Numerical investigation of urban geometry impact on pedestrian wind environment

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ABSTRACT: The main objective of the present study is to assess the influence of urban geometry to the wind environment of pedestrian space based on numerical simulation on airflow over urban-like obstacle. Large-eddy simulation (LES) is use to simulate the airflow over staggered uniform arrays with various plan area density and various aspect ratios. The spatially averaged profiles of mean wind speed and pedestrian wind environment were determine and compared. The result indicates that (1) the spatially-averaged mean wind speed monotonically decreases with the increases of packing density and aspect ratio and (2) the pedestrian mean wind shows the power law relationship to the frontal area ratio of building. In addition simple power law equation presents to explain the relationship.

KEYWORDS: LES, mean wind speed, aspect ratio, plan area ratio, frontal area ratio, pedestrian wind environment

1 INTRODUCTION

The urban wind environment is one of important factors determining the quality of life of urban habitants. Actually, the airflow within urban canopy layer is a driving force of wind-induced ventilation of room air of urban buildings, thus, urban wind condition affects the efficiency of passive control of room air quality. In addition, the transfer phenomena of heat, vapor, and other various types of scalar around urban buildings are deeply related with urban microclimate and Thermal comfort of pedestrian space [1].

Therefore the physical relation between urban geometry and pedestrian wind environment has been studied aiming for application in urban planning and building design toward more comfort and healthy city. For example, Kubota et al. [2] performed multi-point measurement of mean wind speed using scaled models of real urban districts in a wind tunnel, and revealed that pedestrian mean wind speed decreases linearly with building coverage. Studies focusing on airflow around idealized block arrays have also done [3-4]. Using such idealized block arrays allows them to identify significant and insignificant parameters on urban configuration efficiently. For example, Hang & Li [3] conducted CFD simulation on the effect of geometry on the air exchange rate inside the canyon and revealed that the air exchange rate depends on height of building and $\lambda_p$. Next, Zhang et al. [3] concluded that wind environment around the building strongly depends on the building layout and the wind direction.

In general, pedestrian wind environment is associated with the scalar dispersion which is strongly affected by the process of buoyancy and advection. Li X-X et al. [5] performed Large-Eddy Simulation (LES) on airflow of 2D street canyon with various conditions of building-heights to street-width ratio and reported that the low aspect ratio enhances effectively pollutant
removal. Boppana et al. [6] performed LES of scalar dispersion of 3D block arrays and investigated the influence of heterogeneous block height. They found that tall blocks located in a non-uniform height array generate a larger vertical flux above mean canopy height and weaker streamwise advection.

In the present work, we investigate the relationship between mean wind speed at pedestrian level of uniform urban block arrays and urban geometry parameters, such as plan area ratio (ratio of building roof to ground surface area, \( \lambda_p \)), frontal area ratio (ratio of building frontal area to ground surface area, \( \lambda_f \)) and building aspect ratio (ratio of building roof to frontal area, \( \alpha_p \)). Large-Eddy Simulation (LES) with fine Cartesian grid size is done to estimate the spatially distribution of scalar velocity and turbulent statistic within urban canopy layer. The accuracy of the calculated profiles is confirmed by comparing the data with numerical result of Kono et al. [7] and experimental data by Cheng & Castro [8]. Subsequently, mean wind speed at pedestrian derived from the present data of LES is presented under various conditions of urban geometry with a comparison against the experimental result by Kubota [2].

2 NUMERICAL SIMULATION

2.1 PALM

Detailed distributions of velocity over idealized urban arrays comprising uniform blocks are simulated using urban version of Parallelized LES Model (PALM) code firstly developed at Institute of Meteorology and Climatology, University of Hannover [9]. PALM can simulate the convective atmospheric boundary layer with explicitly resolved solid obstacles within three-dimensional domain on Cartesian grid. This code solves filtered Navier–Stokes equations with non-hydrostatic incompressible Boussinesq approximation. Finite difference method is used for the discretisation of the differential equation and 3rd order Runge-Kutta scheme is applied for time integration. Massive passing interface (MPI) is use for parallel communication. The further details of urban version of PALM code are described in [10].

<table>
<thead>
<tr>
<th>Arrays</th>
<th>Case</th>
<th>( \lambda_p ) (%)</th>
<th>( \alpha_p )</th>
<th>Block base size</th>
<th>Block height ( h )</th>
<th>Computational domain size ( L_x \times L_y \times L_z )</th>
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<tr>
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<td></td>
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<td>( L )</td>
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<tr>
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<tr>
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<td>( L )</td>
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<tr>
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<tr>
<td></td>
<td>RB1-44</td>
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<td>( L )</td>
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<td>( 3L )</td>
<td>( L )</td>
<td>( 9L \times 9L \times 4L )</td>
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</table>
2.2 Simulation set-up

Table 1 shows the geometry of the arrays analyzed in this study. All arrays consist of uniform rectangular blocks with square base are arranged in staggered layout; the geometry of them were decided based on our previous wind tunnel experiment [11]. A basic length scale of blocks defined as 25m (hereafter $L = 25m$) in all cases of this simulation which is 1000 times of basic length scale of the wind tunnel experiment [11]. Figure 1 shows the shape of the elements that constitute the arrays.

Periodic boundary conditions are imposed for both spanwise and streamwise boundaries to simulate a horizontal infinite block array. At the bottom of the domain, non-slip condition with Dirichlet type is imposed, and free-slip condition with Neumann type is used at the top of the domain. Because of periodicity, the domain consists of only four unit blocks in staggered arrangement (see Figure 2). The computational domain height ($L_z$) is 4 times of canopy height. The grid size for all cases is fixed to $L_z/64 (0.39m)$.

The fully developed flow inside computational domain was driven by height-independent constant pressure gradient using the following expression:

$$\frac{\partial P}{\partial x} = -\frac{\rho u_*^2}{L_z}$$

where $u_*$ = friction velocity and $L_z$ = computational domain height.

The $u_*$ is based on the friction velocity calculated by wind tunnel experiment [11]. It refers to the condition of roughness Reynolds number, $Re_*$, ranging from $1.1 \times 10^5$ to $4.0 \times 10^5$, based on the friction velocity ($u_*$) and roughness length ($z_0$) with the assumption that roughness length is about 10% of canopy height. According to Snyder and Castro [12], the fully rough turbulent flow is supposed to develop for condition of $Re_*$ exceeds $O(1)$. In addition, Uehara [13] mentioned that critical Reynolds number for canopy flow to be independent of viscous effect ranging be-
tween 2100 and 15000. Since the current simulation setting satisfies these criteria of Re*, the viscous effect is supposed to be negligible for all cases. A sequence of $200T$ ($T = h/u_*$, $h$ indicates block height) of the time series calculation data after initial duration about $200T$ is analyzed as data converge statistically to steady state. Although the duration $200T$ is shorter than that proposed by Coceal et al.[14], we confirmed the validity of the duration by comparing mean wind profiles within canopy derived from data of several durations.

2.3 Validation

Figure 3 shows vertical profiles of normalized streamwise mean velocity over a cubical array ST1 ($\lambda_p = 0.25$) derived from the current simulation, LES result by Kono et al. [7] and a wind tunnel measurement by Cheng & Castro [8] at four locations. The plots for all four measurement points show good agreement with the former data for $z/h < 2$. However the present result underestimates the streamwise mean velocity for $z/h > 2$ as compared to Kono et al.[7]. It is probably due to the different domain height. In their study, the domain height is about $7.5h$ which is greater than that of our simulation. In contrast, the present data qualitatively well agree with the measurement data by Cheng & Castro [8].

![Figure 3](image1)

Figure 3. Profile of mean streamwise velocity $u$, normalized by friction velocity $u_*$ at four different location of a cubical staggered arrays with $\lambda_p = 25\%$. (a) above a cube, (b) behind a cube, (c) in front of a cube and (d) in gap. Solid line: RB1-25; dashed line: LES data by Kono et al. [9]; symbol: wind tunnel data from Cheng & Castro [10].

![Figure 4](image2)

Figure 4. Vector and contour plot of normalized mean wind speed $V/V_{ref}$ of RB1-44 arrays at different horizontal plane height. The data at (a) $z = 0.05h$, (b) $z = 0.1h$, and (c) $z = 0.25h$. 
RESULT AND DISCUSSION

3.1 Flow structure

Mean wind speed within canopy is effective information to assess the thermal comfort of pedestrians. It is consists of mean part ant turbulent part as follows,

\[ V = \sqrt{\bar{u}^2 + u'^2 + 2\bar{u}u'} \]  

(2)

where \( i = \) indices (1,2, and 3).

A height of 1.5m from the ground surface can be translated into 0.05\( h \), 0.1\( h \) and 0.25\( h \) with the assumption that buildings have 10, 5 and 2 stories respectively and a floor height is 3 m. Since the Reynolds number effect is supposed to be negligible for the current simulation condi-
tion as mention before, the spatio-temporal average of mean wind speed at 0.05\(h\), 0.1\(h\) and 0.25\(h\) derived from the current simulation can be treated as the pedestrian wind speed in an urban building array with a building story of 10, 5 and 2, respectively.

We first present the normalized flow pattern of horizontal plane of RB1-44 to show the different trend of pedestrian airflow according to height in Figure 4. The vector plots indicate that reverse flow occurs in front of the block at \(z = 0.05h\) and 0.1\(h\) (see Figure 4a and b). Figure 4a shows a stronger reverse flow compared to Figure 4b. It might be due to the effects of both shear stress at the ground surface and strong downdraft occurs close to the ground surface. Unlike the similar vector plots for at \(z = 0.05h\) and \(z = 0.1h\), the result of \(z = 0.25h\) shown in Figure 4c shows different tendency. In this figure, a recirculating vortex pair occurs behind a block has high velocity in front of the block. These three figures indicate that the flow pattern systematically varies depending on the height. In addition, the wind speed decreases with the increase of the height especially at a height \(z = 0.25h\).

Next Figure 5 shows the effect of different block aspect ratio \(\alpha_p\) on flow pattern under the condition of \(\lambda_p = 44\%\). Comparison between Figures 5a and 5c, both contour and vector plot shows that the normalized wind speed increases especially between adjacent blocks for lower aspect ratio conditions. The reason why the array (RB1.5) shows very low mean wind speed near a street might be caused by the fact that the flow around an array consists of slender blocks is less affected by the longitudinal vortices generated in upward of blocks compared with the flow around a block array with low aspect ratio.

![Figure 6. Wind profiles inside canopy normalized by values at canopy height against \(\lambda_p\) (a) mean streamwise velocity (b) mean wind speed.](image)

![Figure 7. Wind profiles inside canopy normalized by values at canopy height against \(\alpha_p\) (a) mean streamwise velocity (b) mean wind speed.](image)
3.2 Spatially-average mean flow profile

Figure 6 indicates the vertical profiles of spatio-temporal average of velocity over cubical arrays (ST1) under various $\lambda_p$ conditions for streamwise velocity and mean wind speed $V$. The values are normalized by those at canopy height. The result of normalized streamwise velocity (see Figure 6a) indicates that the values of arrays with higher $\lambda_p$ are approximately lower, but the difference of velocity among arrays varies according to the height. In addition, the spatially averaged velocity of arrays with $\lambda_p$ over 33% show strong reverse flow below 0.16$h$ due to skimming flow regime. As a natural consequence, the mean wind speed profile is dependent with $\lambda_p$ similar to streamwise velocity, however, the values of arrays with $\lambda_p$ condition over 25% have an inflection point at a height of around 0.02$h$ because of the reverse flow near the street surface as we discussed in section 3.1.

Next, Figure 7 shows the profiles of spatially averaged streamwise velocity and mean wind speed of arrays with different block aspect ratio under the condition of $\lambda_p = 44%$. From Figure 7(a), it is clearly found that the streamwise velocity of array RB0.5-44 is significantly negative below $z = 0.35h$, and has the strongest reverse flow within canopy layer among four arrays, despite array block aspect ratio of RB0.5-44 is neither largest nor smallest. In contrast, the streamwise velocity of arrays RB1-44 and RB1.5-44 are nearly constant and zero within lower half of the canopy, and the mean wind speed of the arrays show small compared with the others. Since an array with high block aspect ratio refers to deep street canyon, it is supposed to be reasonable tendency. The mean wind profiles of all arrays are different from the curves of streamwise velocity profiles, and it suggests that the contribution of turbulence part to total kinetic energy is large in pedestrian space. In addition, wind speed profiles of arrays with block aspect ratio below 1.0 have inflection points.

3.3 Effect of building geometry on pedestrian wind speed

3.3.1 Dependencies of plan area ratio and block aspect ratio

Kubota et al. [2] reported that the plan area ratio strongly affects mean wind speed ratio (the wind speed around the models measure at 5 mm height in the wind tunnel divide by the wind speed at the same height without models) of scaled models of real urban districts consist of various building types. In the present study, mean wind speed ratio was computed by the scalar velocity at pedestrian level normalized by the value at half of computational domain height ($2h_{max}$). Figure 8 shows the relationship between the mean wind speed ratio and the plan area ratio for 3 types of building height, 10, 5, and 2 stories. The wind tunnel data of Kubota et al. [2] are used for comparison. The data of the present experiment shown in Figure 8 (a), (b) and (c) are calculated based on assumption that buildings are 10, 5 and 2 storey respectively.

The mean wind speed of each array monotonically decreases as plan area ratio increases. Such decreasing tendency is consistent with that of the experiment using scaled real urban districts by Kubota. However, the scattering data of mean wind speed due to different block aspect ratio ($\alpha_p$) at $\lambda_p = 44.4%$ suggests that plan area ratio is not a parameter to assess universally the pedestrian wind speed. The mean wind speed for arrays with low $\alpha_p$ is higher than that for arrays with high $\alpha_p$. It is reasonable tendency; because arrays with low $\alpha_p$ refer to shallow street canyon.
3.3.2 Dependencies of frontal area ratio

Frontal area ratio $\lambda_f$ is another important building parameter to evaluate the urban effect on wind environment, because the frontal area of the block is a factor where the pressure drag exerting on the flow [16]. Figure 9 shows the relationship between $\lambda_f$ and mean wind speed ratio, in which the data derived based on three different assumptions of building height as mentioned before are illustrated. Figures 9a, b and c indicate that the relationship between $\lambda_f$ and $V/V_{2h}$ is similar to that between $\lambda_p$ and $V/V_{2h}$, but the former one is more universal.

3.4 Simple estimation of pedestrian wind environment

A simple mathematical equation can be derived from the present result to estimate the effect of urban geometry on pedestrian wind speed. Based on the non-linear least square method, the mean wind speed velocity ratio can be expressed by simple power law equation as a function of $\lambda_f$ as below,

$$V/V_{2h} = 2.5 \lambda_f^{-4/5}$$  \hspace{1cm} (3)

Figures 9a, b and c include the estimates based on equation (3), which agree well with the LES result for all conditions especially in higher frontal area ratio. Thus it is supposed that the equation can be used for assessment of the effect of urban building density on pedestrian wind environment especially in densely packed cities like Tokyo or Hong Kong.

Figure 8. Relationship between $\lambda_p$ and mean wind speed ratio of cases. (a) $z=0.05h$; (b) $z=0.1h$; (c) $z=0.25h$. 
4 CONCLUSION

We have performed Large-eddy simulation of flow over block arrays with various conditions of $\lambda_p$ and $\alpha_p$, and the following conclusions are reached. First, the flow patterns clearly indicate the effect of both $\lambda_p$ and $\alpha_p$. Different distribution of the wind speed at different horizontal plane height can be translated the pedestrian wind distribution of urban street with different building height. Secondly, the mean wind speed within canopy region is strongly influenced by $\lambda_p$ and $\alpha_p$. The mean wind speed increases with decreasing $\lambda_p$ and $\alpha_p$ within the canopy, and it indicates that the porosity of the building arrays affect the efficiency of ventilation in pedestrian space. Thirdly, the wind speed at pedestrian level show a relatively universal relationship with the frontal area ratio regardless of block aspect ratio and building height, and the tendency can be expressed by a simple power law equation.

5 ACKNOWLEDGEMENTS

The authors wish to express our gratitude to Dr Kono and Professor Kubota, for providing data sets that have been valuable in the validation of our work. This research was financially supported by grant-in aid for scientific research (22360238) from the Ministry of Education, Science and Culture of Japan, and Asahi glass foundation. These simulations were performance on the Kyushu University IBM supercomputing centre.

6 REFERENCES