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Large-Eddy Simulation of Wind Flow within a Canyon between Modified Idealized Terraced Houses

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ABSTRACT

Adequate wind flow in residential neighbourhood is important for providing a comfortable and healthy environment. It can significantly affect the diffusion of heat; lowering the temperature around it, and the dispersion of traffic-related pollutants between urban surfaces and the atmosphere. In this study, large-eddy simulation, using the Smagorinsky subgrid-scale model, was used to investigate the effect that modifications to a terraced house canyon would have on its wind flow characteristics. The configuration of an idealized terraced house canyon includes a height-to-width ratio h/w = 1/3, and secondary-roughness elements were installed in a staggered, square layout, at 0.5h from the ground. Secondary-roughness elements are treated as modifications to a terraced house building (large-roughness elements). The interaction between an idealized terraced house canyon and secondary-roughness elements has been studied by estimating wind velocity profiles within the terraced house canyon. The velocity profiles have been compared with previous studies to validate the accuracy of the simulation. This study reveals that the modification of the canyon can also affect the wind flow regimes, which might alter the micro climate in the surrounding area, owing to smaller canyon width and sheltering effect from the new obstacle.

Keywords: *Large-Eddy Simulation, Terraced House Canyon, Secondary-Roughness Elements, Velocity Profile.*

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Introduction

Wind flow is strongly affected by surface roughness, which can be classified into two categories: large and secondary. Large-roughness elements include buildings, and secondary-roughness elements include garages, extension rooms, roofs, and street furniture. Surface roughness may alter the micro climate (i.e. wind flow) in its surroundings [1, 2, 3], and so it can significantly affect the diffusion of heat and dispersion of traffic-related pollutants between urban surfaces and the atmosphere [4, 5, 6].

Most previous studies focused on idealized large-roughness elements, such as cubical uniform buildings [1, 2, 7], non-uniform buildings of varying layout [3, 8], and long street canyons [4, 5, 6]. Kanda (2006) investigated the detailed of coherent structures of square and staggered building arrays with packing densities, λ_p = 3-44%, using large-eddy simulation (LES) [1]. Azli *et al.* (2012) investigated the relationship between frontal area ratio and average pedestrian wind velocity. This was achieved using a uniform and non-uniform height for a staggered building array with packing densities λ_p = 4.4-44.4% also using LES [7]. Castro et al. (2006) investigated the changes in the near-wall flow over staggered building arrays with packing densities λ_p = 25%, using a zero-pressure gradient boundary layer wind tunnel [2]. In addition, Hagishima *et al.* (2009) investigated the aerodynamic effects (drag coefficient (C_d), roughness length (z_o), and displacement height (d)) of uniform arrays with a square, staggered, and diamond layout, using wind tunnel experiment [3]. Meanwhile, Zaki *et al.* (2011) conducted the same experiment using random arrays [8]. As a continuation, Zaki *et al*. (2012) investigated the spatial distribution of the pressure drag acting on the walls of rectangular block arrays; staggered, square, and diamond layouts with packing densities λ_p = 7.7-39.1% using wind tunnel experiment [9]. Faiz *et al.* (2015) further investigated the pressure distribution on heterogeneous buildings of staggered layout with packing densities λ_p = 4.4-39.1% using LES [10]. Hunter *et al.* (1990) investigated the relationship between street canyon dimensions and air flow regimes [4]. Michioka *et al*. (2012) investigated the effects of the incoming flow on pollutant removal from the street canyon [5], while Hideki and Ryozo (2013) investigated the relationship between roof-height levels and concentrations of the pollutants inside the street canyon [6].

Salizzoni *et al*. (2007) investigated the interaction between large roughness and secondary roughness in different flow regimes on the top of a building, with specific emphasis on secondary roughness [11]. Takano and Moonen (2013) investigated the effect of roof shape on flow and pollutant dispersion, by conducting wind-tunnel experiments using idealized street canyon models [12]. Faizal *et al.* (2014) and Faizal *et al.* (2015) conducted a Reynolds-averaged Navier-Stokes (RANS) and LES simulation using an idealized terraced house and street canyon. In these studies, the effects of different porch lengths towards the ventilation performance of buildings and in-canyon flow pattern were examined [13, 14]. Liyana *et al.* (2015) investigated the effect of setback distance for idealized terrace house models towards ventilation performance using LES [15]. However, of the previous studies involving idealized urban-like buildings, very few considered the effect of small roughness on the wind flow surrounding them.

The main objective of this study was to investigate the effect of a modified terraced house on the wind flow pattern within a canyon for a typical Malaysian residence. An idealized modified terraced house with square and staggered layouts was used in this study to understand the effect of secondary-roughness towards wind flow within the canyon.

Numerical Setup

Idealized modified terraced house

The size of the original terraced house for a single unit was taken from the Manual Guidelines and Selangor State Planning Standards (Second Edition – November 2010) [16]. The length, width, and height of the original terraced house are 12 m, 6 m and 6 m, respectively, while the length and width for the renovation given are both 6 m. The size of the terraced house model is based on the scale 1:300.

We defined a typical terraced house in Malaysia, as shown in Figure 1 (a), as a long street canyon; elongated buildings consisting of many dwelling units, with a flat roof consisting of pairs of single storey which are located upstream and downstream of the main road for the simulation, as shown in Figure 1 (b) and Figure 2.

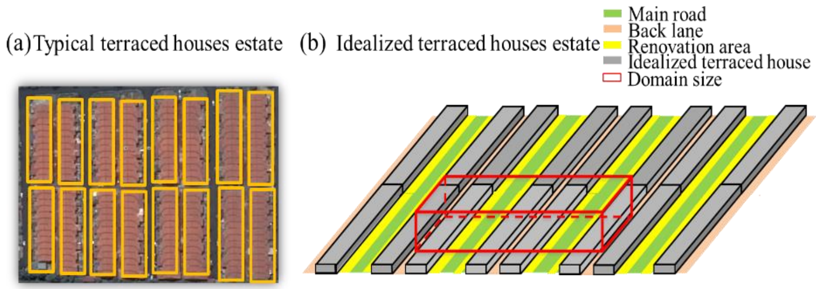


Figure 1: (a) Plan view of typical terraced house estate, and (b) schematic of idealized terraced house estate

Numerical settings

The height of the building is represented by *h*, which is 20 mm. *Lx*, *Ly*, and *Lz* represent the streamwise, spanwise, and vertical domain length with dimensions 16*h*, 4*h*, *and* 4*h* respectively. The front of the house faces a main road, which is the main traffic route and contains free space for modification. One row of terraced houses consists of four unit houses. A periodic boundary condition in the spanwise direction is applied to simulate a long-terraced house, as shown in Figure 2. There were four rows of terraced houses used in this domain. An example of the modification of a terraced house is shown in Figure 2.

Three cases with two types of modifications were tested in this study. The goal was to investigate the effects of different arrangements of secondary roughness on turbulent flow characteristics within the canyon between the houses. First, the effect of canyon dimension was tested with a non-modified terraced house canyon (hereafter referred to as NR). Next, to examine the effect of house modification, small roughness elements (which are assumed to be modifications of terraced house buildings) are installed as a small cubical at 0.5*h* from the ground. The arrangement of this secondary roughness is square (hereafter referred to as R-SQ), and has a staggered layout (hereafter referred to as R-ST) (refer Table 1). Four measuring locations were set up in the canyon to measure the wind velocity profiles. Numerals 1, 2, 3, and 4 in Figure 3 represent the measuring locations for each respective case.

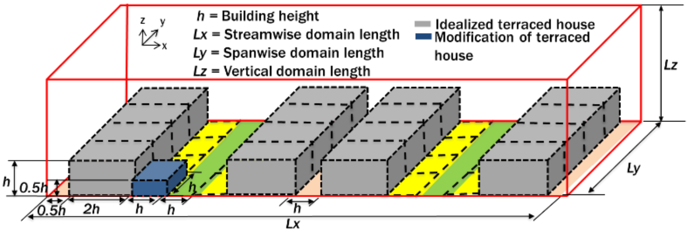


Figure 2: Schematic of the computational domain.

Table 1: Details of the measured models.

Case	Layout of modification	Computational domain size	Remarks
NR	None	16*h* x 4*h* x 4*h*	Small cubical for modification (*h* x *h* x 0.5*h*) (*h* = 0.02 m)
R-SQ	Square		
R-ST	Staggered		

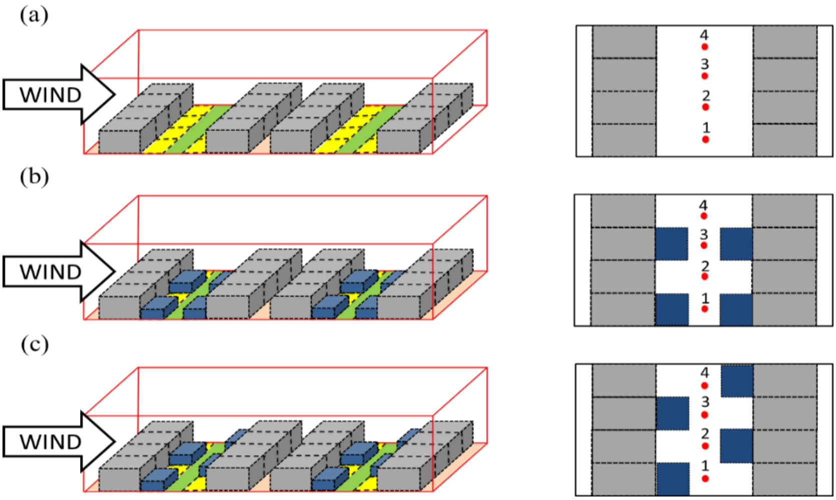


Figure 3: (left) is the diagram of the computational domain for all cases, and (right) plan view of measuring locations in canyon: (a) NR case, (b) R-SQ case, and (c) R-ST case. Numerals 1, 2, 3, and 4 denote the measuring locations for respective cases.

The continuity and Navier-Stokes (NS) equations are solved using an open source CFD tool called OpenFOAM (version 2.1.1). The LES Smagorinsky model (Smagorinsky Constant Cs = 0.168) is employed in order to reproduce the turbulent nature generated by the roughness elements. The PISO algorithm implemented in OpenFOAM is employed for the coupling of the pressure and flow fields. Boundary conditions of the computational domain were set as follows:

- A periodic boundary condition was imposed on the velocity in the streamwise and spanwise directions to simulate an infinite array and to reduce computation time.
- A no-slip condition was imposed at the bottom of the domain and on the surfaces of all blocks.
- A free-slip condition was imposed on the top of the domain.

Applying a cyclic boundary condition in the terraced house models creates an unlimited spread of built-up area and reduces the domain and calculation time for the simulation. The flow is driven by an additional source term u_τ^2/δ (u_τ is the total friction velocity and δ is the boundary layer height) in the NS equations to ensure that the average flow through the whole domain is constant at u_{bulk} = 8 m/s.

Sensitivity analysis of CFD results

The detailed analyses of grid resolution and convergence time were conducted using NR as summarized in Table 2. First, the grid resolutions were conducted accordingly, by setting 10, 20, and 40 cells per block height (hereafter referred to as H/10, H/20, and H/40). A duration of 10 s (200*T*) were required for the convergence of the flow for all cases, where $T = h / u_\tau$ is the eddy turnover time for the largest eddies shed by the model. This duration fulfils the criteria suggested by Coceal *et al.* (2006) of 200*T* for the initial run, and a minimum of 400*T* for statistical analysis [17]. For grid resolution analysis, results for 200*T* had been compared for all three cases.

Figure 4 shows the vertical profiles of the normalized, spatially averaged, streamwise velocity, and the Reynolds shear stress for different grid resolutions. From the averaged streamwise velocity profile, a similar trend is observed for all cases throughout the domain with the exception of the area near the top of the block (z/h=1) and also near the bottom part of the domain. This might be due to the different grid resolution used in this study. The Reynolds shear stress within the canyon for H/10 and H/20 are slightly underestimated compared to those estimated from H/40. This indicates that a finer resolution is needed to produce acceptable wind flow characteristics. Finer grid cells i.e. H/80 should be simulated to ensure the accuracy for H/40, however, take into account the time required will be longer, the number of grid cell accordingly by setting 40 cells per block height had been chosen for further analysis.

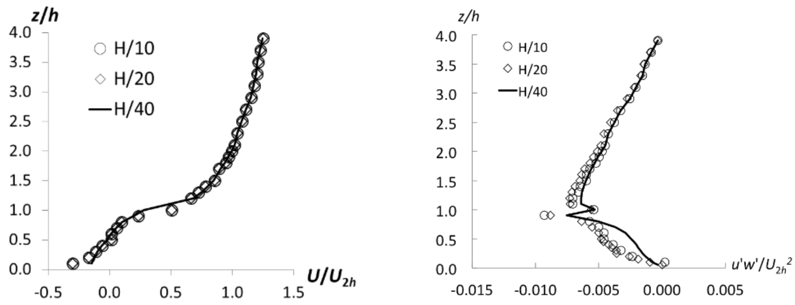
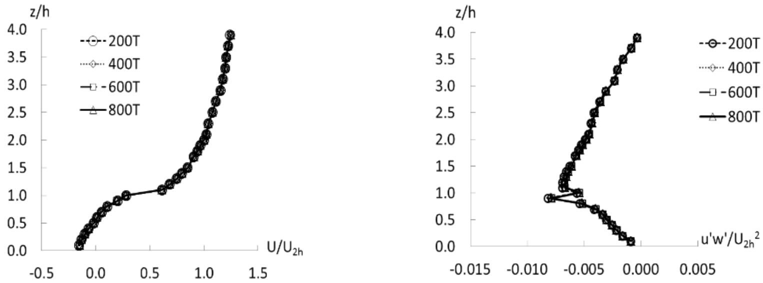


Figure 4: Vertical profiles of spatially averaged streamwise velocity for 200*T*: (a) mean streamwise velocity U/U_{2h}, (b) Reynolds shear stress $u'w'/U_{2h}{}^2$ for different grid resolutions.

Secondly, the convergence period had been carefully checked to make sure the result is fully converged and appropriate for further analysis, using grid resolution H/40. A duration of 30 s after the initial duration (~800T) was simulated for the data analysis of the convergence period.

Figure 4 shows the vertical profiles of the normalized, spatially averaged, streamwise velocity and Reynolds shear stress for several durations. Both sets of results demonstrate that a consistent trend is observed throughout the domain for all convergence times. We can conclude that the simulation had fully converged and that the convergence period of 400T had been chosen for further analysis based on minimal period as suggested by Coceal *et al*. (2006) for statistical analysis.



(a) (b)

Figure 5: Vertical profiles of spatially averaged streamwise velocity: (a) mean streamwise velocity U/U_{2h}, (b) Reynolds shear stress $u'w'/U_{2h}^2$ for convergence period study.

Both grid and time resolutions were held constant at all times and in all directions to ensure that the mean Courant number was less than unity. This can be seen in Table 2:

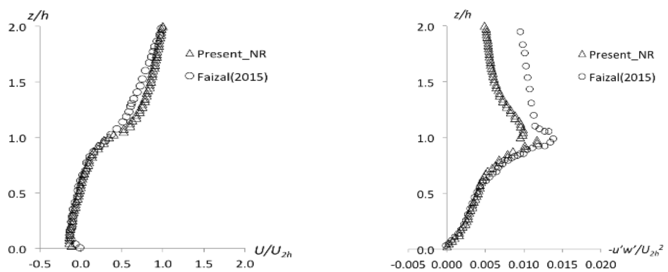
Table 2: Details of sensitivity analysis.

Case	Total grid cells	Time resolution	Number of processors used	Convergence period	Computational time
H/10	250, 000	5 x 10^{-4}		200T	2~3 days
H/20	380, 000	2 x 10^{-4}		200T	6~7 days
H/40	630, 000	1 x 10^{-4}	8	200T	13~14 days
				400T	23~24 days
				600T	31~32 days
				800T	41~42 days

Results and Discussion

The wind flow for the non-modified terraced house canyon

Figure 6 shows a comparison of vertical profiles of the normalized, spatially averaged, streamwise velocity and Reynolds shear stress from the NR results. It also shows the LES results, measured by Faizal *et al*. (2015) [14], for an idealized street canyon with a canyon aspect ratio h/w = 1/3. The current results of the mean velocity profiles show excellent agreement with Faizal [14]. For Reynolds shear stress profiles, the current results show excellent agreement with Faizal [14]; for z/h < 1, however, the results also show discrepancies above the canopy level. This might be due to the limited domain height. The current results indicate that the limited domain height did not have much effect on the wind flow within the canyon (our focus area) and further analysis can be carried out.



(a) (b)

Figure 6: Vertical profiles of spatially averaged streamwise velocity: (a) mean streamwise velocity U/U_{2h}, (b) Reynolds shear stress $u'w'/U_{2h}{}^2$ for different canyon dimensions.

Effect of canyon modification

Figure 7 shows the vertical profiles of the normalised, averaged, streamwise velocity for R-SQ and R-ST at four different locations, while Figure 8 shows comparison on the vertical profiles of the normalised averaged streamwise velocity for NR, R-SQ, and R-ST at different measuring locations.

From Figure 7, it can be concluded that the profiles of locations 1 and 3, and 2 and 4, are almost identical for both R-SQ and R-ST cases. For case R-SQ, the wind flows at locations 1 and 3; where modification had taken places at both leeward and windward houses For z/h<0.5*h*, it can be observed that it had become slower compared to locations 2 and 4; where no modification had been involved, maybe due to the modification that had narrowed the respective canyon. On the other hand, the wind flow at location 2 and location 4 can be observed not significantly interrupted by the neighbour's modifications. For case R-ST, it can be observed that the changes in wind flow rely on the modification of the leeward row. If the modification is only done at the windward row (location 1 and location 3), the wind flow is not significantly interrupted. However, if the modification is only done at the leeward row (locations 2 and 4), the wind flow might become slower owing to sheltering effect. This might affect pedestrian comfort and pollutant dispersion in the surrounding area.

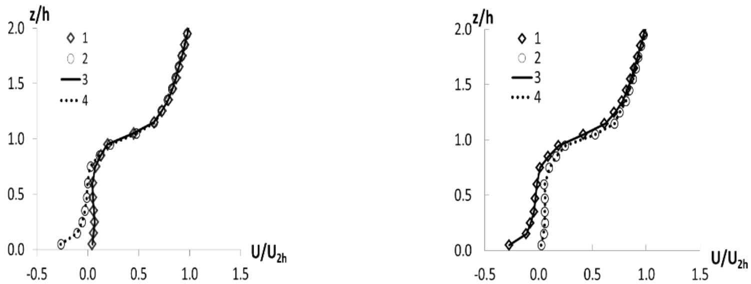


Figure 7: Vertical profiles of averaged streamwise velocity, U/U_{2h} at different measuring locations: (a) R-SQ, and (b) R-ST.

In Figure 8, as the profiles of locations 1 and 3, and 2 and 4, both R-SQ and R-ST cases are almost identical; only location 1 and 2 for both cases are plotted. It can be observed that the wind flow at location 2 for R-SQ and location 1 for R-ST have almost identical wind flow for NR. In contrast, it can be observed that the wind flow at location 1 for R-SQ and location 2 for R-ST at z/h<0.5h becomes slower than NR. These results might be due to narrow canyon or sheltering effect after modification had taken place as mentioned above. It indicates that wind characteristics are strongly affected by the location of modification.

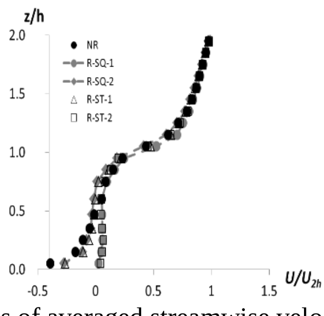


Fig. 8: Vertical profiles of averaged streamwise velocity, U/U_{2h} at different measuring locations for NR, R-SQ, and R-ST cases.

Concluding Remarks

In this study, LES was performed to simulate a fully rough flow over the canyon between modified terraced houses. The goal was to analyse the wind characteristics within the canyon. To represent an accurate flow pattern within the canyon, a grid resolution of H/40 and time period 400T were selected based on the sensitivity analysis that had been conducted. The simulation accuracy had been validated by previous work, and the velocity profile results had shown good agreement, especially below canopy level.

In the main numerical simulation, it was highlighted that flow regime characteristics are strongly dependent upon the location of the modified house. From R-SQ results, the modification of houses had narrowed the involved canyon area and might affect the wind flow at surrounding area. From the R-ST results, it is noticeable that the sheltering effect from the house modification was more obvious when the modification was conducted at windward row to the wind flow. This condition might contribute to the poor ventilation and dispersion of pollutants in surrounding areas.

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