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Modeling of Ventilation Efficiency

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1. Introduction

There are two types of pollution sources: high level sources such as tall stacks and low level sources such as automobile stacks. With respect to high level sources, Gaussian Plume Model (GPM) (Chock, 1977 and Kanda, 2006) is usually applied to estimate the pollutant concentrations, where the obstacles (such as buildings) little influence the diffusion characteristics of pollutants at such levels. In the case of low-level stacks, it is not appropriate to estimate the pollutant concentrations using GPM due to the effect of surrounding obstacles which make the pollutant removal efficiency by the applied wind vary from location to another in the same domain. In addition, the GPM do not take some architectural factors such as the form of building, the configuration of building, street widths, and relative positions of pollution source into account. Therefore, this model is not generally applicable to the built environment. Practically, in order to predict the concentration of pollutants in urban space, wind tunnel experiments and CFD simulation are used to estimate the pollutants concentration for this type of sources.
Many researchers have studied the distribution of pollutants inside urban domains such as street canyons (Xiaomin et al., 2005; Tsai et al., 2004; Baker et al., 2001; Ahmad et al., 2005) and densely built-up areas (Ahmad et al., 2005, Bady et al., 2008). However, based on these studies, it is thought that the determination of pollutant concentrations alone is insufficient to obtain a complete picture of the air quality in urban domains. In other words, if the pollutant source changes, the concentration distributions will also change. In such case, it is difficult to comprehend the removal capacity of pollutants by the wind within urban domains. In order to obtain a complete evaluation for the removal efficiency of pollutants by the natural wind within such domains, other parameters have to be considered in addition to the concentration. Consequently, there is a need to set an index (or a group of indices) that completely describes the air quality of the domain. Such index (or indices) may be used as a guide while designing new areas, or when the evaluation of air quality for urban domains is needed. At the same time, there is a concept of ventilation efficiency (VE) for indoor environments, which indicates the removal capacity of pollutants within indoor domains. This concept is thought to be suitable for evaluating the air quality of urban domains as well. Indeed, the air flow characteristics within outdoor environments are different from those of indoor environments as a result of the unsteadiness caused by fluctuations of wind in both speed and direction. This means that; some additional indices might be needed to evaluate outdoor air quality due to wind variations. In another study by

our group (Bady et al., 2008), the fluctuations of wind conditions within urban sites is considered and investigated using the exceedance probability concept. Such probability was introduced as a parameter or as a measure of the ventilation performance of the applied wind within a domain when the wind conditions of the site are varying.
The air quality of indoor domains in terms of VE indices has been studied by many researchers, such as (Sandberg, 1992; Ito et al., 2000; Kato et al., 2003). With respect to outdoor environments (Uehara et al., 1997) studied experimentally the diffusion of pollutants emitted from a line source located within an urban street canyon and they defined a concept similar to purging flow rate (PFR). More recently, it was confirmed that the ventilation efficiency indices of enclosed environments are also effective in evaluating the air quality of urban domains, as mentioned by (Huang et al., 2006).

2. Ventilation Efficiency Indices

Before presenting the ventilation efficiency indices, it is worth mentioning the fact that the distribution of pollutant concentrations in urban areas is not uniform, which represents a problem when analyzing the removal capacity of pollutants within urban domains. At the same time, the accuracy of the calculated VE indices depends on the uniformity of the pollutant generation strength within the considered local domain (local domain is a term introduced in order to represent a partial zone within the whole urban space such as a pedestrian zone). Thus, the VE indices were estimated in this study based on average values.
Ventilation efficiency indices can be evaluated mainly through CFD simulations since they are principally based on spatial distribution characteristics of pollutants (tracer diffusion). Until now, it is difficult to use wind tunnel experiments to obtain such indices. The problem is that the data needed to evaluate the VE indices is very difficult to be obtained through wind tunnel experiments. For example, to be independent of the source location within the study domain, a uniform generation rate is required, a condition which is difficult to satisfy using wind tunnel experiments. Another difficulty is that to calculate the visitation frequency of the pollutants, the total inflow flux to the study domain is needed which is difficult to estimate experimentally.
In addition to the above difficulties, there are many problems that reduce the chance of achieving successful experimental results. These problems include:
1) Symmetrical condition along the sides of the flow field is not easy to satisfy in wind tunnel experiments due to the lateral flow of wind to the domain.
2) The assumption of steady wind flow is wholly impractical.
3) The assumed boundary layer profile is over-simplistic compared with reality.
4) Fluctuations in the applied wind direction are not considered in the analysis.
These problems make the process of evaluating the VE indices experimentally very difficult. However, many trials were conducted by the authors of this study to estimate purging flow rate and visitation frequency experimentally, but unfortunately the results of these experiments were not readily useable. One way to generate the pollutant uniformly within the considered domain was through the use of four movable point sources which were adjusted in a certain manner to cover the total volume of the domain and then applying the principle of superposition to estimate the domain's average concentration. This low number of release points was selected based on the fact that the greater the presence of gas release

points within the domain, the more wind flow characteristics are affected. The behaviour of the plumes from the four point sources was totally different from those which were emitted from the whole volume. In addition, the measured data showed that the averaged domain concentration is quite sensitive to the source location. This led to inaccurate results.

There are different indices such as the age theory (Sandberg, 1983), purging flow rate, visitation frequency (Kato et al., 2003) and the six indices SVE1-6 (Kato et al., 1992) that are used to assess the air quality of a room or a domain located within an enclosed environment. Among these indices, three indices were adopted to implement the present study, i.e. purging flow rate (PFR), visitation frequency (VF), and pollutant residence time (TP).

Values of VE indices for a domain are of practical importance in reflecting the effect of the geometrical characteristics of such domain, i.e. the PFR value for a domain represents the local ventilation effectiveness of such domain. A small purging flow rate means that this domain is weakly ventilated. Also, higher values for the visitation frequency and residence time of pollutants are indications of poor removal efficiency of the pollutants by the applied wind. In the following section, definitions of the three indices will be explained in details.

2.1 Purging flow rate

The purging flow rate is the most important index for defining the ventilation efficiency of a local domain. It can be considered as the local ventilation efficiency. For a domain, PFR is defined as the effective airflow rate required to remove/purge the air pollutants from that domain (Kato et al., 2003). In other words, the purging flow rate can be considered as the net rate by which the pollutants are flushed out of the domain. It reflects the capacity at which the wind removes the pollutant from the domain. The following equation is used to calculate PFR:

$$PFR = \frac{q_p}{c_p} = \frac{q_p}{c \times \rho} \quad (1)$$

where:

q_P denotes pollutant generation rate (kg/s).

c_P is the domain-averaged concentration (= $c \times \rho$) (kg/m^3).

ρ is the air density (kg/m^3).

c is the mass concentration (kg/kg).

It is important to mention that PFR can be defined for a source point, not for the whole domain, but in this study, it is defined as common to the domain. Moreover, in addition to average concentrations, PFR can be estimated using the peak concentration of the domain. In such cases, the calculated PFR reflects dilution properties more than removal properties.

2.2 Visitation frequency

There are many parameters which affect the diffusion characteristics of pollutants within urban areas. These factors can be related to wind characteristics itself such as wind speed and direction, and it can be related to the geometry of the urban area such as obstacles dimensions, obstacles exits, and variable pollutant sources and strengths. So, it is important to study not only the level of the pollutant concentration but also the pollutant behaviour within these domains, including how many returns, circulates and stays inside it.

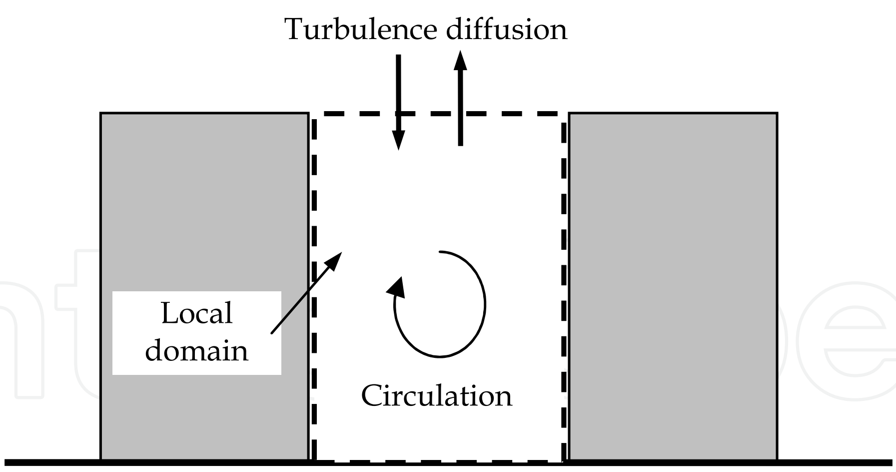


Fig. 1. Pollutant circulation

The index that can describe the pollutant history within a domain is the visitation frequency VF, which represents the number of times a particle enters the domain and passes through it. VF = 1 means that after being generated, a particle stays only one time in the domain. VF = 2 means that a particle stays in the domain for the first time, is transported to the outside and then returns again to the domain, due to recirculation flow for only one time. A schematic of pollutant circulation within a domain is illustrated in Fig. 5. In order to calculate VF, the following equation is applied, as mentioned by (Kato et al., 2003):

$$VF = 1 + \frac{\Delta q_p}{q_P} \quad (2)$$

where:

$$\Delta q_p = \rho \sum_{i=1}^{n} A_i \left(uc + \overline{u'c'} \right)$$
$$q_p = V \times S \quad (3)$$

where:
Δq_p is the inflow flux of pollutants into the domain (kg/s).
A_i is the inflow area of a face i (m^2).
u is the inflow wind speed (m/s).
c is pollutant concentration at the boundary of the face i (kg/kg).
n is the number of faces subjected to flow.
V is the domain volume (m^3).
u' is the velocity fluctuation (m/s)
c' is the concentration fluctuation (kg/kg).
uc together with ρA_i represents the convection part of the inflow flux (kg/s).
$\overline{u'c'}$ together with ρA_i represents the diffusion part of the inflow flux (kg/s).
S is the uniform generation source strength ($kg/m^3/s$).
Visitation frequency can be calculated using the particle tracking method based on Large Eddy Simulation (LES) or by using the passive pollutant flux method based on the Reynolds

Averaged Navier–Stokes (RANS). Although large-eddy simulation (LES) models attract much interest, their use is restricted because it is computationally expensive. For this reason, RANS models are widely used in urban flows and dispersion research. In the present study, calculation of VF based on RANS method was applied.

2.3 Average residence time

One of the most promising parameters being used as an indication of the ventilation performance is the average residence time of pollutants in a domain. It represents the average residence times of all particles inside the domain. For one particle, the residence time is defined as the time the particle takes from once coming (or being generated) into the domain to its leaving (Kato et al., 2003).

Average residence time of domain pollutants is a measure of the air freshness and thus the dilution capability of wind inside such domain (Hui et al., 1997). It is calculated according to the equation:

$$TP = \frac{V}{PFR \times VF} \tag{4}$$

Applying the principle of average values, the multiplication of the visitation frequency by the particle residence time (VF × TP) indicates the average residence time of all particles within the considered domain.

3. Method of calculating the ventilation efficiency indices

Ventilation efficiency indices are estimated using dynamically passive pollutants, which means that the flow field is not influenced by the pollutants. This makes it possible to calculate the flow field at first and then this calculated flow field is used in estimating the VE indices. Thus, the first step is to solve the flow filed. Second, after the flow filed is calculated, the pollutant concentration is calculated through the solution of the convective-diffusion equation for a passive scalar (Ferzigere & Peric, 1997):

$$\frac{\partial(\rho u_i c)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(K\frac{\partial c}{\partial x_i}\right) + S \tag{5}$$

where:

K is the mass diffusivity coefficient for the concentration (kg/m/s);

x_i is the Cartesian coordinates (m);

u_i is the Cartesian components of the velocity (m/s).

A uniform generation rate within the study domain is considered to be independent of the source location within the domain. In the third step, the pollutant average concentration within the domain is estimated and PFR is calculated according to Equation (1). Finally, the total domain inlet flux is calculated and VF is estimated from Equation (2), while TP is obtained according to Equation (5).

It is worth mentioning here the fact that the numerical simulation for diffusion is sometimes inaccurate. This can be attributed to two main reasons: insufficient spatial resolution and the steep concentration gradients that exist within the same calculation domain. These steep gradients are explained as follows: upwind of a source, the pollutant concentration is zero, while in the region closest to the source; the concentration is at a maximum and decreases as the plume travels downwind of the source. Accordingly, there is a significant variation occur in the concentration values between adjacent cells which lead to steep concentration gradients. To overcome these two problems, a huge number of cells is needed to produce gradual concentration gradients, which is computationally expensive. In this study, in order to overcome the problem of insufficient spatial resolution, a grid-convergence analysis has been carried out during the design of the mesh systems of the building models and in each case; a reasonable number of grids was attained.

Another important matter to be mentioned here relates to the diffusivity coefficient K which is a function of the turbulent Schmidt number ($K = \nu_t / Sc_t$). It is known that the value of Sc_t is not constant and varies from one location to another within the same calculation domain. In high concentration regions –which means high concentration gradients– the turbulent Schmidt number is less than one, while in low concentration regions –which means that the mixing of pollutants with ambient fluid is almost finished– its value is sometimes greater than one. This means that the diffusivity coefficient is not equal to the eddy diffusivity of the momentum. However, in this work, Sc_t is assumed to be constant. This assumption has been applied in many of the previous studies (Xiaomin et al. 2005; Tsai et al., 2004). The authors consider that this simplification is accepted at this stage of the research.

4. Numerical simulations

Numerical simulations for wind environments in urban areas were performed using CFD code STAR-CD. The standard k-ε model was considered to simulate the turbulence effects. Steady-state analysis was adopted, and the Monotone Advection and Reconstruction Scheme (MARS) was applied to the spatial difference (He et al., 1997).

At the inflow boundary, the turbulent kinetic energy was set to be constant as given by Equation (6), while the turbulent dissipation rate was calculated according to Equation (7), which arises from the assumption of local equilibrium (Lien et al., 2004).

$$k \cong 1.5\left(u \times I\right)^2 \tag{6}$$

$$\varepsilon \cong C_\mu^{1/2} \times k \times \frac{\partial u}{\partial z} \tag{7}$$

where k is the turbulent kinetic energy (m^2/s^2), I is the turbulent intensity of the applied flow, and C_μ is a constant (= 0.09).

Free slip condition was applied to the top and side boundaries. The logarithmic law with the parameter E = 9 was applied to the boundaries at ground level; (i.e. streets and traffic roads) and for building walls, as smooth surfaces. Table (1) summarizes all parameters used in the simulations together with the applied boundary conditions.

Turbulent Model	The standard k-ε model
Differential scheme	MARS scheme [18]
Inflow conditions	$u = u_o (z/z_o)^{0.25}, u_o = 1\,m/s \;\&\; z_o = 74.6\,m$ $k = 1.5(u \cdot I)^2$ $\varepsilon = C_\mu^{1/2} \cdot k \cdot \frac{\partial u}{\partial z},\ C_\mu = 0.09$
Sides and sky	Free slip
Building walls and ground	Generalized logarithmic law

Table 1. CFD simulation parameters together with applied boundary conditions

5. Examples of Applying the Ventilation Efficiency Indices

Urban street width and street building heights are considered the most important parameters in controlling the air quality of the pedestrian level domain (Bady et al., 2008). Also, the arrangement of building arrays within urban areas is very important in controlling the air quality of the pedestrian level domains by enhancing more wind to these domains. Thus, it is worth investigating the effects of these parameters on the air quality of urban domains in terms of the ventilation efficiency indices, in a way that explains the method of applying such indices. Indeed, there are other parameters which may influence the air quality of urban domains such as wind direction, wind velocity, and building roof geometry, etc., but in the present study only the above parameters are considered.
A wind environment containing two buildings of dimensions 5 (L) × 25 (W) × (H) m, was simulated and a street was considered to have one building on each side. The study domain has the dimensions (D × 10 × H) and occupies the mid-third of the whole domain of the street. An isometric view of the model configurations is presented in Fig. 2, while Fig. 3 shows the wind flow domain around the buildings together with the applied boundary conditions.

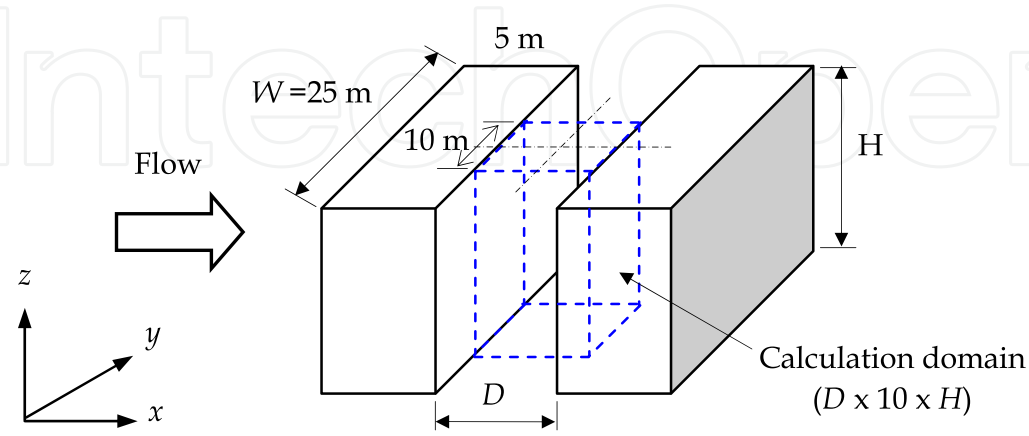


Fig. 2. Building model.

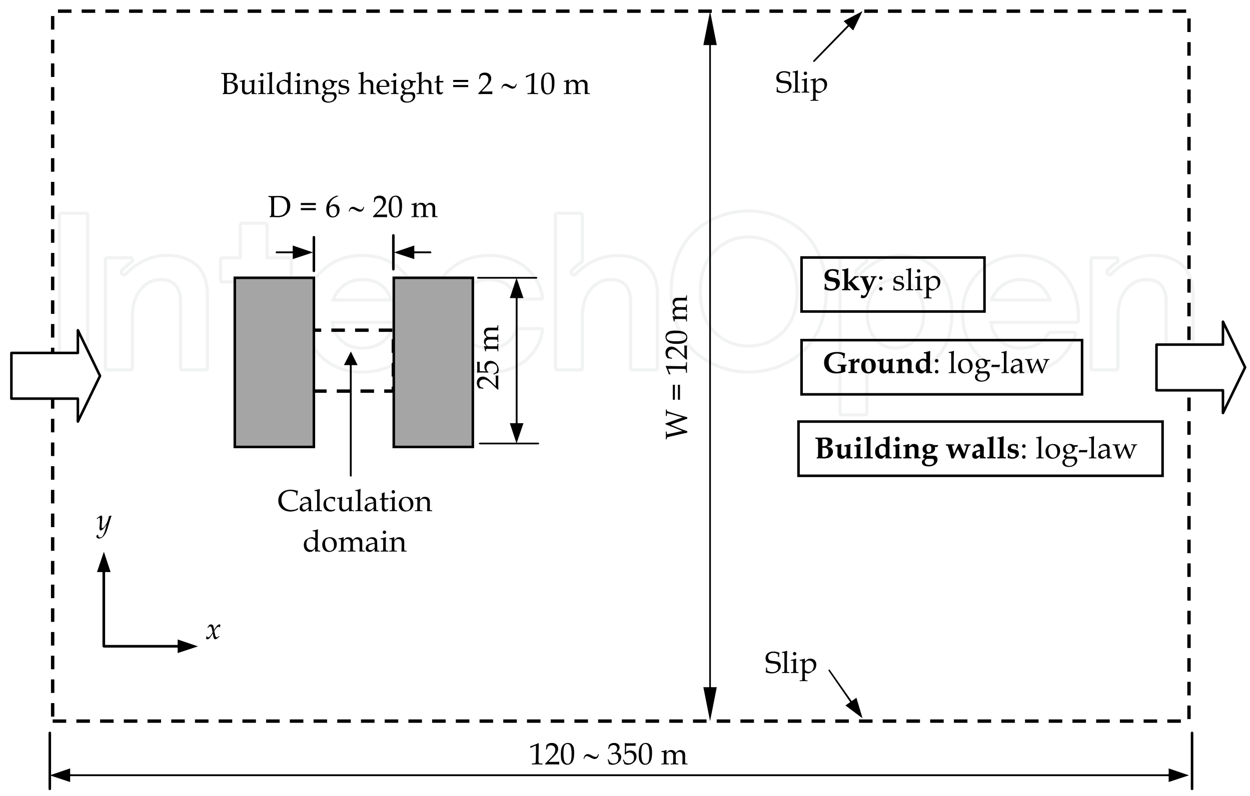


Fig. 3. Calculation conditions and boundary conditions of the wind flow domain.

5.1 Effect of street width (D)

Effects of varying the street width (D) on the wind flow patterns and ventilation efficiency indices are displayed in Figs. 4-7. Figure 4 shows the wind flow field within the mid section of the street for four selected cases of D/H (i.e. D/H = 0.6, 1.0, 1.5 and 2.0).

In the subplot (a), nearly there is no vortex circulation occurred inside the domain which is reflected in a small rotating speed which in turn leads to difficulty in removing the pollutants out of the domain. In Fig 4(b), a small vortex circulation covers the upper right hand side of the domain was generated. The domain average wind speed in this case is greater than that of case (a), which was resulted in a lower average concentration compared with the previous case. In the cases of D/H = 1.5 and 2.0 which are illustrated in Figs. 4(c) and (d), clockwise vortex circulations are generated within the domain when the wind is blown across the shear layer at the buildings height level. These vortices have large rotating velocities and hence transport the pollutant outside the domain from the windward side of the buildings.

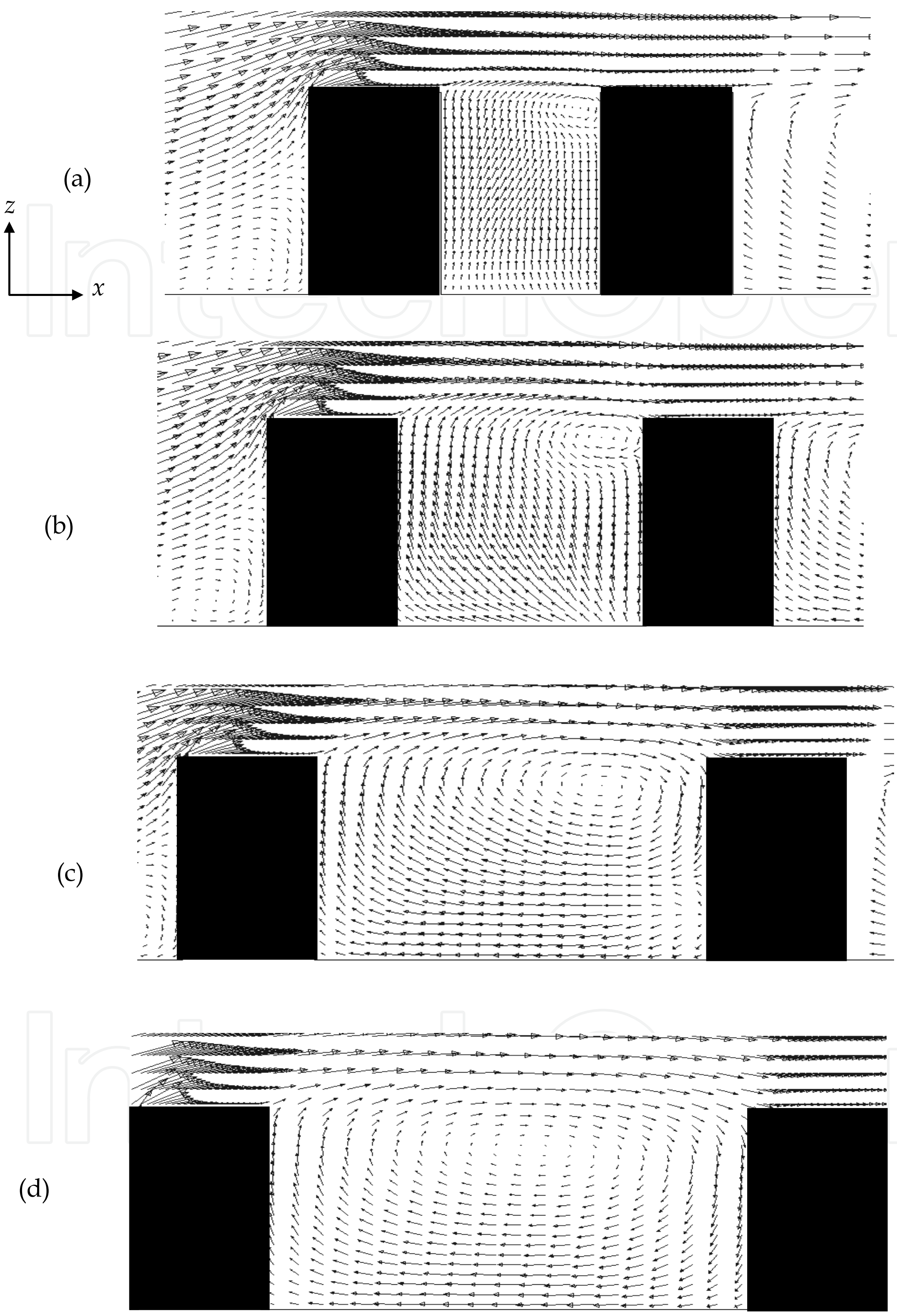


Fig. 4. Influence of street width on the wind flow pattern within the domain (y/W = 0.5)
(a) D/H = 0.6 (b) D/H = 1.0 (c) D/H = 1.5 (d) D/H = 2.0

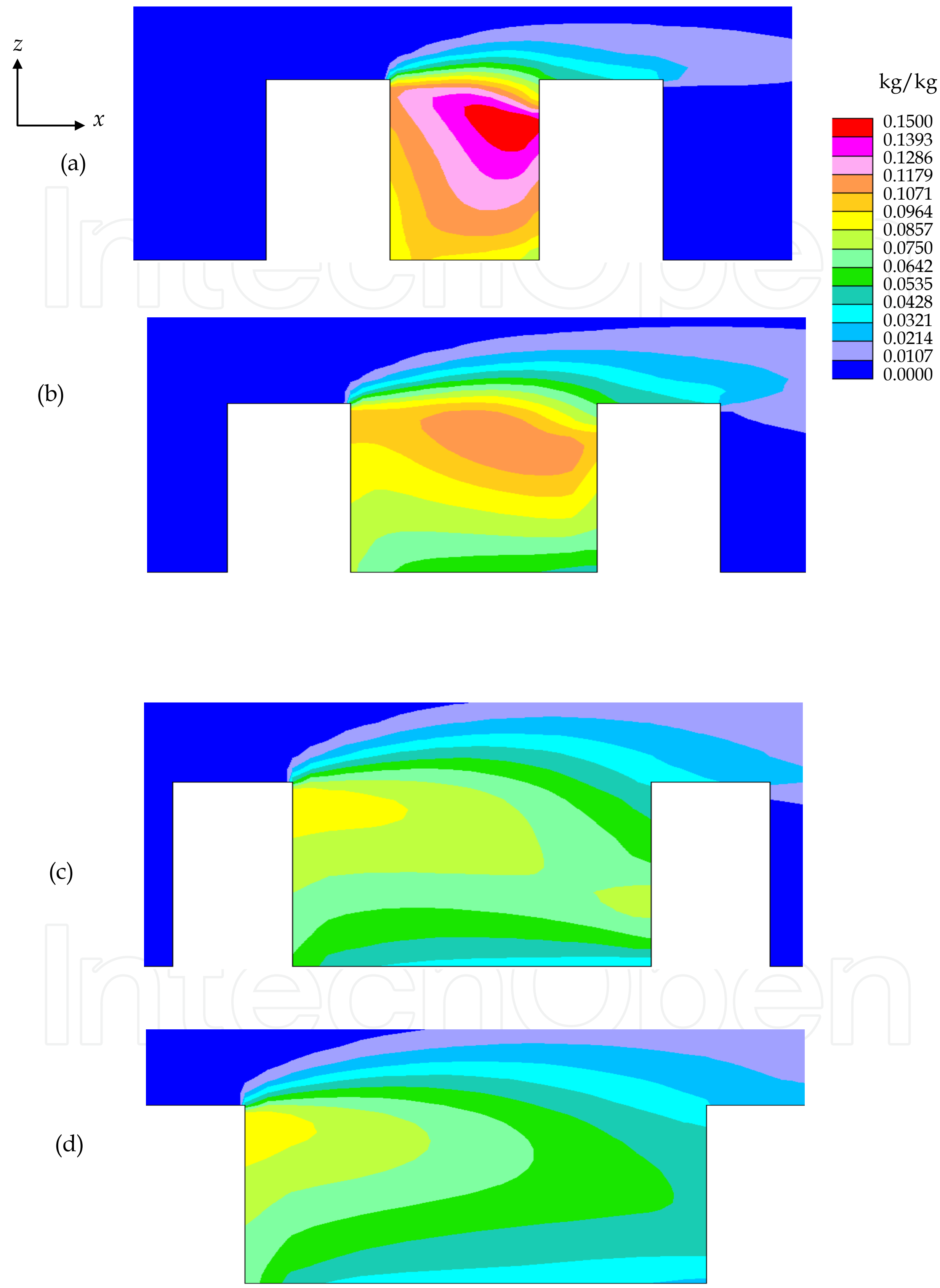


Fig. 5. Concentration fields for different widths of the street domain (y/W = 0.5).
(a) D/H = 0.6 (b) D/H = 1.0 (c) D/H = 1.5 (d) D/H = 2.0

Figure 5 shows the concentration fields within the study domain for the same values of D/H. The figure shows that the level of pollutants within the domain was decrease as D increased, due to the variation of the wind flow characteristics within the street domain with the variation of its width as explained above. Also, the figure shows that the size of the region of influence (Mfula et al., 2005) at which the pollutants disperse becomes larger as the street widens. The wide spread of such region is referred to the increase of the circulation strength (which is generated inside the domain), which improves the wind removal efficiency for purging the pollutants towards the domain exit (Bady et al., 2008).
Effect of street width on the average concentration within the domain is shown in Fig. 6. From this figure, it is obvious that the increase of D has a desirable effect on the concentration, since the concentration decreases as the street widens.
As the street width becomes 20 m (i.e. D/H = 2.0), the concentration level was reduced by about 50 % of its value at D/H = 0.6. This note reflects the fact that the street width is very important parameter in controlling the air quality of urban domains. However, increasing the widths of urban streets depends primarily on the space availability of the construction sites.

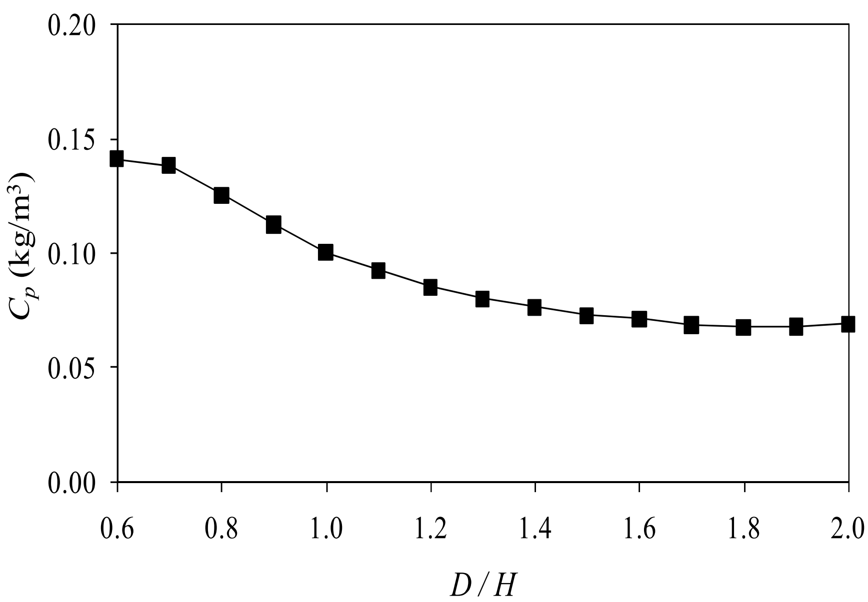


Fig. 6. Effect of street width D on the domain averaged concentration.

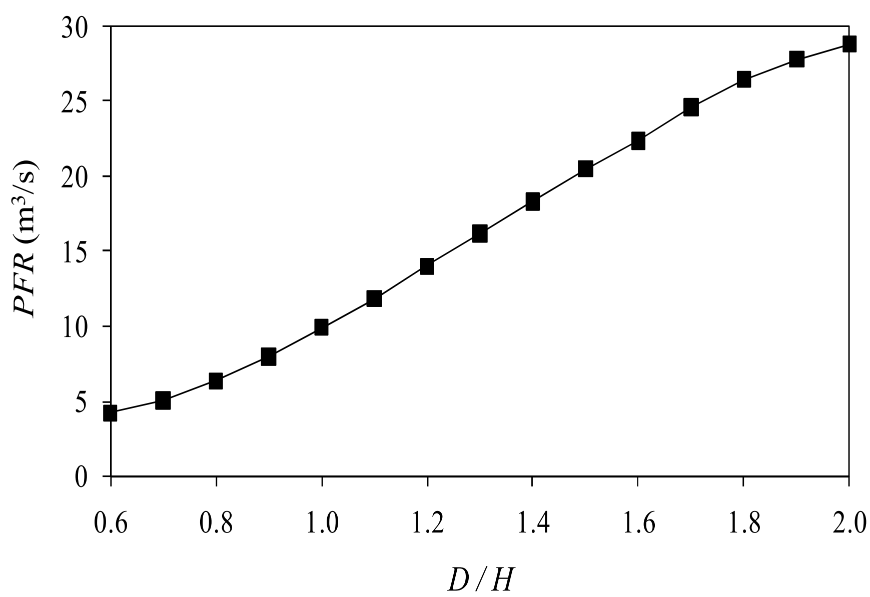
Figure 7 shows the influence of D on the wind removal efficiency for the domain's pollutants in terms of the ventilation efficiency indices. The figure shows the normalized PFR and also the air exchange rate which represents the rate at which the total volume of air inside the study domain is replaced with fresh air (AER is calculated through dividing PFR by the volume of the corresponding domain, AER = PFR/V).
As mentioned previously, PFR represents how much fresh air is supplied to the domain which means that PFR has strong dependence on the domain size. Consequently, it is expected that increasing the domain volume increases PFR. This conclusion agrees exactly with the simulation result as shown in Fig. 7, where PFR increases in nearly a linear way with the domain volume.

The second index of the ventilation efficiency indices is the visitation frequency. Figure 7(c) shows that, increasing the width of the street decreases the visitation frequency of the pollutants to it. The trend of VF can be interpreted as follows: the increase of D increases the area subjected to the inlet flux from the boundaries of the domain, which increases the domain inlet fluxes. As a first thinking, increasing the total inlet flux is expected to increase the value of VF as given by Equation (2). This conclusion is not absolutely true because the value of VF depends on the value of the inlet flux as well as the value of the domain volume. The ratio between these two quantities determines the value of VF.

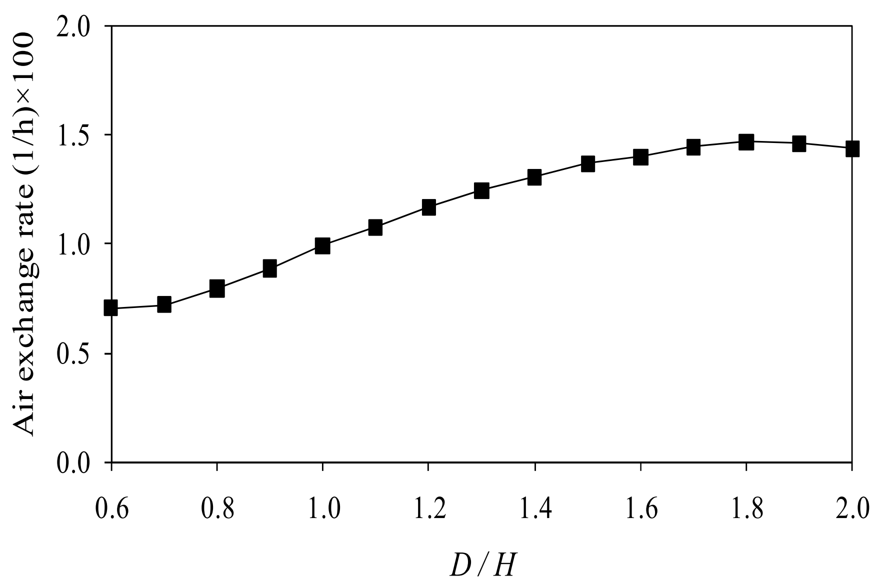
Regarding the residence time of pollutants, Fig. 7(d) shows that the greater the street width, the smaller the time the pollutants stay within the domain. This behaviour is referred to the increased purging capability of the domain wind for pushing the pollutants towards the outside as its volume increases, which reduces the time it takes towards the exit.

The above results for the VE indices supported absolutely that increasing urban streets widths purposefully reduces the air pollution levels (and hence improves the air quality) in the most heavily used streets by enhancing ventilation from the prevailing winds (Bady et al., 2008).

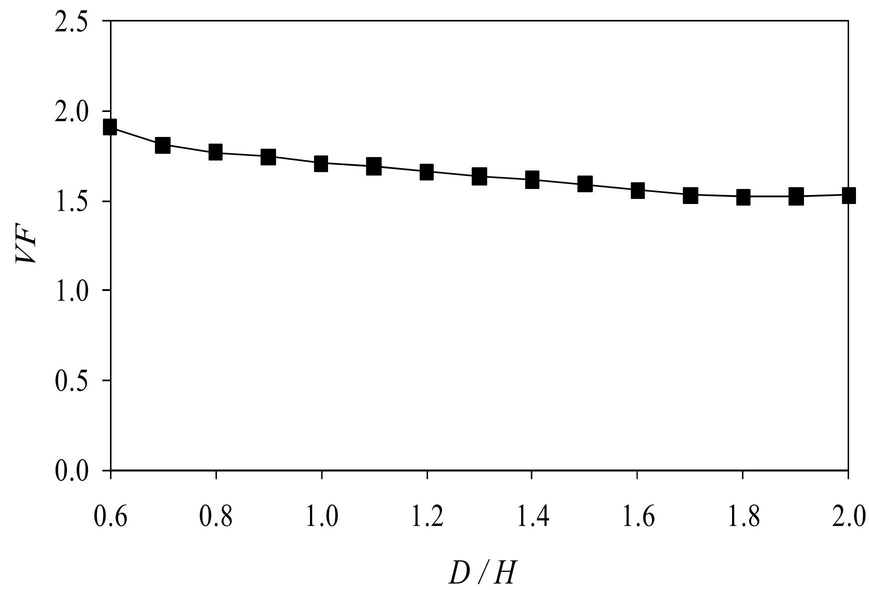
(a)



(b)



(c)



(d)

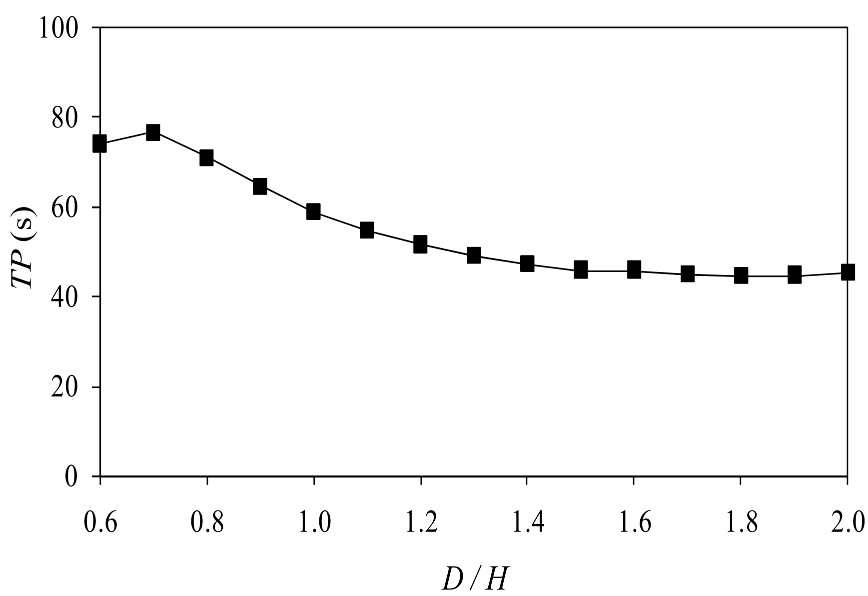


Fig. 7. Effect of street width on the VE indices within the study domain (H = 10 m).
(a) Purging flow rate; (b) Air exchange rate; (c) Visitation frequency; (d) Residence time

5.2 Effect of street buildings height (H)

The other parameter that affects the air flow characteristics in urban domain is the height of street buildings. Figure 8 displays the configuration of the velocity field for four selected cases of H/D (D = 5 m). It can be observed that, as the buildings height increases, a large clockwise vortex circulation is generated along the void between the buildings. The airflow at the center of the vortex circulation is slow and it becomes faster when it approaches the wall of the buildings and the ground level. Changing the height H affects the characteristics of the vortex circulation inside the domain, which in turn affects the diffusion process of the pollutants.

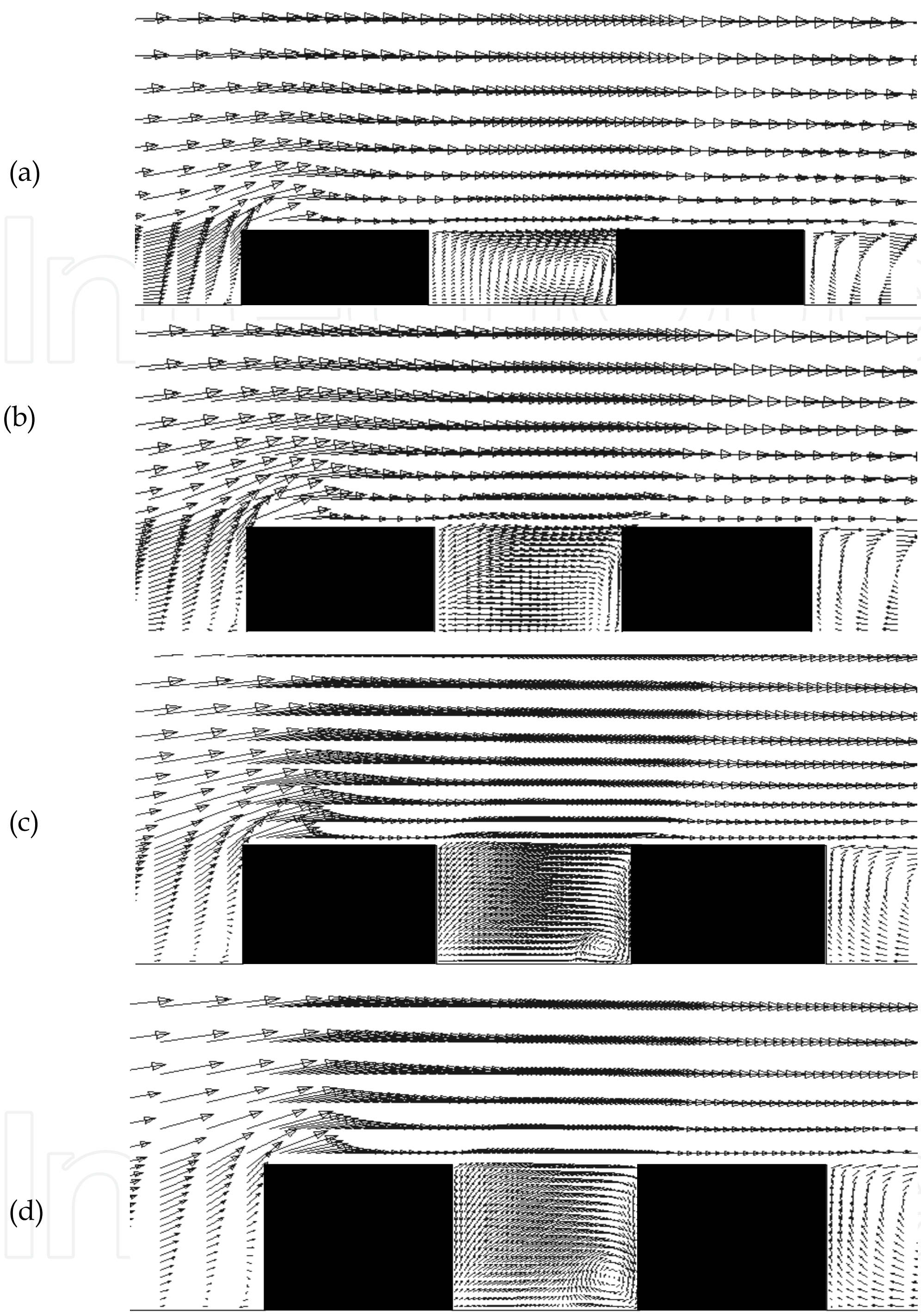


Fig. 8. Influence of building height on the flow pattern within the domain (y/W = 0.5)
(a) H/D = 0.4 (b) H/D = 0.6 (c) H/D = 0.8 (d) H/D = 1.0

Figure 9 shows the concentration fields inside the street at different values of H. In the subplot (a), the pollutant in the study domain is well dispersed and diluted, and the concentration value in such case is the lowest among the four cases. When H increases as shown in the subplots (b) and (d) (i.e. H/D = 0.6 and 0.8), the pollutant dispersion is limited and high concentration zones are observed within the study domain. With the further increased H (i.e. H/D = 1.0), the high concentration zone increased and covered a large area between the two buildings.

(a)

(b)

(c)

(d)

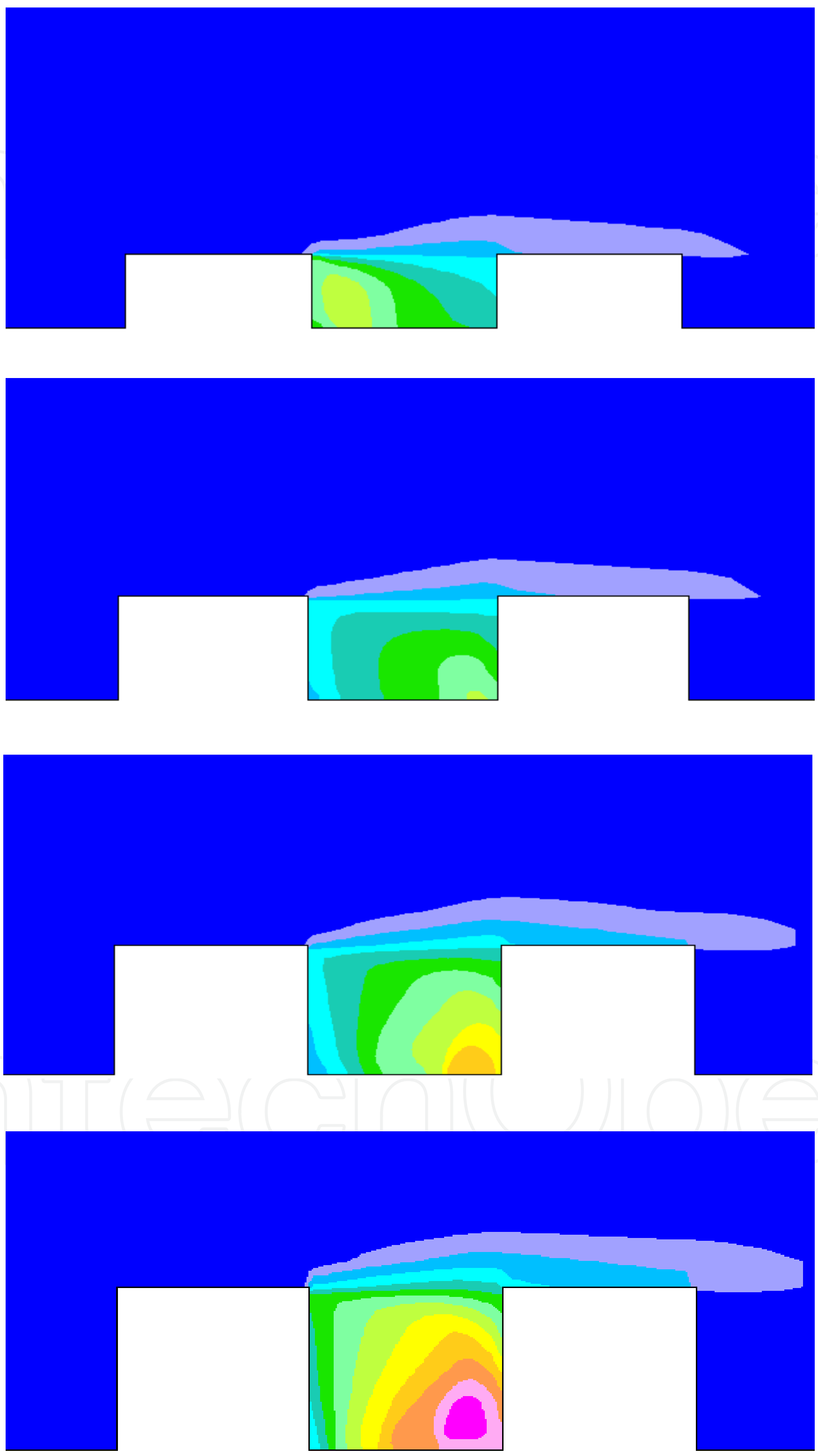
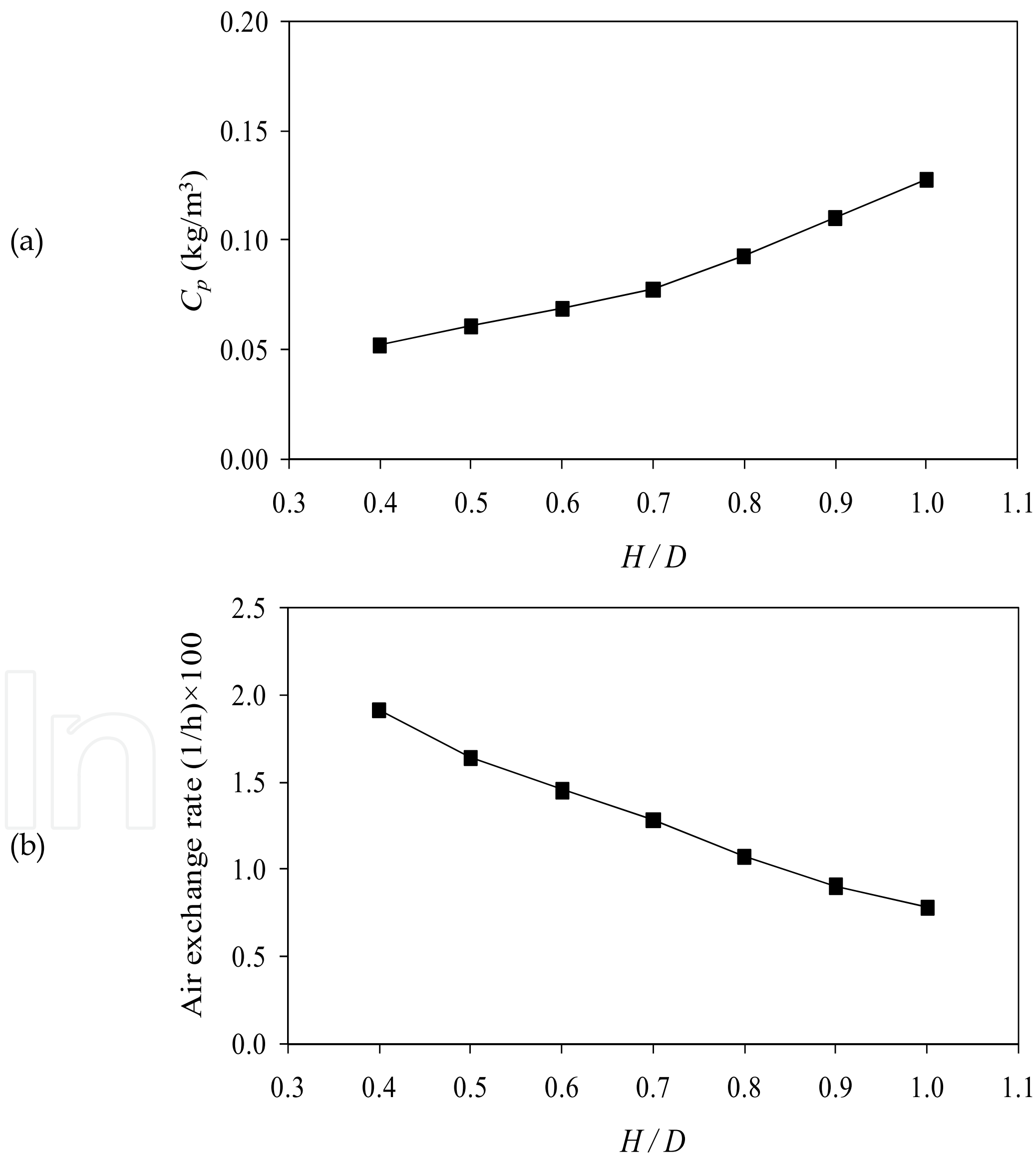
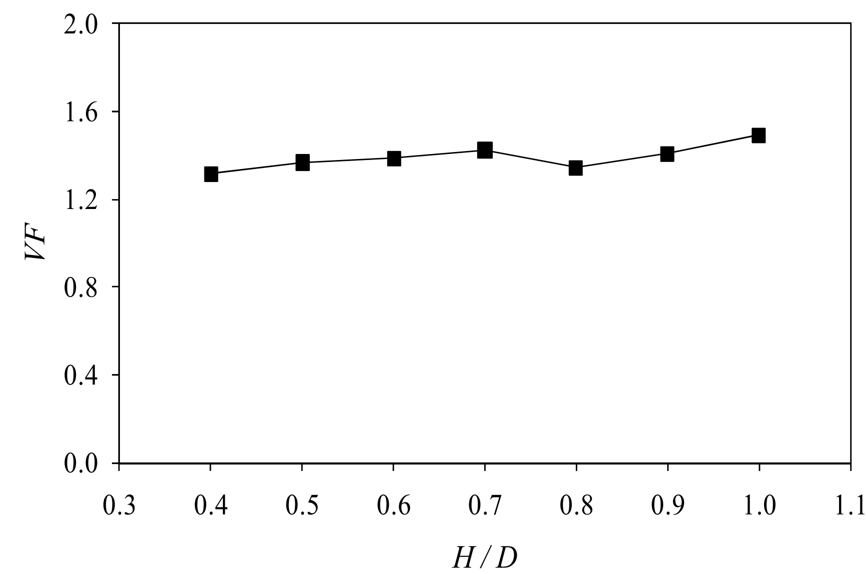


Fig. 9. Concentration fields for different heights of the street buildings (y/W = 0.5).
(a) H/D = 0.4 (b) H/D = 0.6 (c) H/D = 0.8 (d) H/D = 1.0

Figure 10 shows the effect of increasing the street buildings height H on the air quality parameters. As shown, the average concentration increases as the height of the buildings increases which in turn decreases the air exchange rate within the domain. Such effect is attributed to the fact that; increasing the height H weakens the street wind and decreases its ability to purge the pollutants outside the domain as illustrated in Fig. 10; in other words, the pollutants were trapped along the lower part of the domain. The figure shows also that the greater H, the greater the VF values. This can be referred to the increased domain inlet flux with increasing H. Also, the figure shows that the values of VF are greater than one which means that the return or circulation of pollutants is confirmed in the study domain. The relation between the residence time and the building height H is illustrated also in Fig. 10, in which TP increases with the increase of H. This behaviour reflects bad removal efficiency of the wind inside the domain due to the lower vortex strength as the street buildings height increases.



(c)



(d)

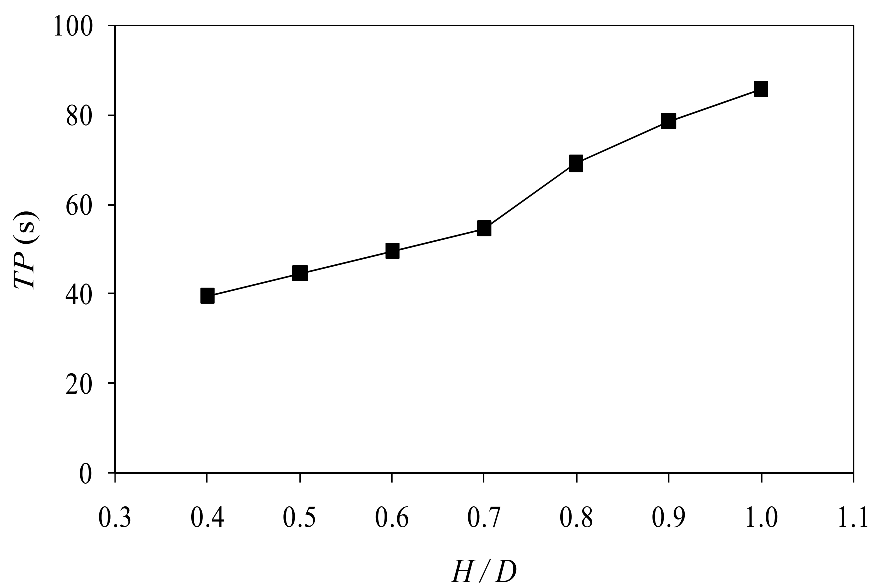


Fig. 10. Effect of street building's height on the air quality parameters within the study domain (D = 5 m); (a) Domain averaged concentration, (b) Air exchange rate, (c) Visitation frequency, (b) Average residence time

5.3 Effect of wind direction

Figure 11 presents the wind vector fields for the five inlet wind directions. According to the incident wind direction, simulated flows can be classified into three patterns regarding the characteristics of the flow circulation generated behind the upwind building (Kim et al., 2004). The first flow pattern appears when the inlet wind angle is 0^o. In such case, the horizontal distribution of the wind vector shows symmetric separation located at each lateral side of the upwind building. The figure shows that, there is apparently no motion in the y-direction which reflects a bad removal efficiency of the domain local wind against the pollutant.
The second pattern appears when the flowing wind angle is located in the range $0^o < \theta < 90^o$. This pattern appears in the cases of $\theta = 30^o, 45^o, 60^o$ in the above figure. For such pattern,

only one vortex appears at the right edge of the upwind building as the incoming wind enters from that side. As the angle θ increases, the vortex size decreases and the flow towards the domain exit in the y-direction increases. This pattern shows an improvement in the domain wind removal efficiency compared with the case of normal wind.

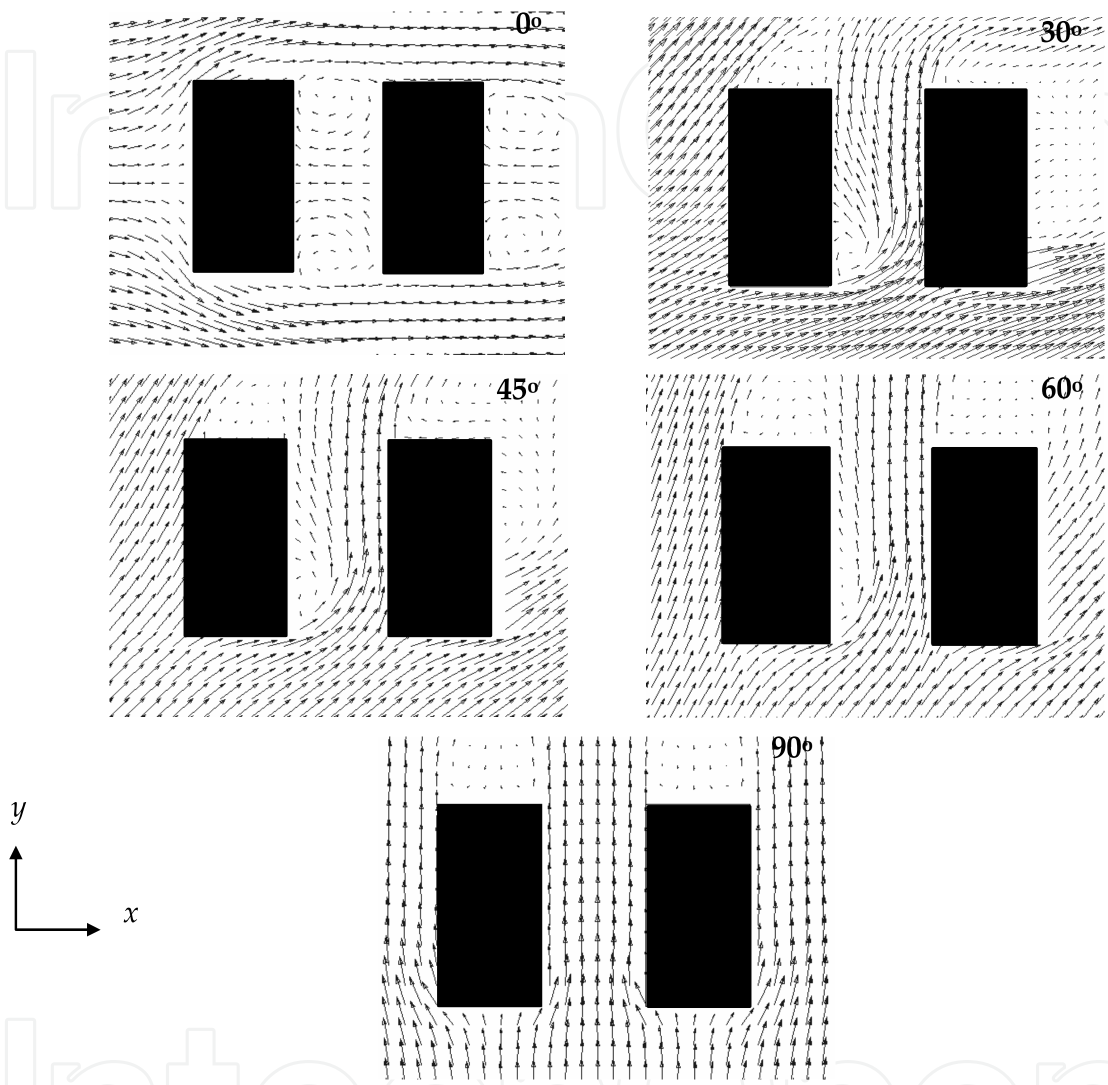


Fig. 11. Horizontal wind vector fields at different wind directions (z = 0.05 m).

The third pattern appears when the wind flows with an angle of 90°. The vortex in that case diminishes and the wind flows smoothly towards the domain exit, which indicates that the removal efficiency of the domain local wind in that that pattern is the best over the above two patterns. Results of the numerical approach for the pollutant concentration inside the street canyon are displayed in Fig. 12. The figure shows the concentration fields at z = 0.05 m for the five wind directions. In the case of normal wind, the concentration field shows symmetry around the central section of the street. It is observed that, high concentration regions appear inside the street canyon, while very low concentration regions appear outside it. That note means that the domain local wind has no ability to carry the pollutants outside the canyon.

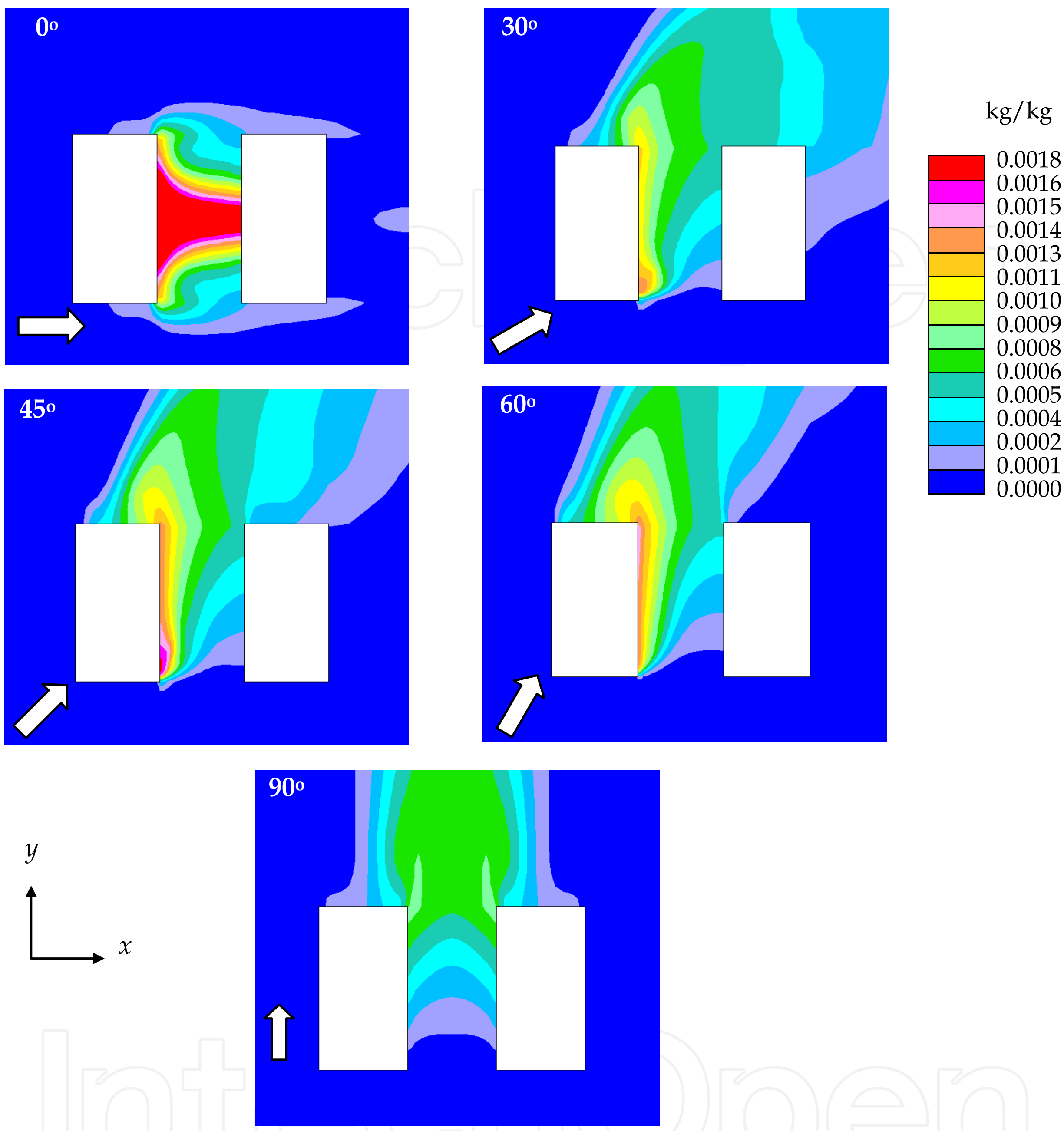
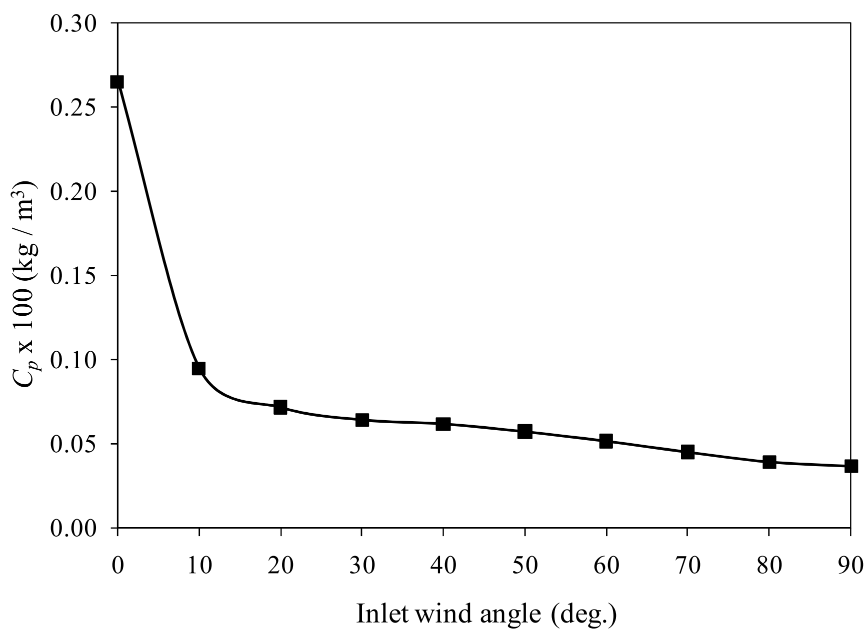


Fig. 12. Concentration fields for different wind directions (z = 0.05 m).

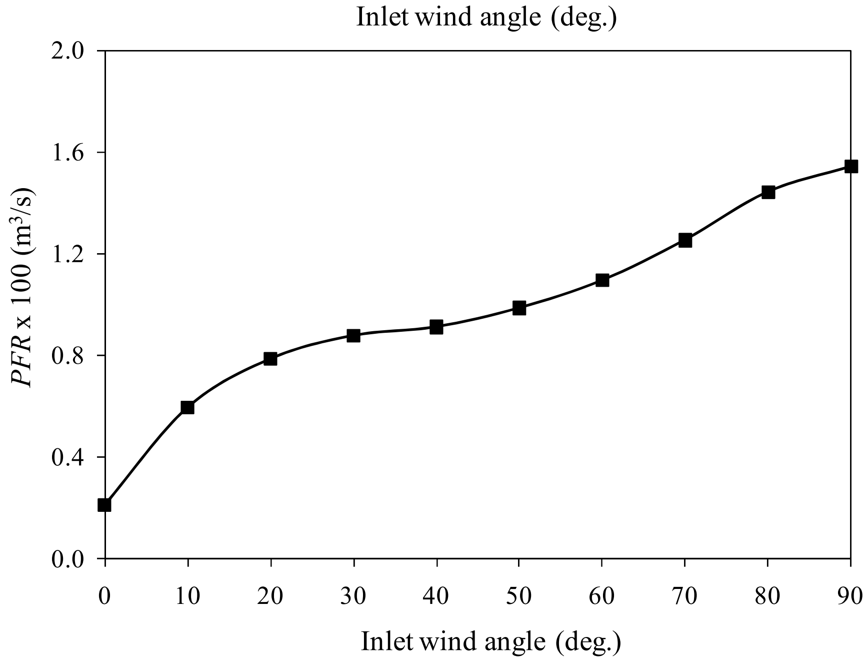
In the cases θ = 30°, 45°, and 60°, the concentration field increased to cover a wide area outside the study domain due to pollutant diffusion towards the outside in the same wind direction. As the maximum concentration area decreases with increasing θ, the canyon averaged concentrations are expected to be lower than the concentration of the case of normal wind as clean air continuously comes into the canyon from outside and dilutes the domain polluted air. Also, it is observed that, very low concentrations exist in the lower part of the figure where clean air arrives. In the case of θ = 90°, a large percentage of the maximum concentration area is shifted outside the canyon, which indicates that the domain average concentration in this case has the lowest value among all of the cases.

The three figures below presents the effects of the applied wind direction on the domain average wind speed, domain pollutant concentrations and on the PFR, inside the study domain. All quantities were normalized by the similar quantities evaluated at the case of normal wind. Figure 13 displays the variation of the air quality parameters with the inflow wind angle. The concentration decrease significantly to about 80% of its value as the flowing wind angle changes from 0° to 90°. That behaviour can be attributed to the increased domain average wind speed. That figure indicates that the domain average speed increases as the wind angle increases it reaches to about 2.5 times as the flow becomes parallel. As the average concentration inside the study domain decrease with increasing the applied wind angle, while the domain volume is kept constant, the PFR is expected to increase. The figure shows that the PFR increases by more than 6 times as the wind flow changes from 0° to 90°. In addition, the trends of VF and TP demonstrate that the ventilation effectiveness within the domain increases as the inflow wind angle increases.

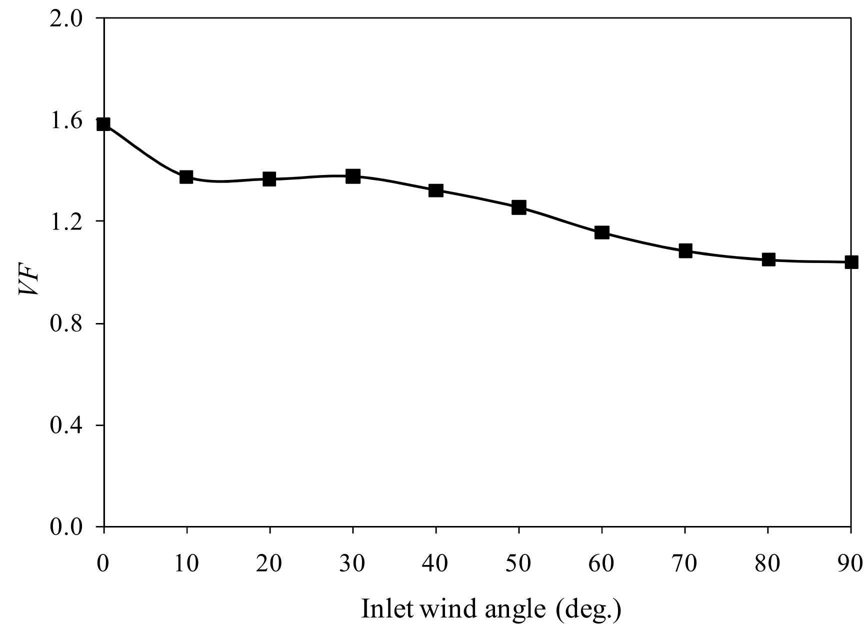
(a)



(b)



(c)



(d)

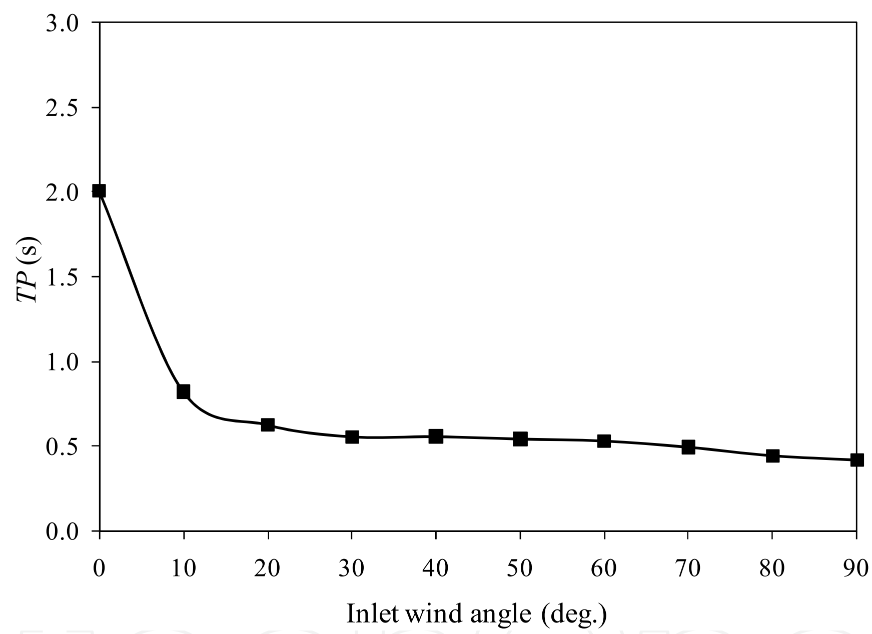


Fig. 13. Air quality parameters within the study domain for variable wind directions; (a) Domain averaged concentration, (b) Purging flow rate, (c) Visitation frequency, (d) Average residence time

5.4. Effect of computational domain height (h)

This section is concerned with investigating the effect of the computational domain height (h) on the VE indices of such domain. The height of the domain was started from 2 m and increased gradually until 10 m, while the width D and the building height H were kept constant at 6 m and 10 m respectively. Figure 14 shows the concentration fields within the street domain for four selected values of h/H (i.e. h/H = 0.2, 0.5, 0.8 and 1.0). Also, Fig. 15 shows the VE indices for different values of the domain height h. In these figures, it is clear that the average concentration increases as the height of the computational domain increases, which in turn decreases the air exchange rate within the domain. In the same time, the variation of h has no considerable influence on the visitation frequency of the pollutants to the domain. This can be attributed to the fact that both the domain inflow flux and domain's volume are increasing in nearly the same linear way, which is reflected in small changes in the value of VF according to Equation (2). With the increase of domain's volume, the residence time is expected to become higher since the pollutants take more time to be flushed out of the domain.

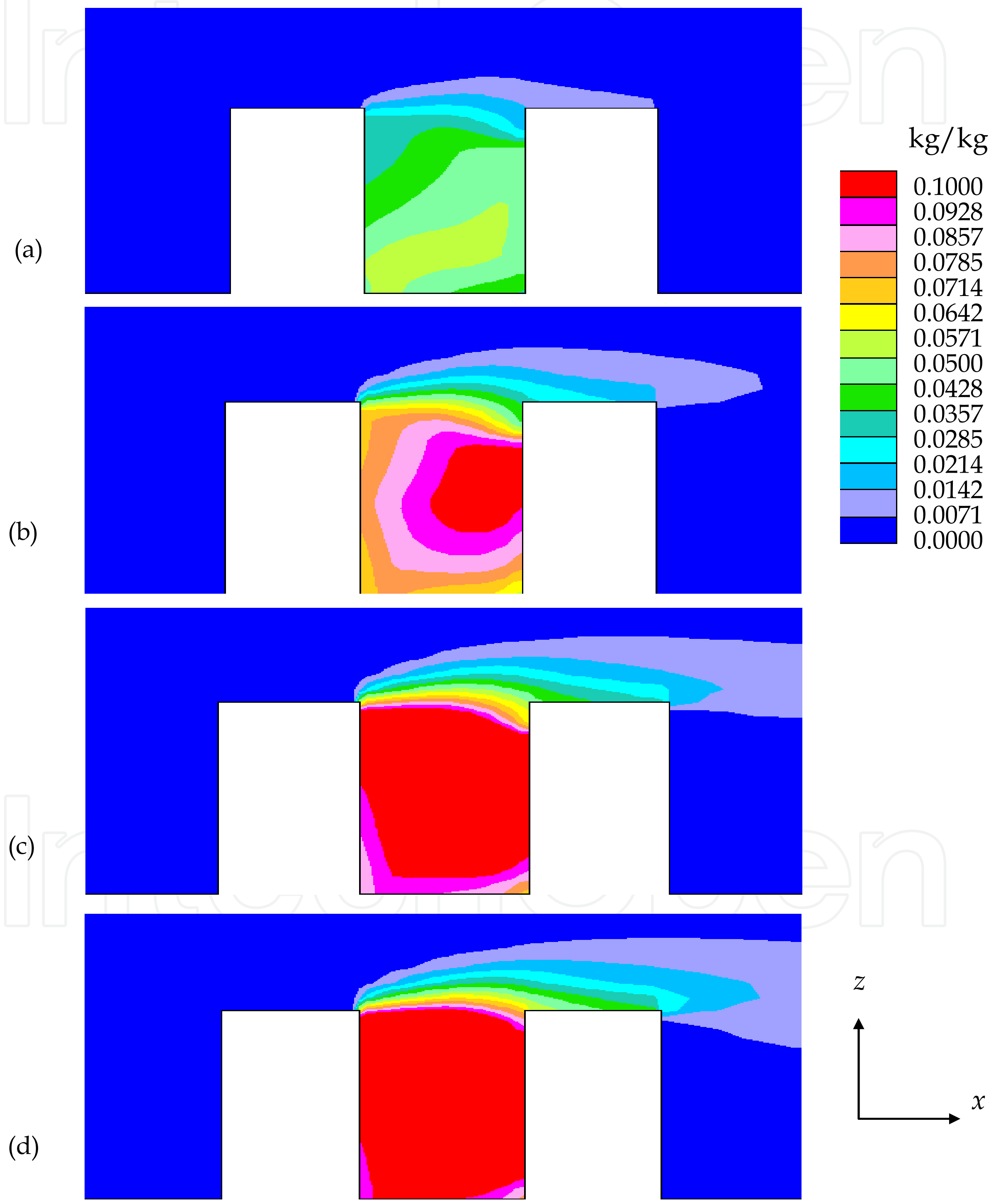
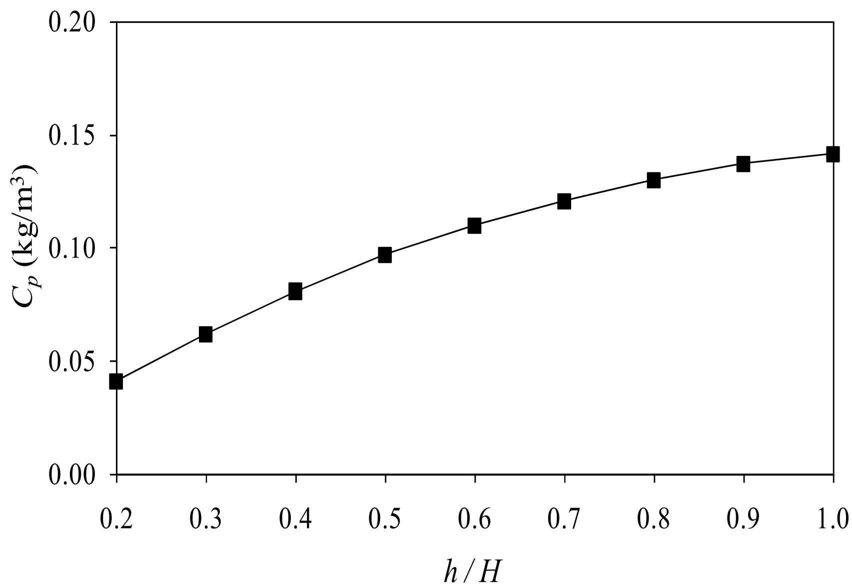
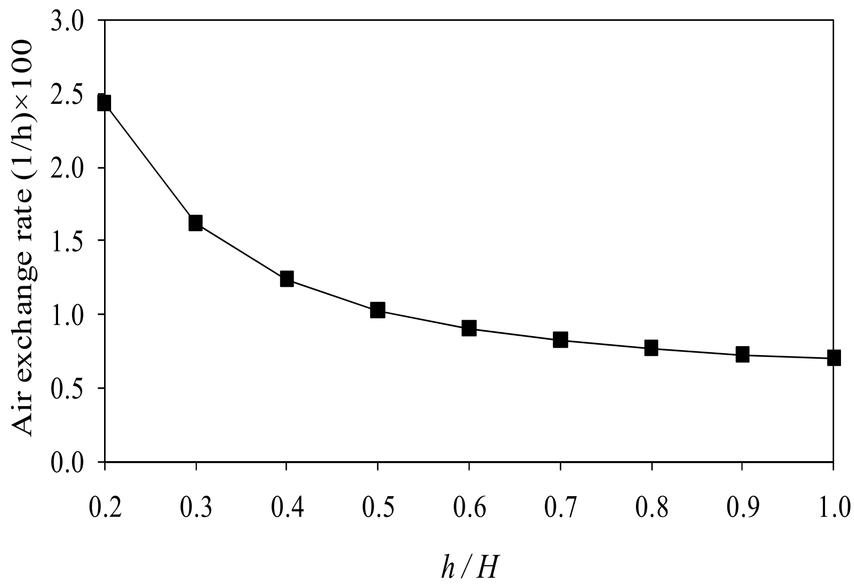


Fig. 14. Concentration fields within the street for different heights of the computational domain (y/W = 0.5); (a) h/H = 0.2, (b) h/H = 0.5, (c) h/H = 0.8, (d) h/H = 1.0

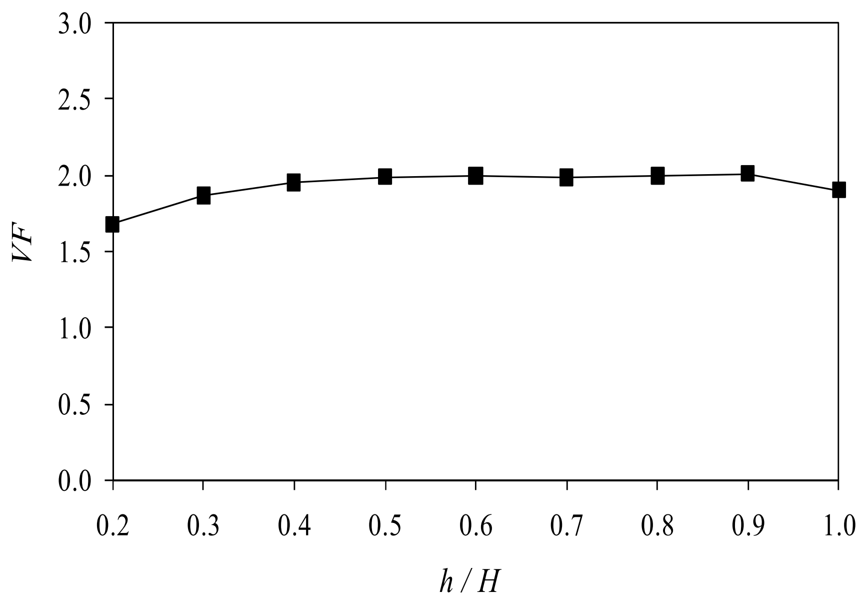
(a)


0.20
0.15
0.10
0.05
0.00
C_p (kg/m³)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
h / H

(b)


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Air exchange rate (1/h)×100
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
h / H

(c)


3.0
2.5
2.0
1.5
1.0
0.5
0.0
VF
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
h / H

(d)

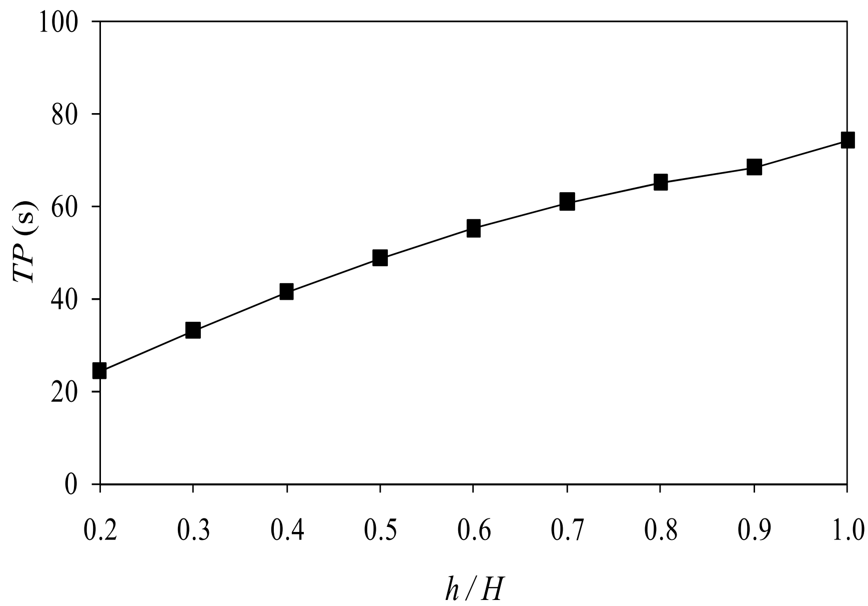


Fig. 15. Effect of computational domain height on the VE indices (D = 6 m, H = 10 m); (a) Domain averaged concentration, (b) Air exchange rate, (c) Visitation frequency, (d) Average residence time.

5.5 Effect of building array configurations

In this section, CFD simulations of the wind flow in densely urban areas – as an example of applying the VE indices in evaluating the air quality of urban domain – are presented. In this example, the VE indices are applied to one of the previously published works (Davidson et al., 1996). Figure 16 shows two building array configurations – aligned and staggered. The two configurations are fundamentally different as the staggered array diverts flow onto neighbouring obstacles whereas the aligned array presents channels through which the flow can pass (Davidson et al., 1996). The aligned array has 42 blocks, while the staggered array is composed of 39 blocks. The dimensions of each block are: 2.3 m height (H), 2.2 m width (W), and 2.45 m breadth (B).

To compare the wind ventilation performance for the two building patterns, seven domains were considered within these arrays, domain (1 ~ 7), as shown in Fig. 16. Wind flow fields were calculated for two directions of 0^{o} and 45^{o}. Figure 17 shows the flow fields around the building patterns for the two directions.

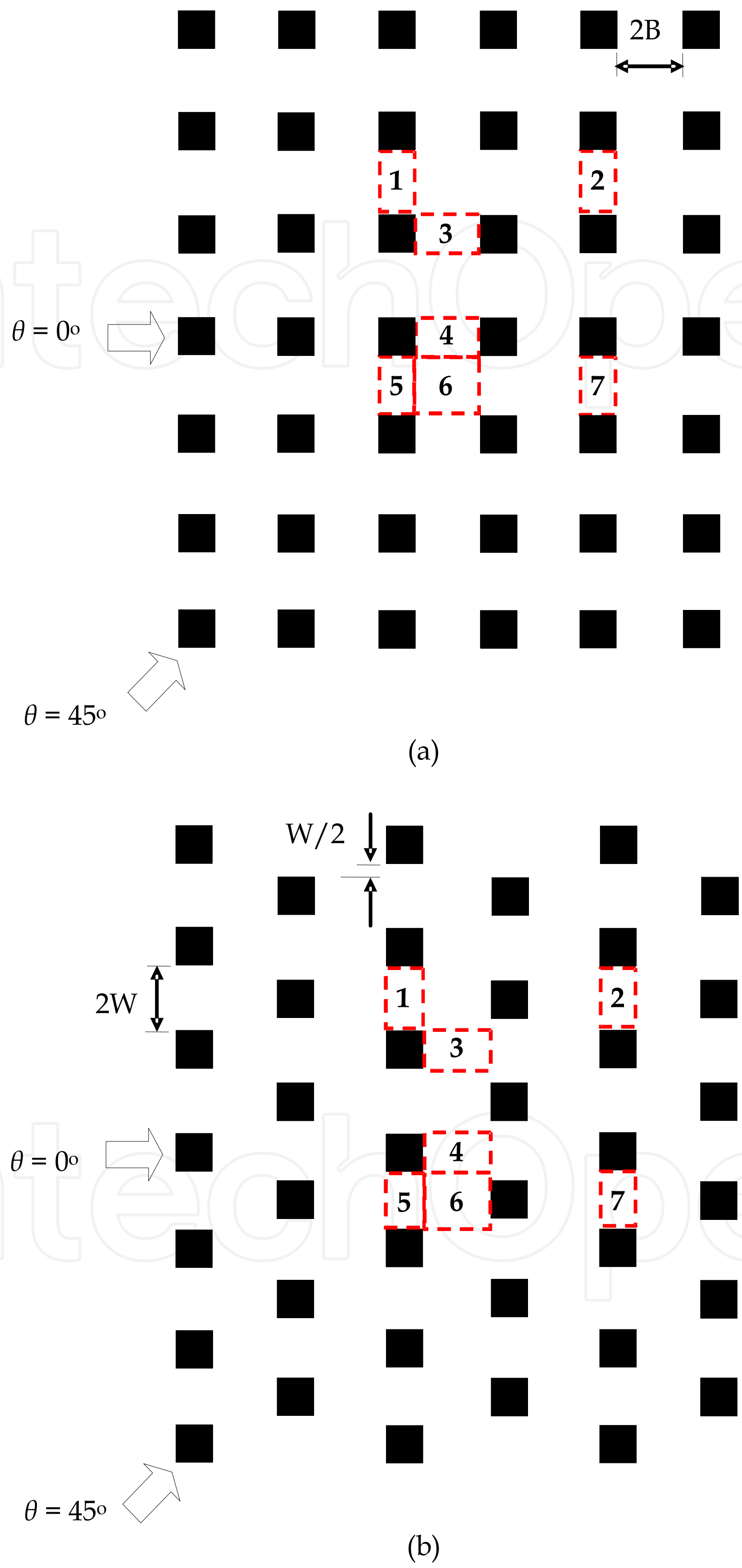
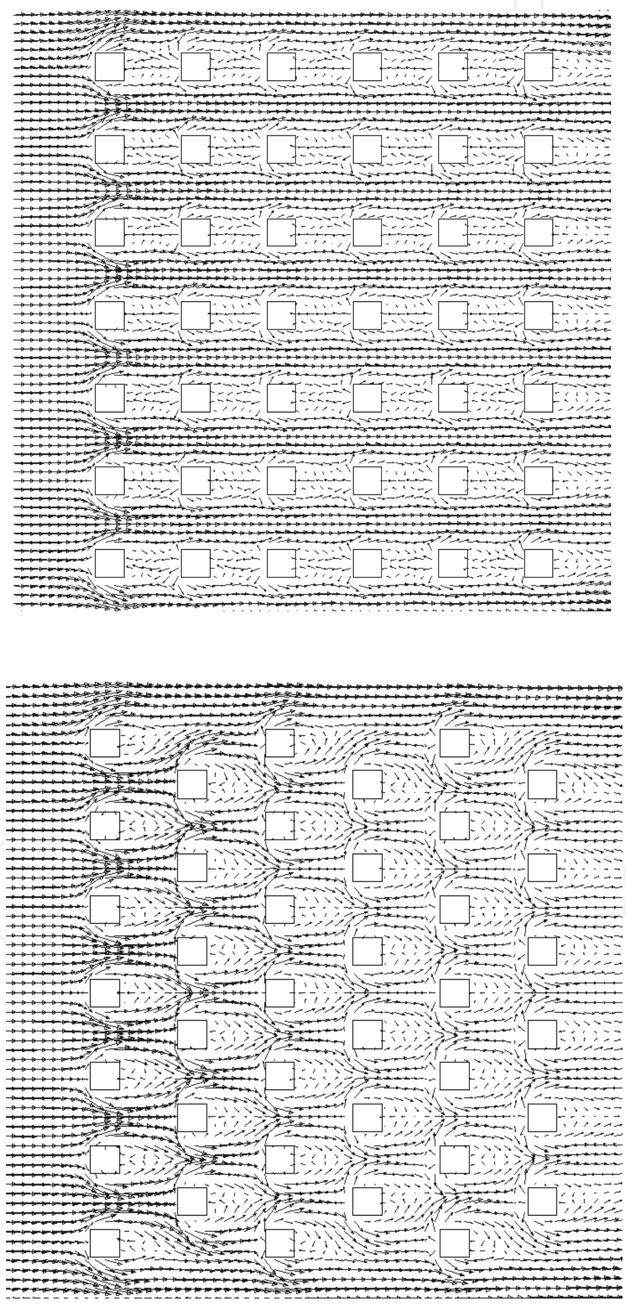


Fig. 16. Schematic of two different building arrays showing the selected domains; (a) aligned, (b) staggered.

The calculated VE indices for the seven domains are shown in Fig. 18. The figure show large variation in the air quality parameters. In the case of θ = 0º, the staggered array shows undesirable air quality conditions within the selected domains compared with the case of aligned blocks except for domains 3 and 4. High pollutant concentrations and low air exchange rates are observed in this case. Additionally, the purging capability of the natural wind for the staggered distribution was lower than that of the aligned one, reflected by high values for VF and TP. This can be referred to the fact that the staggered distribution of blocks prevents the direct flow between the blocks, which decreases the wind capability in removing the pollutants. On the other hand, the smooth flow of the wind within the aligned array at such wind direction dilutes the pollutant concentrations, and hence improves the air

(a)

(b)



(c)

(d)

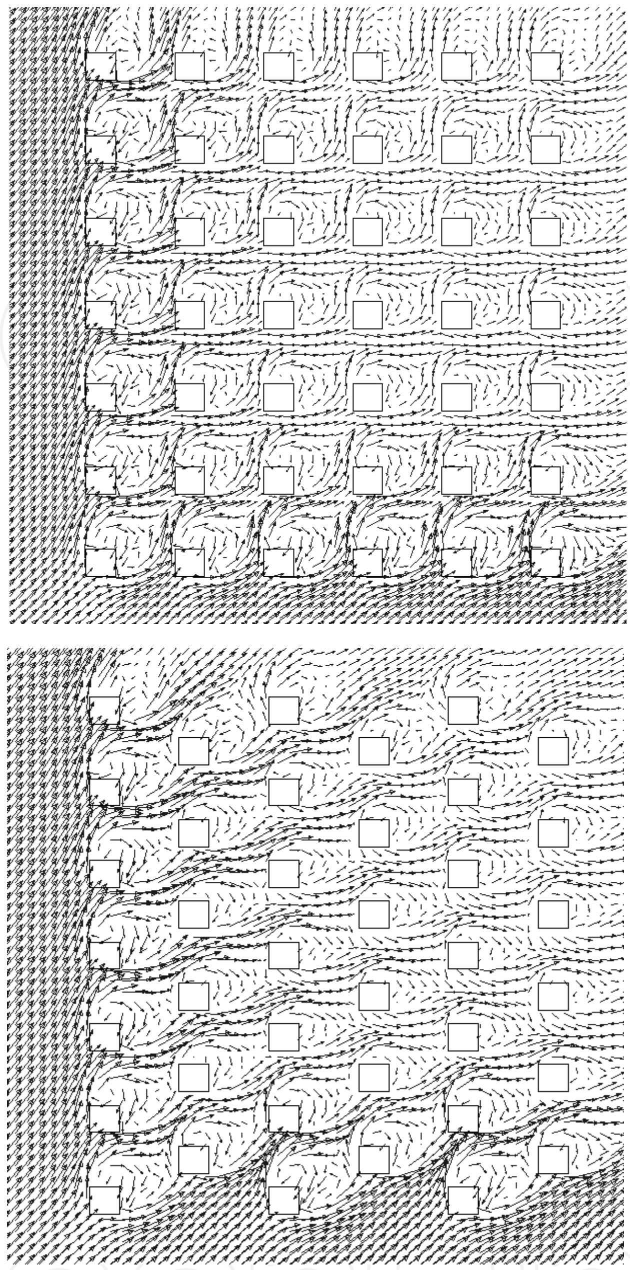
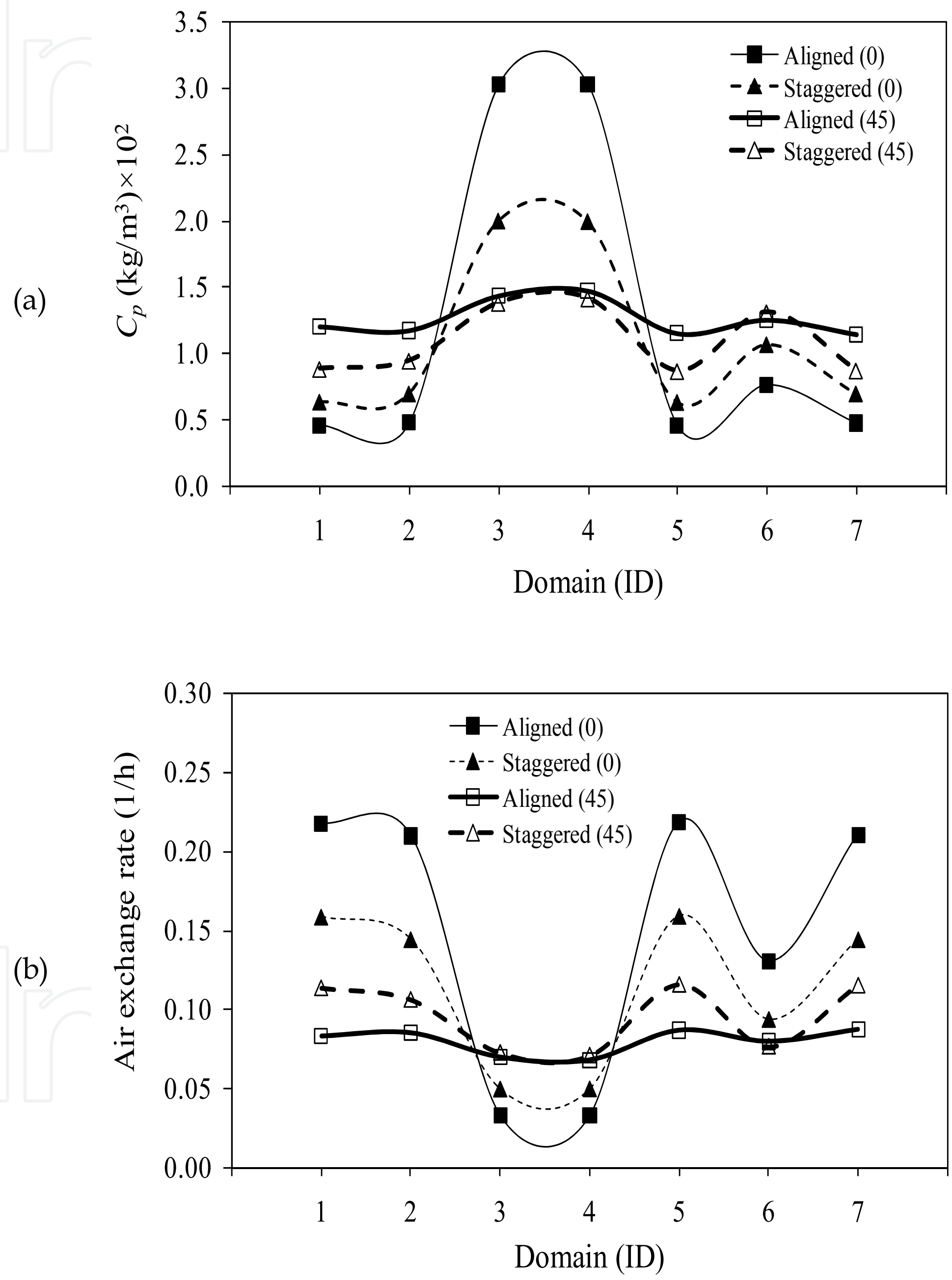


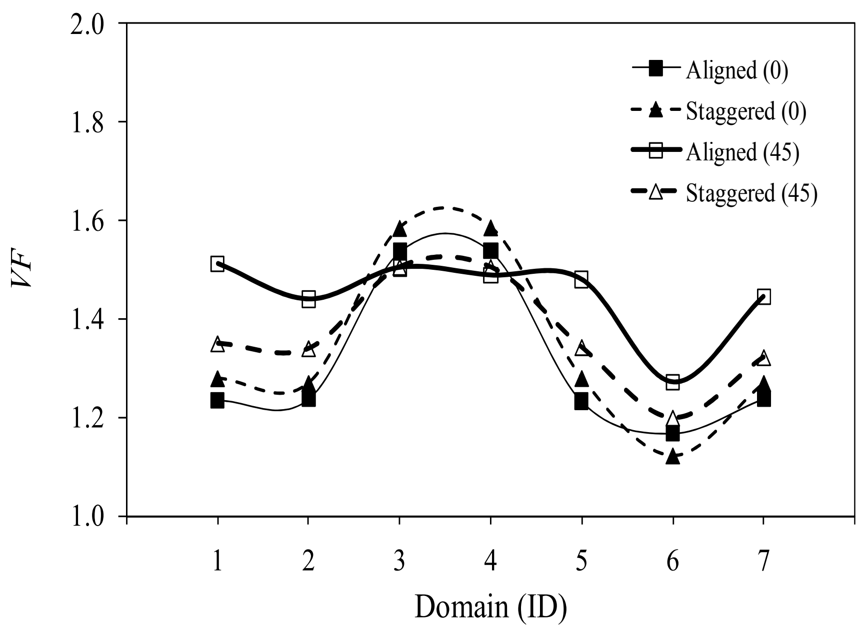
Fig. 17. Wind flow fields around the two building arrays for the two directions (z/H = 0); (a) aligned 0°, (a) staggered 0°, (a) aligned 45°, (a) staggered 0°.

quality of the considered domains. With respect to domains 3 and 4, the locations of such domains within the aligned array are worse than their locations within the staggered one. The geometry of the aligned blocks allows such domains to have three open boundaries, while in the staggered distribution they have four boundaries. Such geometry decreases the ventilation performance of the applied wind of these domains due to the lower inlet flux compared with the other five domains. In the case of θ = 45°, the situation is reversed, where the staggered array show good removal efficiency compared with the aligned array for almost all domains. Such behavior can be attributed to the circulatory vortices that were established around the aligned blocks at such wind direction. These circulatory flows decrease the wind ventilation performance since it reduces the wind velocity within the array domains.

The results of such example show that the ventilation performance of the natural wind within a domain may be changed for the same domain at different conditions of the incident flow. In addition; the results shown confirm that the ventilation efficiency indices are able to reflect the flow characteristics within urban domains very well.



(c)



(d)

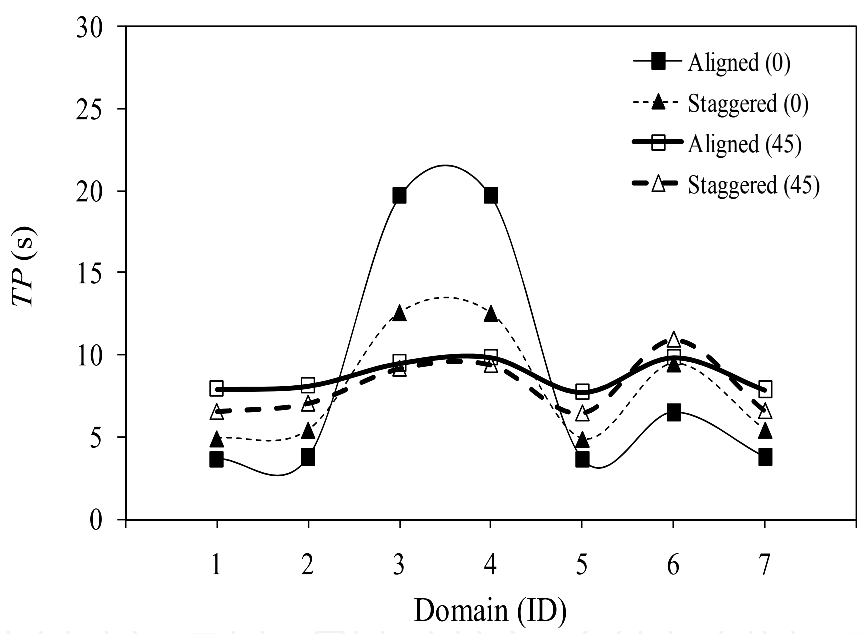


Fig. 18. Air quality parameters within selected domains for the two building arrays; (a) Domain averaged concentration, (b) Air exchange rate, (c) Visitation frequency, (b) Average staying time.

6. Conclusions

Ventilation efficiency indices of indoor environments were applied in evaluating the air quality of urban domains. There are many indices which represent the ventilation efficiency of indoor domains but three indices only are considered here: purging flow rate, visitation frequency and residence time. The calculations of these indices were carried out based on the average flow field analysis using computational fluid dynamics (CFD). Five case studies for evaluating the air quality of urban domain in terms of the VE indices were considered. In the first and second cases, effects of the geometry of an isolated urban street (street width and street building height) on the air quality within the street domain were investigated. In the third one, the influence of wind direction on the air quality was investigated. In the fourth case, the effect of the computational domain height was investigated. Finally, in the fifth case, the effect of building arrangements on the air quality in dense urban areas was studied.

In conclusions, it can be said that the ventilation efficiency indices of indoor environments appear to be a promising tool in evaluating the air quality of urban domains as well. One of the features of applying these indices is that it is not necessary to consider the location of the pollutant source within the study domain. In addition, the VE indices are able to describe the pollutant behavior within the domain, which is very important for obtaining a complete assessment for the wind ventilation performance within urban domains.

7. References

Chock, D. (1977). A simple line-source model for dispersion near roadways, *Atmospheric Environment*, Vol. 12(4), pp. 823-829.

Sandberg, M. (1992). Ventilation effectiveness and purging flow rate – A review, *Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness*; pp. 1-21, Tokyo, Japan.

Ito, K.; Kato S., & Murakami, S. (2000). Study of visitation frequency and purging flow rate based on averaged contaminant distribution–Study on evaluating of ventilation effectiveness of occupied space in room, *Japanese Journal of Architecture Planning and Environmental Engineering (Transaction of AIJ)*, Vol. 529, pp. 31-37, (in Japanese).

Kato, S.; Ito, K. & Murakami, S. (2003). Analysis of visitation frequency through particle tracking method based on LES and model experiment, *Indoor Air*, Vol. 13 (2), pp. 182-193.

Uehara, K.; Murakami, S.; Oikawa, S. & Wakamatsu, S. (1997). Wind tunnel test of concentration fields around street canyons within the stratified urban canopy layer, Part 3: Experimental studies on gaseous diffusion in urban areas; *Journal of Architecture Planning and Environmental Engineering (Transaction of AIJ)*, Vol. 499, pp. 9-16 (in Japanese).

Huang, H.; Ooka, R.; Kato, S. & Jiang, T. (2006). CFD analysis of ventilation efficiency around an elevated highway using visitation frequency and purging flow rate, *Journal of Wind and Structure*, Vol. 9 (4).

Sandberg, M. (1983). The use of moments for ventilation assessing air quality in ventilated Room, *Building and Environment*, Vol. 18 (4), pp. 181-197.

Kato, S. & Murakami, S. (1992). New scales for ventilation efficiency and their application based on numerical simulation and of room airflow, *Proceedings of ISRACVE*, The University of Tokyo, Japan, pp. 22-37.

Mfula, A.; Kukadia, V.; Griffiths, R. & Hall D (2005). Wind tunnel modelling of urban building exposure to outdoor pollution, *Atmospheric Environment*; Vol. 39 (15), pp. 2737-2745.

He, P.; Katayama, T.; Hayashi, T., Tanimoto, J. & Hosooka, I. (1997). Numerical simulation of air flow in an urban area with regularly aligned blocks, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 67&68, pp. 281-291.

Lien, S.; Yee, E. & Cheng, Y. (2004). Simulation of mean flow and turbulence over a 2-D building array using high resolution CFD and a distributed drag force approach, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 92, pp. 117-158.

Kim, J. & Baik, J. (2004). A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyon using the RNG k-ε turbulent model, *Atmospheric Environment*, Vol. 38, pp. 3039-3048.

Ferzigere, J. & Peric, M. (1997). Computational methods for fluid dynamics, Springer, Third Edition.

Xiaomin, X.; Zhen, H. & Jia, S. (2005). Impact of building configuration on air quality in street canyon, *Atmospheric Environment*, Vol. 39 (25), pp. 4519-4530.

Kanda, I.; Uehara, K.; Yamao, Y.; Yoshikawa, Y., & Morikawa, T. (2006). A wind tunnel study on exhaust gas dispersion from road vehicles -Part II: Effect of vehicle queues, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 94(9), pp. 659-673.

Tsai, Y. & Chen, S. (2004). Measurements and three-dimensional modelling of air pollutant dispersion in an urban street canyon, *Atmospheric Environment*; Vol. 38(35), pp. 5911-5924.

Baker, C. J. & Hargreaves, D. M. (2001). Wind tunnel evaluation of a vehicle pollution dispersion model, *Journal of Wind Engineering and Industrial Aerodynamics*; Vol. 89(2), pp. 187-200.

Ahmad, K.; Khare, M. & Chaudhry, K. (2005). Wind tunnel simulation studies on dispersion at urban street canyons and intersections- A review, *Journal of Wind Engineering and Industrial Aerodynamics*; Vol. 93 (9), pp. 697-717.

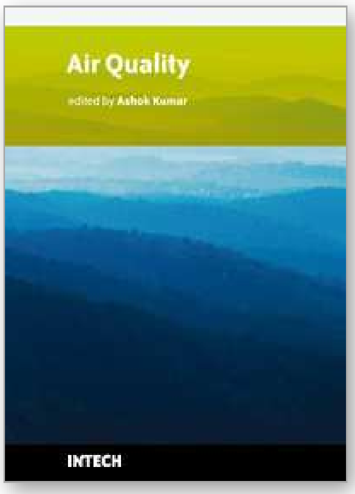
Bady, M.; Kato, S.; Takahashi, T. & Huang, H. (2008). An experimental investigation of the wind environment and air quality within a densely populated urban street canyon. Submitted.

Bady, M.; Kato, S.; Ishida, Y.; Huang, H; & Takahashi, T. (2008). Exceedance probability as a tool to evaluate the wind environment within densely urban areas". *Journal of Wind and Structure*, Vol. 11(6).

Hui, S.; & Davidson, L. (1997). Towards the determination of the local purging flow rate, *Building and Environment*; Vol. 32(6), pp. 513-525.

Bady, M.; Kato, S.; & Huang, H. (2008). Towards the application of indoor ventilation efficiency indices to evaluate the air quality of urban areas, *Building and Environment*, Vol. 43(12).

Davidson, M.; Snyder, W.; Lawson R. & Hunt J. (1996). Wind tunnel simulation of plume dispersion through groups of obstacles, *Atmospheric Environment*; Vol. 30(22), pp. 3715-3731.



Air Quality
Edited by Ashok Kumar

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Air pollution is about five decades or so old field and continues to be a global concern. Therefore, the governments around the world are involved in managing air quality in their countries for the welfare of their citizens. The management of air pollution involves understanding air pollution sources, monitoring of contaminants, modeling air quality, performing laboratory experiments, the use of satellite images for quantifying air quality levels, indoor air pollution, and elimination of contaminants through control. Research activities are being performed on every aspect of air pollution throughout the world, in order to respond to public concerns. The book is grouped in five different sections. Some topics are more detailed than others. The readers should be aware that multi-authored books have difficulty maintaining consistency. A reader will find, however, that each chapter is intellectually stimulating. Our goal was to provide current information and present a reasonable analysis of air quality data compiled by knowledgeable professionals in the field of air pollution.

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