Evaluating the Use of Ventilation Efficiency Indices to Improve Urban Ventilation

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Removing heated or polluted air is one of the most difficult tasks to accomplish when it comes to ventilating urban environments. This study is an effort to satisfactorily describe the ventilation performance in outdoors by means of ventilation efficiency indices. The ventilation efficiency indices studied were: local age of air defined as the time taken by fresh air to replace old air after it enters a given zone, purging flow rate that represents net rate by which the pollutants are flushed out the domain, and air exchange efficiency that describes the efficiency in providing rural air into the urban canopy.

Introduction

The concept of ventilation is referred as the process by which “clean” air is provided into a specific space to remove or replace the existing air. So, for the urban environments, the city ventilation is being defined as the replacement of air in an outdoor area by surrounding (rural or sea) fresh air. For outdoor uses, the effectiveness of this replacement or removal hasn’t quite been defined, satisfactorily.

Ventilation efficiency indices, mainly known for indoor applications, have been employed to evaluate the ventilation performance and air quality in outdoors. Bady et al. 1) studied the ventilation efficiency indices to describe the pollutant behavior, the results indicated remarkable advances when obtaining a complete assessment of the wind ventilation performance. Later in two studies conducted by Hang et al.: one in an idealized city model 2) and the other in an idealized high-rise urban area 3), the city ventilation was evaluated by using the concepts of local mean age of air and air exchange efficiency. In addition, Buccolieri et al. 4), used the mean age of air to define the city “breathability” term and measure the ventilation in the city. Results showed the methodology was practical, but the application of these results to real scenarios require further analyses.

Hu and Yoshie 5) estimated the effects of building arrangements on the average ventilation efficiency in newly-built residential areas at pedestrian level by means of ventilation efficiency indices such as spatially-averaged wind speed ratio, spatially-averaged normalized concentration, and visitation frequency. Ramponi et al. 6) specified that outdoor ventilation is very important for a healthy and livable urban environment and mentioned that it is strongly influenced by wind speed and direction, which in turn are affected by urban morphology. However, they indicated that there was a clear lack of studies for urban configurations where not all parallel streets have equal street widths.

Surely, many studies have been carried out about the urban parameters related with the ventilation efficiency, however, we want to be able to find a ventilation efficiency index good enough to describe the airflow that blows down to the ground where there are buildings or to evaluate not only the horizontal movements but also vertical. This sort of studies is important because architects, researchers, city designers, government, engineers and all the institutions involved in the urban development process are able to precisely project and describe the building wind environment, and recreate spaces with better ventilation. The aim of this research is by means of ventilation efficiency indices to describe the behavior of the wind within the urban environment and evaluate the urban ventilation based on different configurations of urban spaces.

1. Ventilation efficiency indices

1.1 Local age of air

The local age of air is defined as the time taken by fresh air to replace old air after it enters to a given zone and if the local mean age of air from outside is equal to zero. The term was introduced for first time by Etheridge and Sandberg 7) for practical applications. Equation 1 represents the local age of air (s) for a homogenous emission and all variables are explained in Table 1:

$$\bar{\tau}_p = \frac{c}{\dot{m}} \qquad (1)$$

The local age of air indicates that the younger the air, the better is its dilution capability of that specific area, so if the spatial distribution of the local mean age of air is predicted, the spatial variation of ventilation effectiveness in an environment can be known.

1.2 Purging flow rate

The purging flow rate is the effective airflow rate required to remove or purge pollutants from a domain. In other words, the purging flow rate can be considered as the net rate by which the pollutants are flushed out. Equation 2 is used to calculate the purging flow rate (m^3/s), and variables are presented in Table-1:

$$U_p = \frac{\dot{m}_p}{c} \qquad (2)$$

Low purging flow rate reflects the presence of recirculation, consequently higher concentrations.

Table-1 Nomenclature

$\bar{\tau}_p$	local age of air (s)
c	local concentration (mg/m^3)
$\dot{m}$	effective uniformly distributed emission rate ($mg/m^3/s$)
U_p	purging flow rate (m^3/s)
$\dot{m}_p$	release rate (mg/s)
ε_a	air exchange efficiency (%)
$\tau_n = \frac{V}{q}$	τ_n nominal time constant (s) V volume of the domain (m^3) q supply airflow (m^3/s)
$\tau_{exc} = 2\langle\bar{\tau}\rangle$	τ_{exc} average time of exchange of air or contaminant (s) $\langle\bar{\tau}\rangle$ mean internal age or mean age of air (s)
Cn	normalized concentration (-)
C(t)	concentration in steady state (mg/m^3)
$\dot{m} \cdot \Delta t$	release rate (1 mg/m^3) by time step (1 s)

1.3 Air exchange efficiency

The air exchange efficiency denotes the efficiency (%) in providing rural air into the urban canopy and it is described by the Equation 3 and the variables explained in Table-1.

$$\varepsilon_a = \frac{\tau_n}{\tau_{exc}} \times 100 = \frac{\tau_n}{2\langle\bar{\tau}\rangle} \times 100 \qquad (3)$$

The limit of the air exchange efficiency is 100 %, which occurs for ideal piston flow. In Table 2, the air-exchange efficiency for different flow conditions is shown.

Table-2 Air exchange efficiency for different flow conditions

Flow pattern	Air-exchange efficiency ε_a
Ideal piston-flow	100 %
Ventilation by displacement	$50 \le \varepsilon_a < 100$ %
Complete and instantaneous mixing	$\varepsilon_a = 50$ %
Short-circuiting	$\varepsilon_a < 50$ %

Modified from Etheridge and Sandberg 7)

2. Model setups and descriptions of cases

The urban environment was modeled by an open source CFD software, OpenFOAM version 4.0. The air was modeled as a continuum, incompressible, three dimensional, with isothermal conditions, steady state and no external forces. The equation of passive scalar transport was presented unsteady state and the turbulent flow was solved by the standard k-ε model. Schmidt number was defined as 1.02 and the turbulent Schmidt number 0.9. The conservation equations of mass and momentum, and the scalar transport equation were discretized by finite volume method.

To assess the ventilation efficiency indices interaction in locations with high and low area density and different building height: Hiranomachi (34.69N, 135.50E) and Maishima (34.66N, 135.40E) were selected. The information about length, width, and number of floors of every building were obtained by the results of the survey on land use conducted by Osaka City in 2005. The size of the calculation domain for both cases was set to be 1000 m in x-coordinate, 1000 m in y-coordinate and 180 m in z-coordinate. Figure 1 shows the city domain defined as x:355 m and y: 365 m, and analysis domain size x: 177 m and y: 183 m. The grid resolution in the city domain was 2.5 m in both of x- and y-direction, outside this area the grid resolution had an increase of about 10%. In z-direction, the grid resolution was 0.5 m until the height of 20 m, and from 20 m an increase of about 10% was used until reach the limit of the domain. The number of hexahedral cells generated was approximately 3.4 million.

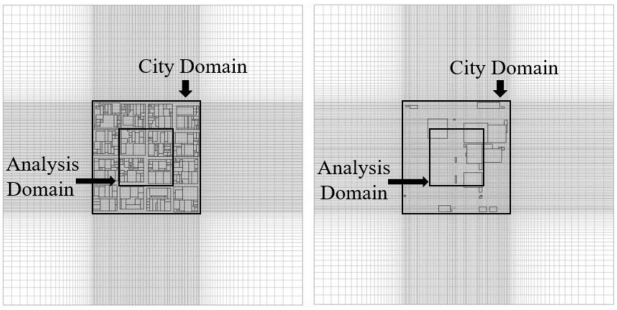

Figure-1 x-y mesh view of the calculation domain for Hiranomachi (left) and Maishima (right)

Besides from the previous cases, three symmetric arrays with the same total building volume and building height, but with different street width were studied (Figure 2). The calculation domain size was x: 984 m, y: 984 m and z: 330 m, the size of the city domain x: 384 m and y:384 m and the size of the analysis domain x:192 m and y :192 m. The horizontal mesh in the city domain was 2.0 m in x- and y-direction, then the grid resolution has an increase of about 10%. For the z-direction, the grid resolution measured 1 m from the ground until the height of 13 m, and from 13 m until reaching the limit of the domain an increase of about 10% was used. The number of hexahedral cells generated was approximately 3.3 million.

The boundaries conditions for wind velocity were the same for all the cases: power law boundary condition in the inlet (west), with a reference wind velocity of 3 m/s at 10 m height. For all solid surfaces the no-slip boundary condition was used.

For the east (outlet) boundary, the zero gradient boundary condition was employed.

The concentration was set constant at zero for the inlet and a source of homogenous emission of 1 mg/m^3/s in the analysis domain from z: 0 m to z: 36 m for Hiranomachi and Maishima, from z: 0 m to z: 30 m for the symmetric array. These heights represent the maximum building height within the analysis domain.

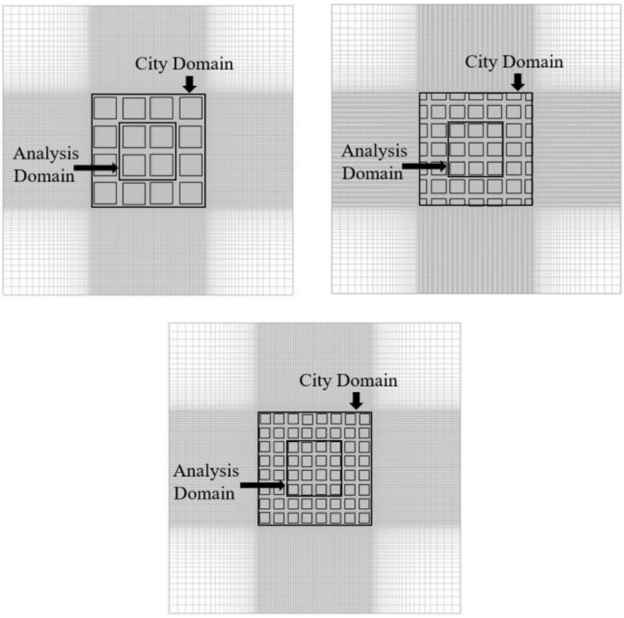

Figure-2 Mesh x-y view of the calculation domain for Case A (top left), Case B (top right) and Case C (bottom center)

3. Results and discussion

In this section, the ventilation efficiency indices are presented. The passive contaminant approach was used to calculate the flow field first, after he ventilation efficiency indices were estimated. Concentration fields were described by the normalized concentration C_n (-), which indicates the ratio of the concentration in steady state to the emission per unit time (Equation 4 and Table -1):

$$C_n = \frac{C(t)}{\dot{m} \cdot \Delta t} \qquad (4)$$

3.1 Effect of building area densities

The first index is the local age of air. The results shown in Table 1 indicate that the time required for Hiranomachi (128 s) is at least four times higher than the time required to refresh the analysis domain in Maishima (30 s). Figure 3 shows the concentration field at z: 1 m in steady state. We can see, the concentration fields in Hiranomachi and Maishima analysis domain show a large amount of tracer gas mainly located in the leeward side of the buildings. Moreover, some of the tracer gas are kept in enclosed areas at Hiranomachi, the main reason may be the low wind speed.

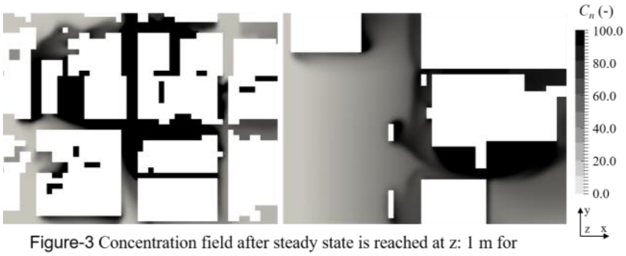

Figure-3 Concentration field after steady state is reached at z: 1 m for Hiranomachi (left) and Maishima analysis domain (right)

The purging flow rate represents the ability at which the wind can remove pollutant from the domain. If we look at Figure 3, we can observe the contaminants being removed or purged at a higher rate in Maishima analysis domain 32377 m^3/s, because the concentration of tracer gas is lower, and 5220 m^3/s for Hiranomachi because it has higher concentration.

The air exchange efficiency is an indicator of how the air should flow, so the air of a specific area is replaced with new air and not just a part of it. The air exchange efficiency in Hiranomachi represents a short circuit flow pattern of 35 %, for Maishima the air exchange efficiency reaches as high as 77 % that indicates that the ventilation is done by displacement.

Table-3 Effect of building area densities

	Local age of air (s)	**Purging flow rate (m^3/s)**	**Air exchange efficiency (%)**
Hiranomachi	128	5220	35
Maishima	30	32377	77

3.2 Effect of street width

The following results indicate the influence of the number of building and the street width on the capacity of the wind to refresh the urban environment, however there isn't a great difference among Case A, Case B and Case C, as we can observe in Figure 4. The local age of air is higher when the width of the street is narrower, the time require to refresh the space is 149 s for Case A, 188 s for Case B and 192 s for Case C.

Table-4 Effect of street width

	Local age of air (s)	**Purging flow rate (m^3/s)**	**Air exchange efficiency (%)**
Case A	149	3252	31
Case B	188	2577	30
Case C	192	2521	30

The purging flow rate for Case A is 3252 m^3/s, Case B 2577 m^3/s and Case C 2521 m^3/s, these results show that higher concentration indicates more recirculation and the contaminants are purge at a lower rate.

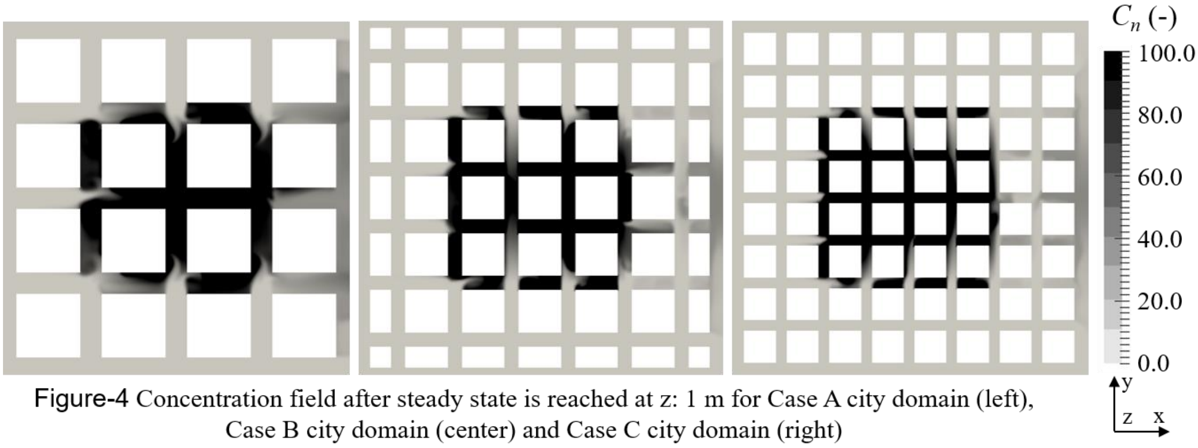

Figure-4 Concentration field after steady state is reached at z: 1 m for Case A city domain (left), Case B city domain (center) and Case C city domain (right)

Finally, when we analyze the air exchange efficiency we can see it is pretty low, around 31 % for Case A, 30 % for Case B and 30 % for Case C. The results for Case C and Case B are quite the same because the air exchange efficiency relies closely on pollutants behavior and the contamination is almost the same for both cases, so the air exchange efficiency tends to behave in that same way. The closeness of the buildings (street width is narrow) tend to behave as one big block of buildings and don’t allow the circulation of wind from west to east. However, the straight forward relation between street width and air exchange efficiency cannot be explained clearly at this point of the work.

4. Conclusions

This study introduces three ventilation efficiency indices that describe different characteristics of the ventilation performance in urban environments. The indices were the local age of air, the purging flow rate and the air exchange efficiency.

In summary, cities with higher area density and narrow street don’t allow the proper removal of pollutants, making increasingly difficult for the fresh air to help with the ventilation of urban areas.

All the three cases (Case A, Case B and Case C) and Hiranomachi describe a short-circuiting flow pattern. This result tells us that supplied air exist in a short time without passing the occupied space. For indoor application (when these indices are mainly used) short-circuiting may occur when both the supply and extract points are located above the occupied space.

Although the results showed to be satisfactory, further studies are required to clarify the air exchange efficiency viability when applied to outdoor ventilation and how to improve the outcomes for city planning.

Acknowledgements

We are grateful to Osaka City Government for providing building data from their survey on land use conducted in Osaka City in 2005.

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