Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2006
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Curitiba, Brazil,- Dec. 5-8, 2006

Paper CIT06-0964

A REVIEW ON THE MODELLING OF POLLUTANTS DISPERSION IN STREET CANYONS

Janaína Ferreira Batista Leal
EEL-USP, Rodovia Lorena-Itajubá Km 74.5, Lorena – SP 12600-970
janaina@debas.faenquil.br

Jurandir Itizo Yanagihara
Poli-USP, Av. Prof. Mello Moraes 2231, São Paulo – SP 05586-060
jiy@usp.br

Abstract. *Despite significant improvements in fuel and engine technology, present day urban environments are mostly dominated by traffic emissions, representing a serious hazard for human health. The pollutants are carried by the wind towards the buildings and theirs dispersion depends on a number of parameters, such as the building geometry, street dimension, thermal stratification, plume buoyancy, vegetation or landscape and surface roughness. Since this kind of flow is complex, many experimental and numerical works have been carried out to clarify the dispersion mechanisms and to predict the amount of pollutant dispersed. The objective of the present paper is to review the relevant bibliographical information on modelling of pollutant dispersion in street canyons and present some possible improvements on the models for future studies. The majority of the flow field studies are steady-state simulations of the turbulent field based on the* κ–ε *model and its variations (RNG and realizable) for different geometries and boundary conditions. There is also a growing interest on the effect of thermal stratification and non-steady effects, although the latter implies in larger computational cost. Finally, some commentaries toward a model for the simulation of pollutant dispersion in a typical street canyon of Sao Paulo city are addressed.*

Keywords: Street canyon, pollutant dispersion, turbulence modelling

1. The problem of dispersion of pollutants in street canyons

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 big cities. This term is frequently utilized for the urban streets with buildings on both sides, where high pollutant concentrations can be found. Air pollutants related to the traffic are carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons and particles, besides sulphur and its combinations. Some pollutants burden immediate impact on the human health, such as the carbon monoxide (CO), a suffocating and odorless gas, extremely harmless, mainly in high concentrations. The nitrogen oxides (NOx) are a mixture of NO (nitric oxide) and NO_2 (nitrogen dioxide). The nitric oxide combined with oxygen makes the nitrogen dioxide (NO_2) which is much more hazardous than the NO. Its toxicity is approximately four times higher than the one of the NO, causing illnesses such as pneumonia and bronchitis. Concerning the hydrocarbons, a large amount of them is released through vehicle motors via incomplete combustion and chemical reactions which produce components such as benzene, toluene, ethane, ethylene, pentane, etc. The benzene, for instance, shows cumulative effect on the health and may lead to cancer. The particulate matters are emitted principally by motors using diesel and gasoline. Therein, it is extremely relevant to develop models that can predict pollution levels in urban environments such as street canyons. Parameters directly and indirectly related to the problem must be investigated, aiming the preservation of the air quality standard, and consequently, of the human health.

According to Vardoulakis et al. (2003), the expression street canyon has also been used as a broader definition, including urban streets that do not necessarily have contiguous buildings on both sides, but have some openings in one side of the street. The dimensions of the street canyon can be expressed through the aspect ratio which is defined as the canyon height (H) divided by the width (W). Thus, a *regular canyon* will be found for an (H/W) aspect ratio approximately equal to 1 and without opening on the walls. A wider canyon may have an aspect ratio below 0.5, also called *avenue canyon*, and a *deep canyon* may present an aspect ratio equal to 2. Besides this parameter it is possible to have a canyon length (L) that identifies it as a *short canyon* for values $L/H \approx 3$, *medium canyon* for values of $L/H \approx 5$ and for *long canyons* values of $L/H \approx 7$. Concerning the height of the buildings, it can be found *symmetric* or *even street canyons*, for buildings approximately the same height and *asymmetric* with significant differences among the buildings.

It should be made a distinction between the *synoptic* wind flow (free-stream velocity) that is related to the wind conditions above the top of the roof and the *local* wind flow within the canyon cavity. From the type of synoptic wind it is possible to identify three main conditions for dispersion:

- low wind conditions, for synoptic winds inferior to 1.5 m/s;
- perpendicular or almost perpendicular flow, for synoptic winds above 1.5 m/s blowing in angle superior to 30º with respect to the canyon axis;

- parallel or almost parallel flow, for winds superior to 1.5 m/s blowing from all directions.

When a perpendicular airstream flow, with respect to the canyon axis, is found, the up-wind side of the canyon is usually called *leeward*, and the downwind is called *windward*, as it can be seen in Fig. 1 (Dabberdt et al., 1973). When the airstream flow above the roof is perpendicular to the canyon and the wind velocity higher than 1.5 to 2 m/s, the flow can be divided in three basic regimes according to Oke (1988). The Fig. 2 shows these regimes. The first regime is the *isolated roughness flow*, found in wide canyons (H/W < 0.3), where the buildings are distant from each other and the airstream flow goes through a downwind distance sufficient enough to get to the posterior building. If the buildings are closer (H/W ≈ 0.5), the airstream flow experiences some perturbation due to the insufficient distance to self-readjust before reaching the downwind building; this regime is called *wake interference flow*. In the case of the regular canyons (H/W ≈ 1), the bulk of the synoptic flow skims over the canyon producing the *skimming flow*. This regime is characterized by the circulation of a vortex within the canyon (Hunter et al., 1992 and Vardoulakis et al., 2003).

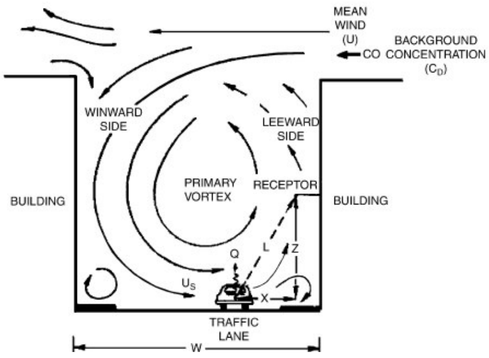

Figure 1. Pollutant Dispersion in a Regular Street Canyon (Dabberdt et al., 1973).

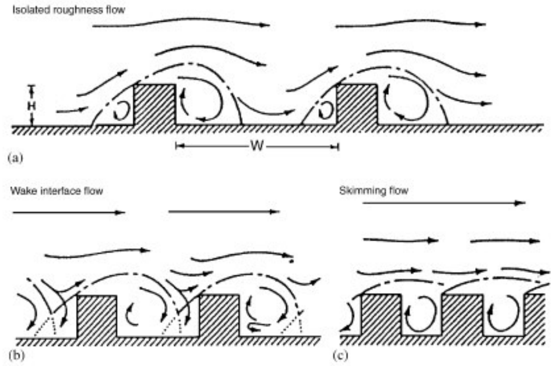

Figure 2. Perpendicular flow regimes in urban canyons for different aspect ratios (Oke, 1998).

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).

2. General vision on empiric and semi-empiric models

According to Vardoulakis et al. (2003), the pollutant dispersion models can be divided in parametric (operational) and numeric. The operational models are divided in empiric and semi-empiric.

2.1. Empiric models

These models include statistic models and are very useful, especially for real time predictions and at short term. It can be cited, as examples, the linear stochastics model, the deterministics/stochastics models, the methods of simulation of Monte Carlo, the multivariate regression models and, more recently, the models based on artificial neural networks (ANN) and fuzzy logic theory (FLT) that provide an alternative to the classic and conventional dispersion models. There are few applications of the stochastics models for prediction of vehicle exhaustion dispersion (Sharma et al., 2001).

2.2. Semi-empiric models

The Gaussian Plume Models are one of the most popular models to estimate pollutant concentration due to their relative simplicity and the possibility of including other parameters. They were designed to simulate punctual sources in open sites, but they can be used in other types of source such as the street canyon. They are widely suitable for scientific and engineering applications. As the main disadvantage, it can be mentioned the application to only few canyons with different configurations and the large number of entries required (Vardoulakis et al., 2003).

The Street model was developed by Johnson et al. (1973) and is usually used as a screening model, with some simplified considerations with respect to initial dispersion and the traffic induced turbulence (Mensink et al., 2006). The leeward and windward sides have specific formulas to concentration calculate, whenever the wind direction is within 60º to its perpendicular axis. When the wind blows in another directions is applied the arithmetic average of formulations (Mensink et al., 2006 and Vardoulakis et al., 2003).

The Operational Street Pollution Model or OSPM (Berkowicz,1998) evolved from the CPBM (Canyon Plume Box Model) according to Vardoulakis et al. (2003) and it is a semi-empirical model that calculates concentration of pollutants on both sides of a street canyon. In this model is used a Gaussian plume model for the calculation of the direct contribution from the traffic emissions and a box model for provide the recirculation component. A logarithmic relationship is used to the interaction between street and roof-level winds (Vardoulakis et al. 2003). The mechanical turbulence in the street due to the wind and vehicle traffic is included in the model (Mensink et al., 2006 and Vardoulakis et al., 2003). This model to be used in regulatory applications needs a simplified chemistry algorithm to take into account the transformation of reactive species inside a street canyon as NO_x (Vardoulakis et al., 2003).

Mensink and Lewyckyj (2001) developed the Street Box model that considers a uniform concentration distribution into a street canyon, with the concept of a turbulent intermittence in the shear flow shed from the upwind roof. The Prandtl-Taylor hypothesis is used for describe the turbulent diffusive flux. The concentrations of benzene, CO and NO_x were compared with OSPM model applied in a street canyon in Hannover, it was found a discrepancy of 30% between the predictions of the models (Vardoulakis et al., 2003).

Mensink et al. (2006) compared three semi-empirical street canyon models applied at an urban station in Antwerp (Belgium) to verify the concentration of NO_x, SO_2, PM_{10}, CO and benzene. The authors studied the following models: the Street model, the OSPM model and the Street Box model. These models are convenient for regulatory applications because they do not require larger computational time. The concentration C (μgm^{-3}) inside the canyon was calculated by all models relative to a certain background concentration. The emission input data were derived from an urban traffic emission model and the meteorological data from nearby meteorological towers in Antwerp. A regional air quality model, which is used as reference model for air quality and deposition calculations in Flanders, Belgium was used to provide background concentration values, that is a fast lagrangian trajectory model for long-term simulations. The observations from a monitoring station of same local were used to compare the results of the models, that provided good estimates of the annual averages for the pollutants; OSPM and Street Box were the models that provided the best estimates.

3. Experimental studies

A large number of experimental studies on pollutant dispersion in street canyons have been performed for decades. Different modellings and monitoring techniques have been adopted according to the objective. These studies are based on full scale and/or reduce scale measurements.

3.1. Field measurements

Louka et al. (1998) investigated the turbulent airstream flow in the canyons and its coupling with the flow above the roofs. A field experiment was performed in a street canyon formed by two long farm buildings. The authors found out, from the outlet velocity distribution at the level of the roof, that the shape affects significantly the air recirculation in the street canyon, and between the street canyon and the environment air.

Boddy et al. (2005) studied how the background wind flow direction influences the carbon monoxide (CO) dispersion in two street canyons with different geometries in York, England. They found great differences for the wind outflow and dispersion standards when varying the street geometry and the background winds. With the direction of the background winds perpendicular to the street axis, there has been a formation of vertical and horizontal vortices, which may have contributed to the appearance of CO mean concentrations in the leeward side with a factor twice higher than in the windward side. Between the two street canyons analyzed, a difference of around two-fold mean concentrations was observed, being that the two highest mean concentrations were found in narrower street canyons.

Assimakopoulos et al. (2006) analyzed the airstream flow within three typical deep street canyons in Athens with different geometries. The field data were collected during a summertime three consecutive day experimental campaign and compared with the data obtained numerically through the MIMO micro-scale model via tri-dimensional modeling.

Eliasson et al. (2006) performed a long-term field experiment in order to analyze wind fields, temperature, radiation and energy in an urban canyon. The experiment was performed for a street canyon with aspect ratio H/W= 2.1 in Gothenburg, Sweden, during the summer and the fall of 2003. The authors noticed the existence of a single helicoidal vortex for an outflow transversal to the canyon (within 60 º orthogonality). It was observed the dependency between the environment outflow direction with respect to the axis along the canyon and the outflow profile within and above the canyon. They also verified, in the building windward side, higher values of turbulent kinetic energy and vertical mixture.

Tsai and Chen (2004) carried out measurements of the pollutants: carbon monoxide, nitrogen oxides and sulphur dioxides and traffic outflow rates according to the type of vehicles circulating in a street in the city of Fung-Shan, capital of Kaoshiung county, Taiwan. The authors used a tri-dimensional scheme through RNG κ–ε turbulence model with the finite volume method and compared the numerical data with the field data. It was used a street canyon with aspect ratio H/W = 0.8 and the relation between the canyon length and width equal to 3. The authors noticed that the pollutant concentration becomes smaller as the heights increases and higher in the leeward side than in the windward side. Yet, it was noticed that the motorcycles contribute most for the pollutant emissions, followed by the automobiles and the vehicles that use diesel.

3.2 Wind tunnel measurements

Gerdes and Olivari (1999) investigated the pollutant dispersion in two-dimensional street canyons simulated in a wind tunnel to the models “open country” and “urban roughness”. The parameters investigated were: the landscape upstream of the canyon, the ratio between the heights of the upstream and downstream canyons walls, and the spacing between the canyon walls. In Sagrado et al. (2002) it is studied the pollutant dispersion numerical and experimentally in a two-dimensional street canyon. The experimental part was performed in the wind tunnel of the Von Karman Institute and the numerical modeling was made by the FLUENT 5.2 code, with the κ–ε turbulence model, presenting a good concordance with the experimental results. The authors varied the downstream building height and considered the cases of isolated street canyon or open country configuration, where there is no other close building and the case of non-isolated street canyon configuration, where a third building is placed in the front part of the street to be studied. The conclusion was that in both cases the airstream flow collides with the first upstream building being separated and accelerated. In the case of isolated street canyon where a pattern of airstream flow with recirculation was noticed, it was also found higher pollutant concentrations, mainly in the right corner for symmetric canyons. In cases of non-isolated street, especially with the downstream buildings 4 and 5 cm taller, it was noticed that there is fresh air admission, lowering the pollutant concentrations.

Pavageau and Schatzmann (1999) examined some turbulence characteristics and field statistics properties of a regular street canyon concentration field through a wind tunnel. The authors presented results referent to the mean concentrations and the variance of fluctuations of the concentration. Kastner and Plate (1999) presented the results of the pollutant concentration profile along the buildings of a street canyon simulated in a wind tunnel. They defined the buildings dimensions and configuration, wind direction and roof geometry as important parameters.

Ahmad et al. (2002) performed studies in wind tunnels on the exhaust dispersion, utilizing sophisticated models that simulate real traffic situations, called MVSM (Model Vehicle Movement System) by the authors. Urban streets with various configurations with variations in the traffic velocity and volume were studied. The results showed pollutants reduction in street canyons surrounded by tall buildings for weak wind conditions considering the turbulence due to the traffic. Seong-Kyu et al. (2004) studied the vehicles dispersion emission through tests realized in a wind tunnel, applying the tracer gas techniques. The leading test parameters were the street canyon aspect ratio (street width/buildings mean height) and the outer wind direction.

Kastner-Klein et al. (2001) investigated the turbulence and mean airstream flow in a wind tunnel and compared them with full-scale airstream flow measurements in an urban street canyon. The data obtained by the authors suggest airstream acceleration above the roof level. They studied models for one-way and two-way lanes and observed significant differences in the outflow and turbulence patterns.

Uehara et al. (2000) used a stratified wind tunnel to study the atmospheric stability on the urban street canyon airstream flow. The authors varied the atmospheric stability from stable ($Rb = 0.79$) to unstable ($Rb = -0.21$). Airstream outflow and temperature, besides turbulence intensity, shearing tension and heat low distribution were measured. They concluded that, under stable atmospheric conditions, there was a street canyon windward side airstream outflow weakening due to the natural convection.

Chang and Meroney (2001) made a numerical and physical modeling of a tri-dimensional urban street canyon arrangement for pollutant bluff body flow and dispersion analysis. The experimental tests were performed in the Wind Engineering Research Field Laboratory building at Texas Tech University. Visualization, velocity and intensity turbulence profiles, pressure on building surface and dispersion of gas simulating pollutants data were presented.

Ahmad et al. (2005) made a review on wind tunnel simulation studies in street canyons/intersections presenting the effects of some parameters that has influence on flow fields an exhaust dispersion. Kovar-Panskus et al. (2002) conducted an experimental and numerical study to investigate the flow regimes in a street canyon varying the aspect ratio. The experimental part was made in a University of Surrey wind tunnel and numerical analysis was performed with a two-dimensional model using the CHENSI code and a standard κ–ε turbulent model.

4. Numerical models for pollutant dispersion in isothermal conditions

The CFD (Computational Fluid Dynamics) modelling is applied to the study of systems that involves fluid flow, heat transfer, pollutant dispersion and other associated phenomena (chemical reactions, for instance) utilizing numerical methods. The CFD numerical models use the Eulerian approach and present great capacity in dealing with more complex geometries and different contour conditions, being able to reproduce all the outflow field and pollutant dispersions for any street canyon configurations. They are based on the numerical solution of the governing equations on fluid outflow and dispersion derived from the mass conservation equation (continuity), momentum conservation equation (Navier-Stokes) and the pollutants concentration equation, as shown below.

Continuity equation:

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

Momentum equation:

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

where U is the mean velocity, u' is the velocity fluctuation, P is the mean pressure and ν is the kinematic viscosity.

For the treatment of the atmospheric turbulence process it should be adopted the turbulent models that are classified in two general categories: classic models based on Reynolds Averaged Navier-Stokes (RANS) flow equations and Large Eddy Simulation (LES) models. For the development of the numerical studies based on Reynolds Averaged Navier-Stokes (RANS) flow equations, the turbulence pattern κ–ε models and modified models as, for instance, the RNG κ–ε (Renormalization Group) model and the κ–ε realizable model can be coupled.

The momentum equations include turbulent fluxes $-\overline{u_i' u_j'}$ which are modelled using the Boussinesq hypothesis so that Reynolds stresses can be linked to the mean rates of deformation

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

where ν_t is the eddy viscosity (or turbulent viscosity), k the kinetic energy and δ_y the Kronecker delta.

The eddy viscosity ν_t is related to the turbulent kinetic energy k and its rate of dissipation ε. The eddy viscosity is modelled by Eq. (4):

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

where C_μ is a constant.

Two additional conservation equations must be solved: one for the turbulent kinetic energy k and other for its rate of dissipation ε. In Eq. (5) the last two terms represents the turbulent kinetic energy rates of production and destruction, respectively. The same can be said about Eq. (6) for the kinetic energy dissipation ε.

$$\frac{\partial}{\partial x_i}\left(U_i k\right) = \frac{\partial}{\partial x_i}\left(\nu + \frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + P_k - \varepsilon \tag{5}$$

$$\frac{\partial}{\partial x_i}\left(U_i \varepsilon\right) = \frac{\partial}{\partial x_i}\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{6}$$

where P_k is the rate of production of kinetic energy, and σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants of the standard k-ε model. The rate of production of turbulent kinetic energy is calculated by Eq. (7).

$$P_k = \nu_t \frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{7}$$

The species (pollutants) transport equation is

$$\frac{\partial}{\partial x_i}\left(U_i C\right) = \frac{\partial}{\partial x_i}\left(D\frac{\partial C}{\partial x_i} - \overline{u_i' c'}\right) \tag{8}$$

where C is the mean concentration, c' is the fluctuation of concentration and D is the molecular diffusion.

The modelling of the last term of Eq. (8) is done by considering that the transport of the scalar *C* is proportional to its gradient as indicated by Eq. (9). In Eq. (9) the molecular diffusion term presented in Eq. (8) is ignored since the turbulent diffusion term is predominant.

$$\frac{\partial}{\partial x_i}\left(U_i C\right)=\frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_C}\frac{\partial C}{\partial x_i}\right) \tag{9}$$

There are various commercial CFD codes that have been widely used in street canyon applications and among them it can be mentioned PHOENICS, FLUENT, STAR-CD, CFX-TASC-flow and Fluidin-PANACHE.

4.1 Two-dimensional numerical models

Xie Xiaomin et al. (2006) utilized a κ–ε pattern turbulence model to examine the impact of an urban street configuration on the atmospheric environment and validated their results with the Meroney et al. (1996) wind tunnel data and Sini et al. (1996) and Jeong and Andrews (2002) simulated results. The authors studied the impact on the layout of a street canyon on the local atmospheric environment. Different street configurations were studied where there was a variation of aspect ratio (height of building leeward/street width) and another aspect ratio defined as the rate between the height of building leeward and the height of the building windward. The authors, taking into account the geometric parameters, defined three airstream flow regimens which characterize the vortices and the dispersion of the pollutants. It was noticed that according to the type of airstream flow in the canyon and the exchange between the canyon and the air above the roof, large variations in pollutant transport and diffusion were found. It was also concluded that there is strong influence of the street layout over the wind area and the diffusion of pollutants that depend mainly on the vortex structure.

Nazridoust and Ahmadi (2006) studied the gas dispersion and particles exhaust emissions in different two-dimensional street canyons, analyzing geometrical aspects and the wind velocity. The authors also studied particles deposits, verifying a reduction connected to a wind velocity increase. The analysis was performed mostly through stress turbulence models and other turbulence model predictions were also analyzed, presenting a favorable conformity between the models simulated and available wind tunnel data.

Li et al. (2005) studied the air exchange rate (ACH) for street canyons idealized with the use of two-dimensional renormalized-group (RNG) κ–ε turbulence model. This model validation was based on comparisons with other models (large eddy simulations, LES and κ–ε) and wind tunnel results. The ACH estimates for street canyons with different aspect ratios (building height/street width) presented good consonance with the ones estimated by the LES model, and utilized less computational time and computer resources.

Xie et al. (2005c) provided a numerical simulation of the vehicle exhaust emissions in an urban environment street canyon comparing three turbulence models: standard, RNG and Chan-Kim κ–ε turbulence model. The numerical results were validated with wind tunnel experimental data of the Meteorological Institute of Hamburg University, Germany. The studies show the impact of the configuration of the building in a street canyon with a different roof shape performed for a bi-dimensional simulation and different combinations of buildings on the quality of the air. The two-dimensional results show that the vortex configuration inside the street canyon and the characteristics of dispersion of pollutants endure a huge influence of the roof shape and environment building arrangement.

Lien et al. (2004) presented a numerical simulation of the irregular outflow through and over a two-dimensional set of street canyons with rectangular buildings. The steady-state Reynolds-averaged Navier-Stokes equations were used and, for the Reynolds tensions, the linear and non-linear turbulent viscosity were used. The authors employed a high Reynolds number formulation for the κ–ε turbulence model closure to determine the turbulent viscosity. The wall contour conditions were based on an approximated standard wall function. The authors compared four different turbulence models and concluded that their results presented good qualitative and quantitative concordance with experimental wind tunnel data. Nevertheless, the κ–ε non-linear model presented a better performance among the models studied.

Chan et al. (2002) investigated the fluid outflow and the pollutant dispersion in a street canyon isolated utilizing a two-dimensional model based on Reynolds averaged Navier-Stokes equations associated to the standard κ–ε turbulence model, Renormalization Group (RNG) and realizable κ–ε. The code used was the FLUENT and the model validated by the comparison with the Meroney et al. (1996) wind tunnel data of the Meteorological Institute of Hamburg University, Germany. The κ–ε RNG model revealed to be the best among the model studied. The measured and estimated non-dimensional pollutant concentrations showed to be less dependent on the wind velocity variation and source strength conditions for the regular street canyon. On the other hand, the influence of the street canyon configuration was significant on the pollutant dispersion. The vortices generated by the fluid outflow transport the pollutants from the source to the walls. The non-dimensional pollutant concentrations on the leeward side decrease exponentially from the bottom of the building upstream, being that on the windward side the pollutant concentrations are almost constant along the height of the downstream building. It is noticed that the pollutant concentrations appear more in the leeward side than in the windward side due to the transportation of pollutants by the vortices circulation. According to the authors definition, for a regular street canyon (aspect ratio W/H = 1) the circulation of a rotating vortex is noticed, for H/W = 4 it was noticed the circulation of two co-rotating vortices and for H/W = 1/3 it was noticed the circulation of two counter-rotating vortices. These vortex circulations lead to different pollutant concentration distributions in the buildings under different street canyon configurations.

Sini et al. (1996) studied the outflows and pollutant vertical exchanges in a two-dimensional street canyon with the use of the κ–ε turbulence model and the CHENSI code. They observed the outflow separation in three regimes, according to described by Oke (1988) and also detailed such regimes considering the aspect ratio influence and the recirculation outflow structure in the street canyon. The authors verified how the vertical change rates are influenced by vortex number and structure.

Assimakopoulos et al. (2003) studied numerically the pollutant dispersion in street canyons with different geometric configurations and building heights through the two-dimensional microscale model MIMO. The numeric results were validated with data from experiments in two-dimensional wind tunnel for the configurations of square street canyon and deep street canyon. In this study, the aspect ratio H/W = 1 was used for the square canyon and the relation W/H = ½ was used for the deep street canyon. Yet, considering asymmetric buildings the authors defined the terms "step-up notch" configuration, where the upwind building is lower than the downwind building, and "the step-down notch" which represents just the opposite configuration. The authors concluded that there is a strong influence of the street geometry over the airstream flow field and over the pollution dispersion standards. Depending on the building geometry pollutant concentrations can be found in different sites. In the case of the square canyon a higher concentration of pollutants in the upwind building lower corner was noticed, with an increase of 27% from the top to lower corner of the upwind building wall. In the step-up notch, the pollution levels in the canyon were reduced. In the step-down notch configuration the pollution levels increased in both sides of the building. In the symmetric deep canyon it was noticed twice the pollutants concentration found in the square canyon. The interaction between the airstream flow inside and above the canyon was more intense for the wide streets than for the narrow ones. It is noticed that the wider streets present good pollutant dispersion conditions.

Baik and Kim (1999) studied an urban street canyon with a two-dimensional numerical model using the κ–ε turbulent closure scheme to analyze the flow and pollutant dispersion. It was observed that with the increase of aspect ratio, the number of vortices also increases. Close to the windward side, the wind shears has more intensity causing higher turbulent kinetic energy. It was found a critical value of the ambient wind speed, the distribution pattern of vortices is the same to values higher than this critical point.

Huang et al. (2000) developed a two-dimensional air quality numerical model to predict the pollutant concentration within a street canyon using a κ–ε turbulent model. The numerical results were compared with data from a set of street canyon air tracer experiments showing good agreement. A detailed study has been done where the height of the buildings and the wind direction was changed. It was observed a higher dilution of the pollutants considering cases of street canyons with lower height, with step down configuration, higher wind speed and inflow wind direction towards the street. Leitl and Meroney (1997) studied the effect of changing source design and source emission rate on the flow field and pollutant dispersion in a street canyon. The numerical study was carried using the FLUENT code with the turbulence standard κ–ε model and the RNG turbulence model. The two-dimensional and three-dimensional numerical simulations were compared with the results from wind tunnel experiments conducted by Rafailids et al. (1995).

4.2 Three-dimensional numerical models

Xie et al. (2005c) performed two-dimensional calculations and a second set of calculations showing a tri-dimensional simulation in order to investigate the influence of the building geometry on the pollutant dispersion. In the 3-D simulation, the influence of the geometry of the building on the dispersion of pollutants was investigated and the results obtained were much in accordance with the results from the wind tunnel experiments (Rafailidis and Schatzmann, 1995) and with the conclusions from the 2D simulations.

Kim and Baik (2004) used a three-dimensional model and investigated the effects of the surrounding wind direction on the airstream flow and pollutant dispersion around a group of buildings. The authors identified three patterns of airstream flow, with different characteristics of circulation of the mean airstream flow according to the surrounding wind direction in the street canyons. It was noticed that when the incident wind angle is 45º, the airstream flow is diagonally symmetric in the back of the upwind building. The study shows that when the wind angle of incidence increases, the pollutants become confined by the vortex portal with high local concentrations, except when the wind is perpendicular to the buildings. When the wind is perpendicular, the pollutants are transported to both sides verges of the street canyon through the outward airstream flow which is prevalent when close to the end of the street and the pollutants escape from the street canyon. The study demonstrates the change in the pollutants spatial distribution, consequence of the big differences in the circulation of the mean airstream flow due to the wind direction variation.

Chan et al. (2001) analyzed the pollutant dispersion for a tri-dimensional street canyon through a κ–ε turbulence model. The numerical code used was CFX-5, with the use of tetrahedral finite elements. The results were compared with the wind tunnel data (Uehara et al. 2000, Pavageau and Schatzmann, 1999 and Theurer, 1999). It could be noticed that the pollutant transport and diffusion are strongly dependent on the type of airstream flow in the canyon and on the exchange between the canyon and the air above the roof. The authors identified the critical street canyon configurations with high pollutant concentrations, delivering some considerations for the urban planning: to avoid building height and canyon width and length uniformity. Wider canyons provide better pollutant diffusion: the source position is not important and the concentrations are higher in the leeward wall foundation. Chan et al. (2003) studied the pollutant airstream flow and dispersion area for different geometries of building sets, considering a three-dimensional street canyon localized within this set, with a κ–ε turbulence model. The authors observed that the airstream flow and the pollutants dispersion are greatly influenced by the geometrical configurations, and that the results may be different from the ones obtained for a single street canyon.

Leitl and Meroney (1997) performed calculations for a simplified three-dimensional street canyon to investigate the presence of secondary flow patterns found in the physical model and it was observed a good agreement between the calculated velocity components and measured in the wind tunnel. Hunter et al. (1992) studied a three-dimensional flow within an urban canyon with a κ–ε turbulence model to identify the main parameters that are relevant to the transition between the flow regimes for synoptic winds perpendicular to the street axis. The change from skimming to wake interference is much important, because the skimming flow is relatively ineffective in removing pollutants, heat and moisture. The studies of Chang and Meroney (2001), Tsai e Chen (2004) and Assimakopoulos et al. (2006), discussed in the previous section, also present numerical results for three-dimensional modelling.

5. Numerical models of pollutant dispersion including thermal effects

The study of thermal effects such as building surface or street-canyon bottom heating has a great importance in determining flow pattern and pollutant dispersion in street canyons. The density is a function of temperature for incompressible turbulent inert flow. In the cases where it is considered the heating of building walls and bottom, the air density changes due to the air temperature increase. 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 density and the other physical parameters do not change except for the density in the buoyancy forces term, as shown below,

$$\frac{\partial}{\partial x_i}\left(U_i U_j\right)=\left(\frac{\rho-\rho_n}{\rho_n}\right)g_j-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\nu\frac{\partial U_i}{\partial x_i}\right)+\frac{\partial}{\partial x_i}\left(-\overline{u_i' u_j'}\right) \tag{10}$$

where g_j is the components of the gravitational acceleration, ρ is the fluid density and ρ_n is the reference density.

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

$$\frac{\rho-\rho_n}{\rho_n}=-\beta\left(\Theta-\Theta_n\right) \tag{11}$$

where Θ is the mean temperature and β is thermal expansion coefficient.

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

$$\frac{\partial}{\partial x_i}\left(U_i k\right)=\frac{\partial}{\partial x_i}\left(\nu+\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right)+P_k-\varepsilon-\beta g_j\overline{u_i\theta} \tag{12}$$

$$\frac{\partial}{\partial x_i}\left(U_i\varepsilon\right)=\frac{\partial}{\partial x_i}\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_i}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(P_k-\beta g_j\overline{u_j\theta})-C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{13}$$

$$-\overline{u_i\theta}=K_t\frac{\partial\Theta}{\partial x_i} \tag{14}$$

$\overline{u_i\theta}$ is the turbulent heat flux and K_t is the turbulent diffusivity coefficient.

The energy equation (Eq. 15) takes into account the thermal effects, allowing the calculation of the temperature field.

$$\frac{\partial\left(U_i\Theta\right)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(K_t\frac{\partial\Theta}{\partial x_i}\right) \tag{15}$$

Various research works presented in this section are based on configurations similar to that shown in Fig. 3.

Nakamura and Oke (1988) considered measurements of air temperature and the time evolution of temperature, airflow and stability in a street canyon. The authors show that, depending on the hour of the day, the direction of the vortex varies with the sunshine conditions. According to Sini et al (1996) the canyon geometry and the differential heating of the wall of the buildings in a street canyon influence the in-street flow and the diffusion process.. Sini et al. (1996) simulated a street canyon with aspect ratio W/H = 0.89 and three sunlit wall configurations, with the temperature of the surfaces (ground, leeward and windward) 5 °C warmer than the incoming flow, and the neutral upwind atmospheric thermal stratification. In the cases of warm ground or leeward wall, the flow structure is quite similar to the isothermal case, although the intensity of the only vortex is increased by the action of dynamics and thermal buoyancy, generating a net increase in the vertical exchanges. When the windward wall is heated, the buoyancy flux tends to oppose the recirculation motion, dividing the vortex and resulting in a change of the flow regime from the one vortex skimming flow to multi-vortex skimming flow, generating a large reduction of the vertical exchanges. For the modelling it was used the Boussinesq assumption with the Reynolds-averaged Navier-Stokes equations, solved using the CHENSI code.

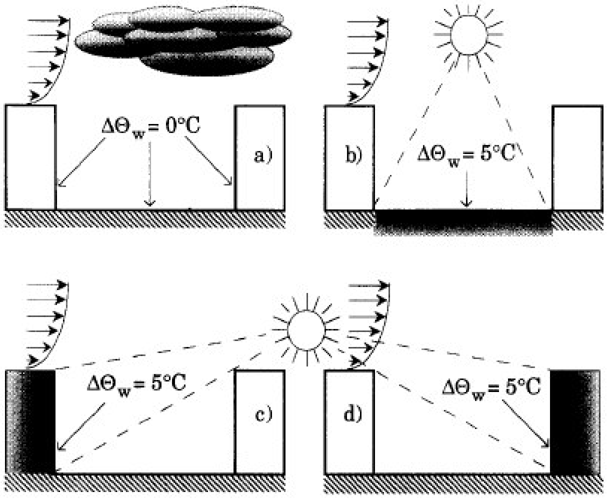

Figure 3. The sunlit wall configurations (Sini et al., 1996).

Xie et al (2005b) evaluated the effect of solar radiation on the airflow and the dispersion within street canyons for different configurations. It was investigated the symmetrical, step up notch and step down notch configurations with the temperature difference between the surfaces and ambient air of 10 °C. The authors observed that the street geometry has a strong influence on the wind field and pollution dispersion patterns. The heating from surfaces of the street canyons that receive solar radiation leads to an upsurge in a strong buoyancy flow close to the wall or the ground, leading to a combined thermally and mechanically induced flow that affects the flow structure and the pollutant dispersion in the canyon. The numerical results were compared with the wind-tunnel data of Uehara et al (2000). Xie et al. (2005a) examined the influence of the thermal effects on vehicles emission dispersion in street canyons. It was used a two-dimensional street canyon with the aspect ratio H/W = 1. The authors showed the flows and concentration profiles for different wind speeds and temperatures ranges. The relative influence of the effects of the thermal radiation on the flow was estimated by parameter Gr/Re^2. For $Gr/Re^2 = 1$ the flow is induced by thermal and mechanical effects, for $Gr/Re^2 < 1$ the thermal effects can be ignored. Fixing the street geometry, the parameter Gr/Re^2 varies with the temperature difference and wind speed. Low wind conditions and large temperature differences cause large thermal effects.

Kim and Baik (1999) studied the thermal effects on the flow and pollutant dispersion in urban street canyons with the aspect ratio (H/W) varying from 0.5 to 3. It was used a non-steady two-dimensional model with a κ–ε turbulent closure scheme, where the thermal situations studied were no heating, upwind and downwind building-wall heating and street canyon bottom heating, with the temperature difference between the air and the surfaces of 5 °C. The authors observed the emergence of one vortex regardless of aspect ratio for the case of upwind building-wall heating. They also shown that at the street level the dispersion of pollutants released is quite dependent upon the aspect ratio and the location of the heat source. It was verified that the residue concentration ratio is greatly influenced by the vortex number and intensity in the street canyon. The study indicated that the surfaces (wall and bottom) heating significantly affect flow and dispersion in urban street canyons. Kim and Baik (2001) investigated the flow in street canyons considering the street-bottom heating to various aspect ratios and different heating intensities. It was employed a non-steady two-dimensional numerical model with a κ–ε turbulence closure scheme. The authors identified five flow regimes that are characterized according to the vortex structure and intensity. The numerical results were compared with the wind-tunnel data of Uehara et al. (2000) showing a good agreement. Kim and Baik (2005) used a circulating water channel to study experimentally the effects of street bottom heating and inflow turbulence on the flow of a regular street canyon, which produced a canyon vortex with higher intensity.

Moussiopoulos et al. (2005) described numerically the influence walls heating and building shading on the flow and dispersion of pollutant in a street canyon. The model MIMO was used with an introduction of a heating module and the results were compared with the code CFX-TASC flow. 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 modelling. The authors used the RNG $\kappa - \varepsilon$ turbulence model and one of the observations was that with the increase of heating condition the pollutant concentration decreases. Liu et al. (2003) studied experimentally non-symmetrical street-canyons using a water tank to observe the convection flow induced by bottom heating and the effects of the ambient wind on the flow. In a wide street canyon, it was verified more than two vortices induced by convection; in a narrow street canyon it was observed only one vortex.

6. Toward the modelling of pollutant dispersion in a street canyon of São Paulo city

According to studies of the Experimental Atmospheric Pollution Laboratory of the Faculty of Medicine of the University of São Paulo, the atmospheric pollution in São Paulo city is responsible, indirectly, by the death of eight people per day, in average. Yet, according to the researches, the inhabitants of the city have diminished the life expectation in two years for they live in polluted places. Among the most common health problems resulting from the inhalation of pollutants, it can be mentioned the pneumonia, infarct of the myocardium and emphysema especially in older people. According to the CEInfo (Coordination of Epidemiology and Information), Health Municipal Office, pneumonia was the third main cause of death in 2004. The vehicle exhaust gases are the main source of the atmospheric pollutant in São Paulo city, as there are 7 millions cars running in the metropolitan area. Although there are efforts to improve the air quality in the city, such as the Program of Control of Pollution by Automotive Vehicles (PROCONVE), the situation is far from adequate.

The main problems related to the pollutant dispersion in São Paulo city are the topography, which includes valleys, and street canyons that prevent the gases and particulates to dissipate. The thermal inversion phenomenon which occurs during the winter aggravates the situation as the dispersion by wind is severely constrained. Numerical and experimental studies, including field and wind tunnel measurements, are necessary to address this problem. The next steps for this study will include the characterization of a typical street canyon in São Paulo city with high concentration of atmospheric pollutants and the screening of field data to set the boundary conditions. The modified $\kappa - \varepsilon$ turbulent model, proposed by Mello and Yanagihara (2006) for open field atmospheric pollutant dispersion, will be tested along with other major models described herein.

Figure 4. Typical street canyon in São Paulo city

Figure 5. Atmospheric pollutant in São Paulo city

7. References

Ahmad, K., Khare, M. and Chaudhry, K. K., 2002, "Model Vehicle Movement System in Wind Tunnels for Exhaust Dispersion Studies under Various Urban Street Configurations", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 90, pp. 1051-1064.

Ahmad, K., Khare, M. and Chaudhry, K. K., 2005, "Wind Tunnel Simulations Studies on Dispersion at Urban Street Canyons and Intersections – A Review", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 93, pp. 697-717.

Assimakopoulos V. D., Georgakis, C. and Santamouris, M., 2006, "Experimental Validation of a Computational Fluid Dynamics Code to predict the Wind Speed in Street Canyons for Passive Cooling Purposes", Solar Energy, Vol. 80, pp. 423-434.

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

Baik, J. J and Kim, J.J., 1999, "A Numerical Study of Flow and Pollutant Dispersion Characteristics in Urban Street Canyons", Journal of Applied Meteorology, Vol. 38, pp. 1576-1589.

Berkowicz, R., 1998, "Street Scale Models", In: Fenger, J., Hertel, O., Palmgren, F. (Eds.), Urban Air Pollution – European Aspects. Kluwer Academic Publishers, Dordrecht, pp. 223-251.

Boddy, J. W. D., Smalley, R. J., Dixon, N. S., Tate, J. E. and Tomlin, A. S., 2005, "The Spatial Variability in Concentrations of a Traffic-Related Pollutant in Two Street Canyons in York, UK – Part I: The Influence of Background Winds", Atmospheric Environment, Vol. 39, pp. 3147-3161.

Chan, A. T., So, E. S. P. and Samad, S. C., 2001, "Strategic Guidelines for Street Canyon Geometry to achieve Sustainable Street Air Quality", Atmospheric Environment, Vol. 35, pp. 5681-5691.

Chan, A. T., Au, W. T. W. and So, E. S. P., 2003, "Strategic Guidelines for Street Canyon Geometry to achieve Sustainable Street Air Quality- part II: Multiple Canopies and Canyons", Atmospheric Environment, Vo. 37, pp. 2761-2772.

Chang, C. H. and Meroney, R. N., 2001, "Numerical and Physical Modeling of Bluff Body and Dispersion in Urban Street Canyons", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 89, pp. 1325-1334.

Chan, T. L., Dong, G., Leung, C. W., Cheung, C. S. and Hung, W. T., 2002, "Validation of a Two-Dimensional Pollutant Dispersion Model in an Isolated Street Canyon", Atmospheric Environment, Vol. 36, pp. 861-872.

Dabberdt, W. F., Ludwig, F. L., Johnson, W. B., 1973, "Validation and Applications of an Urban Diffusion Model for Vehicular Pollutants", Atmospheric Environment, Vol. 7, pp. 603-618.

Eliasson, I., Offerle, B., Grimmond, C.S.B. and Lindqvist, S., 2006, "Wind Fields and Turbulence Statistics in an Urban Street Canyon", Atmospheric Environment, Vol. 40, pp. 1-16.

Gerdes, F. and Olivari, D., 1999, "Analysis of Pollutant Dispersion in an Urban Street Canyon", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 82, pp. 105-124.

Huang, H., Akutsu, Y., Arai, M. and Tamura, M., 2000, "A two-dimensional Air Quality Model in an Urban Street Canyon: Evaluation and Sensivity Analisys", Atmospheric Environment, Vol. 34, pp. 689-698.

Hunter, L. J., Johnson, G. T. and Watson, I. D., 1992, "An Investigation of Three-Dimensional Characteristics of Flow Regimes within the Urban Canyon", Atmospheric Environment, Vol. 26B, No. 4, pp. 425-432.

Jeong, J. J. and Andrews, M. J., 2002, "Application of the κ–ε Turbulence Model to the High Reynolds Number Skimming Flow Field of an Urban Street Canyon", Atmospheric Environment, Vol. 36, pp. 1137-1145.

Kastner-Klein, P., Fedorovich, E. and Rotach, M. W., 2001, "A Wind Tunnel Study of Organized and Turbulent Air Motions in Urban Street Canyons", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 89, pp. 849-861.

Kastner-Klein, P. and Plate, E. J., 1999, "Wind-Tunnel Study of Concentration Fields in Street Canyons", Atmospheric Environment, Vol. 33, pp. 3973-3979.

Kim, J. J and Baik, J.J., 2004, "A Numerical Study of the Effects of Ambient Wind Direction on Flow and Dispersion in Urban Street Canyons using the RNG κ–ε Turbulence Model", Atmospheric Environment, Vol. 38, pp. 3039-3048.

Kim, J. J. and Baik, J. J., 2005, "Physical Experiments to Investigate the Effects of Street Bottom Heating and Inflow Turbulence on Urban Street-Canyon Flow", Advances in Atmospheric Sciences, Vol. 22, pp. 230-237.

Kim, J. J. and Baik, J. J., 2001, "Urban Street Canyon Flows with Bottom Heating", Atmospheric Environment, Vol. 35, pp. 3395-3404.

Kim, J. J. and Baik, J. J., 1999, "A Numerical Study of Thermal Effects on Flow and Pollutant Dispersion in Urban Street Canyons", Journal of Applied Meteorology, Vol. 38, pp. 1249-1261.

Kovar-Panskus, A., Louka, P., Sini, J. F., Savory, E., Czech, M., Abdelqari, A. andMestayer, P. G. and Toy, N., 2002, "Influence of Geometry on The Mean Flow within Urban Street Canyons-A Comparison of Wind Tunnel Experiments and Numerical Solutions", Water, Air, and Soil Pollution, pp. 365-380.

Leitl, B. M. and Meroney, R. N., 1997, "Car Exhaust Dispersion in a Street Canyon. Numerical Critique of a Wind Tunnel Experiment", Journal of Wind Engineering and Industrial Aerodynamics, pp. 293-304.

Li, X.-X., Liu, C.-H. and Leung, D. Y. C., 2005, "Development of a κ–ε Model for the Determination of Air Exchange Rates for Street Canyons", Atmospheric Environment, Vol. 39, pp. 7285-7296.

Lien, F. S, Yee, E., and Cheng, Y., 2004, " Simulation of Mean Flow and Turbulence over a 2D Building Array using High-Resolution CFD and a distributed Drag Force Approach", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 92, pp. 117-158.

Liu, H. Z., Liang, B., Zhu, F. R., Zhang, B. Y. and Sang, J. G., 2003, "A Laboratory Model for the Flow in Urban Street Canyons induced by Bottom Heating", Advances in Atmospheric Sciences, Vol. 20, pp. 554-564.

Louka, P., Belcher, S. E. and Harrison, R. G., 1998, "Modified Street Canyon Flow", Journal of Wind Engineering and Industrial Aerodynamics, pp. 485-493.

Mensink, C. and Lewyckyj, N., 2001, "A Simple Model for the Assesment of Air Quality in Streets", International Journal of Vehicle Design, Vol. 27, pp. 242-250.

Mensink, C., Lefebre, F., Janssen, L. and Cornelis, J., 2006, "A Comparison of Three Street Canyon Models with Measurements at an Urban Station in Antwerp, Belgium", Environmental Modelling & Software, Vol. 21, pp. 514-519.

Meroney, R.N., Pavageau, M., Rafailidis, S. and Schatzmann, M., 1996, "Study of Line Source Characteristics for 2D Physical Modeling of Pollutant Dispersion in Street Canyons", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 62, pp. 37-56.

Mello, P.E.B. and Yanagihara, 2006, "Prediction of gas concentration fluctuations and pollutant dispersion in the atmosphere using a numerical model", Journal of Wind Engineering & Industrial Aerodynamics, submitted.

Moussiopoulos, N., Ossanlis, I. and Barmpas, P., 2005, "A Study of Heat Transfer Effects on Air Pollution Dispersion in Street Canyons by Numerical Simulations", International Journal of Environment and Pollution, Vol. 25, pp. 131-144.

Nakamura, Y. and Oke, T. R., 1988, "Wind, Temperature and Stability Conditions in an East-West Oriented Urban Canyon", Atmospheric Environment, Vol. 22, pp. 2691-2700.

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

Oke, T. R., 1988, "Street Design and Urban Canopy Layer Climate", Energy and Buildings, Vol. 11, pp. 103-113.

Park, S.-K., Kim, S.-D. and Lee, H., 2004, "Dispersion Characteristics of Vehicle Emission in an Urban Street Canyon", Science of The Total Environment, Vol. 323, pp. 263-271.

Pavageau, M. and Schatzmann, M., 1999, "Wind Tunnel Measurements of Concentration Fluctuations in an Urban Street Canyon", Atmospheric Environment, Vol. 33, pp. 3961-3971.

Rafailids, S. and Schatzmann, M., 1995, "Studie on Different Roof Geometries in a Simplified Urban Environment", http: //www.mi.uni-hamburg.de/technische_meteorologie/windtunnel/

Rafailids, S., Pavageau, M. and Schatzmann, M., 1995, "Wind Tunnel Simulation of Car Emission Dispersion in Urban Street Canyons", Annalen der Meteorologie, Deutsche Meteorologische Gesellschaft, Munich.

Sagrado, A. P. G., van Beeck, J., Rambaud, P. and Olivari, D., 2002, "Numerical and Experimental Modeling of Pollutant Dispersion in a Street Canyon", Journal of Wind Engineering and Industrial Aerodynamics, Vol 90, pp. 321-339.

Sharma, P. and Khare, M., 2001, "Modelling of Vehicular Exhausts – a Review", Transportation Research Part D, Vol.6, pp. 179-198.

Sini, J. F., Anquetin, S. and Mestayer, P. G., 1996, "Pollutant dispersion and thermal effects in urban street canyons", Atmospheric Environment, Vol. 30, pp. 2659-2677.

Theurer, W., 1999, "Typical Building Arrangement for Urban Air Pollution Modeling", Atmospheric Environment, Vol.33, pp. 4057-4066.

Tsai, M. Y. and Chen, K. S., 2004, "Measurements and Three-Dimensional Modeling of Air Pollutant Dispersion in an Urban Street Canyon", Atmospheric Environment, Vol. 38, pp. 5911-5924.

Tsai, M. Y., Chen, K. S and Wu, C. H., 2005, "Three-dimensional Modeling Dispersion in an Urban Street of Air Flow and Pollutant Canyon with Thermal Effects", Journal of the Air & Waste Management Association, Vol. 55, pp. 1178-1189.

Uehara, K., Murakami, S., Oikawa, S. and Wakamatsu, S., 2000, "Wind Tunnel Experiments on How Thermal Stratification Affects Flow in and Above Urban Street Canyons", Atmospheric Environment, Vol. 34, pp. 1553-1562.

Vardoulakis, S., Fisher, B. E. A., Pericleous, K. and Gonzales-Flesca, N., 2003, "Modelling Air Quality in Street Canyons: a Review", Atmospheric Environment, Vol. 37, pp. 155-182.

Xie, X., Huang, Z., Wang, J. and Xie, Z., 2005a, "Thermal Effects on Vehicle Emission Dispersion in an Urban Street Canyon", Transportation Research Part D: Transport and Environment, Vol. 10, pp. 197-212.

Xie, X., Huang, Z., Wang, J. and Xie, Z., 2005b, "The Impact of Solar Radiation and Street Layout on Pollutant Dispersion in Street Canyon, Building and Environment, Vol. 40, pp. 201-212.

Xie, X., Huang, Z. and Wang, J., 2005c, "Impact of Building Configuration on Air Quality in Street Canyon", Atmospheric Environment, Vol. 39, 4519-4530.

Xie, X., Huang, Z. and Wang, J., 2006, "The Impact of Urban Street Layout on Local Atmospheric Environment", Building and Environment, Vol. 41, pp. 1352-1363.