THE IMPACT OF TRAFFIC-RELATED POLLUTANT ON INDOOR AIR QUALITY IN BUILDINGS NEAR MAIN ROADS

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ABSTRACT

Traffic–related pollutant has been recognized as an air pollution hot spot due to its large emission rate and great health impacts for the exposed population. In the present investigation, a computational fluid dynamics technique is used to evaluate the effect of traffic pollutions on indoor air quality of a naturally ventilated building. The transport of street-level nonreactive pollutants emitted from motor vehicles into the indoor environment is simulated using the RNG k-ε model of the turbulent flows and the pollutant transport equations. Three typical configurations of street canyons and six ventilation scenarios are considered. It is found that the layout of street canyon affects not only the airflow pattern but also the ventilation rates, paths and indoor air quality for that building. When the studied building is located in the street canyon with aspect rate 0.2, using the leeward cross-flow ventilation with windward upper vent can effectively lower incoming vehicle pollutants and maintain a desirable air change rate during traffic rush hours. But when the street canyon aspect rate is equal to 0.5, this ventilation mode has no significant advantage compared with other cross ventilation modes. Moreover, the leeward side vents may become a significant factor contributing to indoor concentration of traffic pollutants when the studied buildings are located in a narrow street such as aspect rate equal to 1.

KEYWORDS

Street canyon, Traffic pollutants, Natural ventilation, Indoor air quality, RNG

INTRODUCTION

Traffic pollution is of increasing concern in many of the world's cities. With the growth in road traffic, the motor vehicle exhaust has become the most predominant source of air pollution in the urban centers over the world, despite significant improvements in fuel and engine technology. It typically accounts for 80% of CO emissions, 25% of fine particulate emissions, 40-50% of VOC emissions and 90% of benzene emissions in many countries, and even higher proportions in some urban areas (Simon Kingham et al. 2003). Although the health effects of these pollutants are not yet fully understood, asthma, other respiratory diseases and some cancers have all been linked to traffic emissions (Kousa A. et al. 2002, Colvile R.N. et al. 2003).

To keep good indoor air quality, ventilation system for buildings in urban environment should maintain required ventilation rate to remove and dilute indoor pollutant, and avoid the adverse effect of outdoor pollutant at the same time. Ekberg (1996) and Green et al. (1998) respectively carried out academic attempts regarding control strategies for reducing the impact of outdoor traffic pollutants on indoor air quality of a building next to busy roads. However, they assumed that all the air entering the room had same pollutant concentration. This assumption ignored the spatial variations in the concentrations of pollutant around buildings. Green et al. (2001) conducted wind-tunnel and full-scale measurement to examine CO levels around a building located in close to busy roads. It was concluded that indoor pollutant concentration could be reduced when air intakes were located in the regions of low concentration of traffic pollution. T. J. Chang (2002) investigated the effect of traffic pollution on indoor air quality of a naturally ventilated building using CFD technology. He claimed that reasonable ventilation design could effectively lower incoming vehicle pollutants and maintain a desirable air change rate during traffic rush hours, and recommended that the ventilation mode using the leeward cross-flow ventilation with the windward roof vent was the most effective one for buildings near main road. Major limitation of this study is to consider only a single building case, which may have great difference from real urban environment.

The main objective of this research is to investigate the transmission of outdoor air contaminant into buildings and find optimum ventilation strategies for naturally ventilated buildings located in street canyon environment, which suffer high concentration of outdoor pollutant. In this paper, the street canyon effect was considered, and both ventilation rate and indoor air quality were investigated in every street canyon configuration and ventilation mode. The appropriate control strategies for lowering incoming vehicle pollutants and maintaining an acceptable air change rate are examined to reduce the impact of outdoor traffic pollutants on indoor air quality.

NUMERICAL SIMULATIONS

Model description

RNG k-ε model is applied in the present paper, because this model is more precious than standard k-ε model and needs less computational source than LES when investigating air flow around buildings (G. Evola and V. Popov. 2006).

The air around buildings can be regarded as an incompressible turbulent inert flow, and the air and pollutant densities are assumed to be constant. These assumptions are reasonable for most lower atmosphere environments as described by Sini et al.(1996). Besides, the turbulence production due to the buoyancy effect is not taken into consideration in the present study.

The equations of mass, momentum are written in Cartesian tensor notation as follows (T.L. Chan et al. 2002):

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}(\overline{u_i' u_j'}) \tag{2}$$

k and ε transport equations in RNG k-ε turbulence model:

$$\frac{\partial k}{\partial t} + \frac{\partial (k u_j)}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\alpha_k \mu_{\text{eff}} \frac{\partial k}{\partial x_j}\right] + \frac{G_k}{\rho} - \varepsilon \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial (k u_j)}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon \mu_{\text{eff}} \frac{\partial \varepsilon}{\partial x_j}\right] + \frac{1}{\rho} C_{\varepsilon 1} G_k \frac{\varepsilon}{k} - \left[C_{\varepsilon 2} + \frac{C_\mu \rho \eta^3 (1-\eta/\eta_0)}{1+\beta\eta^3}\right]\frac{\varepsilon^2}{k} \tag{4}$$

The species (pollutants) transport equation:

$$\frac{\partial C_i}{\partial t} + u_j \frac{\partial C_i}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(D_i + \frac{\mu_t}{Sc_t}\right)\frac{\partial C_i}{\partial x_j}\right] \tag{5}$$

Where

$$-\overline{u_i' u_j'} = \frac{1}{\rho}\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}$$

$-\overline{u_i' u_j'}$ is the Reynolds stress; $\mu_t = \rho C_\mu k^2/\varepsilon$, μ_t is the turbulent viscosity; μ is the molecular viscosity; G_k is the turbulent kinetic energy production; α_k and α_ε are the inverse effective Prandtl number for k and ε respectively; μ_{eff} is the effective turbulent viscosity; $\eta = Sk/\varepsilon$; S is the scalar measure of the deformation tensor; the constants of η_0 and β are 4.38 and 0.012, respectively; C_i is the chemical species (pollutants) concentration; D_i is the diffusivity; Sc_t is the turbulent Schmidt number. All the above calculations were performed using the FLUENT code.

Computational domain and boundary conditions

A two dimensional computational domain is used with wind direction assumed to be perpendicular to the street canyon. The downstream building (B2) is chosen as the studied building. There are two vents on the windward side and leeward sides of B2 respectively, and the height of each vent is 1.5m. Fig.1 shows the computational street canyon configuration and the opens' location on B2, where W is the street width and H is the building height. The vehicular emissions are considered as a line source located at the center of the street. CO is used as a representative automotive emission gas because it is relatively stable, easily measured and comes mainly from vehicle emissions. Initial concentration of emissions is presented in dimensionless form 1.

At the inflow boundary, the inflow vertical wind speed profile is assumed to be in a power- law form as follows:

$$U_i = U_r\left(\frac{z}{z_r}\right)^{0.299} \tag{6}$$

Where z_r and U_r are specified as 10m (the height of buildings) and 0.5ms^{-1}, respectively. The inflow turbulent kinetic energy profile is presented by

$$k_i = aU_i^2 \tag{7}$$

Where a is a parameter that controls the inflow turbulence intensity and specified as 0.005. And the inflow dissipation rate profile is given by

$$\varepsilon_i = \frac{C_\mu^{3/4} k_i^{3/2}}{kz} \tag{8}$$

Where C_μ is a constant (=0.09) and k is the von Karman constant (=0.4).

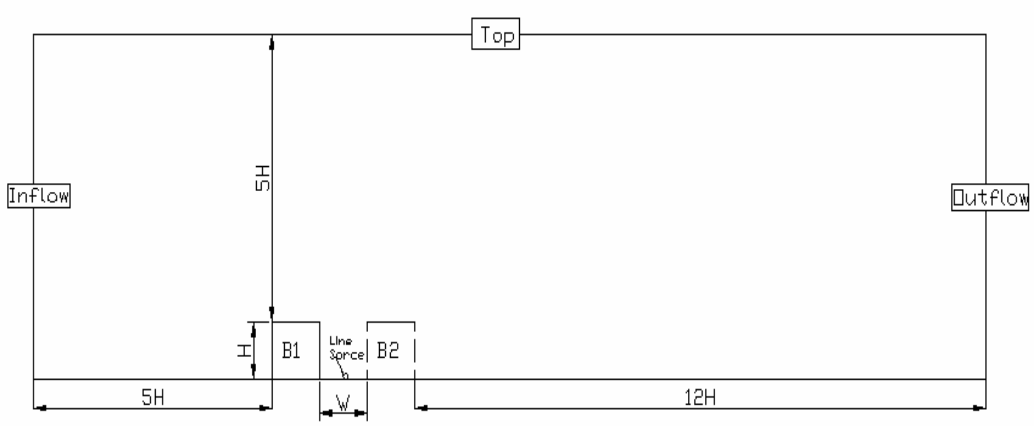

Figure 1 Sketch of the calculation domain

No-slip velocity boundary conditions are applied to all solid surfaces and the ground, and symmetric boundary is used at upper boundary. At the outlet of the computational domain, a constant pressure is assumed. The initial conditions of both the velocity and concentration fields are set to zero in the entire computational domain. A structured grid system with 350 grids in the horizontal and 160 grids in the vertical is used. Finer grids are located close to the building and ground and then expand further away. The expansion ratio in this non-uniform grid system is 1.1. Extensive tests of the independence of the meshes are carried out with increasing mesh number until further refinement is shown to be less significant. The second order linear upwind difference scheme has been used to avoid the errors produced by numerical diffusion when using the first order upwind scheme.

Model validation

The experimental data used for the validation of numerical simulation were obtained from a detailed wind tunnel study by Meroney et al. (1996). Pollutant concentration measurements in the atmospheric boundary layer wind tunnel at the Meteorological Institute of Hamburg University, Germany. The boundary layer was generated using the wind tunnel, which consisted of an inlet nozzle, flow straighteners, Irwin-type vortex generators, a flow establishment section, a test section, anti-swirl devices and a squirrel-cage centrifugal fan. Two wooden bars were laid across the wind tunnel to model two-dimensional multi-story flat-roofed buildings. The precisely designed line source was placed in the center of the street floor between these two bars to model the emission source from the vehicular exhaust. The direction of line source was parallel to the direction of bars.

The measured pollutant concentrations in the wind-tunnel were expressed in the dimensionless pollutant concentration form K, which is defined as:

$$K = \frac{CU_{ref}HL}{Q} \quad (9)$$

Where C is the volume fraction of contaminant; H is the height of building; L is the length of line source; Q is the volume flow rate of contaminant.

Fig. 2 shows the dimensionless pollutant concentration (K) distributions on the leeward side and windward side of the street canyon when the ratio H/W=1. The simulation results present good agreement with the measured data in wind tunnel, but under-predict the dimensionless concentrations on the leeward side of the street canyon, especially at the lower part. In spite of the difference, both profiles are similar to each other suggesting the numerical model can be used for simulating airflow and pollutant dispersion in an urban street canyon.

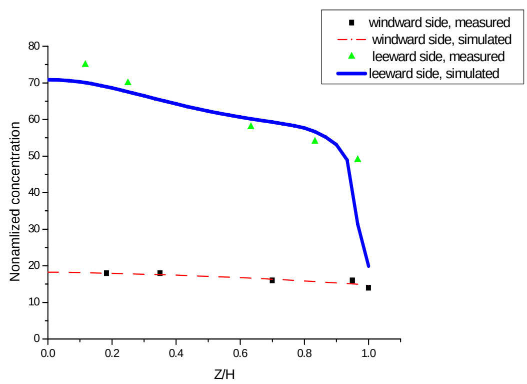

Figure 2 The normalized concentration at the buildings wall: H/W =1, U_{ref}=0.5

Table 1 Summary of the building configurations for each numerical scenario simulation

Scenario	Upper vent on windward side	Lower vent on windward side	Upper vent on leeward side	Lower vent on leeward side	Notation
1	open	open	open	open	
2	closed	closed	open	open	
3	open	open	closed	closed	
4	open	open	open	closed	
5	open	open	closed	open	
6	open	closed	open	open	

RESULTS AND DISCUSSION

Because the aspect ratio *H/W* is one of the most important factors which influence the airflow and dispersion of pollutant, three typical street configurations with aspect ratio 0.2, 0.5 and 1 are considered in the present paper. In each street canyon, six ventilation scenarios are used to investigate the effect of different ventilation strategies on indoor air quality. Mechanical ventilation devices and indoor pollution source are not considered here. The ventilation scenarios are summarized in table1.

H/W=0.2

When the aspect ratio of street canyon is equal to 0.2, the two buildings are well apart and the flow fields associated with the buildings do not interact, which results in the isolated roughness flow (IRF). In this case, the flow pattern around B2 is similar with that without any shields (see Fig. 3).

In this paper, we focus on the transmission process of traffic pollutant into the studied building, so the airflow path and indoor airflow pattern are presented in Fig.4. The ventilation rate and averaged indoor CO concentration, which is normalized by the

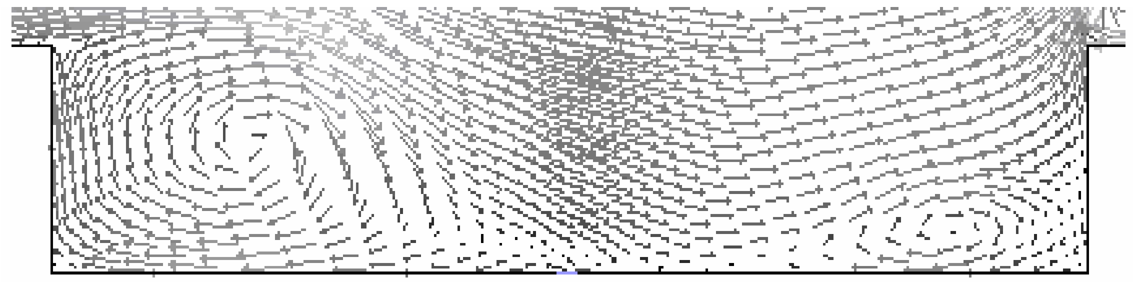

Figure 3 Wind speed vector distribution within the street canyon (H/W=0.2)

Table 2 Result of the numerical scenario simulations (H/W=0.2)

Scenario	Flow Rate at upper vent on windward side(m^3/sec/m)	Flow Rate at lower vent on windward side(m^3/sec/m)	Flow Rate at upper vent on leeward side(m^3/sec/m)	Flow Rate at lower vent on leeward side(m^3/sec/m)	Air Change Rate (hr^{-1})*	Normalized Average Concentration
1	0.564	0.445	-0.507	-0.502	14.5	0.90
2	0	0	-0.221	0.221	3.2	0.33
3	-0.426	0.426	0	0	6.1	0.93
4	0.404	0.345	-0.749	0	10.8	0.74
5	0.412	0.323	0	-0.735	10.6	0.72
6	0.565	0	-0.480	0.085	8.1	0.53

* assuming the opening rate of the studied building is 0.16

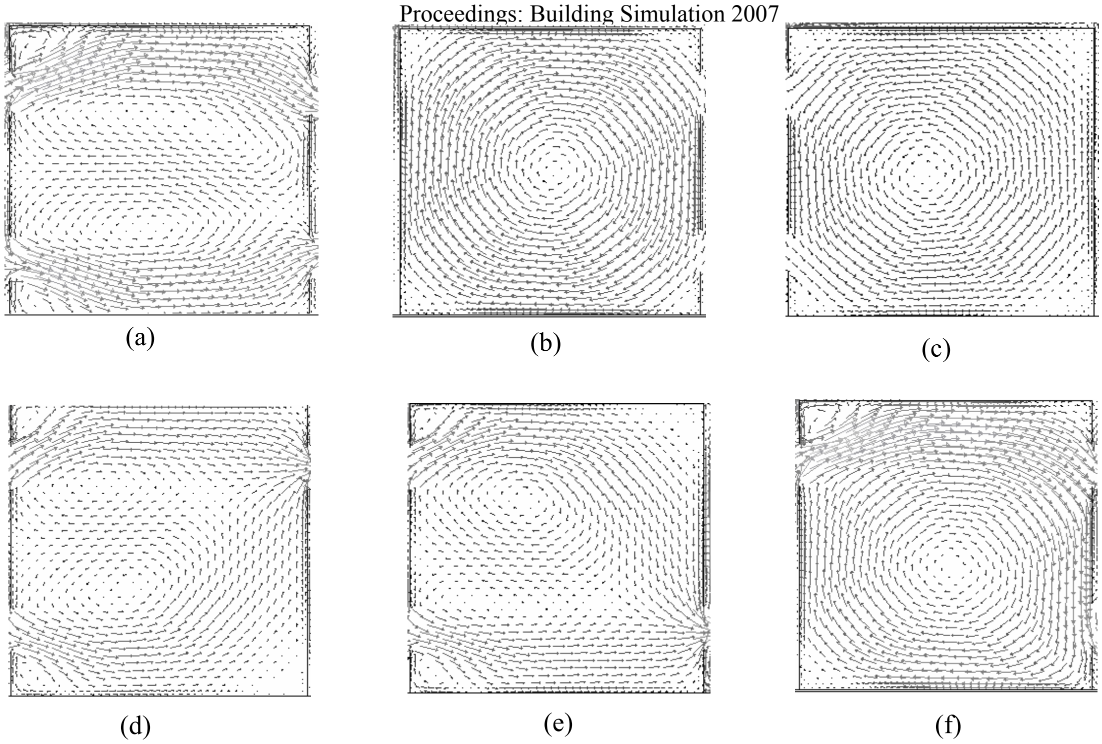

Figure 4 The simulated results of the airflow vector fields in B2 for (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, (d) Scenario4, (e) Scenario 5 and (f) Scenario 6 (H/W=0.2)

maximum value of pollutant concentration at the windward side of the studied building, are reported in table2. When all vents open (scenario 1), the airflow in interior portion of B2 represents an unimpeded airflow pattern between the incoming and outgoing, and the ventilation rate is very high. As a result of larger areas of ventilated region, high levels of the average pollutant concentration within B2 can be observed. When using windward-sided or leeward sided ventilation (scenario 2,3) , the air change rates are relatively low. But in windward-sided ventilation case, the pollutant concentration inB2 is even higher than scenario1. In the three scenarios with cross ventilation (scenario4 to scenario6), the studied building (B2) has similar ventilation rate. It should be noticed that in the street with this configuration, a significant concentration gradient on windward side of B2 is observed, and the concentration of CO near the upper part of the façade is found to be lower. Hence,scenario 6, in which the pollutant concentration is relative lower at the air intakes, can significantly reduce the effect of traffic pollutant on indoor air quality and offer high ventilation rate.

H/W=0.5

When the aspect ratio of street canyon is equal to 0.5,the wake behind the upwind building is disturbed by the recirculation created in front of the windward building, and two vortexes is established in street canyon (see Fig.5). This is the wake interference flow (WIF).

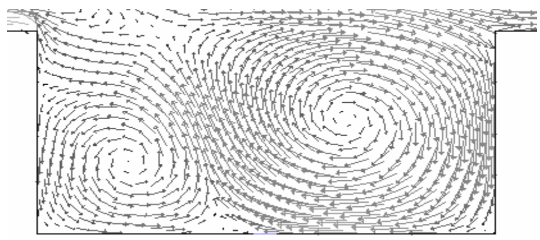

Figure 5 Wind speed vector distribution within the street canyon (H/W=0.5)

Shielded by the upwind building (B1), the ventilation rate of B2 has been reduced in every ventilation scenario, except leeward sided ventilation.When all vents open (scenario 1), a piston-like flow pattern is also observed in interior portion of B2, and the normalized concentration of CO is almost same with the case of H/W=0.2. Due to the effect of the vortex near windward side of B2, the airflow paths of scenario4 and scenario5 change. The outdoor air cannot enter into the studied building from the lower vent of windward side, when both vents on windward side are opened (Fig.6 (c)—(f)).

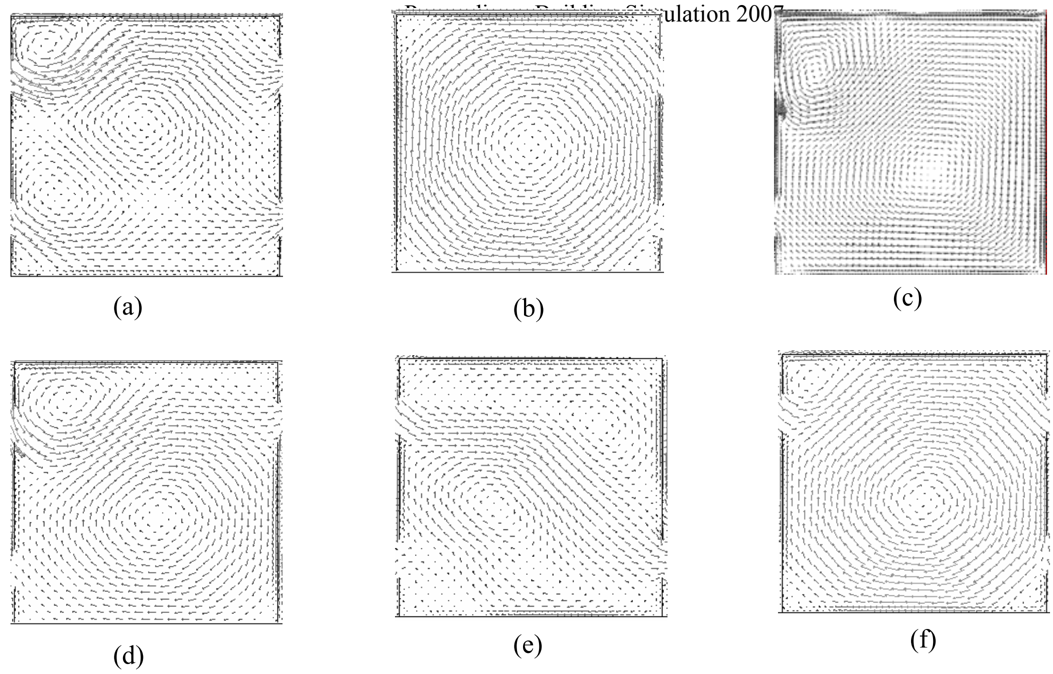

Figure 6 The simulated results of the airflow vector fields in B2 for (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, (d) Scenario4, (e) Scenario 5 and (f) Scenario 6 (H/W=0.5)

Table 3 Result of the numerical scenario simulations (H/W=0.5)

Scenario	Flow Rate at upper vent on windward side(m^3/sec/m)	Flow Rate at lower vent on windward side(m^3/sec/m)	Flow Rate at upper vent on leeward side(m^3/sec/m)	Flow Rate at lower vent on leeward side(m^3/sec/m)	Air Change Rate (hr^{-1})	Normalized Average Concentration
1	0.373	0.254	-0.302	-0.325	9.1	0.89
2	0	0	-0.227	0.227	3.3	0.29
3	0.379	-0.379	0	0	5.45	0.96
4	0.525	-0.079	-0.446	0	7.56	0.68
5	0.518	-0.067	0	-0.451	7.46	0.69
6	0.327	0	-0.406	-0.079	5.8	0.65

Hence, the normalized concentration of CO in B2, using scenario4, scenario5, scenario6 respectively, has no significant difference (Table 3).

H/W=1

When the ratio W/H is 1, the bulk of the above roof flow does not penetrate in canyon and a stable single vortex is established between the buildings (see Fig.7). Because of the vortex's effect, a low pressure zone is created in the two buildings, and the pressure on windward side of B2 is lower than that on leeward side. This phenomenon is also observed by Jie Yang (2003). Using all cross ventilation scenario, outdoor air incomes from vents on leeward side and

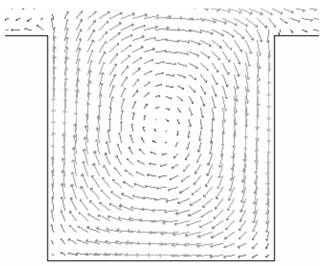

Figure 7 Wind speed vector distribution within the street canyon (H/W=1)

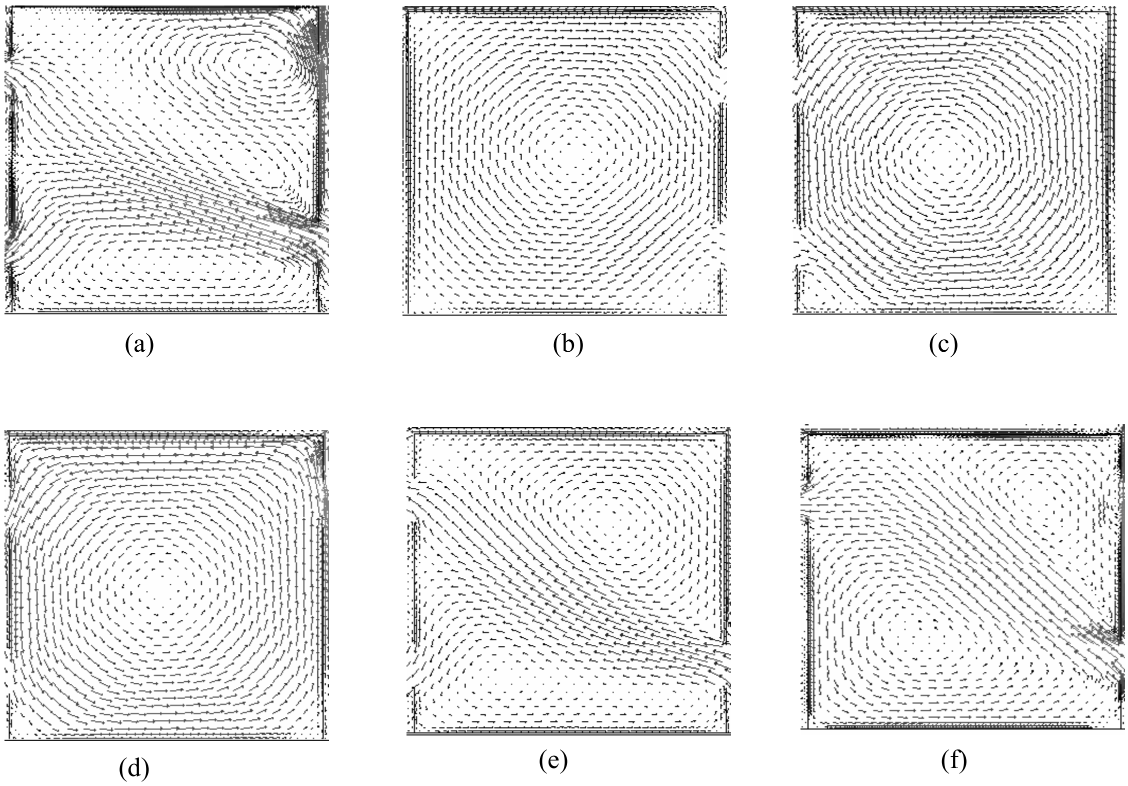

Figure 8 The simulated results of the airflow vector fields in B2 for (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, (d) Scenario4, (e) Scenario 5 and (f) Scenario 6 (H/W=1)

Table 4 Result of the numerical scenario simulations (H/W=1)

Scenario	Flow Rate at upper vent on windward side(m^3/sec/m)	Flow Rate at lower vent on windward side(m^3/sec/m)	Flow Rate at upper vent on leeward side(m^3/sec/m)	Flow Rate at lower vent on leeward side(m^3/sec/m)	Air Change Rate (hr^{-1})	Normalized Average Concentration
1	-0.139	-0.131	0.121	0.149	3.8	0.34
2	0	0	-0.182	0.182	2.6	0.29
3	-0.111	0.111	0	0	1.6	0.99
4	-0.088	0.022	0.066	0	1.3	0.34
5	-0.123	-0.071	0	0.194	2.8	0.32
6	-0.240	0	-0.019	0.259	3.7	0.32

gets out from vents on windward side (Fig.8). This means that concentration near windward side vents is a significant factor contributing to indoor concentration of traffic pollutants when the studied buildings are located in a narrow street with aspect rate 1, except for that using windward single-side ventilation.

CONCLUSIONS

A series of numerical scenario simulations on the effect of traffic pollution on indoor air quality of a naturally ventilated building in different street layout were conducted to quantitatively investigate the relationship among the external airflow pattern, external pollutant dispersion around the building, air change rates, the indoor airflow patterns, and the for various ventilation strategies. Based on the simulated results, the present research has led to the following conclusions:

(1) RNG k-ε model is verified to be a convenient tool to investigate the transport of street-level nonreactive pollutants emitted from motor vehicles through the indoor environment.

(2) Street configurations have great influence on external air flow around the building, airflow paths and ventilation rate of buildings along roads.

(3) The ventilation strategy using the upper vent on windward side and vents on leeward side, which is recommended by T. J. Chang (2002), only has advantage when the street is relatively wide or the buildings along streets is relatively low.

(4) In narrow streets, a low pressure zone will be formed between the two buildings, and the pressure

on the windward side of the downstream buildings may be lower than that on the leeward side. This means that the pollutant concentration in street canyon has little effect on the indoor concentration of traffic pollutants and the concentration on leeward side becomes a significant factor contributing to indoor air quality when using cross ventilation.

This is a pilot study on the effect of traffic pollutants on indoor air quality and natural ventilation control strategy for buildings near busy road. Only symmetric canyons and 2D case are considered in the present paper. Further research on more complicated urban environment and three-dimensional simulations are needed.

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