EVALUATION OF VENTILATION PERFORMANCE IN VOID SPACE BY EXCEEDANCE PROBABILITIES BASED ON CFD SIMULATION

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ABSTRACT

In this present study, annual exceedance probability (AEP) analysis was applied as the method for assessing wind-driven natural ventilation in a street canyon, in which the effects of wind approaching from each direction were comprehensively taken into account. In order to evaluate the overall ventilation performance in specific domain spaces within the street canyon, local air change rate and average kinetic energy were employed to calculate the AEP, instead of using the commonly adopted velocity ratio. Thus, two domain-oriented AEPs, local air change rate-based AEP and local kinetic energy-based AEP, were proposed with the local air change rate and average kinetic energy of the void derived from CFD simulation. A three-dimensional symmetric model including three parallel canyons was used as an illustration to analyze the distributions of AEPs by using the statistical wind data from the Tokyo Meteorological Observatory. The simulation results indicated that the most favorable orientation is “East” and the most adverse is “North-North-East” for a canyon model located in the urban Tokyo area. The influences of width on ventilation efficiency were also investigated by using the distributions of AEPs.

KEYWORDS

Void, Ventilation Performance, Annual Exceedance Probability (AEP), Local Purging Flow Rate (LPFR), Local Kinetic Energy (KE)

INTRODUCTION

With the urbanization process, the built-up areas of big cities are developing with greater numbers of long, narrow streets flanked by buildings. The problems associated with pollution within these so-called street canyons have received increasing attention over the past decades. As flow fields in street canyons are complicated and often characterized with recirculation vortices, their interior contaminants, mainly emitted from vehicles and other human activities, have difficulty escaping the canyon to be dispersed into the outside atmosphere, and often remain trapped at ground level. In this study, these domains, located in the lower tier of a street canyon with high levels of pollutants, are uniformly referred to as “Void” space (Kato and Ishida 2005). Free atmosphere above the roof of these canyons can be deemed the main clean source capable of diluting the interior pollutants by wind-driven ventilation through the open top of the street canyons. Due to the limited street width in most cases, this ventilation performance mainly relies on the strength of the vertical turbulence transport effect between the roof level wind and the circulatory flow inside the canyon. In other words, once the layout of a street canyon and its surrounding buildings is fixed geometrically, the flow characteristics and the pollutant transport phenomena from the void space are governed by the wind speed and direction of the free stream above the roof level.

The void space is closest to the human living environment and has a great influence on the air quality, so it is very important and necessary to assess its ventilation potential and performance correctly and comprehensively. In some research, annual exceedance probability (AEP) methods have been applied

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to assess environmental wind conditions at ground level, in which wind velocity ratios were obtained from measurement in-situ, wind-tunnel experiment or CFD simulation. Ventilation performances for some void spaces in built-up areas were also evaluated based on CFD simulation, using indices, such as Local Purging Flow Rate (LPFR) and SET* (Ishida and Kato 2005). Based on these research studies, this paper proposes a new assessment method for the void space based on a combination of AEP analysis and two domain-averaged indices, local air change rate or local average kinetic energy. A calculation illustration is also given using statistic wind data for Tokyo. The AEP distributions are then analyzed in detail for different street widths and orientations.

STREET CANYON MODEL

Figure 1 shows the configuration of a computational street canyon model. Here, three isolated street canyons are arranged in parallel along the X coordination at a distance apart of 100 m, in order to investigate stream-wise influences. In this model, each canyon is located below ground level, where L = 100 m; L is the canyon length and H = 9 m; H is the height and W is the width varying from 1 m to 6 m. At the centre-bottom of each canyon, a rectangular domain (W × 10 m × 3 m in the X, Y, and Z axes respectively) is defined as void space for further discussion.

As shown in Figure 2, the horizontal plane is divided into 16 azimuths, marked with the symbol n starting from North-North-East (NNE) in a clockwise direction. The direction of the short axis of the canyon is defined as its orientation and the canyon orientation angle is represented by \( \beta \). For the canyon model, the approaching wind is grouped into 16 directions \( i \), starting from the canyon orientation clockwise and the wind incidence angle is represented by \( \theta \).

ANNUAL EXCEEDANCE PROBABILITY METHODS

Velocity-based AEP

In practice, the exceedance probability method has often been used for urban planning and design to assess the impacts of the proposal on the pedestrian wind environment. In making such assessment, wind velocity ratios, which are defined as the ratios between velocities at ground level and velocities at reference point, are required for each wind direction. These ratios are constant based on the assumption of a linear correlation between the velocities and can be determined by measurement, wind tunnel experiment or CFD simulation with the local metrological observatory usually being chosen as the reference point, where wind speed distributions for 16 azimuths can be statistically described by Weibull function. As a result, the total exceedance probability for wind speed at ground level, referred to
hereafter as “velocity-based AEP”, can be expressed as follows:

\[
P(V > V_0) - \sum_{n} P(V > V_n) \frac{A(n)}{\sum_{n} A(n)} = \exp\left\{ \frac{V_0}{R_v(n) \cdot C(n)} \right\}^{\kappa(n)}
\]

where \(P(V > V_n|n)\) is the probability of exceeding a given ground wind velocity (\(V_n\)) for wind approaching from each azimuth \(n\); \(A(n)\) is the relative frequency of wind direction occurrence; \(C(n)\) and \(K(n)\) are Weibull distributions parameters for each azimuth; \(R_v(n)\) is the velocity ratio for each azimuth, expressed by Equation (2):

\[
R_v(n) = \frac{V_v}{V_v(n)}
\]

In the following 3.2 and 3.3, two indices are applied to calculate new-defined AEPs by analogy instead of using the concept of velocity.

Local Air Change Rate-based AEP
The first introduced index is local air change rate, which is applied to assess the total ventilation efficiency of a target domain, referred to hereafter as ‘\(N\)’. As shown in Equation (3), local air change rate can be expressed by local purging flow rate (LPFR) per volume of Void space (\(V_v\)), while LPFR represents the effective airflow rate required to remove/purge pollutant from the specified domain (Ito and Kato 2000).

\[
N = \frac{LPFR}{V_v} = \frac{q_P}{C_P \times V_v}
\]

where \(C_P\) is the local average concentration [kg/m³]; and \(q_P\) is the uniform emission rate of pollutants [kg/s]. By analogy with Equation (1), the annual exceedance probability can also be calculated based on the local air change rate by using Equation (4), referred to hereafter as “local air change rate-based AEP”. Just as velocity-based AEP means the exceedance probability of a given velocity, local air change rate-based AEP indicates the exceedance probability of a given air change rate (\(N_0\)), with the assumption of a linear correlation between the velocity at the reference point and the calculated local air change rate.

\[
P(N > N_0) = \sum_{n} P(N > N_0|n) \frac{A(n)}{\sum_{n} A(n)} \exp\left\{ \frac{N_0 \cdot V_v(n)}{N_0(n) \cdot C(n)} \right\}^{\kappa(n)}
\]

where \(P(N > N_0|n)\), \(N_0(n)\), and \(V_v(n)\) are the probability of exceeding \(N_0\), the calculated local air change rate and the velocity at the reference point for each azimuth respectively.

Local Kinetic Energy-based AEP
The process of the air exchange between the void or the canyon and the free stream above the canyon can also be viewed as a process of energy exchange due to turbulence transport. Thus, the ventilation performance of a specified space can also be investigated from a kinetic energy perspective. In this study, local average kinetic energy, with the definition shown in equation (5), was used as another index to calculate annual exceedance probability, referred to as “KE”.

\[
KE = \frac{1}{V_v} \int_{0}^{\frac{1}{2}} \left( \frac{1}{2} V_x^2 + V_y^2 + V_z^2 \right) \, dv
\]

The corresponding AEP is referred to as “local kinetic energy-based AEP” and is calculated by using equation (6), which takes the similar form as equation (1) and equation (4).
\[
P(K_E > KE_0) = \sum_{n=1}^{16} P(K_E > KE_0 | n) = \sum_{n=1}^{16} A(n) \times \exp \left( \frac{\sqrt{KE_0 \times V_s(n)}}{\sqrt{KE_0 \times C(n)}} \right)^{K(n)}
\]

where \(P(K_E > KE_0 | n)\), \(KE_0(n)\), \(V_s(n)\) are the probability of exceeding \(KE_0\), the calculated local average kinetic energy and the velocity at the reference point from each azimuth respectively.

Though the calculation procedures for the three AEPs above are similar, their meanings and applications are somewhat different. The velocity-based AEP analysis is suitable for assessing wind conditions at some ground locations so as to evaluate whether spot wind velocity is acceptable or not for outdoor human activities, so it is essentially a point-oriented index. Comparatively, the other two AEPs are based on domain-averaged indices, so that makes it possible to assess the overall ventilation performance for a target domain. As the main purpose of this study is to assess ventilation performance for Void space in street canyon, both local air change rate-based AEP and local kinetic energy-based AEP will be applied for detailed analysis.

**CALCULATION OF AEP**

The calculation procedure for AEPs follows three steps. Firstly, for the model shown in Figure 1, CFD simulations are performed to calculate local air change rate or average kinetic energy of the Void space for 16 wind directions respectively. Next, the exceedance probabilities for each azimuth are calculated respectively. Finally, AEPs are summarized from individual directional results by using Equations (4) and (6). Due to the symmetry of this street canyon model, the CFD simulations were performed only for five wind directions. For instance if the orientation of the canyon is ENE (see Figure 2), only five wind directions ENE, E, ESE, SE, SSE are calculated by CFD. These five directions correspond to five wind incidence angles (0.0°, 22.5°, 45.0°, 67.5°, and 90.0°) and are capable of representing all the ventilation conditions from 16 wind directions. For the same reason, AEPs were calculated and analyzed for nine orientations from NNE to S. All the above numerical simulations were performed using STAR-CD in this study and the detailed analysis conditions are shown in Table 1.

<table>
<thead>
<tr>
<th>Turbulent model</th>
<th>Standard k-ε model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential scheme</td>
<td>Convection terms: MARS*1</td>
</tr>
<tr>
<td>Inflow(^n) (Murakami 1988)</td>
<td>(U = U_0 \times (Z / Z_0)^{1/4})</td>
</tr>
<tr>
<td>&amp; (k = 1.5 \times (i \times U)^2, i = 0.1)</td>
<td></td>
</tr>
<tr>
<td>&amp; (C = C_{LS} \times k^{3/2} / L)</td>
<td></td>
</tr>
<tr>
<td>&amp; (L = 4(C_{LS} \times k)^{1/3} \times \frac{U_0}{\sqrt{k}})</td>
<td></td>
</tr>
<tr>
<td>Side, sky</td>
<td>Free slip</td>
</tr>
<tr>
<td>Wall</td>
<td>Generalized logarithmic law</td>
</tr>
<tr>
<td>Other</td>
<td>Void pollutant is assumed to be passive pollutant with a uniform emission rate of 0.001 kg/(m³s)</td>
</tr>
</tbody>
</table>

\(^*1\) MARS: Monotone Advection and Reconstruction Scheme, second-order scheme (STAR-CD 2001)
\(^*2\) Reference height \(Z_0=74.5\) m; Reference velocity \(U_0=1.0\) m/s

The aspect ratio, which is defined as the ratio of the canyon height to its width (H/W), has been regarded as one of the main factors affecting the interior flow and pollutant transport behavior. In this study, the height of the canyon model has a constant value of 9 m, and widths from 1 m to 6 m were
investigated, with corresponding relatively high aspect ratios from 1.5 to 9. Under these circumstances, the interior canyon flows are all in the skimming flow regime accompanying complicated recirculation (Oke 1988). In summary, a total of 30 cases with combinations of different widths, varying from 1 m to 6 m, and five wind incidence angles were simulated and investigated. The distributions of AEPs in the range $N_0 = 0-400$ h$^{-1}$ and $KE_0 = 0-0.1$ m$^2$/s$^2$ were calculated and analyzed for each case. The geographical location of the canyon model was assumed to be located in the urban area of Tokyo for the present study. Accordingly, the Weibull distribution parameters and frequency of occurrences of 16 wind directions in Tokyo were adopted (the Wind Rose is shown in Figure 3). This statistical data is based on 10 years of measurements recorded at the Tokyo Meteorological Observatory from 1995 to 2004 (Japan Association for Wind Engineering 2005). As evidenced from Figure 3, the annual prevailing wind in Tokyo is prominent from NNW (20.6%), compared with the other directions. However due to the model’s symmetry, wind blowing in a specific direction has the same “cleaning” or “cooling” effect as that from its opposite direction. So the frequency of occurrences of two opposite directions should be coupled together to evaluate the ventilation performances, referred to hereafter as “wind-direction group”. In light of this, the three prevailing wind-direction groups in Tokyo are SSE-NNW (22.9%), S-N (18.6%), and NE-SW (17.7%) with no apparent differences, while the non-prevailing wind-direction groups are ESE-WNW (5.6%), E-W (6.1%), and SE-NW (7.7%).

RESULTS AND DISCUSSION

Local Air Change Rate (N) & Local Kinetic Energy (KE)

The CFD simulation results of local air change rate and local average kinetic energy of the Void spaces were firstly compared among the three canyons along the stream-wise direction. Taking the case of $W = 4$ m as an illustration, the results of each canyon are almost the same (see Figure 4) because there is sufficient distance between the three canyons, and similar conditions can also be found for other canyon widths. Therefore, the results for Canyon (1) will be used for further discussions.

The simulation results for local air change rate and average kinetic energy for all cases are shown in Figures 5-(a) and 5-(b) respectively. The results for the air change rate indicate that the minimal value occurs for all widths when the incidence angle is 0.0°, in other words when the wind direction is perpendicular to the canyon, the Void space has the worst ventilation. As the wind incidence angle increases, air change rate shows an increasing tendency and increases sharply from 45.0° to 67.5°. The peak value is reached at $\theta = 67.5^\circ$ for cases where $W > 2$ m and at $\theta = 90.0^\circ$ for the other cases with a narrower width. For canyons with wider widths, strong spiral flows could be created at $\theta = 67.5^\circ$ by the wind blowing down from the upper part of the canyon, which leads to ground-level emissions being effectively cleared from the Void spaces. However, this effect is quite weak in narrow canyons where the maximum value is obtained when the wind blows along the canyon axis. In all cases, the air...
change rate increases with an increase in canyon width. Thus, \( W \) has a great influence on the improvement of the air change rate in Void spaces, especially when the width increases from 1 m to 3 m; however this effect becomes insignificant for widths exceeding 4 m. The results for average kinetic energy show similar distributions in general (see Figure 5-(b)), with the exception that average kinetic energy remains almost the same value for a given canyon width where the incidence angle is within 45.0°. On the whole, both wind incidence angle and width are important factors affecting the ventilation performance, from which come the differences in ventilation performance in the Void space.

**Influence of Canyon Orientation on AEPs**

The AEPs were calculated for \( N_c = 0\text{~h}^{-1} \) and \( K_{E_c} = 0\text{~m}^2\text{s}^2 \) respectively for each case based on the above simulation results. By way of illustration, the distributions of AEPs for \( W = 4 \text{~m} \) are presented in Figure 6. Figure 6-(a) indicates that the distributions of air change rate-based exceedance probabilities are quite different for canyon orientations. As a whole, the AEP has the highest value when the orientation of the canyon is East (E), while the lowest value is observed for North-North-East (NNE). From the CFD results of 5.1, ventilation performance in the Void space is to a great extent influenced by the incidence angle 67.5° and 90.0°. That is to say, for the canyon facing E, the predominant wind directions are SSE, S, SSW, NNW, N and NNE. These directions are nearly coincident with the three prevailing wind-groups in Tokyo, SSE-NNW, S-N and NE-SW, and this clearly explains why orientation E has the highest ventilation potential. Similarly, the worst natural ventilation performance can be found for the canyon with orientation NNE, where the wind incidence angles 67.5° and 90.0°are coincident with the non-prevailing wind-groups ESE-WNW, E-W, SE-NW. From the mathematical point of view, as shown in Equation (4), the canyon facing E has a larger \( N_c(n) \) than those facing other orientations, for predominant wind-direction groups. With the increase of \( N_c \), the distributions of AEPs represent an
exponential decay process, while this process is comparatively slow for the canyon with an E orientation owing to its smaller exponent index. Figure 6-(b) shows the distribution of average kinetic energy-based exceedance probabilities within the range of 0~0.1 m²/s². The maximum value and the minimum value are also found at orientation E and orientation NNE respectively. Moreover, similar AEPs’ distributions patterns can be found for other widths.

Influence of Width on AEPs
Figure 7-(a) shows the local air change rate-based AEP distributions and Figure 7-(b) shows the local kinetic energy-based AEP distributions, for different canyon widths at orientations E and NNE, which correspond to the most favorable orientation and most adverse orientation in terms of ventilation efficiency in the Void space respectively. As indicated from Figure 7-(a), for the local air change rate-based AEP, the change is remarkable at both orientation E and NNE when the width is below 3 m, but it becomes insignificant for widths from 4 to 6 meters. Since the AEP values for other orientations are distributed between those of E and NNE, as a consequence the canyon model in this study can be regarded as having a saturation value of 4 m with regard to local air change rate-based exceedance probability. That also implies that one cannot effectively improve the ventilation capacity in a Void space by widening the canyon width over a certain range in some cases. However, it is somewhat different in terms of the local kinetic energy-based AEP. At orientation E, the saturation value can also be obtained at 4 m or thereabouts, nevertheless it is found that the AEP continues to show an increasing tendency with the increasing of the canyon width at orientation NNE, namely the saturation width for orientation NNE, which is believed to exceed the widest width (6 m) in this study, and so further investigation is required.

CONCLUSIONS
In this study, the methods for assessing wind-driven natural ventilation performance in the Void spaces of street canyons were investigated and illustrated using a simple canyon model. Some conclusions were reached:

- The concept of annual exceedance probability (AEP) was applied as the assessment method in this study. As an extension from the commonly used velocity-based AEP, local air change rate-based AEP and local kinetic energy-based AEP were proposed. Both of these two AEPs are well suited to numerical analysis of wind environment for domain spaces; the local air change rate and local average kinetic energy are to be calculated for each azimuth by CFD simulation.
- The influences of two factors, canyon width and wind incidence angle, were investigated for local air change rate and local average kinetic energy. Six widths from 1 m to 6 m, corresponding to aspect ratios from 1.5 to 9, together with five wind incidence angles from 0.0° and 90.0°, were calculated and analyzed for a symmetric canyon model. The simulation results indicate that wind incidence angle has the most influence on ventilation performance in Void space. Generally speaking, the minimum value
occurs at $\theta = 0.0^\circ$ for all widths, while the maximum occurs at $\theta = 67.5^\circ$ for widths above 3 m, or at $\theta = 90.0^\circ$ for the other widths. For all the incident angles, the wider the canyon, the more efficient the canyon ventilation effect. The difference between the two indices lies in that when wind incidence angle is within 45.0°, the kinetic energy remains almost the same value while the air change rate shows an increasing tendency with $\theta$, and that also explains the differences in the AEPs calculated by the two indices.

The distributions of two AEPs were calculated in the range $N_a = 0\sim400$ h$^{-1}$ and $KE_0 = 0\sim0.1$ m$^2$s$^{-2}$ respectively based on 10 years of meteorological data (Japan Association for Wind Engineering 2005). By virtue of these results, we can comprehensively assess the ventilation environment inside Void space. Both the orientation and the width have a critical influence on the AEPs distributions as well as natural ventilation efficiency in the void. The calculation results also indicate that the most favorable orientation is “East” and the most adverse is “North-North-East” for a canyon model located in the urban Tokyo area. In general, the most favorable orientation is the direction at which local prevailing wind-groups are coincident with the incidence angles which afford the Void with a high ventilation rate or energy, while conversely, the worst orientation is that where the non-prevailing wind-groups are coincident with the incidence angles which provide the Void with a low ventilation rate or energy. As for the influence of canyon width on AEPs, a saturation width can be found in most cases, namely when the canyon width exceeds a certain value, the AEPs cannot be further improved, and the saturation value is 4 m or so for the canyon model used in this study.

REFERENCES