Thai Journal of Mathematics
Volume 5(2007) Number 1 : 109–125
www.math.science.cmu.ac.th/thaijournal

Numerical Simulations of Airflow around Elevated Expressways over Street Canyons

M. Tanulert, A. Luadsong and D. Sukawat

Abstract : The dispersion of pollution in street canyon is mainly dominated by meteorology conditions such as wind speed and direction and by building configurations including various obstacles such as expressway. Two-dimensional numerical simulations for investigating velocity field around elevated express ways over street canyons are performed. The governing equations for incompressible airflow are discretized by using finite volume method (FVM) and the SIMPLE algorithm is used to solve these discretized equations. The effects of elevated expressways on airflow were analyzed in different positions over street canyons and different street canyon geometries. Results show that the elevated express ways and street canyon geometries strongly influence wind field in street canyons.

Keywords : Finite volume method; SIMPLE algorithm; Airflow; Expressway; Street canyon

1 Introduction

Increased motor vehicles especially in urban area often results in severe traffic congestion and lead to air pollution in street canyons, which is one of the most important elements in urban area. The elevated expressways, which create structurally complicated street canyon are constructed to smooth the heavy traffic flow in urban area.

The dispersion of pollution in street canyon is mainly dominated by meteorological conditions such as wind speed and direction and by building configurations including various obstacles such as expressways.

Street canyon can cause flow re-circulations and/or stagnant conditions that prohibiting the dispersion of pollutants away from the street. These behaviors have direct impact on human health, especially people working nearby the street.

However, there is very few fundamental studies of airflow focused on elevated expressways over street canyon which may be enhance air pollution. The airflows in these areas are difficult to analyze. Numerical simulations are necessarily used to study the airflow in these areas.

In this research, a two-dimensional numerical simulation for airflow around elevated expressways over street canyon is performed. The governing equation for the two-dimensional incompressible unsteady state flow is discretized by finite volume method (FVM) and the SIMPLE algorithm is employed to iterate for the pressure correction and convergence of the velocity field. The model is then used to study the effect of an elevated expressways on airflow in street canyon.

2 Expressways over Street Canyon Characteristics

2.1 Canyon Geometry

Street canyon usually refers to a relatively narrow street with buildings lined up continuously along both sides (Nicholson, 1975). However, it may be used to refer to larger streets, also called avenue canyons. In the real world, street canyons are not necessarily flanked by buildings continuously on both sides, allowing for some openings on the walls of the canyon. Street canyons are usually charac-

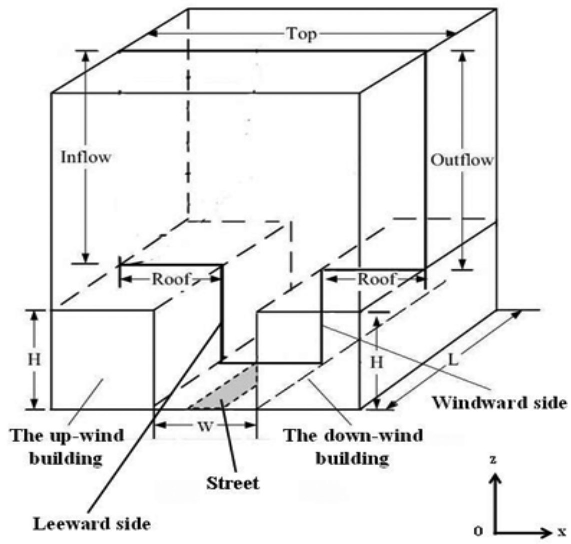


Figure 1: Street canyon geometry

terized by their aspect ratio, which is the height (H) of the canyon divided by the width (W) of the street. If a canyon has an aspect ratio close to 1 and no major openings on the walls, it is called regular. An avenue canyon has an aspect ratio below 0.5, while a deep canyon has an aspect ratio approximately equal to 2.

Urban streets might be also classified in symmetric (or even) canyons, if the buildings flanking the street have approximately the same height, and in asymmetric, if there are significant differences in building height. (Vardoulakis et al.2003)

2.2 Wind Flow

Airflow and pollutant dispersion are controlled by the characteristic of street canyons. Three different dispersion conditions for different wind velocities can be identified. These are:

(i) low wind conditions for wind speed lower than 1.5m/s,

(ii) perpendicular flow for wind speed over 1.5m/s blowing at an angle more than 30° to the canyon axes, and

(iii) parallel or near-parallel flow for wind speed over 1.5m/s blowing at an angle less than or equal to 30° to the canyon axes.

Depending on the wind direction, asymmetric canyons may be sub-divided into two categories: (i) step-up canyons, when the downwind building is higher than the upwind building, and (ii) step-down canyons, when the down-wind building is lower than the upwind building.

In the case of perpendicular flow, the upwind side of the canyon is usually called leeward, and the downwind side is windward (Vardoulakis et al.2003).

2.3 Expressways over Street Canyon Geometry

To decrease the heavy traffic due to increased vehicles, expressways are constructed. Most of expressways are positioned over street canyon and sometime are constructed more than one layers.The expressway over street canyon in urban areas can be simplified as shown in Figure 2. It consists of buildings and expressways which position over the street. The size of buildings and expressways and street width can be adjust to satisfy the interested location.

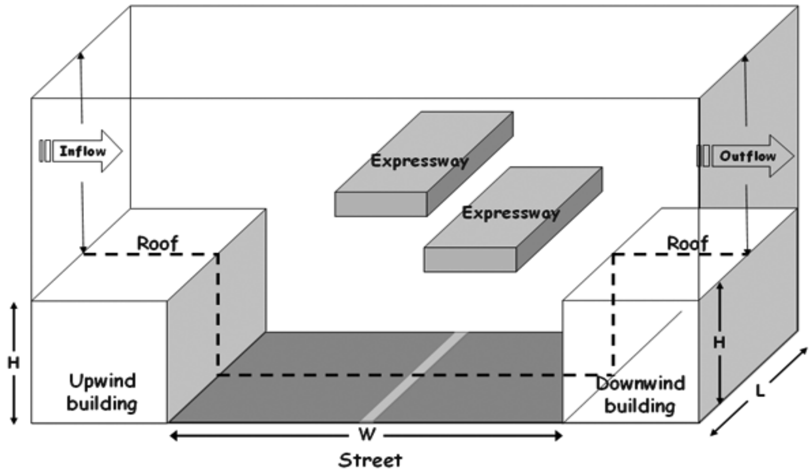


Figure 2: Expressways over street canyon geometry

Here only a two-dimensional model for laminar airflow around elevated expressways over street canyons is considered. The cross-sectional elevated expressways over street canyon is shown in Figure 3.

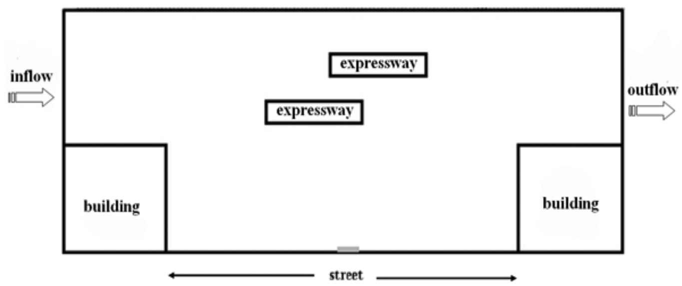


Figure 3: 2-D geometry

The street canyon is conducted with rectangular cross-sectional buildings and expressways. There is a street between two buildings. The wind is orthogonal to the direction of street and move from left to right.

3 Numerical Calculation

3.1 Computational Domains

In all cases, the domain size is 60m in the x-direction, 35m in the y-direction and the street width is 34m (Figure 4). The dimension of the expressways is 10m width and 3m height. The computational domains were constructed with $\delta x = 0.5$ and $\delta y = 0.5$. So the computational domains consist of 120×70 cells of equal size including all buildings and expressways.

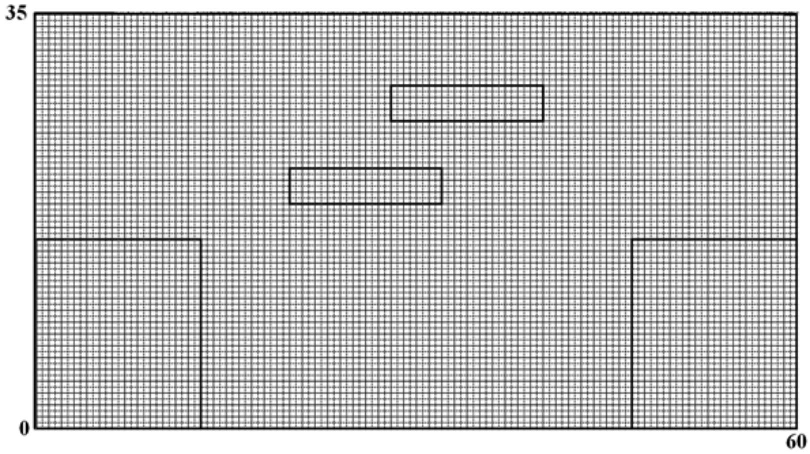


Figure 4: Computational domain

3.2 Initial and Boundary Conditions

The initial velocity is set to equal zero. Velocity inlet boundary conditions is used for the main inlet wind flow. Simulations are performed with u = 1m/s, v = 0m/s for low speed flow and u = 10m/s, v = 0m/s for high speed flow. An outflow boundary condition is assumed for the outlet at the right end of the domain. A free slip condition is used at the top of domain. All solid surfaces of the domain (street, expressways, and building walls) are defined as walls with no slip condition (Figure 5).

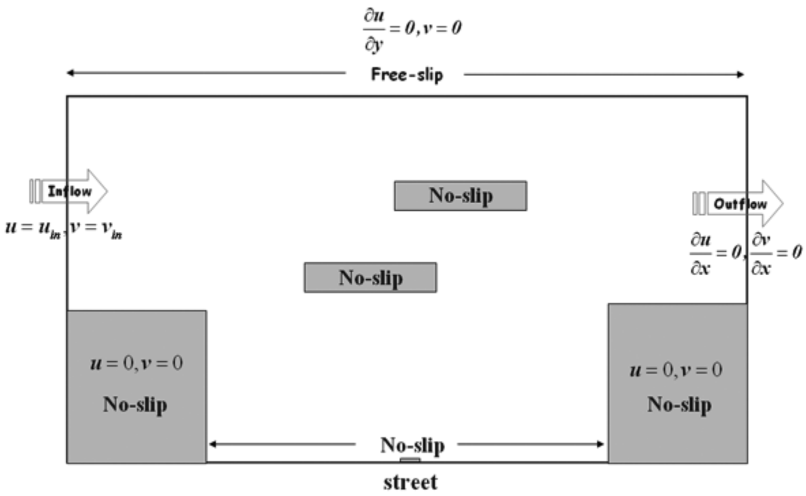


Figure 5: Boundary condition

3.3 Governing Equations of Airflow

In this research, The Navier-Stokes equations for 2-D incompressible unsteady flow is solved to study the airflow around elevated expressways. In the absence of source terms, these equations can be written:

- *Momentum equations*

$$\frac{\partial \varrho u}{\partial t} + \frac{\partial(\varrho u u)}{\partial x} + \frac{\partial(\varrho v u)}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) - \frac{\partial P}{\partial x}, \quad (3.1)$$

$$\frac{\partial \varrho v}{\partial t} + \frac{\partial(\varrho u v)}{\partial x} + \frac{\partial(\varrho v v)}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) - \frac{\partial P}{\partial y}, \quad (3.2)$$

- *Continuity equation*

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \quad (3.3)$$

For convenience, these equations may be written in compact form as:

- *Momentum equations*

$$\frac{\partial \varrho u}{\partial t} + \mathrm{div}(\varrho \vec{\mathbf{u}} u) = \mathrm{div}(\mu \text{ grad } u) - \frac{\partial P}{\partial x} \quad (3.4)$$

$$\frac{\partial \varrho v}{\partial t} + \mathrm{div}(\varrho \vec{\mathbf{u}} v) = \mathrm{div}(\mu \text{ grad } v) - \frac{\partial P}{\partial y} \quad (3.5)$$

- *Continuity equation*

$$\mathrm{div}\vec{\mathbf{u}} = 0 \tag{3.6}$$

Two problems are associated with the solution of equation set (3.1)-(3.3) or (3.4)-(3.6)

- The convective terms of the momentum equation contain non-linear quantities, for example the second term of equation (3.1) is the x-derivative of $\varrho uu \left(\dfrac{\partial \varrho uu}{\partial x}\right)$.
- All three equations are intricately coupled because every velocity component appears in each momentum equation and the continuity equation. The most complex issue to resolve is the role played by the pressure. It appears in both momentum equations, but there is evidently no (transport or other) equation for pressure.

The non-linearity make problem difficult or impossible to solve for a general closed form solution so the numerical method is employed. These equations will be discretized by finite volume method (FVM) on backward staggered grid with equal size of control volume. And both problems associated with the non-linearities in the equation set and the pressure-velocity linkage can be resolved by the SIMPLE algorithm which is iterative procedure for the pressure and the velocity field.

4 The Experiments

Four experiments are created to study effects of wind speed, effects of expressways, effects of canyon geometry and effects of position of expressways. The open canyon geometry are symmetric canyon, step-up canyon and step-down canyon with and without expressways over the street. The inlet boundary used is 1m/s for low speed flow and 10m/s for high speed flow.

4.1 Experiment 1: Symmetric Canyon with Two Expressways

Experiment 1 is constructed for study the effects of wind speed. In this experiment, The model configuration is conducted with two buildings on the left and right hand side of the model and two expressways over the street. Both buildings are of equal size of 16m (H1=H2=16). This experiment is considered for two cases of inlet boundary conditions which are low speed flow and high speed flow.

4.2 Experiment 2: Symmetric Canyon in Low Speed Flow

Experiment 2 is constructed for study the effects of expressways on airflow. The model configuration is conducted with two buildings on the left and right hand side of the model. Both buildings are of equal size of 16m (H1=H2=16).

The inlet boundary is set to 1m/s. This experiment is considered for three cases depending on number of expressways over the street which are no expressway, one expressway and two expressways.

4.3 Experiment 3: Low Speed Flow with Two Expressways

Experiment 3 is constructed for study the effects of canyon geometry. In this experiment, the model configuration is conducted with two buildings on the left and right hand side of the model and two expressways over the street. The size of both buildings depend on canyon geometry. This experiment is considered for three cases of canyon geometry which are symmetric canyon, step-up canyon and step-down canyon.

4.4 Experiment 4: Symmetric Canyon with Different Positions of Expressways

Experiment 4 is constructed for study the effects of expressway positions. In this experiment, the model is conducted with two buildings on the left and right hand side of the model and two expressways over the street. Both buildings are of equal size of 16m (H1=H2=16). The inlet boundary is set to 1m/s. There are three cases of positions of expressways over the street.

Table 1: Model configuration for the experiments

Experiment	**Canyon geometry**	**Expressways**	**Inlet boundary**	**Effect of**
Experiment 1	symmetric canyon	two expressways	1m/s 10m/s	wind speed
Experiment 2	symmetric canyon	-no expressway -one expressway -two expressways	1m/s	expressways
Experiment 3	-symmetric canyon -step-up canyon -step-down canyon	two expressways	1m/s	canyon geometry
Experiment 4	symmetric canyon	two expressways (three patterns)	1m/s	positions of expressways

5 Results and Discussion

The computer simulation results in various experiments are shown in this section. Effects of inlet boundary conditions, effects of expressways, effects of canyon geometry and effects of positions of expressways over street on airflow are studied. The time step used is 0.05 second for low speed flow and is 0.02 second for high speed flow. All simulation results presented below are at t=20min.

5.1 Effects of wind speeds

In experiment1, the effects of inlet boundary conditions are studied in symmetric canyon with two expressways above the street. The inlet boundary conditions is set to 1m/s for low speed flow and 10m/s for high speed flow. Both buildings are of equal size of 16m (H1=H2=16) with two expressways above street. The flow fields for this experiment are shown in Figure 6.

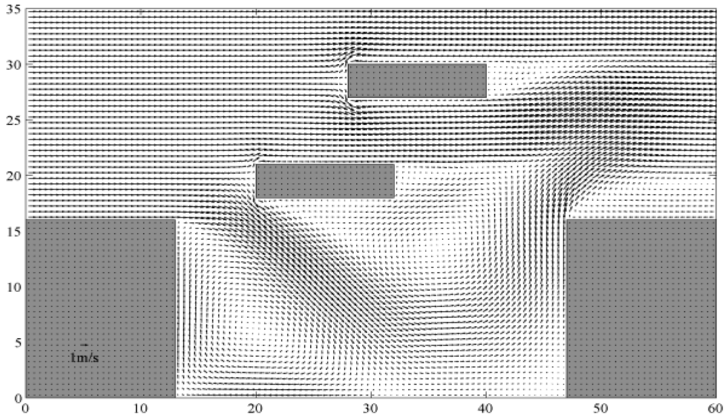
Figure 6 shows the velocity vector fields for different wind velocities in symmetric canyon with two expressways above street. The pattern of the airflow in low speed flow is similar to that in high speed flow. The basic flow is split by each expressway. There are two large vortex circulations with different directions inside the street. However, the airflow strength in cavity also depend on the wind speed, i.e., the airflow in high speed flow is stronger than that in low speed flow.

5.2 Effects of Expressways

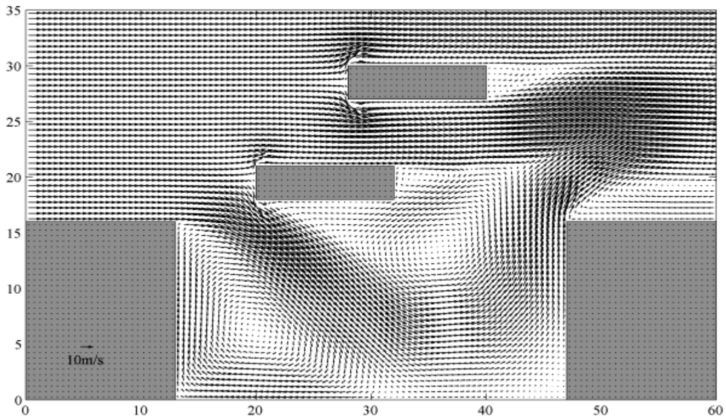
In experiment2, the simulated results in symmetric canyon geometry with and without expressways are performed to study the effects of expressways. The experiment1 shows that the wind speed does not affect the flow pattern. The simulated results are then shown only in the case of low speed flow. In low speed flow, inlet boundary condition is set as u_{in} = 1.0m/s and v_{in} = 0.0m/s. Both buildings are of equal size of 16m (H1=H2=16). The flow fields for this experiment are shown in Figure 7.

In the case of no expressway in Figure 7a: no expressway, the basic flow moves parallel to the ground. The flow in cavity is weaker than the basic flow, and it is the weakest in this case. There is a large clockwise elliptic circulation inside the street canyon. The center of the circulation is located in the middle of the two buildings. The airflow velocity near center of the circulation is rather low ,which can provide a trap for pollutants and it becomes stronger when it approaches the wall of buildings and the floor surface of street.

When expressway appears above the street as in Figure 7b: one expressway, the synoptic flow is split into two parts by the expressway. The airflow above the expressway is a strong flow and appears to move parallel to the ground. The lower part of the basic flow enhances the flow in cavity and causes the airflow in cavity to be stronger than the previous case (a). The shape of clockwise elliptic circulation inside the street is changed, and its center is shifted towards the upwind building. When the airflow is blown strongly from left to right at the upper right of this

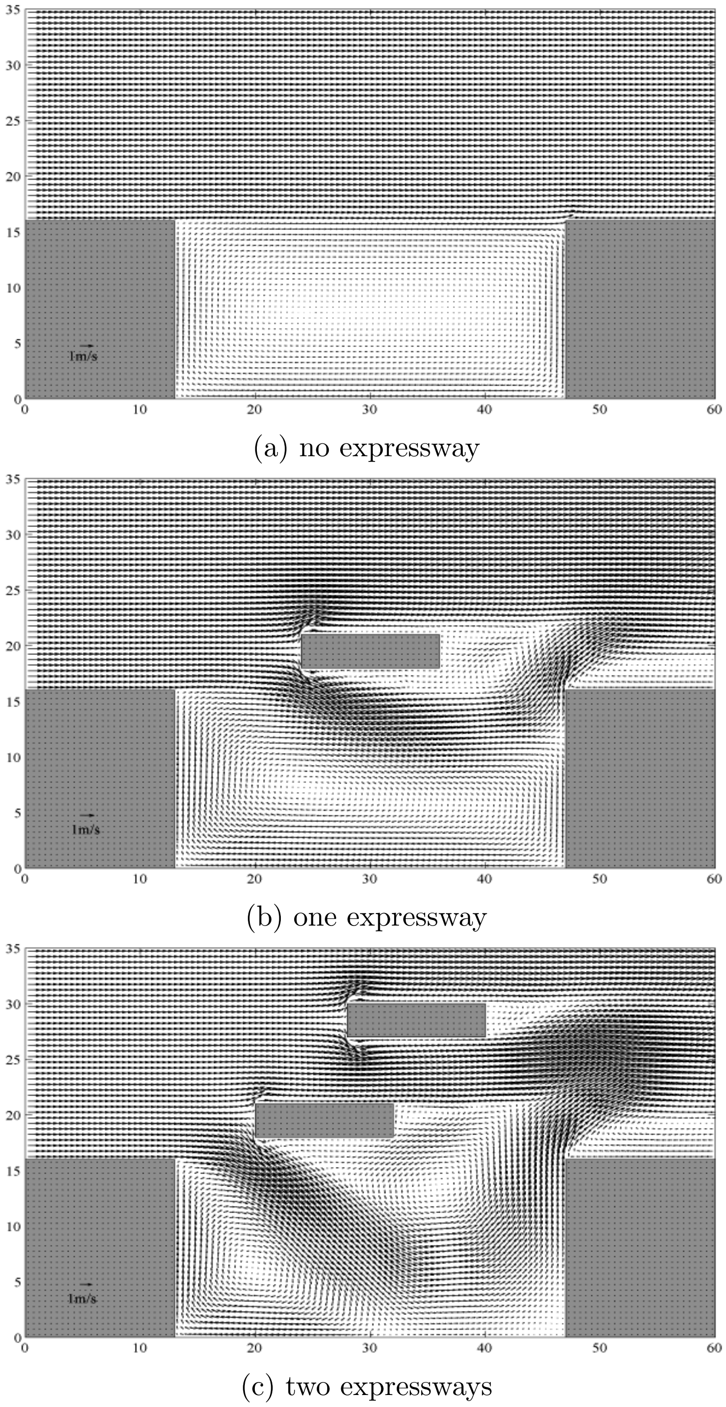


(a) low speed flow



(b) high speed flow

Figure 6: Wind vectors in different inlet boundary conditions for experiment 1: (a) low speed flow, (b) high speed flow



(a) no expressway

(b) one expressway

(c) two expressways

Figure 7: Wind vectors in the symmetric canyon with and without expressways for experiment 2: (a) no expressway, (b) one expressway, and (c) two expressways

main circulation, it is restrained by the wall of downwind building. It leads to the upward flow and produces a counter-clockwise circulation at the upper left corner of downwind building. The airflow at the upwind corners of the expressway is strong, and the airflow beneath the expressway is weak. There is another clockwise circulation on the roof of downwind building. Furthermore, there is a tiny clockwise circulation on the right side of the expressway.

In the case of two expressways in Figure 7c: two expressways, the flow pattern is quite different from two previous cases. The basic flow is also split by each expressway. The airflow between expressways is strong, and moves parallel to the ground. But the airflow beneath the lower expressway is weak. The airflow in cavity is strongest in this case. A couple of large circulations with different directions are generated inside the street canyon, i.e., a clockwise triangular circulation which its center is located near the upwind building and a counter-clockwise circular circulation in front of, and over the downwind building. A smaller clockwise circulation is generated on the roof of downwind building. The upper part of this circulation is very strong flow and stronger than that in the previous case because it is enhanced by the strong flow which moves from between expressways. Tiny circulations can be found on the right side of the both expressways.

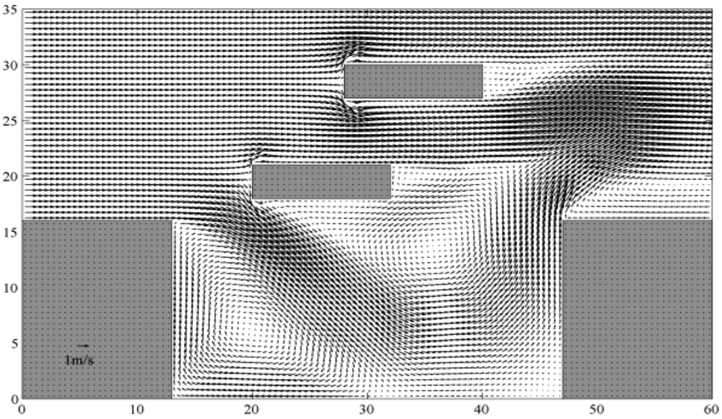
5.3 Effects of Canyon Geometry

In experiment3, the effect of canyon geometry: symmetric canyon, step-up canyon, and step-down canyon; with two expressways over street on airflow are studied. The inlet boundary conditions is set as $u_{in} = 1.0$m/s, $v_{in} = 0.0$m/s (low speed flow). The flow fields for this experiment are shown in Figures 8.

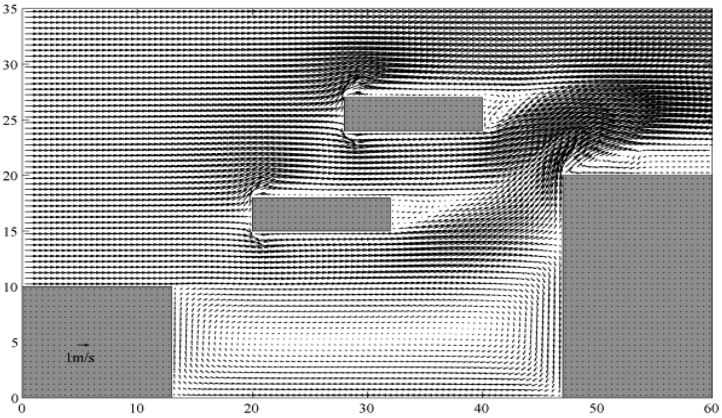
In the case of symmetric canyon in Figure 8a: symmetric canyon, there are two large circulations inside the street, i.e., a clockwise triangular circulation is generated near the upwind building and a counter-clockwise circulation is generated in front of, and over the downwind building. Furthermore, there is a small clockwise circulation over the downwind building. The airflow at the upper left corner of the downwind building to upper part of this circulation is strong.

In the case of step-up canyon in Figure 8b: step-up canyon, the flow pattern in the cavity is different from the previous case (a). There is a unique clockwise vortex circulation inside the street. The airflow around the upper left corner of downwind building to the upper part of vortex circulation over the downwind building is stronger than those in the previous case (a) and it is the strongest in all cases.

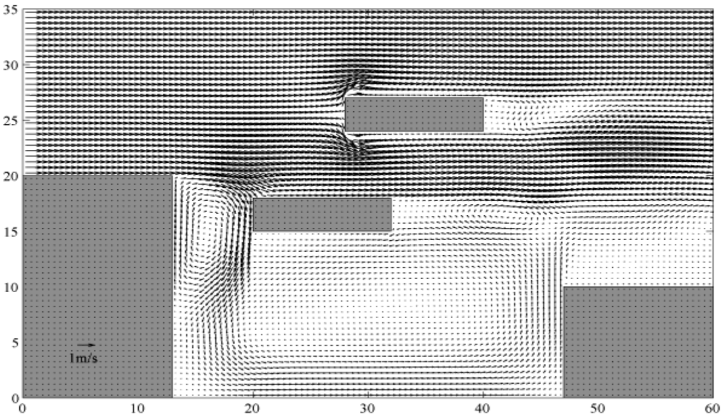
In the case of step-down canyon in Figure 8c: step-down canyon, the flow pattern is different from case (a) and (b). The airflow in cavity is the weakest in this case. There is a strong clockwise circulation between the upwind building and the lower expressway. A large counter-clockwise circulation is generated inside the street. The airflow near the center of this circulation is very weak and becomes stronger when it approaches the street and the wall of buildings. While the airflow over the downwind building is the weakest.



(a) symmetric canyon



(b) step-up canyon



(c) step-down canyon

Figure 8: Wind vectors in different canyons with two expressways for experiment 3: (a) symmetric canyon, (b) step-up canyon, and (c) step-down canyon

5.4 Effects of Expressway Positions

In experiment4, the effects of expressway positions above street on airflow in symmetric canyon are studied in 3 patterns of expressways. The results from 3 patterns of expressways over street are presented with inlet boundary condition of $u_{in} = 1.0$ m/s, $v_{in} = 0.0$ m/s (low speed flow). The flow fields for this experiment are shown in Figures 9.

For pattern1 in Figure 9a: pattern1, the basic flow is split by the expressways. The airflow beneath the lower expressway is weak. A couple of circulations with different directions are generated inside the street canyon, i.e., a clockwise circulation is generated near the upwind building, and a larger counter-clockwise circulation is generated in front of, and over the downwind building. There is also a clockwise circulation at the roof of the downwind. The airflow at the upper part of this circulation is strong. While tiny circulation can be found on the right side of both expressways.

For pattern2 in Figure 9b: pattern2, the flow pattern of the basic flow is similar to that of pattern1, but the flow pattern in the cavity is different. There is only a large clockwise circulation inside the street canyon extending from the upwind building to the downwind building.

For pattern3 in Figure 9c, the flow pattern is very similar to that of pattern2.

6 Conclusion

In this research, two-dimensional numerical simulations for airflow around elevated expressways over street canyon are performed. The governing equation for the two-dimensional incompressible unsteady state flow is discretized by finite volume method (FVM) and the SIMPLE algorithm is employed to iterate for the pressure correction and convergence of the velocity field. The model is then used to study effects of inlet boundary conditions, expressways, canyon geometry and position of expressway on airflow in street canyon .

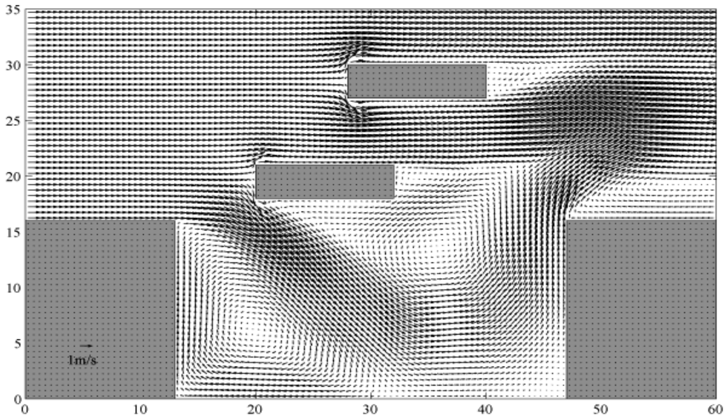
Effects of inlet of boundary conditions are studied in two conditions for low speed flow and high speed flow. The inlet condition is set as $u_{in} = 1.0$ m/s, $v_{in} = 0.0$ m/s for low speed flow and $u_{in} = 10.0$ m/s, $v_{in} = 0.0$ m/s for height speed flow. Three street canyon geometry are used in these simulations; symmetric canyon, step-up canyon and step-down canyon.

Results from the experiments show that, there are circulations appearing inside the street between two buildings in all cases. The shapes and strength of the circulations depend on geometry of street canyon and expressway above street.

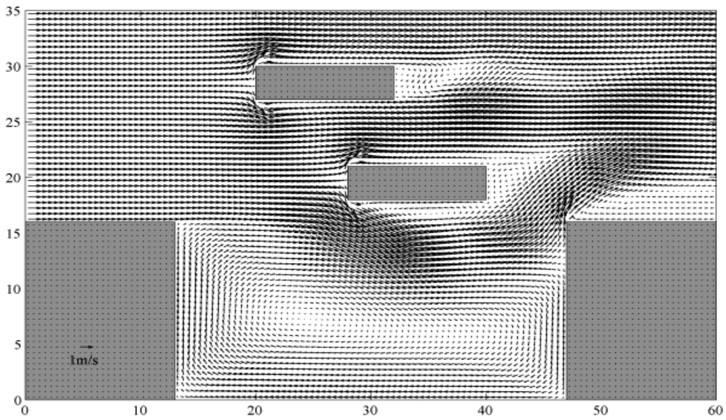
The inlet boundary conditions have no significant effect on the patterns of airflow in all street canyon geometry, but the strength of circulation inside street increases as the wind speed increases.

The expressways has effects on the airflow in the the symmetric canyon. The elevated expressways enhance the flow in cavity and over the downwind building, and has effects on the circulation pattern.

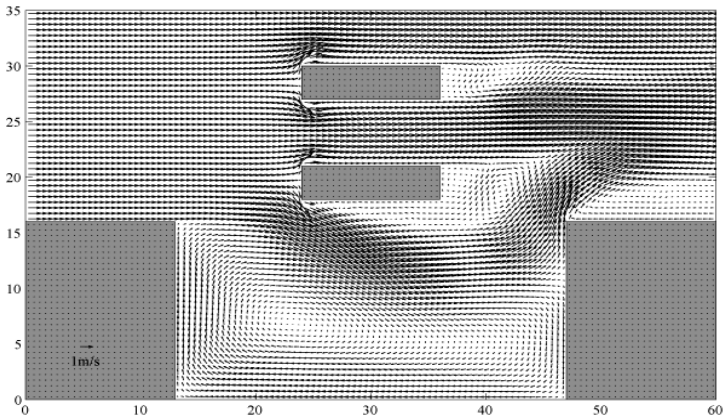
Geometry of canyon has strong effects on the strength and the circulation



(a) pattern1



(b) pattern2



(c) pattern3

Figure 9: Wind vectors in symmetric canyon with different pattern of expressways for experiment 4: (a) pattern1, (b) pattern2, and (c) pattern3

pattern of the airflow in cavity, especially, in the case of step-down canyon. The strength of vortex circulation in the cavity is the weakest in the step-down canyon.

The position of expressways above street in symmetric canyon does not affect the basic flow but it has effects on the circulation pattern of the airflow in cavity.

References

[1] Nazridoust, K., G.,Ahmadi, 2006, "**Airflow and Pollutant Transport in Street Canyons**", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 94, pp. 491-522.

[2] Xie, X., Z., Huang and, J., Wang, 2005,"**Impact of building configuration on air quality in street canyon**", Atmospheric Environment, Vol. 39, pp. 4519-4530.

[3] Chan, T.L., G., Dong, C.W., Leung, C.S., Cheung and, W.T., Hung, 2001,"**Validation of a Two-Dimensional Pollutant Dispersion Model in an Isolated Street Canyon**", Atmospheric Environment, Vol. 36, pp. 861-872.

[4] Tokairin, T., T., Kitada, 2003, "**Numerical Investigation of The Effect of Road Structures on Ambient Air Quality for Their Better Design**", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 92, pp. 85-116.

[5] Baik, J.J., J.J., Kim and, H.J.S., Fernando, 2003, "**A CFD Model for Simulating Urban Flow and Dispersion**", Journal of Applied Meteorology, Vol. 42.

[6] Cheng, X., F., HU, 2004, "**Numerical Studies on Flow Fields Around Buildings in an Urban Street Canyon and Cross-Road**", Advance in Atmospheric Sciences, Vol. 22, No. 2, pp. 290-299.

[7] Griebel, M., T., Dornseifer, T., Neunhoeffer, 1998, "**Numerical Simulation in Fluid Dynamics**", Society for Industrial and Applied Mathematics, Philadelphia, pp. 11-20.

[8] Kondo, H., K., Asahi, T., Tomizuka and, M., Suzuki, 2006, "**Numerical Analysis of Diffusion around a Suspended Expressway by a Multi-Scale CFD Model**", Atmospheric Environment, Vol. 40, pp. 2852-2859.

[9] Vardoulakis, S., B.E.A., Fisher, K., Pericleous and, N., Gonzalez-Flesca, 2002, "**Modelling Air Quality in Street Canyons: A Review**", Atmospheric Environment, Vol. 37, pp. 155-182.

[10] Versteeg, H.K., W., Malalasekera, 1995, "**An Introduction to Computation Fluid Dynamics: The Finite Volume Method**", Longman Scientific and Technical, England, pp. 85-102.

[11] Assimakopoulos, V.D., H.M., Apsimon, N. Moussiopoulos, 2003, "**A Numerical Study of Atmospheric Pollutant Dispersion in Different Two-Dimensional Street Canyon Configurations**", Atmospheric Environment, Vol. 37, pp. 4037-4049.

(Received 14 January 2007)

M. Tanulert, A. Luadsong and D. Sukawat
Department of Mathematics,
King Mongkut's University of Technology Thonburi,
Bangkok, Thailand
E-mail: `nookie_mtl@hotmail.com, anirut.lua@kmutt.ac.th, and dusadee.suk@kmutt.ac.th`