0.45, -0.25, 0, 0.25 and 0.45. The Square Dot Lines Refer to the: Grid 8 (Coarse), Dash Line: Grid 16 (Medium) and Solid Line: Grid 32 (Fine)

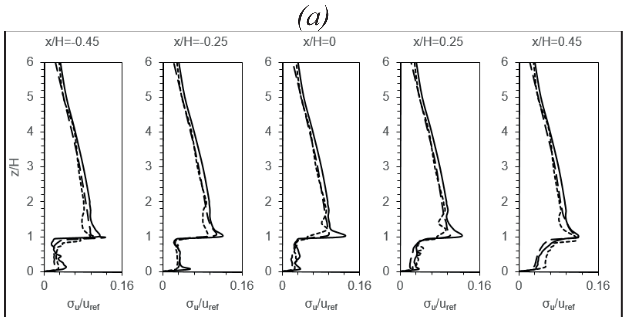
3.2.2 Standard Deviation Components

Fig. 10 and Fig. 11 show the vertical distributions of the standard deviations of streamwise and vertical velocities ($\sigma(u)$ and $\sigma(w)$), highlighting the effect of grid resolution on LES performance within the 2D street canyon with various size domains. Within the canyon ($z/H \leq 1.0$), all runs produced comparable results, except for the coarse grid, which exhibited noticeable deviations in $\sigma(u)$ (Fig. 10). The maximum $\sigma(u)$ and $\sigma(w)$ occurred near the rooftop, representing strong shear-induced turbulence, and were well captured in the medium and fine grid cases but underpredicted by the coarse grid.

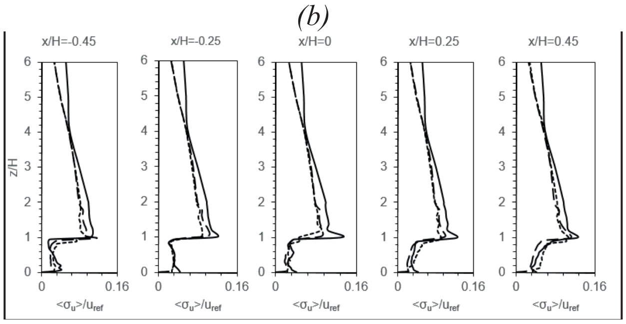
Both $\sigma(u)$ and $\sigma(w)$ decreased toward the canyon floor due to the no-slip boundary condition, where viscous effects dampened velocity fluctuations and suppressed turbulence generation. Above the canyon ($z/H \geq 1.0$), stronger variability in $\sigma(u)$ appeared, particularly in the small domain (C1G). At $z/H = 5$, $\sigma(u)$ for the coarse grid (G8) was about 20% lower than for the medium (G16) and fine (G32) grids, while percentage differences for C2G and C3G ranged from 3.2–11.4% and 2.4–28%, respectively. A steeper $\sigma(u)$ gradient was also observed for the fine grid in the large domain (C3G) above $z/H > 4$, indicating improved resolution of shear structures.



(a)



(b)



(c)

Figure 10. Vertical Profiles of the Streamwise Standard Deviation for All Cases of Domain Sizes; (a) Case1 (b) Case2 and (c) Case3 with Different Grid Resolution at x/H=-0.45, -0.25, 0, 0.25 and 0.45. The Square Dot Lines Refer to the: Grid 8 (Coarse), Dash Line: Grid 16 (Medium) and Solid Line: Grid 32 (Fine)

As shown in Fig. 11, $\sigma_{(w)}$ exhibited similar behavior with greater variation above the canyon. At z/H = 5, differences among grid resolutions were 20.5–42.8% for C1G, 14.2–25.5% for C2G, and 3.7–16.7% for C3G. Both $\sigma_{(u)}$ and $\sigma_{(w)}$ magnitudes increased from leeward to windward, reflecting intensified shear and recirculation near the windward wall. Overall, coarse grids dissipated small-scale turbulence and underestimated velocity fluctuations, whereas finer grids more accurately resolved the energy-containing eddies and provided higher fidelity in representing the canyon flow dynamics.

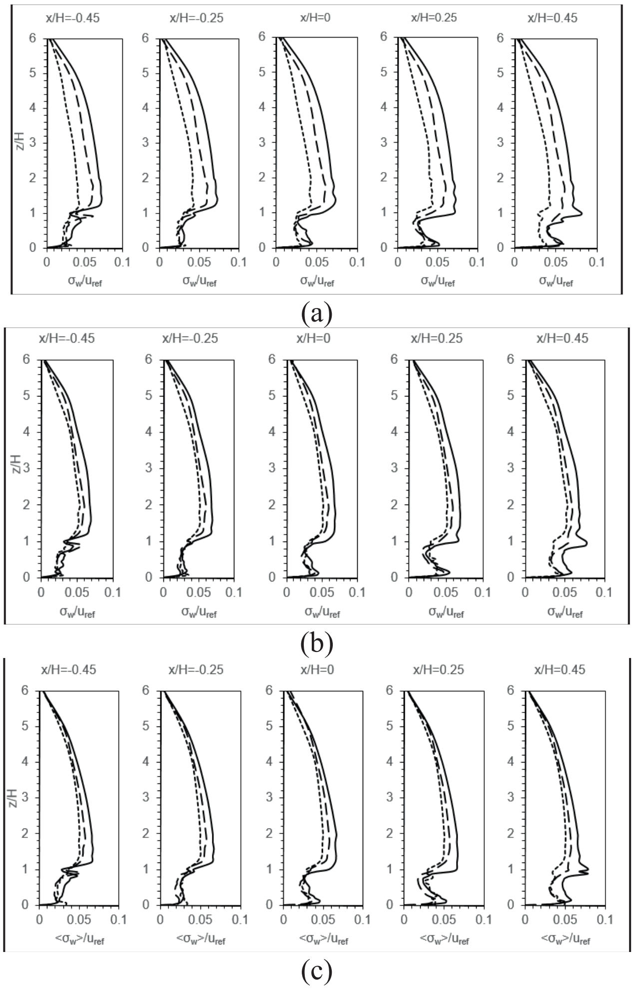


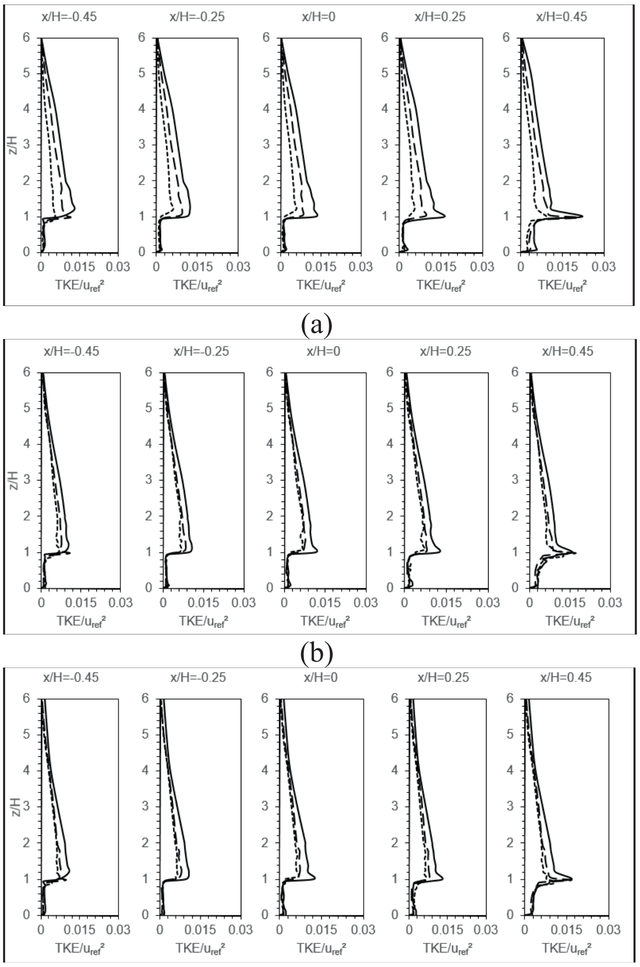
Figure 11. Vertical Profiles of the Vertical Standard Deviation for All Cases of Domain Sizes; (a) Case1 (b) Case2 and (c) Case3 with Different Grid Resolution at x/H=-0.45, -0.25, 0, 0.25 and 0.45. The Square Dot Lines Refer to the: Grid 8 (Coarse), Dash Line: Grid 16 (Medium) and Solid Line: Grid 32 (Fine)

3.2.3 Turbulence Kinetic Energy (TKE)

Similar to the mean velocity components, the turbulence kinetic energy (TKE) was normalized using the reference velocity ($u_{(ref)}$) measured at z = 2H, as shown in Fig. 12. The decomposition of instantaneous flow into mean and fluctuating components produced variance terms, whose square roots represent the velocity fluctuations. Half the sum of these variances corresponds to the mean kinetic energy per unit mass contained in the turbulent motions. TKE is a key parameter for evaluating LES performance, as it reflects the ability of the model to capture energy-containing eddies. To examine the effects of grid and domain size, TKE values were extracted at z/H = 1.0 (roof level) and z/H = 5.0 (above the canyon) for all simulation cases.

Fig.12 shows the vertical profiles of TKE inside and above the street canyon. A distinct TKE peak appeared near the rooftop (z/H = 1.0) for all simulations except the coarse-resolution case (G8), where only a mild peak was observed. Large discrepancies were evident among the coarse-grid runs (C1G, C2G, and C3G), confirming the resolution sensitivity of LES results. In general, TKE values above the canyon were substantially higher than those within the canyon, as the shear layer generated strong turbulence over the roof, while the weaker recirculating flow below produced relatively uniform and low TKE distribution [48].

To quantify the grid resolution effect, the TKE variation ratio between coarse and fine grids was computed. At z/H = 1.0, variations of 27–55.6%, 23.2–30.2%, and 25.5–32.0% were recorded for runs C1G, C2G, and C3G, respectively. Above the canyon, the coarse-grid profile exhibited a steeper gradient than the finer-resolution cases, indicating less stable turbulence representation. Despite general agreement below roof level, the differences near z/H = 1.0 highlight the critical influence of grid size on LES performance in urban canyon flows.



(a) (b) (c)

Figure 12. Vertical Profiles of TKE for All Cases of Domain Sizes; (a) Case 1 (b) Case 2 and (c) Case 3 with Different Grid Resolution at x/H=-0.45, -0.25, 0, 0.25 and 0.45. The Square Dot Lines Refer to the: Grid 8 (Coarse), Dash Line: Grid 16 (Medium) and Solid Line: Grid 32 (Fine)

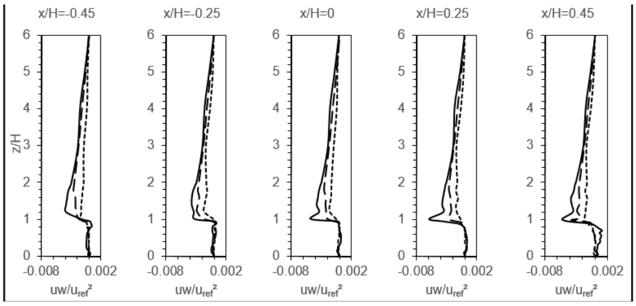
The TKE peak near the windward wall corresponded to the shear layer formed by flow separation at the leeward building edge—recognized as the primary source of turbulence in isothermal canyon flows. High TKE values at the roof corners confirm this mechanically driven turbulence production. Conversely, smaller and more uniform TKE distributions near the leeward wall indicated low local velocity gradients. Among the simulations, C3G (fine resolution, large domain) produced the most consistent and realistic TKE distribution, while coarse-grid runs systematically underestimated TKE magnitudes. These discrepancies align with the observed underprediction of velocity (Fig. 8-9) and standard deviation components (Fig. 10–11), suggesting that coarse grids failed to fully capture the energy exchange between the high-momentum flow above the canyon and the low-momentum recirculating air below, as similarly reported by Cui et al. [40].

3.2.4 Reynold Shear Stress

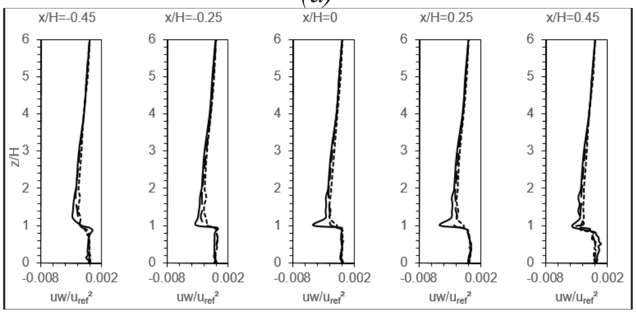
Fig. 13 presents the Reynolds shear stress profiles obtained from the LES simulations for different grid resolutions (C1G, C2G, and C3G) at five locations within the target street canyon. An increase in Reynolds shear stress magnitude was observed above the canyon for all cases as grid resolution improved from coarse to fine. The coarse and medium grid runs generally underestimated the Reynolds shear stress and failed to capture a distinct peak near the building height. In contrast, the fine grid simulations produced well-defined profiles, showing clear maxima at the windward roof edge, consistent with the expected location of strong shear-layer formation.

The most pronounced increase in Reynolds shear stress with grid refinement occurred in the small-domain case (C1G), as shown in Fig. 13 (a). At z/H = 1.0, the coarse grid predicted values approximately 32.4–59.9% lower than the medium and fine resolutions. For C2G and C3G, the variation was less significant, with percentage differences of 25.4–36.8% and 27.3–32.6%, respectively. At higher elevations (z/H ≥ 4), the shear stress profiles tended to converge across all cases, indicating improved agreement above the canyon except for the coarse grid in the small domain. Within the canyon, all simulations showed relatively small shear stress values compared to those above the rooftop, consistent with weaker turbulence intensity below the shear layer.

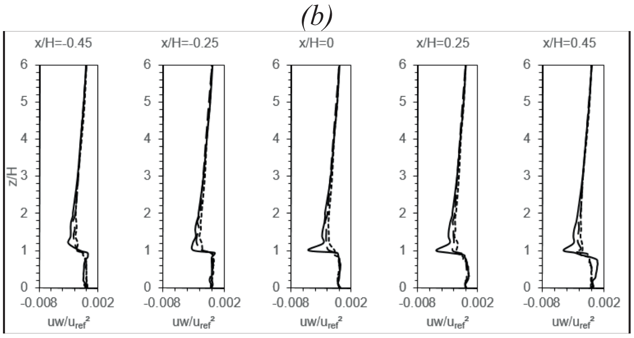
The discrepancies observed for coarse and medium grids were consistent with the low TKE values reported in Fig. 12. This correlation suggests that reduced TKE production is associated with lower Reynolds shear stress, highlighting the coupling between turbulent kinetic energy and momentum transport in the flow field. The insufficient grid resolution limits the ability of LES to resolve small-scale eddies, resulting in underpredicted shear stress magnitudes.



(a)



(b)



(c)

Figure 13. Vertical Profiles of Reynold Shear Stress for All Cases of Domain Sizes; (a) Case 1 (b) Case 2 and (c) Case 3 with Different Grid Resolution at x/H=-0.45, -0.25, 0, 0.25 and 0.45. The Square Dot Lines Refer to the: Grid 8 (Coarse), Dash Line: Grid 16 (Medium) and Solid Line: Grid 32 (Fine)

Overall, the fine grid resolution (G32) yielded the most accurate and consistent representation of Reynolds shear stress, effectively capturing the momentum exchange between the velocity fluctuations within and above the canyon. Furthermore, regardless of the domain size (Case 1, Case 2, or Case 3), the Reynolds shear stress profiles were in good agreement when simulated with fine grid resolution, confirming that grid refinement has a more dominant influence on LES performance than the computational domain size.

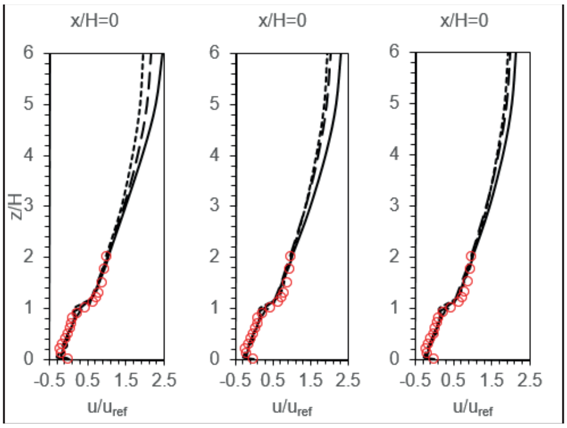
3.3 Data Comparison: Computational Domain and Grid Resolution

The streamwise mean velocity and velocity fluctuation of standard deviation as well as the Reynold shear stress components were used to represent the performance of the LES data. The percentage variation of ratio value for each component cases are presented in graph to determine the contribution of both parameters that could influence the accuracy of LES simulation inside and above the street canyon. Secondly, comparison was then conducted on those three components using the results from the wind tunnel data by Michioka et. al., [42].

3.3.1 Mean Velocity

Fig. 14 compares the streamwise mean velocity profiles from the LES simulations with the wind tunnel measurements of Michioka et al. [42] at x/H = 0. All simulation cases showed good agreement with the experimental data, particularly within the canyon and near the rooftop level. Noticeable variations among cases appeared only at higher elevations, especially for the grid resolution runs (Figures 14 a–c).

Overall, the current LES successfully reproduced the mean velocity distribution and yielded comparable results regardless of the computational domain size. In contrast, variations in grid resolution had a minor but consistent effect, where refinement from coarse to fine grids slightly increased the mean velocity magnitude without significantly altering the overall statistical profile. This suggests that the mean velocity field is relatively insensitive to both domain size and grid resolution, a trend consistent with the findings of Cui et al. [40] and Cheng and Liu [41]. Considering computational efficiency, the use of a smaller domain with medium or fine grid resolution is deemed sufficient and reliable for predicting mean flow characteristics in a two-dimensional urban street canyon.



(a) (b) (c)

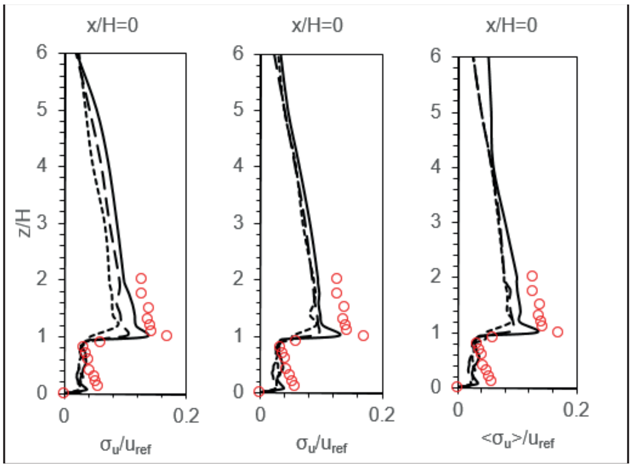
Figure 14. Comparison of Vertical Profile Streamwise Mean Velocity by Domain Run and Grid Resolution Run; (a)(b) and (c) with Wind Tunnel Experiment by Michioka et al., (2011) [6]. Symbol Refer as Previous

3.3.2 Standard Deviation

Fig. 15 compare the streamwise velocity fluctuation components (standard deviation) for different computational domains and grid resolutions. Larger variations were observed in the coarse-resolution (G8C) and small-domain (C1G) simulations compared to other cases, indicating stronger grid dependence under limited domain conditions.

When compared with the wind tunnel experiment by Michioka et al. [42], the LES-predicted standard deviations were generally lower, as shown in Fig. 15. This discrepancy can be attributed to the restricted computational domain and the absence of a refined mesh near the roof level, where strong wind shear and turbulent mixing occured. The smaller domain may have constrained the shear layer development above the buildings, resulting in weaker resolved velocity fluctuations [50]. Additionally, the exchange of high-momentum air above the canyon and low-momentum air within the canyon was less active in the coarse-grid simulations compared with the fine-resolution cases [40], further reducing turbulence intensity.

Despite these limitations, the overall profile patterns indicated that fine-grid LES runs successfully captured the dominant turbulent velocity fluctuations inside the canyon, largely independent of domain size (Fig. 15 (a)–(c)). This finding suggests that a medium computational domain combined with a fine grid resolution offers a practical balance between computational efficiency and simulation accuracy. Such a configuration was able to reproduce the essential turbulent characteristics within the street canyon while minimizing computational cost without significant loss of fidelity.



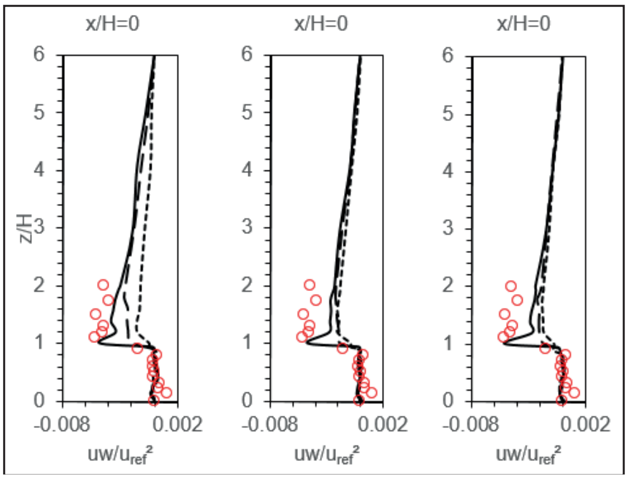
(a) (b) (c)

Figure 15. Comparison of Vertical Profile Streamwise Standard Deviation by Domain Run and Grid Resolution Run; (a)(b) and c with Wind Tunnel Experiment by Michioka et al., (2011) [6]. Symbol Refer as Previous

3.3.3 Reynold Shear Stress

Fig. 16 presents the comparison of Reynolds shear stress for the different computational domains and grid resolution cases. As observed in Fig. 16 (a), the trend closely mirrors that of the velocity fluctuation results discussed in Section 3.3.2, where larger variations occurred in the coarse-resolution (G8C) and small-domain (C1G) simulations compared with other cases. The Reynolds shear stress within the street canyon showed minimal sensitivity to domain length, indicating that extending the computational domain did not substantially enhance turbulence representation. However, grid resolution had a more pronounced effect on the momentum transport characteristics within the urban boundary layer. The fine-grid simulations (G32) provided better-resolved and more comparable results, effectively capturing the shear-layer dynamics and momentum exchange processes above the canyon.

These results also aligned well with the wind tunnel data, although the LES slightly underpredicted the Reynolds shear stress magnitude. This difference is likely due to the limitations in grid resolution and subgrid-scale modeling, which may dampen small-scale turbulence production.



(a) (b) (c)

Figure 16. Comparison of Vertical Profile Reynold Shear Stress by Domain Run and Grid Resolution Run; (a)(b) and (c) with Wind Tunnel Experiment by Michioka et al., (2011) [6]. Symbol Refer as Previous

Overall, grid resolution was found to have a greater influence on LES performance than domain size. While the small-domain simulation adequately reproduced the general fluctuation trends, it exhibited less smoothness compared with the medium and large domains. Hence, the present study suggests that a medium computational domain, coupled with a fine grid resolution, offers an optimal balance between computational efficiency and accuracy for momentum transport analysis in urban street canyons.

CONCLUSION

This study evaluated how grid resolution and computational domain size influence LES predictions of turbulent flow within an idealized street canyon. The results show that mean velocity profiles were only marginally affected by grid refinement and were largely independent of domain size, with all simulations agreeing well with available wind-tunnel data. Mean flow characteristics could therefore be captured reliably even with a small domain when medium or fine grid resolutions were used.

In contrast, turbulence quantities such as velocity fluctuations, Reynolds shear stress, and momentum transport, were strongly dependent on grid resolution. Domain size had a weaker influence, and LES systematically underpredicted these turbulence statistics compared with wind-tunnel measurements. This discrepancy was attributed to limited domain extent and insufficient mesh refinement near the roof level, which restricted the formation of large eddies and reduced momentum transfer.

Overall, grid resolution played a more critical role than domain size in reproducing the turbulent structure of canyon flow. For accurate turbulence analysis, a fine grid combined with a sufficiently large domain is recommended. However, a medium domain with fine resolution may offer an acceptable balance between computational cost and accuracy, particularly when mesh refinement is applied in key regions. These findings provide practical guidance for optimizing numerical resources in LES studies of urban street canyons without compromising predictive reliability.

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