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Aerodynamics effects on pollution concentrations of through-passages in building indoors urban street canyon

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Abstract

In this study, the numerical investigation was carried the effects of Through-passages under building in urban street canyons on traffic pollutant dispersion. A three-dimensional computational fluid dynamics (CFD) model is used to evaluate air flow and pollutant dispersion within an urban street canyon using Reynolds-averaged Navier–Stokes (RANS) equations based on k-ε turbulence model to close the equation system. The numerical model is performed with ANSYS-CFX code. Whereas vehicle emissions of sulfur hexafluoride (SF6) taken as tracer gas are considered as double line sources along the street canyon. The numerical model was validated by the wind tunnel experiment results. Having established this, the wind flow and pollutant dispersion in urban street canyons. The numerical simulation results agree reasonably with the wind tunnel data. Then, the numerical simulations were extended to explore the impacts of the effects of through-passages under building on SF6 dispersion; the results indicated that through-passages under building generally increase dispersion of SF6 concentrations in symmetric street canyons. Overall results indicate the decreasing of the concentration normalized in the critical region located on the centerline in the leeward and windward wall successively.

I. Introduction

Automobile transport is now an inherent part of our civilisation, and as it happened with much other technological advancement, the negative aspects are becoming more and more pronounced. One of them is air pollution from car exhaust gases. This pollution has many adverse effects; the road traffic is known to be the major contributor to the anthropogenic emissions and it is expected that these emissions will continue to increase with the steadily increasing amount of traffic. Urban areas can still not be considered as homogeneous entities; the largest pollution levels occur in street canyons where dilution of car exhaust gases is significantly limited by the presence of buildings flanking the street.

The evaluation of spatial and temporal distribution of different pollutants concentration who was emitted from road traffic in urban street canyon level; has attracted much interest from the scientific community; from the both monitoring and modeling points of view. The study on wind flow and pollutants transport inside urban street canyons have attracted great concern during the past two decades mainly due to increasing air pollution levels and the concentration of pollutants and also their adverse impacts on human health [1,2]. The dispersion of pollutants is a major source of urban air pollution, their effect on atmospheric air quality and on human health necessity find solutions for reduced or dispersed in the atmosphere. Not only gaseous emissions, but also particulate matter resulting from combustion processes, abrasion of brake discs and tires as well as road dust suspension contributes to a deterioration of air quality. In dense built-up areas, air exchange between street level and the atmospheric wind above roof top level is limited. Near ground traffic-released emissions are not effectively diluted and removed, but remain at street level, resulting in high pollutant concentrations. In this context, the question arises how can the method of control passive has decrease the concentration of pollutant and their exchange processes in urban street canyon. A number of recent researches have been identified and investigated as potential passive control to improve air quality.

So far, a great deal of air quality studies in urban areas has been performed [3-9]. These investigations comprise both experimental and numerical works. All studies mentioned above deal with prevailing atmospheric wind directed perpendicular to the street length axis, since this wind regime is seen to be the most critical for pollutant accumulation in street canyons. Various wind tunnel experiments and numerical investigations have been carried out into the influence of tree planting on the dispersion of traffic emissions in street canyon; for this reason some researchers investigated wind flow patterns [10-13], canyon aspect ratios and impact different configurations of built [14-16].

Similarly research has been carried out into the effect of noise pollution barriers on air pollution dispersion. These have in effect been shown to be dual purpose in the urban environment providing reduction in noise and air pollution[17-22]. Furthermore, investigations have been carried out into the effect of low boundary walls (LBW) on pollutant dispersion. [23],[24]. In addition to their influence on street canyon dispersion, numerous investigations have shown that trees and other forms of vegetation act to induce the deposition of particulate matter PM and vehicles exhaust emissions. [25-27].

The passive control of air pollution emissions through the manipulation of natural pollutant dispersion patterns in urban street canyons is being put forward as a viable option in the protection of human health. In contrast to methods which aim to reduce air pollution emissions this technique aims to increase local dispersion to reduce air pollution concentrations. Using low boundary walls, trees, on-street parking, hedgerows, noise pollution barriers and other common urban features, investigators have highlighted the ability of such obstacles to influence the dispersion of air pollution from traffic in a typical street canyon Investigations have revealed that these obstacles may be positioned within an urban street canyon in such a way as to increase the amount of dispersion which takes place between the tailpipe emission of air pollutants and their inhalation by pedestrian's cyclists on the edge of a roadway. The volume of pollutants emitted from the road surface was simply to provide a generic concentration to compare between a model with and without hole under building.

Consequently, the continuous increase of the pollutants concentration in the urban street canyon has become necessary to implement wise strategies and solutions for urban street canyon, for providing a clean environment, in this context, the question arises, how can the method of control passive has decrease the concentration of pollutant and their exchange processes in urban street canyon?.

In this work, a three dimensional (3D) numerical model with the code CFD was prepared to examine a method of potential passive control using the k-ε turbulence closure model and the influence of crossing under building on the dispersion of pollutants in asymmetrical urban street canyon which are compared with reference model to improve air quality in urban street canyon.

In general terms passive controls can present a barrier between car emission and pedestrians in a street canyon. Passive controls can also act to significantly alter air flow patterns within a street canyon whereby air pollution emissions are re-directed away from the edge of the roadway resulting in very significant reductions in personal exposure.

2. Numerical method

2.1The standard $k - \varepsilon$ model

The set transport average equation for a Newtonian and incompressible fluid, the flow field can be characterized by conservation laws; these are continuity equation and the Navies–Stokes (RANS) equations are solved through the use of numerical methods. The over bar indicates a filtered variable.The system of governing equation for turbulent flow field can be written in the following form;

The continuity equation:

$$\frac{\delta \bar{u}_i}{\delta x_i} = 0 \qquad (1)$$

The momentum conservation equation:

$$\bar{u}_j \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\overline{\delta p}}{\delta x_j} + \upsilon \frac{\delta}{\delta x_j}\left[\frac{\delta u_i}{\delta x_j}\right] - \overline{\grave{u}_j \frac{\partial \grave{u}_i}{\partial x_j}} \qquad (2)$$

Where ρ is the density, u the velocity, p the pressure, and subscript i denotes direction. Where the overbear variables are the Reynolds time-average mean velocity components $\overline{u_i}$ and pressure$\bar{p}$;and υ is the kinematic molecular viscosity of the fluid.

The equation of transport of a pollutant:

$$\bar{u}_j \frac{\partial \bar{c}}{\partial x_j} = D \frac{\partial^2 \bar{c}}{\partial {x_j}^2} - \frac{\partial \overline{\grave{u}_j \grave{c}}}{\partial x_j} + \bar{S} (3)$$

The equation for the transport of TKE, k:

The turbulence kinetic energy k and its rate of dissipationε are obtained from the following transport equations:

$$\rho\bar{u_J}\frac{\delta K}{\delta x_j} = \tau_{ij}\frac{\delta u_i}{\delta x_j} + \frac{\delta}{\delta x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\delta k}{\delta x_j}\right] - \rho\varepsilon \quad (4)$$

$$\rho\bar{u_J}\frac{\delta \varepsilon}{\delta x_j} = \frac{\delta}{\delta x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\delta \varepsilon}{\delta x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{K}\tau_{ij}\frac{\delta \bar{u_i}}{\delta x_j} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{K} \quad (5)$$

The turbulent viscosity

$$\mu_t = C_\mu\frac{k^2}{\varepsilon} \quad (6)$$

Where,u_i and u_j , are the mean velocity components in ith and jth direction coordinates, respectively; μ the laminar viscosity; g the gravitational acceleration; σ_k and $\sigma_\varepsilon$are the turbulent prandtl numbers for k and ε ,respectively; C the mean pollutant concentration; the used coefficient for this model are $C_\mu = 0.09$,$\sigma_k = 1.0$,$\sigma_\varepsilon = 1.2$,$C_{1\varepsilon} = 1.44$, and $C_{2\varepsilon} = 1.92$.These equations were solved using the finite volume method by using an unstructured grid discretized.

2.2.Dispersion modeling

The diffusion of passive tracer is solved by the code CFD model by computing the diffusive mass flux in turbulent flows which satisfies the conservation of mass as follows:

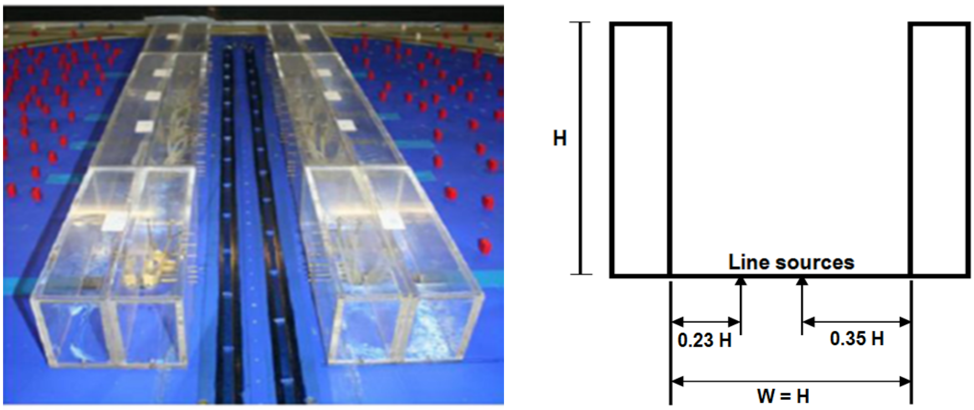
$$J = -(\rho D + \frac{\mu_t}{Sc_t})\nabla M_t \quad (7)$$

Where D is the molecular coefficient,μ_t is the dynamic eddy viscosity (Eq (6)), $\nabla M_t$is the mass fraction passive scalar of pollutant and $Sc_t = {\mu_t}/{\rho D_t}$ is the turbulent Schmidt number, where is the turbulent diffusivity, the default values of$Sc_t = 0.7$were used and fine tuning was avoided as recommended by [33].

3. Modeling approach

3.1 Experimental Setup

The experience has been in the Laboratory of Building and Environment Aerodynamics, Karlsruhe Institute of Technology (KIT).The database is known by the acronym **CODASC** which stands for Concentration Data of Street Canyon. Flow field and concentration level measurements were performed for a scale street canyon in the atmospheric boundary layer. A boundary layer flow with mean velocity, *u(y)* profile exponent, *α*= 0.30 and turbulence intensity, *Iu* profile exponent, α_I= 0.36, according to the power law formula were reproduced in the test section. Fig.1 shows the cross section of wind tunnel experiment and the position of line source in the road.



(a) (b)

Figure 1:(a) Configuration of street canyon in Wind tunnel experiment, (b) Dimension of street canyon used in the experiment by the Laboratory of Building and Environment Aerodynamics [28].

According to the power law formulas (Equations 7 and 8) were reproduced in the experiment test [12,25,24],the boundary layer of database, concerning level measurements of pollutants concentrations and flow fields were obtained from street canyon are the velocity *u(y)*, profile exponent (*α*= 0.30) and turbulence intensity I_u, profile exponent (α_I= 0.36).

$$\frac{u(y)}{u(y_{ref})} = \left(\frac{y}{y_{ref}}\right)^{\alpha} \quad (8)$$

$$\frac{I_u(y)}{I_u(y_{ref})} = \left(\frac{y}{y_{ref}}\right)^{-\alpha_I} \quad (9)$$

The line sources exceed the width of building by approximately 10% on each side; for taking into account the traffic exhausts released on sidewise street intersections[25]. The tracer gas were carried out in this study was sulfur hexafluoride (SF_6) to simulate the vehicle emissionsin this context the emission rate Q was maintained at 10 g.s^{-1}, while C^+ signify the pollutant concentrations of the gas were measured at the canyon walls and normalized according to the Equation (10):

$$C^+ = \frac{CHu_H}{Q/l} \quad (10)$$

With C being measured concentration, u_H flow velocity at height H in the undisturbed approaching flow and Q/l tracer gas source strength per unit length; l is the length of the line source.

3.2 Simulation Setup and boundary condition

A method of passive control is selected, to get the estimations of effects range of these methods onto the air quality in symmetrical urban roads. For this purpose the through-passages in buildingwere introduced in ICEM-CFX code (Fig.4), however Fig.2, shows the computational domain in 3D, whereas, L and H are the length and height of the building, W the width of specifying the street canyon. The heights of upstream and downstream of the building and the width of the canyon floor W are equivalents to H (H=18m).

The length of the domain of street canyon is 30H; however the sub-domain of street canyon is located at 7 H from lateral extension of symmetry wall and 8H from the inlet plane. 19H, is the distance between the downstream building and outflow.

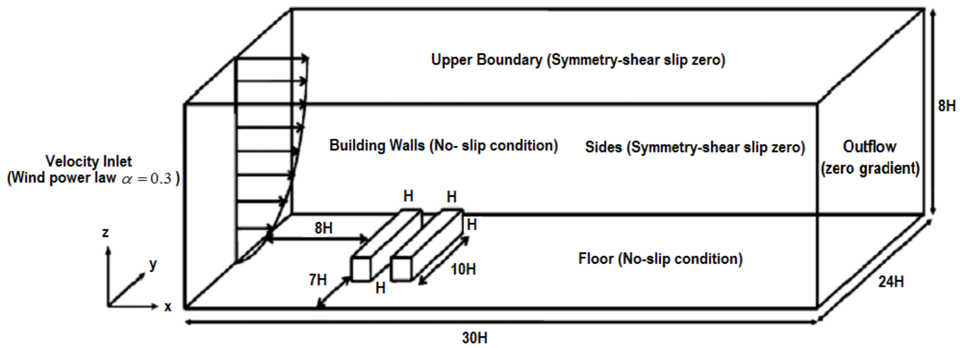


Figure 2:Computational domain and boundary conditions [25].

According to the medel of refernce [38] that mentioned in Figure 2, the three-dimensional model with through-passages in building with vehicular emissions represented as double line source across the road surface.However, Figure 3 shows an example of Canopy model with crossings under the building; while the dimension of each crossing is about 18 m in length and 4.5 m in the height.

The source of the vehicle emission can be taken as double line sources located in the middle of the road in the numerical modeling cases, however the source boundary conditions for emission of the passive scalar was set as "mass flow inlet", wherever a mass inlet flow rate was specified as the specifying the inlet mass velocity U_{in}, normal in the inlet area A:

$$\rho U_{in} A = \frac{dm}{dt} \quad (11)$$

Where ρ is the density and $\frac{dm}{dt}$ is the differential mass per time that introduced to the computational domain, while the passive scalar mass flow rate of 10 g.s^{-1} was set for each case studied.

Figure 3:Cross section view of real-life street canyons withpassageways under building (Photos from: Louvain-la-neuve, Belgium).

The power law formula takes into account, to show the vertical wind velocity profile of inflow under a neutral stability condition and according to the Eq (8), the inlet wind speed was assumed as a given equation:

$$u(y) = 4.7\left(\frac{y}{0.12}\right)^{0.3} \qquad (12)$$

Where $u(y_{ref})$=4.7 m. s^{-1}, is the velocity at y , a higher above the ground, whereas the equations concerning k and ε are givens as:

$$k = \frac{u_*^2}{\sqrt{C_\mu}}\left(1 - \frac{y}{\delta}\right) \qquad (13)$$

$$\varepsilon = \frac{u_*^3}{Ky}\left(1 - \frac{y}{\delta}\right) \qquad (14)$$

K = 0.4, represent Von-Karman coefficient, u_*=0.54 m.s^{-2}, is the friction velocity and the depth of the boundary layer is δ =0.5 m.

The No-slipping boundaries are set for the solid boundaries, knowing as wall function boundaries used on the closest grids to the wall. The calculations were performed using the second order accurate upwind schemes; the well-known *SIMPLEC* algorithm which discussed by [27]; used for pressure-velocity coupling while the convergences for scaled residuals criteria were set at 10^6.

The grid characteristics of the computational domain concerning each model are meshed, using hexahedral element; the mesh was carried out using different grid sizes. The minimum size of 0.05 m was selected for the model; a surface grid mesh was selected for the canyon floor with a uniform volumetric mesh, for the walls A and B was meshed with hexahedral element of 0.25 m on crossing under the building (Figure 4.b); the interest region was finer than other region to ensure a good resolution which was used for line source and for building.

3. Results and discussion

3.1 Validation of reference model results with measurements data from CODASC

Mean normalised concentration (C^+) profiles at the canyons leeward (Wall A) and windward (Wall B) wells of the refrence model was validated with wind tunnel measurements; the validation shows in Figure 5; therefore the results are very close to those obtained by the measurement of *CODASC*, this confirmed by the increasing of pollutant concentrations at the leeward, however, its decreased at the windward in the both, reference model and data from the experiment.

3.2. Comparaison between crossings under the building model and CODASC data

The numerical results obtained from the simulation concerning the mean concentration profiles on the leeward and windward walls for testing the model of crossings under building are presented in the Figure 6, whereas the simulations about crossing and several crossings under building has been evaluated by those taken from the measurement data without including the crossing model (without control passif), where different altitude are tested as the critical position $(Z/H = 0)$, and extreme altitude $Z/H = 1.26$ and 3.79.

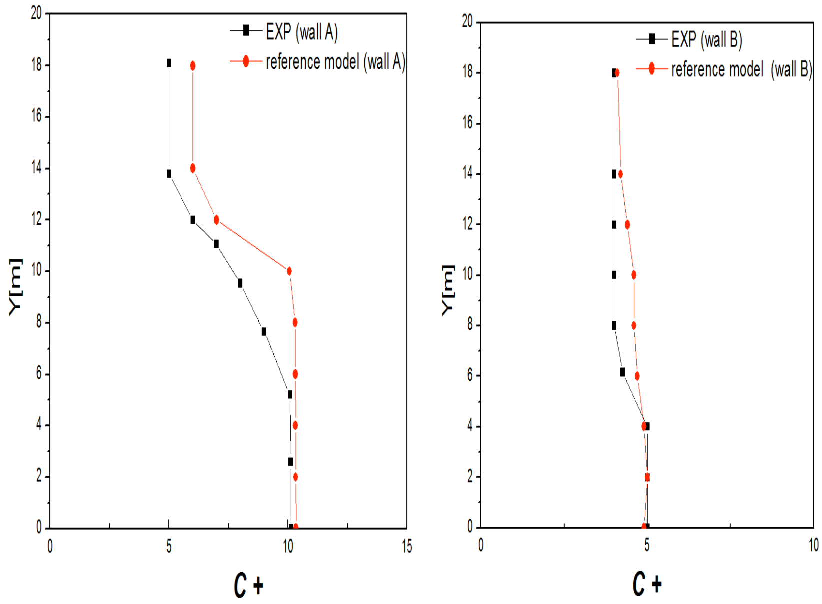


Figure 5: Comparaison of Mean concentration profiles on Wall A (leeward) and Wall B (windward) of reference model with those of data measurements.

From the Figure 6, it can be observed that the pollutant concentrations occurred at the both walls A and B has been decreased in the vicinity of the centerline $(Z/H = 0)$, the highest pollutant concentrations occur at pedestrian level in the central region of the leeward wall A; when the building is constructed with several crossings under building, however a smaller amount of pollutant concentrations has been marked at the position $Z/H = 1.26$ and $Z/H = 3.79$

From the mean concentration plot, it can be observed that the maximum concentration ($C^+ = 2.3$) established at the leeward side, concerning passageways under building models; whereas, at the height of $12m$ close to the roof of building,quantitatively, the mean concentrations are in the order of 5.6 about the sevral crossings under building model, the same as results are obtained at the extreme region $Z/H = 3.79$. The Concentrations decreases towards the ends of street are evidently at the both canyon walls; the results shows a better agreement to the model with several passageways under building than the *CODASC* data; it can be observed from the results mentioned in the Fig.6 that the concentrations peaks in the model with crossings under building are in the range of $C^+ = 7$ at the leeward side of the ends of the street; other than, the maximum mean concentrations results of the emitted gas from the experiment data are in the range of $C^+ = 9$ at the windward side.

The contour of normalized concentration obtaning by the simulation of several passageways under building models of wall A and B has been given in the Figure7. The results presented in last figure are confirmed by normalized vertical velocity V^+; however the distributions of vertical velocity at the middle plane of the canyon $(Y/H = 0)$ are obtainable in Fig 8.

From the Figure7, the flow fields in middle canyon is dominated by a vortex and not by corner eddies; however, on the outside of the canyon, a superposition of two vortexes structures occurs, forcing the laterally incoming air to move in a helix-type motion into the canyon center, it appears onto the wall A of the wind experiment. Other than the introduced the model of passageways under building provide a falling of pollutant concentrations onto the leeward wall, where the lateral air flow exchanged between the ends and the center of the street canyon, even as the model of passageways under building provoke a natural ventilation around the street canyon, therefore it to permit to cleared the pollutant away from the area buildings.

Figure 8 account the dynamic effects of pollution concentrations at different altitude. The primitive vortex situated at the right of the top corner of the canyon derived by the shear layer is moving in clockwise direction while the secondary vortex to be found at the right bottom corner of the canyon is progressed in anti-clockwise direction, dominated by the primitive vortex.

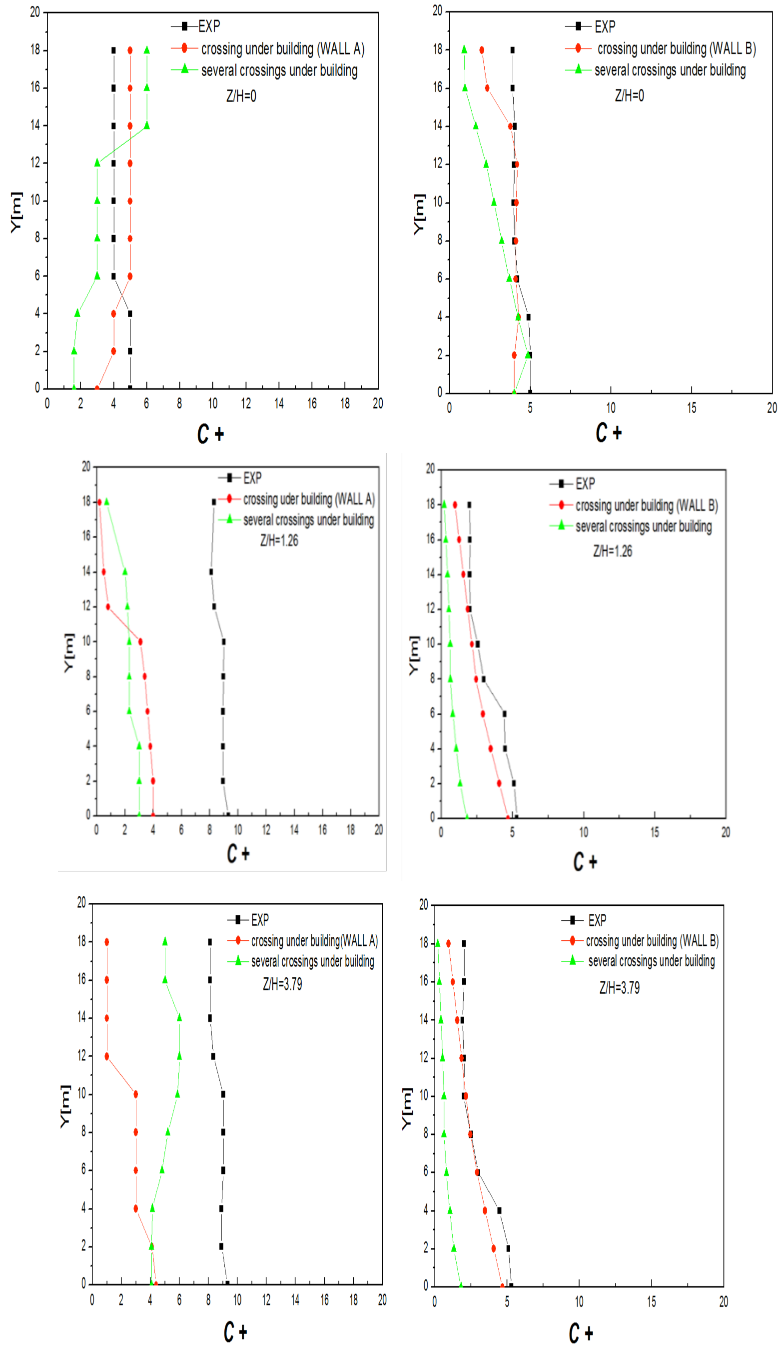


Figure 6:Mean concentration profiles on Wall A (leeward) and Wall B (windward) to compare the different numerical results with single crossing and several crossings under building with data experiment.

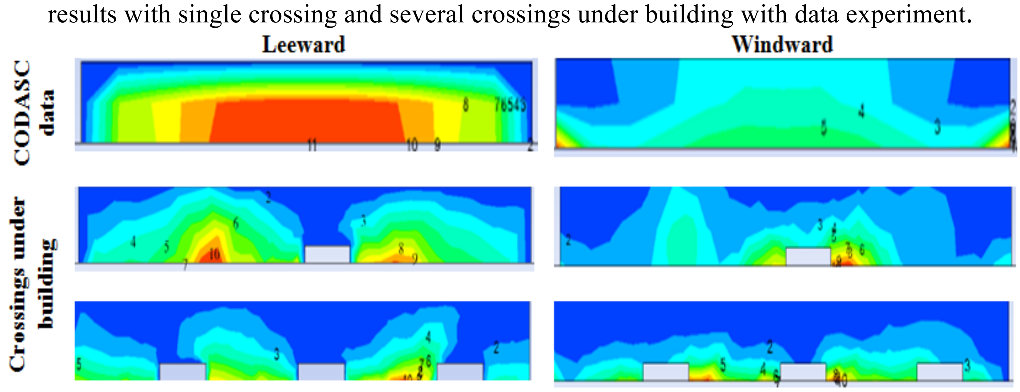


Figure 7: Contour of normalized concentration data on Wall A (leeward) and Wall B (windward) comparing the CODASC data to the different numerical results with crossing under building and to several passageways under building.

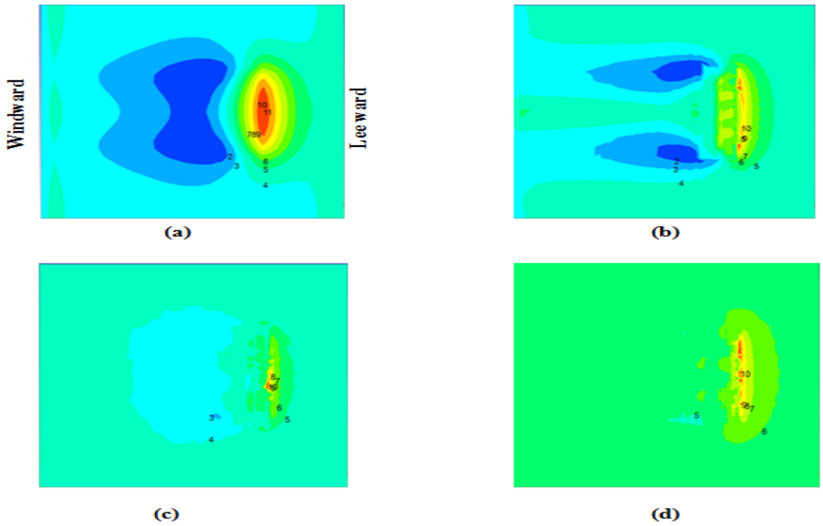


Figure 8:Normalized vertical Velocity V^+ at mid plane of the canyon at centerline $Y/H = 0$ (a) CODASC data, (b) model with LBW center, (c) model with crossing under building, (d) model with several crossings under building.

The numerical results shows that, another small tertiary vortex moving in anti-clockwise direction be in command of the primative and secandary vortexs, however the obtained results agree with those of measurments data, when the street canyon subjugated by a single vortex rotated in the same wind direction [6].

A great variations of vertical velocity distributions has been distinguished between a model with a single crossing and a model with more than crossings under the building, these varitions are due to number of passageways that made under building, in this manner, whenever the number of passageways will be huge, of course all depends the norms of constructions, whenever the distributions of air flow in different sides, will be agreeable for decrease the concentration of pollutant in the street canyon.

Conclusions

The interaction of atmospheric boundary layer with the implementations of crossings under building, particularly in the urban street canyon, is commonly investigated.

A three dimensional (3D) numerical ANSYS-CFX code, rendering it ideal for examining the aerodynamic effects of pollution concentrations, while the employed of Reynolds-averaged Navier–Stokes equations and the enhancement by k-ε turbulence model provides numerical predictions of qualitative agreement to experimental observations.

As a result, it is reasonable to assure that under dynamic wind field and traffic flow, the presence of crossings under the building alters the distribution of the airflow structure inside the street canyon, forming a major vortex affect the pollutant distributions inside and outside the street canyon.

the diminishing of pollutant concentration at the leewards and windward sides, caused by the intense movement of the flow appeared near the upwind region, associated to the vertical velocity when it increased over the roof canyon and it decreased down at the ground surface.

A good correlation was found between the model simulation concerning the normalized concentration where different altitudes are tested and measurement data from CODASC. Large amounts of pollutant concentration can be found onto the canyon walls from the experiment, however, the normalized traffic pollutant concentration has been decreasing at the leeward wall, once the crossings under building model has been practicing in the street canyon, from the results the peak of mean concentrations on the leeward and windward walls are jointly affected by wind speed, crossings under building band vehicle flow.

A great variations of vertical velocity distributions has been distinguished between a model with a single crossing and a model with more than crossing under the building, these variations concerning the wind speed are due to number of passageways where the major vortex expanded inside the street canyon, in this manner when the air is at the compressing stage, the presence of passageways under building increases the pollutant concentrations at the bottom center, but reduces the pollutant concentrations at the windward and leeward.

The model of passageways under building provoke natural ventilation around the street canyon, allows the change of wind speed which would induce a mass exchange between the internal and external air. Such exchange could improve the pollutant diffusion inside the street canyon, therefore the realization of the both models inside the urban street canyon permit to disperse the traffic emission pollutant away from the area buildings.

Consequently, the implementation of passive control as the passageways under building reduction the pollutant concentration, therefore it can improve air quality in the urban street canyon.

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