Large-eddy simulations of air ventilation in parametric scenarios: comparative studies of urban form and wind direction

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ABSTRACT

This study evaluates effects of building form and wind direction on urban ventilation using a large-eddy simulation (LES) model. Numerical simulations of air flow in 80 sets of parametric scenarios are conducted and the results are cross-compared. Main findings and potential recommendations for urban planning are: First, high mean building height is generally not good for ventilation, as vertical momentum is prevented from penetrating inside the street canyon. Second, inhomogeneous building heights tend to decrease the variance of site-averaged velocity ratios compared to homogeneous scenarios. Horizontal ventilation is moderated by the vertical momentum generated by inhomogeneous building heights. Third, rectangular (1:2 horizontal size) building arrays may allow better ventilation than square (1:1 horizontal size) building arrays. Moreover, given a moderate ground coverage ratio in square building arrays, 45° wind input allows better ventilation than 0° wind input. Finally, in cases of square arrays, higher ground coverage ratios result in lower site-averaged velocity ratios. But in the case of rectangular arrays, this negative relationship may be reversed.

1. Introduction

Air ventilation in city design and urban planning is a crucial factor for healthy living and comfortable thermal sensations (Arnfield 2003). In subtropical high-density cities such as Hong Kong, urban ventilation, which can be defined as provision of fresh air to an urban area, is a way of mitigating the negative effects of urban heat islands (Ng and Cheng 2012; Wang et al. 2016). In such cities, air ventilation assessment (AVA) is usually required by the local government prior to construction of new buildings, development of new towns, or redevelopment of old towns (Ng 2009). In AVA practices, computational fluid dynamics (CFD) techniques, such as the Reynolds-averaged Navier-Stokes (RANS) model and large-eddy simulation (LES), are frequently used tools. RANS models have been more commonly used due to their low computational cost. However, LES overcomes the deficiencies of RANS by explicitly resolving large, energy-containing turbulent eddies and parameterizing only small (subgrid-scale) turbulence (Tamura 2008). LES provides not only mean flow fields but also instantaneous turbulences, which are especially important for human comfort at the pedestrian level.

Urban ventilation is strongly influenced by wind speed and direction, which in turn are affected by three-dimensional urban morphology (Skote et al. 2005). As a complex of the individual shapes and dimensions of buildings and their arrangement in the city, urban density can be described by geometric parameters. Parametric studies, which simplify actual urban geometries into idealized configurations, are widely applied in urban ventilation studies for their advantage of linking specific factors to ventilation performance. Parametric studies of outdoor ventilation are often associated with modeling, either wind tunnel tests or numerical simulations. This study focuses on numerical methods using CFD techniques.

Using the RANS turbulence model, Ho, Liu, and Wong (2015) examined flows over idealized two-dimensional street canyons of different building aspect ratios and urban boundary-layer depths for street-level urban ventilation. Lin et al. (2014) investigated urban canopy-layer ventilation with a uniform value of 0.25 in both the ground coverage ratio (CR) and frontal area index but with various urban sizes. Buccolieri et al. (2015) investigated ventilation in dense building arrays with CR values like those of typical European cities. Other studies focused on impacts of specific factors, such as building porosity (Yuan and Ng 2012), building height variation (Chen et al. 2017), and approaching wind direction (Zahid Igbal and Chan 2016; Hang et al. 2013) on urban ventilation. Ramponi et al. (2015) reviewed CFD studies of outdoor ventilation for generic urban configurations and indicated that there is a lack of studies of urban configurations in which all parallel streets do not have equal widths, which initiated their CFD simulation of ventilation in generic urban configurations with different urban densities and equal and unequal street widths. Pedestrian-level wind studies

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for wind comfort assessment using wind tunnel and CFD techniques are reviewed by Blocken, Stathopoulos, and van Beeck (2016).

Most previous studies have used RANS models. More importantly, they have focused on only one or two factors, or have used single buildings or relatively simple setups with a few blocks (Yang et al. 2016; Ai and Mak 2017). Comprehensive parametric studies considering several varying practical parameters are rarely found. The objective of this study is to evaluate ventilation performance in parametric configurations considering different aspects of urban form and wind direction. We use an LES model to produce CFD simulations of air flow in 80 parametric urban scenarios, each containing up to 100 building arrays. The generic scenarios are configured with a local focus of morphological features in Hong Kong. Figure 1(b) demonstrates the CR probability taken from a typical high-density urban area of Kowloon, Hong Kong (the dashed box in Figure 1(a), which is one of the main parameters used in parametric configurations.

2. Methodology

2.1. Parametric scenarios

This study is devoted to linking the effects of building dimensions, urban form, and wind direction to neighborhood-scale urban ventilation. The parametric scenarios are designed to reach this objective. First, a floor area including street areas around the building is assumed as $100 \text{ m} \times 100 \text{ m} (10,000 \text{ m}^2)$. The building is in the middle of this floor area. Two types of horizontal building aspect ratios are considered. X1 represents a ratio of frontal building size (*D*) to lateral building size (*L*) that is 1:1 (square), while X2 means this ratio is 1:2 (rectangle). According to Figure 1(b), we consider 6 values for CR, which is the major variable, from 10% to 60% (Table 1). The horizontal building-street layouts are computed:

$$D \times L = 10000 \times CR \tag{1}$$

$$W_{\rm S} = 100 - D$$
 (2)

$$W'_{\rm S} = 100 - L$$
 (3)

where W_S and W'_S are the parallel and perpendicular (to 0° input wind direction) street width, respectively. In the case of X1, D = L. In the case of X2, L = 2D.

The site area is assumed to be 1 km^2 ; that is, each parametric scenario is a composite of 10×10 building arrays. A three-dimensional schematic diagram of the parametric scenario setup is shown in Figure 2. Another parameter to be investigated is mean building height (H). The urban canopy-layer height is about 60 m in high-density urban areas of Hong Kong (Ng et al. 2011). According to Figure 1(a), we select two mean building heights, 30 and 60 m. For building height differential, both homogeneous (HM) and inhomogeneous (IM) building heights are considered. Homogeneous scenario means all building heights are the same (30 or 60 m) in the entire scenario, while inhomogeneous scenario means that building heights vary randomly. For IM scenarios, building heights are generated by a normally distributed random series, which is given a mean H of the corresponding HM case and a standard deviation of H/4. According to the tolerance intervals of normal distribution, a standard deviation of H/4 can basically (99.99%) ensure that no negative random building heights will be generated. Finally, for input wind direction, 0° and 45° winds are considered in LES experiments. The prescribed values of these parameters are listed in Table 1.

Horizontal dimensions (building sizes and street widths) are computed in Table 1 and Equations (1) – (3). All values are coerced to the closest even-integral numbers, as the horizontal resolution in the LES experiments (introduced in the next section) is 2 m. In case of X2, L will equal (exceed) 100 m when CR is 50% (60%). Therefore, a total combination of 80 scenarios, 48 for X1 and 32 for X2, are obtained. The nomenclature of scenario IDs is given in Table 1 as well. All 80 named scenarios are listed in Table 2.

2.2. Large-eddy simulations

The LES model used in this study is the Parallelized LES Model (PALM) version 4.0 (Maronga et al. 2015). The governing equations are based on the non-hydrostatic, filtered, incompressible Navier-Stokes equations with Boussinesq approximation and are filtered implicitly using the volume-balance approach of Schumann (Schumann 1975). The first law of thermodynamics and an equation for subgrid-scale turbulent kinetic energy are used in the basic model. The Monin-Obukhov similarity theory is applied between the surface and the first grid level. A Prandtl layer is assumed at each surface. The modified version (Saiki, Moeng, and Sullivan 2000) of the 1.5-order Deardorff scheme (Deardorff 1980) is used for turbulence closure.

2.2.1. Output indicator and experimental setups

In AVA studies, we are especially interested in pedestrian-level wind velocity. The velocity ratio (VR) is used as an indicator. VR is calculated by V_p / V_∞ , where V_p is the wind velocity at the pedestrian level (2 m above the ground), and V_∞ is the wind velocity at the top of the boundary layer not affected by ground roughness. In both V_p and V_∞ , only horizontal velocity components are accounted for. A top boundary layer height of 500 m, which is commonly used in AVA, is adopted.

As we are focusing mainly on pedestrian-level VR, the input wind speed is not very important, and if high wind speed is used, more computational time will be needed because the time steps are shorter. Therefore, a low-velocity wind of 1.5 ms^{-1} is prescribed to save computational time. The time step lengths are optimized in the LES model. Winds are input from the left for 0° wind and from the left-bottom for 45° wind. Horizontal grid sizes are equidistantly 2 m. The vertical grid spacing is 2 m below 300 m and stretched with a stretch factor of 1.04 above. The governing equations of PALM are spatially discretized on an Arakawa-C grid. Scalar variables are defined at the grid centres, while velocity components are shifted by half of the grid spacing. Therefore, the horizontal velocity output from the 1 and 3 m levels is linearly interpolated to obtain V_P at 2 m above the ground.

The total simulation time is 6 h. The first 2 h are excluded in the analysis of the results, as the turbulences need this time to spin-up (Letzel, Krane, and Raasch 2008). The simulated results from the 3rd to the 6th hours are averaged for analysis. Cyclic



Figure 1. (a) Urban morphology in typical high-density areas on the Kowloon Peninsula and the northern margin of Hong Kong Island, Hong Kong. (b) Ground coverage ratio calculated in a $2 \text{ km} \times 2 \text{ km}$ domain on the Kowloon Peninsula, enclosed by the dashed box in (a); the sampling grid size is $100 \text{ m} \times 100 \text{ m}$.

Table 1. Prescribed values (nomenclature in parentheses) of 5 parameters for defining 80 scenarios.

Parameters to be investigated			Given			
Horizontal building aspect ratio Ground coverage ratio Building height Height differential Wind direction	1:1 (X1) 10% (CR10) 30 m (H30) Homogeneous (HM) 0° (00)	20% (CR20)	30% (CR30)	1:2 (X2) 40% (CR40) 60 (H60) Inhomogeneous (IM) 45° (45)	50% (CR50)	60% (CR60)

(periodic) boundary conditions are adopted in both the streamwise and spanwise directions. The no-slip bottom boundary condition with a Prandtl layer and the free-slip top boundary condition are applied to horizontal velocity components. The simulations are restricted to neutral atmospheric stratification. Thermal effects are not considered.

2.2.2. Model validation

PALM has been validated and widely used in simulations of street canyon flows and urban ventilation in recent years (Kanda et al. 2013; Park and Baik 2014; Letzel et al. 2012; Keck et al. 2014; Wang, Xu, and Ng 2018; Wang and Ng 2018). In this study, we use the Architectural Institute of Japan (AIJ) guidelines (Tominaga et al. 2008), which are based on cross-comparisons of CFD predictions, wind tunnel tests, and field measurements, to verify the

LES codes. The CFD setups and experimental data can be downloaded on the AIJ website (www.aij.or.jp/jpn/publish/cfdguide/ index_e.htm).

We conducted LES experiments with simple building blocks that comply with AIJ guidelines. The experiments include 9 buildings with a uniform building height of H = 20 m, except the one in the middle, which is prescribed a varying height for each case of 0H, 1H, and 2H, respectively (Figure 3(a)). The buildings are horizontally foursquare, and both the buildings and the streets are 20 m wide. It is noteworthy that such building setups followed the AIJ guidelines only for CFD validation purpose, are different from the parametric scenarios given in Section 2.1. The inlet mean wind profile is the same as that given in the guidelines and shown in Figure 3(b). Two wind directions, 0° and 45°, are included. Velocity (normalized by inflow velocity at the same height) taken from 120 test points at 2 m above the ground

Table 2. Parametric scenario IDs and LES-computed site-averaged velocity ratio (VR).

No.	Scenario ID	VR												
1	X1CR10H30HM00	0.193	17	X1CR10H60HM00	0.141	33	X2CR10H30HM00	0.250	49	X2CR10H60HM00	0.192	65	X1CR50H30HM00	0.199
2	X1CR20H30HM00	0.159	18	X1CR20H60HM00	0.119	34	X2CR20H30HM00	0.253	50	X2CR20H60HM00	0.262	66	X1CR60H30HM00	0.144
3	X1CR30H30HM00	0.166	19	X1CR30H60HM00	0.115	35	X2CR30H30HM00	0.331	51	X2CR30H60HM00	0.298	67	X1CR50H30HM45	0.181
4	X1CR40H30HM00	0.162	20	X1CR40H60HM00	0.096	36	X2CR40H30HM00	0.346	52	X2CR40H60HM00	0.307	68	X1CR60H30HM45	0.146
5	X1CR10H30HM45	0.231	21	X1CR10H60HM45	0.198	37	X2CR10H30HM45	0.212	53	X2CR10H60HM45	0.218	69	X1CR50H30IM00	0.150
6	X1CR20H30HM45	0.222	22	X1CR20H60HM45	0.207	38	X2CR20H30HM45	0.230	54	X2CR20H60HM45	0.213	70	X1CR60H30IM00	0.142
7	X1CR30H30HM45	0.223	23	X1CR30H60HM45	0.158	39	X2CR30H30HM45	0.251	55	X2CR30H60HM45	0.254	71	X1CR50H30IM45	0.181
8	X1CR40H30HM45	0.182	24	X1CR40H60HM45	0.125	40	X2CR40H30HM45	0.339	56	X2CR40H60HM45	0.276	72	X1CR60H30IM45	0.183
9	X1CR10H30IM00	0.191	25	X1CR10H60IM00	0.156	41	X2CR10H30IM00	0.230	57	X2CR10H60IM00	0.182	73	X1CR50H60HM00	0.098
10	X1CR20H30IM00	0.172	26	X1CR20H60IM00	0.156	42	X2CR20H30IM00	0.200	58	X2CR20H60IM00	0.154	74	X1CR60H60HM00	0.121
11	X1CR30H30IM00	0.169	27	X1CR30H60IM00	0.146	43	X2CR30H30IM00	0.225	59	X2CR30H60IM00	0.148	75	X1CR50H60HM45	0.116
12	X1CR40H30IM00	0.161	28	X1CR40H60IM00	0.138	44	X2CR40H30IM00	0.231	60	X2CR40H60IM00	0.160	76	X1CR60H60HM45	0.096
13	X1CR10H30IM45	0.247	29	X1CR10H60IM45	0.204	45	X2CR10H30IM45	0.249	61	X2CR10H60IM45	0.229	77	X1CR50H60IM00	0.140
14	X1CR20H30IM45	0.239	30	X1CR20H60IM45	0.225	46	X2CR20H30IM45	0.220	62	X2CR20H60IM45	0.206	78	X1CR60H60IM00	0.136
15	X1CR30H30IM45	0.212	31	X1CR30H60IM45	0.215	47	X2CR30H30IM45	0.228	63	X2CR30H60IM45	0.214	79	X1CR50H60IM45	0.175
16	X1CR40H30IM45	0.188	32	X1CR40H60IM45	0.193	48	X2CR40H30IM45	0.267	64	X2CR40H60IM45	0.239	80	X1CR60H60IM45	0.189



Figure 2. Schematic diagram of parametric setups. The floor area, including street areas around the building, is 100 m \times 100 m. The building is in the middle of the floor area. Each scenario is a composite of 10 \times 10 building arrays.



Figure 3. LES experimental setups for validation by AIJ guidelines: (a) building arrays of three cases, (b) input mean wind profile, and (c) input wind direction and location of test points (black dots).

is used to validate the LES results. The test point locations are shown in Figure 3(c).

The validation results are shown in Figure 4. Generally, the scatter dots of the 0° wind experiments are located close to the diagonal lines, but the results predicted by LES may have slightly underestimated the near-surface velocity compared to AIJ guidelines, particularly in test points with relatively low wind speed. Linear regression with an R^2 of 0.82, 0.77, and 0.60 can be obtained for cases 0H, 1H, and 2H, respectively. In general, no significant deviations are found in the validations of 0° wind simulations. The scatter dots of the 45° wind experiments are relatively more scattered than those of the 0° wind input. Linear regression with an R^2 of 0.41, 0.65, and 0.54 can be obtained

for cases 0H, 1H, and 2H, respectively. For such point-to-point comparison, the result is acceptable. More importantly, the regression lines are in line with the diagonal line, which implies that the predicted means are consistent with the guideline results. The LES model is therefore deemed reliable for the task at hand.

3. Results and discussion

One major parameter for AVA practices is the site-averaged VR, which defined as the averaged VR in all street (unbuilt) grid points of one scenario. The site-averaged VRs of all 80 scenarios are listed in Table 2. In the calculation of LES-computed VRs,



Figure 4. Linear regression between referential velocity of AIJ guidelines and LES results taken from 120 test points at 2 m above the ground in idealized building blocks for (a) Case 0H with 0° wind, (b) Case 1H with 0° wind, (c) Case 2H with 0° wind, (d) Case 0H with 45° wind, (e) Case 1H with 45° wind, and (f) Case 2H with 45° wind.

we use all data in the entire scenario without a buffer zone. The justifications are: First, due to the cyclic lateral boundary conditions adopted in the simulations and the symmetrical setting of all scenarios, the effects of the lateral boundary on the results are minimized. This can be seen from Figure 5, which demonstrates the entire spatial distribution of VRs from some typical parametric examples. Therefore, buffer zones are not necessary. Second, as the random function in generating IM building height is applied to the entire scenario, all data in the domain should be used in the analysis; otherwise, HM and IM building heights are not comparable.

Boxplots are used to demonstrate how various factors affect ventilation performance. In each box, the central mark is the median value, the edges of the box are the 25th (q_1) and 75th (q_3) percentiles, and the whiskers extend to the minimum and maximum data points, not considering outliers. The maximum whisker length is w = 1.5. Data points are plotted as outliers if they are larger than $q_3 + w(q_3 - q_1)$ or smaller than $q_1 - w(q_3 - q_1)$. Outliers are plotted individually. Based on the generic configurations and LES outputs, the effects of different factors on ventilation are evaluated one by one. An overview is shown in Figure 6. Each box contains 40 samples except Figure 6(c), which has 32 samples in one box.

3.1. Effects of mean building height

We first analyze the effects of mean building height on ventilation performance. The lower mean building height setting of H30 generally provides better ventilation performance than H60 cases (Figure 6(a)). The analysis of variance suggests that the site-averaged VRs from the H30 group and the H60 group are significantly different in terms of sample means at the 0.05 significance level (*p*-value less than 0.05). The main cause should be that a deeper street canyon in the higher mean H setting allows weaker wind loads to penetrate to the pedestrian level. This can be explained by Figure 7, which shows the profiles of vertical momentum flux averaged in all H30 (solid lines) and H60 (dashed lines) scenarios. This flux is obtained simply by multiplying the vertical velocity component and one horizontal velocity component. Figure 7 shows that H30 scenarios provide stronger near-surface momentum penetrations from upper levels than H60 scenarios.

But there are a few exceptions, in which site-averaged VRs in H30 scenarios are slightly smaller than those of H60. For example, in scenarios X1CR30H30IM45 (Figure 5(d)) and X1CR30H60IM45 (Figure 5(h)), the site-averaged VRs are 0.212 and 0.215, respectively, as given in the No. 15 and No. 31 scenarios of Table 2. One explanation for this exceptional case is that the inhomogeneous building height of H60 produces stronger vertical turbulent motion than that of H30, which increases the pedestrian-level wind speed, as the standard deviation of the random function in generating building height is H/4. Larger mean H also means larger inhomogeneity. Above all, high mean building height with deep street canyons, as in urban Hong Kong (Figure 1), is not good for pedestrian-level ventilation. But a few exceptions in the parametric assessment imply that wind speed and turbulence level in the street canyons are very sensitive to building dimensions and urban form, and thus are highly complicated.



Figure 5. Spatial distribution of LES-computed VRs in 16 examples.

3.2. Effects of building height differential

According to Figure 6(b) and analysis of variance, differences between the site-averaged VRs of the HM group and the IM group are nonsignificant. But IM tends to decrease the variance of site-averaged VRs compared to HM. The median of the IM group is close to that of the HM group, while the 25th percentile and minimum are larger, and the 75th percentile and maximum are smaller (Figure 6(b)). This implies that IM tends to increase (decrease) site-averaged VRs of low (high) ventilation scenarios in the HM group. As IM scenarios always generate stronger vertical (downward) motion than HM at the pedestrian level when other factors are the same (Figure 8), vertical momentum generated by inhomogeneity in building height may be a factor in moderating horizontal ventilation. Figures 8 and 9 illustrate this deduction in detail.

Figure 9 divides the boxplot of Figure 6(b) into a few groups according to different factors. Two points can be deduced from

Figure 9: First, the effect of the height differential is nonsignificant for X1H30 cases, but IM is significantly better than HM for X1H60 cases. This is true for both 0° wind (Figure 9(a)) and 45° wind (Figure 9(b)). This is because higher mean building height (H60) also means larger height differential (the standard deviation of the random function in generating IM is H/4). Figure 5(a–h) demonstrates some examples of the effects of building height differential on pedestrian-level ventilation in X1 scenarios. Second, HM is significantly better than IM in X2 with 0° wind cases (Figure 9(c)), while for X2 with 45° wind cases, the effect of height differential is nonsignificant (Figure 9(d)). Figure 5(i–p) shows some examples of the effects of building height differential on pedestrian-level ventilation in X2 scenarios.

When Figures 8 and 9 are examined together, we discover that smaller differences in site-averaged vertical velocity between HM and IM cases at the pedestrian level (2 m above the ground, as denoted by the dashed horizontal line) in Figure 8



Figure 6. Boxplots for identifying the effects of (a) mean building height, (b) height differential, (c) horizontal building aspect ratio, and (d) wind direction on ventilation performance.



Figure 7. Horizontally averaged profiles of the (a) u-component, and (b) v-component of the total vertical momentum flux. Solid (dashed) lines are the average of all H30 (H60) scenarios. Negative values indicate downward propagation.

always correspond to smaller differences in site-averaged VRs in Figure 9. The first two boxes of Figure 9(a and b) correspond to the black lines of Figure 8(a and b), and Figure 9(d) corresponds to Figure 8(d). On the other hand, larger differences in site-averaged vertical velocity between HM and IM cases at the pedestrian level in Figure 8 always correspond to larger differences in site-averaged VRs in Figure 9. The last two boxes of Figure 9(a and b) corresponds to Figure 8(a and b), and Figure 9(c) corresponds to Figure 8(c). But it is noteworthy that in the cases of X1H60, HM has relatively weak ventilation and IM increases ventilation performance, while in cases of X2 with 0° wind input, HM has relatively good ventilation and IM decreases ventilation performance. Therefore, we deduce that vertical momentum generated by

inhomogeneity of building height is a factor in balancing horizontal ventilation.

3.3. Effects of building aspect ratio

Figure 6(c) and the analysis of variance suggest that the site-averaged VRs of the X1 group and the X2 group are significantly different at the 0.05 significance level. X2 scenarios provide obviously better ventilation performance than X1 scenarios. The boxplot of Figure 6(c) is divided into several groups according to different factors and shown in Figure 10, which further shows that X2 is better in most cases. For HM and 0° wind cases (Figure 10(a)), the minimum site-averaged VRs of



Figure 8. Horizontally averaged profiles of vertical velocity (w-component) at low levels for (a) 1:1 horizontal building size ratio and 0° wind, (b) 1:1 horizontal building size ratio and 45° wind, (c) 1:2 horizontal building size ratio and 0° wind, and (d) 1:2 horizontal building size ratio and 45° wind. Black (red) lines represent H30 (H60) scenarios. Solid (dashed) lines represent HM (IM) scenarios. Negative values indicate downward motion.



Figure 9. Ventilation performance associated with building height differential.



Figure 10. Ventilation performance associated with building aspect ratio.

X2 scenarios are larger than the maximum value of X1 scenarios. This is true for both H30 and H60 scenarios. A similar situation is found for the H30IM00 (Figure 10(b)) and H60HM45 (Figure 10(c)) scenarios. For other cases, the differences are not so large, but the ventilation performance of the X2 group is still significantly better than that of the X1 group. As demonstrated in the examples in Figure 5, rectangular building arrays have a much larger parallel-to-perpendicular street width ratio compared to the square building arrays when given a uniform building coverage. Therein, a much larger zonal wind speed can be captured. This is particularly true for HM and 0° wind cases.

3.4. Effects of input wind angle

According to Figure 6(d) and the analysis of variance, the siteaveraged VRs of the 0° wind group and the 45° wind group are significantly different at the 0.05 significance level. It is surprising that 45° wind input provides significantly better ventilation performance than 0° wind input. But Figure 6(d) suggests that the range (from the minimum to the maximum) of 45° wind cases is close to that of the 0° wind cases, especially when including outliers. Therefore, the effects of input wind direction are analyzed by Figure 11 in detail. In Figure 11, all parametric settings are the same in a pair of circles except input wind angle. In X1 and HM cases (Figure 11(a)), 45° wind provides larger site-averaged VRs in all scenarios with CR not larger than 40%; in X1 and IM cases (Figure 11(b)), 45° wind cases are always better ventilated than 0° wind; in X2 and HM cases (Figure 11(c)), 0° wind is better in most scenarios; in X2 and IM cases (Figure 11(d)), 45° wind cases are better ventilated.

We calculate the site-averaged velocity (normalized by inflow velocity at the same height) of the AIJ guidelines that are used in

LES model validation. The guidelines provide only a 1:1 horizontal building dimension ratio, and the ground coverage ratio is 25% (Figure 3). In cases of 0° wind, the site-averaged wind speeds for Case 0H, Case 1H, and Case 2H are 0.657, 0.654, and 0.719, respectively. In cases of 45° wind, the site-averaged wind speeds for Case 0H, Case 1H, and Case 2H are 0.748, 0.804, and 0.921, respectively. These results suggest that the guideline results are in line with our LES experiment in that 45° wind provides better ventilation performance than 0° wind when given a 1:1 horizontal building size ratio and a moderate ground coverage ratio. Theoretically, 45° wind input may create more eddies than 0° wind input. To some extent, these eddies can increase the mean wind speed around buildings. But such accelerations are related to building density (Figure 6(d)).

3.5. Effects of ground coverage ratio

In this study, we prescribe 6 close values of CR (4 for X2 cases) according to Figure 1(b), so as to provide enough statistical samples when focusing on the effects of other factors on ventilation performance. Another reason is that the significance of CR in ventilation has been widely discussed (Wang et al. 2017; Gronemeier, Raasch, and Ng 2017). But parametric studies giving many prescribed CR values have rarely been done. Figure 12 shows that in such cases (given a 10% interval of CR in parametric settings), the effect of CR on site-averaged VRs is not very distinguishable. For X1 cases, higher CR results in lower site-averaged VR (Figure 12(a)). The analysis of variance suggests that the difference is significant at the 0.05 significance level (at least one sample mean is significantly different from the other sample mean in the boxes of Figure 12(a)). For X2 cases, the situation is totally different. It seems that higher CR results in higher siteaveraged VR (Figure 12(b)). The analysis of variance suggests that



Figure 11. Ventilation performance associated with input wind direction. Solid (dashed) lines represent site-averaged VRs of 0° wind (45° wind) cases. In each pair of circles, all parametric settings are the same except input wind angle. The corresponding ground coverage ratio (CR) and mean building height (H) of each pair are listed on the x-axis. (a) X1 and HM scenarios; (b) X1 and IM; (c) X2 and HM; (d) X2 and IM.



Figure 12. Ventilation performance associated with ground cover ratio. (a) X1 cases, and (b) X2 cases.

the difference is significant at the 0.1 significance level (*p*-value is larger than 0.05 but smaller than 0.1).

4. Conclusions

LES has many advantages for the numerical study of urban wind environments. This study employs an LES model to model wind flows in 80 sets of parametric scenarios and to comprehensively evaluate the effects of various factors of urban form and wind direction on urban ventilation. The main findings and potential recommendations for urban planning are: First, higher mean building height with deep street canyons obstructs the penetration of vertical momentum to lower levels; hence it is not good for pedestrian-level ventilation. But exceptions in the parametric assessment imply that wind speed and turbulence level in street canyons are very sensitive to building dimensions and urban form, and thus are highly complicated. Second, inhomogeneous building heights tend to decrease the variance of site-averaged VRs compared to homogeneous scenarios. Vertical momentum flux may be a factor in balancing horizontal ventilation. Third, rectangular building arrays (X2 scenarios), which have larger parallel-to-perpendicular street width ratios, have significantly better ventilation than square arrays (X1 scenarios). This is particularly true for HM and 0° wind cases. Fourth, given a moderate ground coverage ratio in square building arrays, 45° wind input results in better ventilation performance than 0° wind input. This is demonstrated by both experimental results of CFD guidelines and LES outputs. Finally, in cases of square arrays, higher ground coverage ratios result in lower site-averaged VRs. But in cases of rectangular arrays, this negative relationship can be reversed.

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