# COMPUTATIONAL ANALYSIS OF THERMAL EFFECTS ON FLOW AND POLLUTANT DISPERSION IN STREET CANYONS

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***Abstract**. The main source of atmospheric pollution in large cities is the vehicle emission of gases and particulates. Pollutant dispersion in these cities is difficult due to the existence of street canyons in metropolitan areas that prevent the gases and particulates to dissipate. In order to better understand the dispersion mechanisms and to predict the amount of pollutant dispersed, numerical studies were conducted to predict the turbulent flow and pollutant dispersion in typical street canyon geometries. The commercial code ICEM-CFD was used for mesh generation and FLUENT for the numerical simulation. For simulations of the flow field the standard $k-\varepsilon$ turbulence model was used. Canyons with different aspect ratios (building height per street width) were simulated. In the case of isothermal flow conditions, it was observed that regular street canyons (aspect ratio = 1) are characterized by the formation of a single vortex, that provides minimal flushing of the canyon, resulting in a relatively ineffective configuration for removing pollutants. This type of canyon shows increased concentrations of pollutants on the leeward side of the canyon and, decreasing concentrations along with height above the ground on both sides of the street. Another important result observed is that wider streets show good conditions for pollutant dispersion. It was also observed that thermal effects such as heating the building surface or street canyon bottom surface present great influence on the flow patterns and pollutants dispersion. In some cases, the flow structure changed completely with respect to the unheated case, presenting a different number of vortices. Another effect of heating is the upsurge of a strong buoyancy flow close to the heating surfaces, leading to a combined thermally and mechanically induced flow which affects the flow field and the pollutant dispersion in the street canyons.*

***Keywords**: street canyon, pollutant dispersion, thermal effects*

## 1. INTRODUCTION

In urban environments, especially in areas where the population density and traffic of vehicles are relatively high, an increase of the atmospheric pollution is observed. Examples of these sites are the so-called "street canyons", found in the downtown areas of the large cities. This term is frequently used for urban streets with buildings on both sides, where high pollutant concentrations can be found. The vehicle exhaust gases are usually the main source of atmospheric pollutants in the street canyons, which have direct impact on human health. Therein, it is extremely relevant to develop models that can predict pollution levels in urban environments such as street canyons, aiming the preservation of the air quality standard.

The dispersion of pollutants on the street canyons depends on factors such as geometry of the building (height, width and roof shape), street dimensions (breadth and width), environmental conditions (wind velocity and direction), thermal stratification (thermal isolation and orientation of the sun, building and street thermal capacity), plume buoyancy, vegetation or landscape and surface roughness, movement of vehicles (size, number and frequency), etc. (Meroney et al., 1996; Gerdes and Olivari, 1999 and Sagrado et al., 2002).

The canyon aspect ratio is one of the factors that determine flow regimes in urban street canyons. The canyon aspect ratio is defined as the ratio of the building height to the width between buildings. The flow regimes in this kind geometry can be categorized into isolated roughness flow, wake interference flow, and skimming flow (Oke, 1988; Hunter et al. 1992, Sini et al. 1996). Several studies have been conducted to characterize flow and dispersion in street canyons with different aspect ratios (Sini et al., 1996; Leitl and Meroney, 1997; Baik and Kim, 1999; Assimakopoulos et al., 2003; Xie et al., 2005a; Chan et al., 2002 and Nazridoust and Ahmadi, 2006). These studies rely on two-dimensional numerical models. Baik and Kim (1999) observed that with the increase of aspect ratio, the number of vortices also increases. Various researchers have proposed two or three-dimensional Reynolds-averaged Navier-Stokes equations coupled with different turbulence models, such as the Standard $k-\varepsilon$ model, the RNG $\kappa$–$\varepsilon$ model and the $\kappa$–$\varepsilon$ Realizable model, in order to simulate the flow field in street canyons.

The thermal effects such as building surface or street-canyon bottom heating were investigated by Sini et al. (1996) that observed that canyon geometry and the differential heating of the wall of the buildings influence the in-street flow and the pollutant dispersion. Kim and Baik (2001) investigated the flow in street canyons considering the street-bottom heating for various aspect ratios and different heating intensities. Xie et al (2005b) evaluated the effect of solar radiation on the airflow and the dispersion within street canyons for symmetrical, step up notch and step down notch configurations. Moussiopoulos et al. (2005) described numerically the influence of walls heating and building shading on the flow and dispersion of pollutant in a street canyon. Tsai et al. (2005) investigated numerically the thermal effects on airflow and dispersion of pollutants in a street canyon with an aspect ratio of 0.8 and a length-to-width ratio of 3 using a three-dimensional modeling. The authors used the RNG κ–ε turbulence model to investigate the flow fields and the influence of different aspect ratios with isothermal conditions and considering thermal effects such as building surface or street-canyon bottom heating on the pollutants dispersion in a street canyon.

The objective of the present work is to conduct numerical studies to predict the turbulent flow and pollutant dispersion in a typical street canyon in order to better understand the dispersion mechanisms and to predict the amount of pollutant dispersed.

## 2. NUMERICAL MODEL

### 2.1 Isothermal conditions

The finite volume method was used to model the governing equations for fluid flow and pollutant dispersion derived from the mass conservation equation (continuity), momentum conservation equation (Navier-Stokes) and the transport equation for pollutants concentration. The standard $k-\varepsilon$ turbulence model is adopted, which is based on Reynolds Averaged Navier-Stokes (RANS) flow equations. The flow is considered two-dimensional, steady, incompressible and without thermal effects. The mass and momentum conservation equations follow

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

$$\frac{\partial}{\partial x_j}\left(U_i U_j\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\nu\frac{\partial U_i}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \tag{2}$$

where $U$ is the mean velocity, $u'$ is the velocity fluctuation, $P$ is the mean pressure and $\nu$ is the kinematic viscosity. The momentum equations include turbulent fluxes $-\overline{u_i' u_j'}$ which are modeled using the Boussinesq hypothesis so that Reynolds stresses can be linked to the mean rates of deformation. This term is modeled as

$$-\overline{u_i' u_j'}=\nu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\frac{2}{3}k\delta_{ij} \qquad \delta_{ij}=\begin{cases}1 & for\ \ i=j\\ 0 & for\ \ i\neq j\end{cases} \tag{3}$$

where $\nu_t$ is the eddy viscosity (or turbulent viscosity), $k$ the kinetic energy and $\delta_{ij}$ the Kronecker delta. The eddy viscosity $\nu_t$ is related to the turbulent kinetic energy $k$ and its rate of dissipation $\varepsilon$ and is modeled as $\nu_t = C_\mu k^2/\varepsilon$ , where $C_\mu$ is a constant.

Two additional conservation equations must be solved: one for the turbulent kinetic energy $k$ and other for its rate of dissipation $\varepsilon$. In Eq. (4) the last two terms represent the turbulent kinetic energy rates of production and destruction, respectively. The same can be said about Eq. (5) for the kinetic energy dissipation $\varepsilon$.

$$\frac{\partial}{\partial x_i}\left(U_i k\right)=\frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+P_k-\varepsilon \tag{4}$$

$$\frac{\partial}{\partial x_i}\left(U_i \varepsilon\right)=\frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k-C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{5}$$

where $P_k$ is the rate of production of kinetic energy, and $\sigma_k$ , $\sigma_\varepsilon$ , $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants of the standard $k$-$\varepsilon$ model. The rate of production of turbulent kinetic energy is calculated by Eq. (6).

$$P_k=\nu_t\frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right) \tag{6}$$

The species (pollutants) transport equation is

$$\frac{\partial}{\partial x_i}\left(U_i C\right)=\frac{\partial}{\partial x_i}\left(\frac{\nu_t}{S_{ct}}\frac{\partial C}{\partial x_i}\right) \tag{7}$$

where $C$ is the mean concentration. In this equation the molecular diffusion term is ignored since the turbulent diffusion term is predominant and $S_{ct}$ is the turbulent Schmidt number. The constants used in equations above are specified as (Sini et al. 1996):

$$C_\mu = 0.09 \quad C_{1\varepsilon} = 1.44 \quad C_{2\varepsilon} = 1.92 \quad \sigma_k = 1.0 \quad \sigma_\varepsilon = 1.3 \quad Sc_t = 0.9$$

**2.2. Thermal effects**

The density is a function of temperature for incompressible turbulent inert flow. If the heating of building walls and canyon bottom is considered, the air density changes due to the increase of air temperature. The buoyancy forces induce the air motion and these forces are added in the momentum conservation equation. Adopting the Boussinesq approximation, it is assumed that the specific mass and the other physical parameters do not change except for the specific mass in the buoyancy forces term, as shown below,

$$\frac{\partial}{\partial x_j}\left(U_i U_j\right) = \left(\frac{\rho - \rho_n}{\rho_n}\right) g_i - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \tag{8}$$

where $g_i$ is the components of the gravitational acceleration, $\rho$ is the fluid specific mass and $\rho_n$ is the reference specific mass.

The specific mass deviation $\rho - \rho_n$ is related to the temperature through the following linear equation of state:

$$\frac{\rho - \rho_n}{\rho_n} = -\beta\left(\Theta - \Theta_n\right) \tag{9}$$

where $\Theta$ is the mean temperature and $\beta$ is thermal expansion coefficient.

The turbulence production due to the buoyancy effect is included in the momentum transport modeling.

$$\frac{\partial}{\partial x_i}\left(U_i k\right) = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + P_k - \varepsilon \; - \beta g_i \overline{u_i' \theta'} \tag{10}$$

$$\frac{\partial}{\partial x_i}\left(U_i \varepsilon\right) = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}\left(P_k - \beta g_i \overline{u_i' \theta'}\right) - C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{11}$$

$$-\overline{u_i' \theta'} = K_t \frac{\partial \Theta}{\partial x_i} \tag{12}$$

where $\overline{u_i' \theta'}$ is the turbulent heat flux , $K_t$ is the turbulent diffusivity coefficient, ( $K_t = \nu_t / Pr_t$ ), where $Pr_t$ is the turbulent Prandtl number.

The energy equation (Eq. 13) takes into account the thermal effects, allowing the calculation of the temperature field.

$$\frac{\partial\left(U_i \Theta\right)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(K_t \frac{\partial \Theta}{\partial x_i}\right) \tag{13}$$

The constants used in equations are the same specified above, with $Pr_t = 0.7$.

The above governing equation set is solved numerically on a staggered grid system using the finite-volume method following the Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) algorithm described by Patankar (1980). The 2nd order upwind scheme was used for the modeling of the convection-diffusion coupling. All the above calculations were performed using the FLUENT code.

The effects of the street aspect ratio on the flow field and pollutant distribution in urban street canyons are investigated considering different aspect ratios. In order to examine the influence of thermal effects on the flow and pollutant dispersion the following cases are considered: no heating, heating of leeward side of building, heating of windward side of building and heating of bottom of street canyon. Figure 1 shows the model domain configuration where, the domain size is 100 m in horizontal direction and 150 m in vertical direction, and the grid interval is 1.25m in both directions. The street canyon width is 40 m, and the following building heights are considered: 40 m, 80 m and 140 m., with aspect ratios of 1.0, 2.0 and 3.5, respectively.

The initial conditions for wind velocities, turbulent kinetic energy and its dissipation, and air potential temperature are specified as: $U_0 = 2.5\left(z/z_r\right)^{0.299}$, $W_0 = 0$, $k_0 = 0.003U_0^2$, $\varepsilon_0 = \left(C_\mu^{3/4} k_0^{3/2}\right)/\kappa z$ and $\Theta_0 = 293K$, where $z_r$ = 10m is the reference height in meters and $\kappa = 0.4$ is the von Kárman constant. Initially, the shear layer given by profile is assumed to exist up to z = 10 m above the building roof level and above it the velocity is assumed to be constant. No-slip boundary conditions are applied at the ground and building surfaces. At the outflow and upper boundaries, the gradient of any variable is set to zero. The building-wall or street canyon bottom temperature is maintained at 298 K in the case where thermal effects are considered.

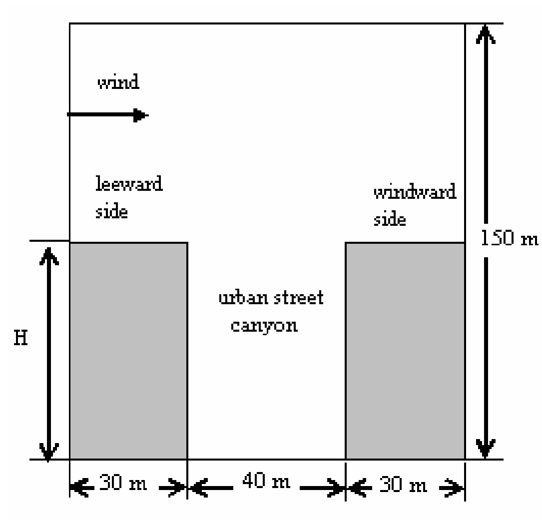



Figure 1. Sketch of the calculation domain

## 3. RESULTS AND DISCUSSION

### 3.1. Isothermal conditions

The wind field and pollutants dispersion in a street canyon with aspect ratio of 0.333 can be observed in Fig. 2. This case belongs to the wake interference flow regime where two clock-wise co-rotative coupled vortices are generated according to the flow identification by Oke (1988) and Hunter et al. (1992). This configuration represents wider streets. The flow field of wider streets (H/W = 0.333) with two clock-wise co-rotative coupled vortices leads to more pollutants on the leeward side than on the windward side of buildings. Furthermore, there are big interactions between the blowing wind above the roofs and within the street, promoting larger air ventilation within the street canyon and hence less pollutant is accumulated in this configuration.

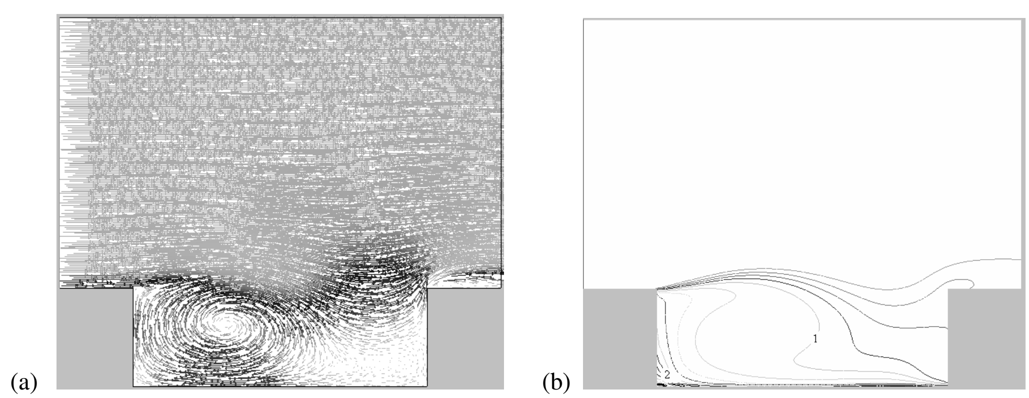



Figure 2. Wind field (a) and concentration distribution (b) for an aspect ratio of 0.333

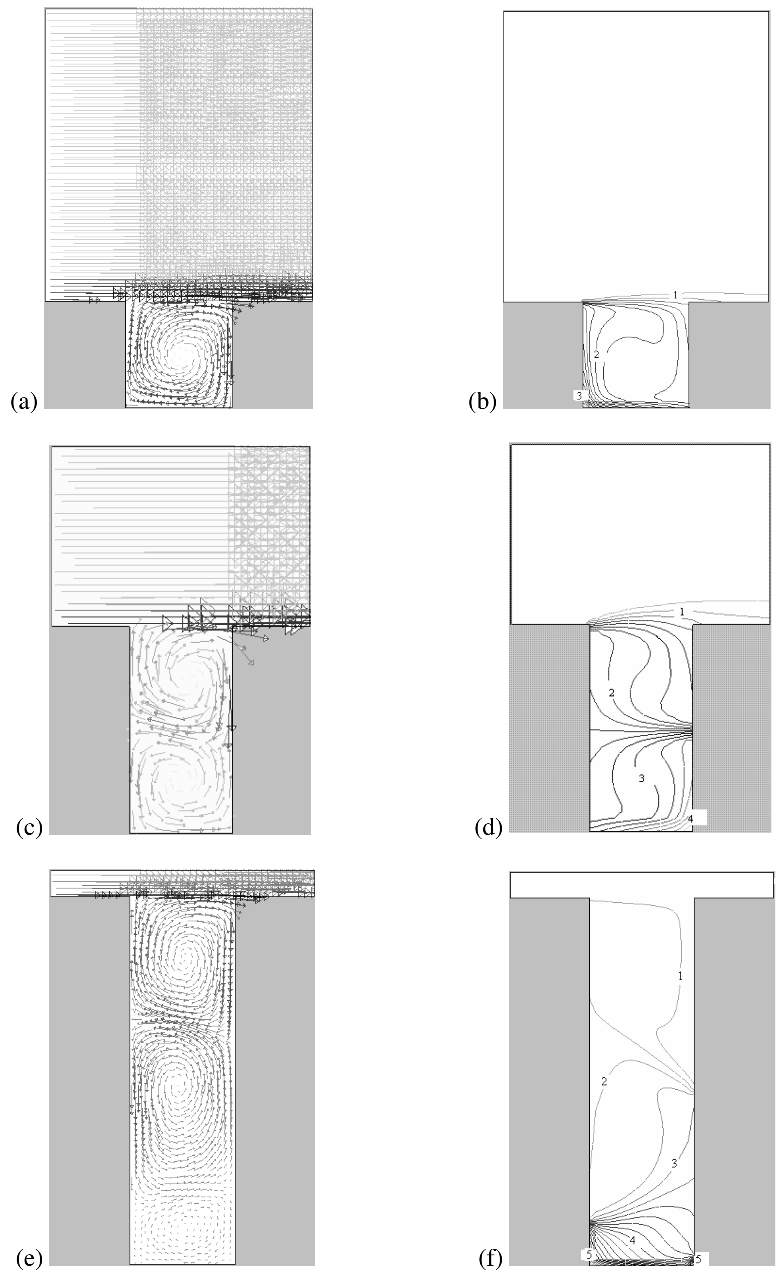



Figure 3. Wind field and concentration distribution in street canyons with aspect ratios of 1 [(a) and (b)], 2 [(c) and (d)], and 3.5 [(e) and (f)]

All the cases with H/W $\geq$ 1, which represent narrow streets, belong to the skimming flow regime where the bulk of the synoptic wind flow (free-stream velocity) skims over the canyon producing the skimming flow. Figure 3 shows that this regime is characterized by the circulation of one or more vortices within the canyon and the number of vortices varies with the aspect ratio. In the case of a regular canyon (H/W =1), a single clockwise vortex is formed within the canyon, for the aspect ratio of 2.0, two counter-rotating vortices are formed and for the aspect ratio of 3.5 there are three vortices with different rotating orientation. In this case the uppermost one is clockwise, the middle one is counter-clockwise, and the lowermost one is clockwise.

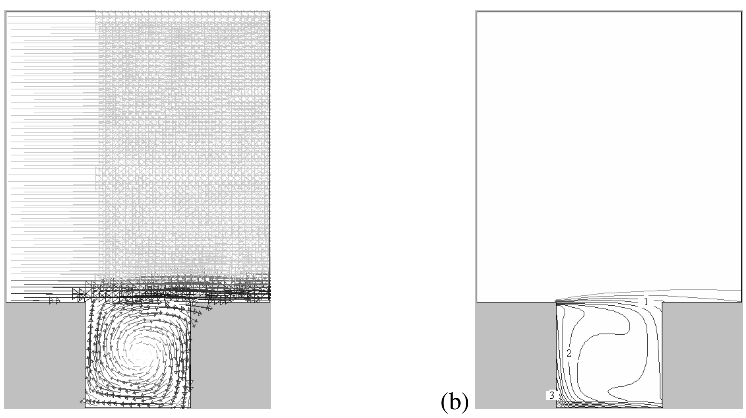
For the study of pollutant distribution is considered the case of street-level emission source, which can be regarded as representing the case of pollutant emission from motor vehicles. The pollutant considered is carbon monoxide, which is relatively stable, easily measured and comes mainly from vehicle emissions. It is considered that pollutant is emitted from a source located at street –level with 32 emission points at a rate of 5 ppb $s^{-1}$.

For the aspect ratio of 1, a low-concentration region at any height of the street canyon can be verified near the windward side of building, where a strong downward motion exists. In this side, the ambient air with relatively low concentration enters the street canyon by the downward vortex circulation. At leeward side there is high concentration at any height of the street canyon, where a strong upward motion exists, and the concentration decreases from the floor to the roof of the upstream building. In this side, highly polluted air passing through the street-level is advected upward on the leeward side. For the aspect ratio of 2.0 there are two different pattern of the concentration distribution in the lower and upper regions. In spite of the difference between these regions, there is a common feature: in the regions of the upward motion there are high pollutant concentrations, that is, on the windward side of the lower region and the leeward side of the upper region. In the regions of the downward motion there are low pollutant concentrations. This feature is directly linked to the two counter-rotating vortices circulation. Highly polluted air passing through the street-level source is advected upward on the windward side of the lower region. The pollutant concentration in this region is high, with the concentration decreasing with height. For the aspect ratio of 3.5 there are three pattern of the concentration distribution which is different from each other. These three patters correspond to the superior region, middle region and inferior region, which are related to the three-vortex circulation. Similarly to the case with aspect ratio of 2.0, it is observed that in the regions of the upward motion there are high pollutant concentrations, that is, on leeward side of the lower region, windward side of the middle region and the leeward side of the upper region. In the regions of the downward motion there are low pollutant concentrations. The lowermost vortex is very weak, thus some of emission pollutants may move to the leeward side and some move to the windward side of the street canyon, the pollutant is accumulated near the floor with high concentration. The results showed that the pollutant concentrations within the street canyon increase with increasing heights of buildings and according to Xie et al. (2006) the street canyon with tall buildings can suppress the air ventilation, and a lot of pollutants may accumulate at the street level within the street canyon. This characteristic lead to direct impact on the drivers, bicyclists, motorcyclist, pedestrians, people working nearby, and vehicle passengers, thus, this kind of street canyon should be avoided in city planning.

### 3.2 Thermal effects

In this section the thermal effects on the flow fields in urban street canyons with different aspect ratios for some cases of upwind building-wall heating, street-canyon bottom heating, and downwind building-wall heating are investigated.

Figure 4 shows the flow field and concentration distribution for the aspect ratio of 1.0, for the case of street-canyon bottom heating. In case of no heating there is only one vortex, as seen before. For this case with bottom heating, there is also one vortex, but, there is the upsurge of a vertical temperature gradient near the street canyon bottom and a horizontal temperature gradient near the leeward side with high values, that induced a thermal upward motion which strengthens the vortex and enhances the upward motion mechanically induced by the ambient wind.

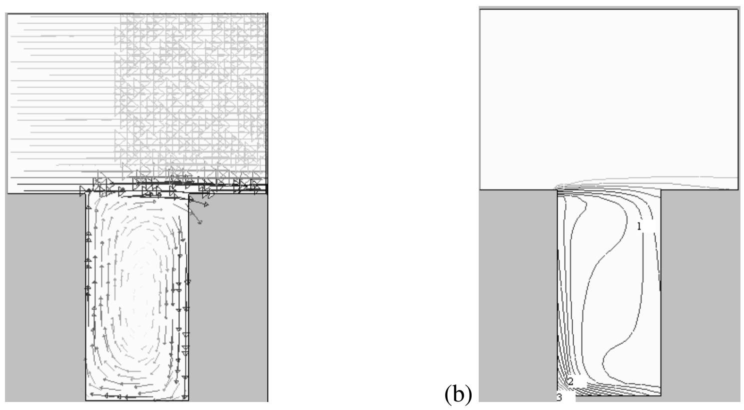



(a) (b)

Figure 4. Wind field (a) and concentration distribution (b) in a street canyon with aspect ratio of 1.0 for bottom heating

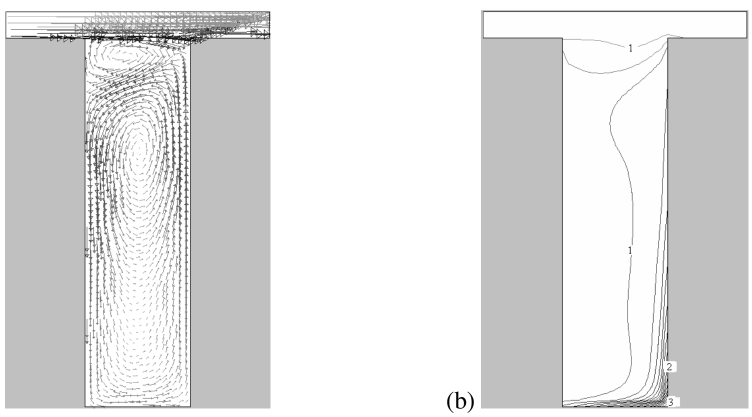
Figure 5 shows the flow field and concentration distribution for the aspect ratio of 2.0 for the case of leeward side heating. As seen before, in the case of no heating there are two counter-rotating vortices mechanically induced by the ambient wind. In the case of leeward side heating, the thermal upward motion near the leeward side is weakened in the lower region, due to the mechanical downward motion in this region. On the other hand, in the upper region, the flow is strengthened due to the mechanical upward motion in the region and, as a result, one vortex is generated in the street canyon.

Figure 6 shows the flow field and concentration distribution for the aspect ratio of 3.5 for the case of windward side heating. In the case of no heating there are three counter-rotating vortices. In the case of windward side heating, there are two counter-rotating vortices, due to a stronger temperature gradient near this side in the lower region that intensifies thermally induced upward motion, where the mechanically induced vortex is weak. This vortex intensity is enhanced by the counter-clockwise vortex of the middle region and this weakens the mechanically induced downward motion in the upper layer, generating the two vortices. Analyzing the pollutant concentration fields for aspect ratio of 1.0, we observed that the pattern of the concentration distribution of the bottom heating case is similar to that of no heating, because in this case only one vortex appears and the concentration distribution is controlled mainly by the vortex circulation. As seen before, near the windward building where the air having relatively low pollutant concentration comes into the street canyon, we observed that the concentration is low at any height, except near the leeward side of building where the air passing through the emission source goes to the upper layer as a result of the advection and diffusion processes. In this region the concentration is high. For the aspect ratio of 2.0 in the case of leeward heating, the concentration distribution in leeward side is similar to that corresponding to an aspect ratio of 1.0 and thus, the transport mechanism of pollutants is also similar, characteristic of a one vortex circulation. For the aspect ratio of 3.5 in the case of windward side heating, the flow field shows two counter-rotating vortices, as seen before, and the counter-clockwise lower vortex has a strong intensity, transporting the pollutants to the windward side.



(a) (b)

Figure 5. Wind field (a) and concentration distribution (b) in a street canyon with aspect ratio of 2.0 for leeward side heating



(a) (b)

Figure 6. Wind field (a) and concentration distribution (b) in a street canyon with aspect ratio of 3.5 for windward side heating

## 4. CONCLUSIONS

A two-dimensional numerical simulation using the $k$-$\varepsilon$ turbulence model was conducted to study the thermal effects on the flow and pollutant dispersion in a street canyon with different aspect ratios. The case of isothermal flow conditions was also investigated and it was observed that regular street canyons (building height is equal to street width) are characterized by the formation of a single vortex that provides minimal flushing of the canyon, resulting in a relatively ineffective configuration for removing pollutants. This canyon type showed increasing concentrations of pollutants on the leeward side of the canyon, and, decreasing concentrations along the height above the ground on both sides of the street. In the case of wider streets (H/W = 0.333), the results showed that this configuration provides larger air ventilation within the street canyon and hence less pollutant is accumulated. Cases with aspect ratios of 1.0, 2.0 and 3.5 were also investigated. It was shown that the number of vortices increases with increasing street aspect ratio. For aspect ratio of 1, a single clockwise vortex is formed within the canyon. For the aspect ratio of 2.0, two counter-rotating vortices are formed and for the aspect ratio of 3.5 there are three counter-rotating vortices. To examine pollutant dispersion in a street canyon it was considered a street-level pollutant source. The pollutant concentrations within the street canyon increase with increasing the height of buildings and the pollutants are accumulated near the floor. Hence, street canyons with tall buildings should be avoided in city planning, due to its direct impact on the drivers, bicyclists, motorcyclist, pedestrians, people working nearby, and vehicle passengers. The thermal effects on the flow and pollutant dispersion were studied for the cases of building surface heating and street canyon bottom heating for some aspect ratios. The results showed that the surface heating has a great influence on the flow patterns and pollutants dispersion. For the aspect ratio of 1, there is one vortex either in the case of no heating or street-canyon bottom heating. For the aspect ratio of 2.0, in the case of leeward side heating, the flow pattern changed from the two counter-rotating vortices (no heating) to one vortex (heating). For the aspect ratio of 3.5, in case of windward side heating, there is the change from the three counter-rotating vortices (no heating) to two counter-rotating vortices (heating). When heating is included in the simulation, there is the upsurge of a strong buoyancy flow close to the heating surfaces, leading to a combined thermally and mechanically induced flow affecting the flow field and the pollutant dispersion in the street canyons. These different circulations of the vortices lead to the different concentration distributions along the wall of buildings and bottom of street canyon. These results showed that the geometrical configuration of the street canyon and the inclusion of surface heating play an important role in determining the number and intensity of vortices which has a significant influence on the pollutant dispersion.

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