STUDY OF THE EFFECTS OF BUILDING DENSITY AND OVERALL SHAPE OF A CITY ON POLLUTANT DISPERSION BY COMBINATION OF WIND TUNNEL EXPERIMENTS AND CFD SIMULATIONS

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Abstract: Despite the improvement made in controlling local air pollution, urban areas are undergoing increasing environmental pressures and poor air quality is one of the major concerns. Recently, much attention has focused on the relationship between urban form and sustainability. There are indications that the density and the overall shape of cities can have implications on street level ventilation and the "compact city" is by many regarded as the most sustainable urban form. In this framework, this paper is devoted to the study of flow and pollutant dispersion from a ground level line source at pedestrian level within different urban configurations. The urban-like configurations vary from the scenario of an urban sprawl to the opposite scenario of a compact city. Wind tunnel experiments and CFD simulations are performed to evaluate pollutant concentrations in each of the idealized city structures.
The overall aim is that of assessing and clarifying the effect of city density on atmospheric flow patterns and pollutant dispersion.

Key words: *wind tunnel experiments, CFD simulations, planar area index, compact city, dispersion.*

1. INTRODUCTION

The problem of pollutant dispersion attracts a great deal of attention due to its practical interest in environmental science. The compact city, i.e. the densely built-up area where the residents live and work with service and transportation provided within a short distance, is considered the best model for the sustainable city (Jabareen, Y. R., 2006). In general, in a compact city buildings are lined-up continuously along the streets and a distinct street network exists both for transportation and for wind. Wind is forced to blow along those streets interacting with each other at street crossings and through open roof at the city top. To understand the consequences on wind and dispersion of such street conurbations and city shape combined wind tunnel and numerical studies are fundamental.

The study of flow and pollutant dispersion within arrays representative of urban areas has been reported in several publications. Recently, Skote, et al (2005) studied the flow balance in some highly idealized short compact cities with round shape and simple street network, finding that the oncoming wind has a choice, to enter the city entry or flow above and around the city. Hang, et al. (submitted) found that the interaction between the city shape of a compact city and the approaching wind has a great influence on the airflow within the street canyon. Air quality studies usually refer to dispersion from a point source. The dispersion from a point source within several building arrays has been studied by Mfula, et al. (2005), who have found that the spread of pollutants is dependent on the packing density.

This paper focuses on flow and pollutant dispersion from a ground level line source in cities of different building packing densities by means of CFD simulations with FLUENT (Fluent, 2005) and wind tunnel measurement. Several idealized cities have been created based on alternative urban planning strategies, varying from the scenario of an urban sprawl to the opposite scenario of a compact city. The k–ε turbulence model has been used in conjunction with transport equations for the mean concentration (advection–diffusion equation). The aim of this study is to contribute to the understanding of how urban planning affects air quality, by investigating the effect of building density and building arrangement on dispersion of pollutants released at street level from a line source. Firstly, to quantify the ventilation, the flow rate has been calculated for the different configurations. Then we have investigated the spread of pollutant at pedestrian level within the different scenarios and quantified the dispersion through the calculation of mean concentration. The combination of the experimental and numerical investigations provides a promising tool to study the flow and the pollutant patterns in different urban configurations and to obtain significant suggestions for urban planners.

2. METHODOLOGY

Description of wind tunnel experiments

Measurements have been carried out at the Department of Technology and Built Environment of the University of Gävle (Sweden). In a closed-circuit boundary layer wind tunnel with a working section of 11 m long, 3 m wide and 1.5 m high, concentration and flow field measurements at a model scale have been performed. A boundary layer flow with mean velocity *U(z)* profile exponent according to the power law (1) has been reproduced:

$$\frac{U(z)}{U_H} = \left(\frac{z}{H}\right)^{\alpha} \quad (1)$$

where U_H is the undisturbed wind velocity at the building height *H*, α=0.35. The velocity and turbulence intensity profile in far upstream flow has been measured in the wind tunnel with a hot-wire.

In the test section, 1:150 scaled models of several arrays constituted by cubical buildings have been mounted perpendicular to the approaching flow. We have kept the lot area constant and increased the packing density of the array by adding new buildings (referred as "standard configurations"), ranging from λ_p=0.0625 to λ_p=0.69, where λ_p is the planar area index (Grimmond, C and T. Oke, 1999). For some cases, we have also put together buildings in new configurations to change the overall building arrangement of the array (Fig. 1) and consequently the aspect ratio W/H (with W the width and H the height) of street canyons within the array. Integrated in the first street model, a line source has been used for simulating the release of traffic exhausts. The aim is that of investigating pollutant spread within the array. The focus is on pedestrian level where people live and to try to establish a good strategy to follow for new built areas to prevent poor air quality.

Nitorus oxide (N_2O) has been used as tracer gas and a gas analyser for concentration analysis. Mean concentrations of the gas have been measured at different positions downstream of the line source l at pedestrian level (~0.2H) and at the top of the buildings and normalized according to equation (2):

$$c^+ = \frac{c\, u_H\, H}{Q/l} \qquad (2)$$

with c the measured concentration and Q/l the tracer gas source strength per unit length. The length of the line source has been l/H=5.5. Velocity and turbulence intensity have also been measured in some points at pedestrian level (~0.2H).

Figure 1. Diagram showing increasing planar area index λ_p and changing building arrangements of the arrays investigated. The wind blows from left. The line source is positioned along the first upstream buildings line.

Description and setup of FLUENT flow and dispersion model

Simulations have been carried out by considering an approaching neutral boundary layer flow. The computational domain has been built using hexahedral elements (~1,000000). Several tests have been performed to verify grid size independence. The distance from the inlet plane to the first building of the street canyon is 5H, the distance from the top of the domain to the building roof is 10H and the distance from the outflow plane to the downstream building is 20H (Fig. 2). For simulating turbulence levels the standard k-ε model (Launder and Spalding, 1974) has been used. Based on wind tunnel experiments, the inlet wind speed has been assumed to follow a power law profile (1). Turbulent kinetic energy and dissipation rate profiles has been specified as follows:

$$k = \frac{u_*^2}{\sqrt{C_\mu}}\left(1-\frac{z}{\delta}\right) \quad \text{and} \quad \varepsilon = \frac{u_*^3}{\kappa z}\left(1-\frac{z}{\delta}\right) \qquad (3)$$

where δ is the boundary layer depth, $u*$ is the friction velocity (known from log-law curve fitting of the wind tunnel mean velocity profile), κ the von Kàrmàn constant (0.40) and C_μ = 0.09. The remaining boundary conditions have been those shown in Figure 2 (Di Sabatino, et al., 2007). Second order discretization schemes have been used to increase the accuracy and reduce numerical diffusion.

The advection diffusion (AD) module has been used. In turbulent flows, FLUENT computes the mass diffusion as follows

$$J = -\left(\rho D + \frac{\mu_t}{Sc_t}\right)\nabla Y \qquad (4)$$

where D is the molecular diffusion coefficient for the pollutant in the mixture, $\mu_t = \rho(C_\mu k^2/\varepsilon)$ is the turbulent viscosity, Y is the mass fraction of the pollutant, ρ is the mixture density. $Sc_t = \mu_t/(\rho D_t)$ is the turbulent Schmidt number, where D_t is the turbulent diffusivity. The source has been simulated by separating a volume in the geometry at the required discharge position and by setting a source term for this volume. The emission rate Q has been set at

$10gs^{-1}$. For medium to large packing densities, Di Sabatino, et al. (2007) have underlined that increasing diffusion in the CFD model to achieve better predictions is required as the ventilation through the street canyon top predicted by the model is too low. So we have used values of $Sc_t = 0.7$ for $\lambda_p = 0.0625$ and $Sc_t = 0.4$ for the remaining cases.

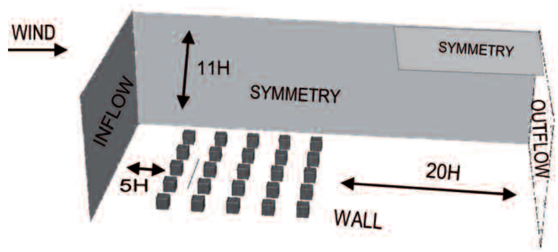

Figure 2. Schematic sketch of geometry and boundary conditions used in CFD simulations.

3. RESULTS AND DISCUSSION

Flow within arrays of different building area density and building arrangement

The ventilation of a city through its street canyons and intersections can be considered to be an unbalanced system because the flow rate through the streets downstream is lower than flow entering the array upstream. It can be argued that resistance offered to the flow implies that a given street-network, for given wind conditions, has a certain capacity (flow capacity) of air transport (Hang, et al., submitted). At the windward side more air than the flow capacity tries to penetrate into the city. This may originate a large vertical transport of air particular at the beginning of the windward side. This aspect is very important in urban ventilation as a mean for providing clean air into the city and for pollutant removal.

In this work, urban ventilation have been quantified by means of CFD simulations. In particular predictions an overall flow balance, that is the flow entering through the street openings and then leaving through the street exits and the open roof have been calculated. The flow rate, normalized by the reference flow rate far upstream, has been estimated for the different configurations investigated. The reference flow rate far upstream is:

$$q_{ref} = \int_A u_{ref} dA_0 \tag{5}$$

where u_{ref} is the horizontal velocity far upstream, A_0 is the area of street entry. The flow rate through the street opening is defined as:

$$q = \int_A \vec{V} \bullet \vec{n} dA \tag{6}$$

where $\vec{V}$ is the velocity vector, $\vec{n}$ is the normal direction of street openings. The normalized vertical flow rate through open roof is expressed similarly.

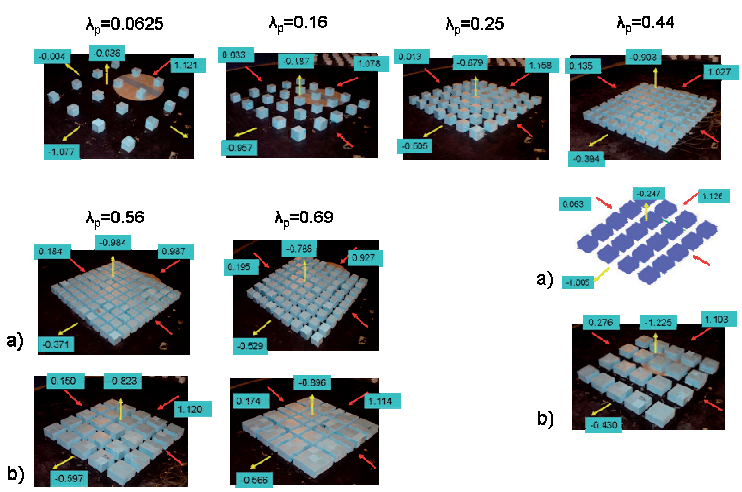

Figure 3. Normalized flow rates; positive value (red arrows): air entering, negative value (yellow arrows): air leaving.

Figure 3 shows ventilation flow rates obtained from CFD simulations for all configurations. Qualitatively, for all cases considered with the exception of the λ_p=0.0625 case, the overall flow field is the same; air is flowing in the city from side streets. For the lowest packing density the direction of the flow is opposite. The air is flowing out along the sides parallel with the wind. From Figure 3, we note that the ventilation through the sides of the array becomes more significant with increasing packing density and clean air from sides is transported into the array.

Changes in building arrangement of the city (shapes “a” and “b” for λ_p=0.44, shapes “b” for λ_p=0.56 and λ_p=0.69) are not crucial in modifying the ventilation, except for the λ_p=0.44 shape “a” case, where we note most of the air going through the array and leaving downstream.

Dispersion within arrays of different building area density and building arrangement

In this section we investigate dispersion results obtained from wind tunnel measurements and CFD simulations. Wind tunnel results are not available for λ_p=0.56 and λ_p=0.69 standard configurations. FLUENT concentration results for all scenarios investigated are in good agreement with experimental data.

Figure 4 shows dimensionless concentrations at pedestrian level (z~0.2H). As suggested from flow results discussed in the previous section, we note that pollutant spread decreases with increasing packing density. This is due to more air entering laterally into the array, which forces the air and pollutant to accumulate in the centre of the array and to blow along the wind direction. The “average plane” concentration at pedestrian level in the area $4<y/H<6.5$ and $-6.5<x/H<6.5$ (close to the edge of the array) decreases with increasing packing density from λ_p=0.11 to 0.56 (Tab. 1). As expected from flow patterns, the only exception is the λ_p=0.0625 case, where the pollutant is channelled in the wide streets along the wind direction and leave the array very rapidly. Results show that the λ_p=0.56 case might be considered as a limiting packing density beyond which the sensitivity of the spread to the packing density diminishes. In fact in the λ_p=0.69 case there was no further decrease of average concentration. Studies on packing densities between λ_p=0.44 and 0.56 would be very informative to determine exactly that limit.

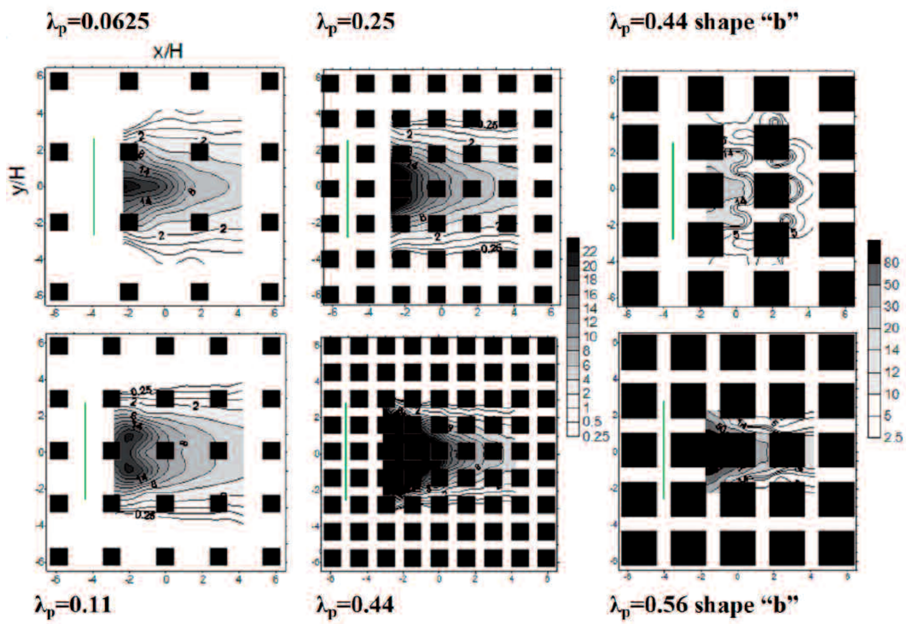

Figure 4. Dimensionless concentrations form wind tunnel experiments at pedestrian level (z~0.2H). The wind blows from left.

An important statement to underline is that this result is differing to investigations of Mfula, et al. (2005), who analysed experimentally the dispersion from a point source within packing densities ranging from λ_p=0.05 to 0.7. They have found that the spread of pollutant released from a point source increased with increasing density up to λ_p=0.44, then no further decrease has been found. At a practical level, we can state that a decreasing of exposure to pollutants released form a ground level line source can be reached by leaving the polluted inner city and relocating people to the edge of the city, characterized by cleaner air.

Table 1 also shows that, considering the entire pedestrian level area, the average concentration increases with increasing packing density. The flow entering the array through the sides makes pollutant to accumulate in the region near the source and in the inner part of the array. This effect becomes more important near the source with increasing packing density: as the aspect ratio of the street canyons forming the array diminishes, the recirculation regions lead to more stagnant conditions. This contributes to the increase of average concentrations.

The changing in building arrangement of the array has a disadvantageous effect at the sides of the arrays as less air is entering the array with respect to the standard configurations (Fig. 3), while it contributes to a decrease of average concentration at pedestrian level in the λ_p=0.44 and 0.56 cases.

Table 1. Average concentration at pedestrian level from CFD simulations

λ	Aspect ratio W/H	Average concentration at pedestrian level between $4<y/H<6.5$ and $-6.5<x/H<6.5$	Average concentration at pedestrian level
0.0625	3	0.10	3.9
0.11	2	0.15	4.8
0.25	1	0.13	6.8
0.44	0.5	0.04	16.2
0.44 "a"	0.75 (wind direction) 1.6 (perpendicular direction)	0.22	9.1
0.44 "b"	1.6 (wind direction) 0.75 (perpendicular direction)	0.12	7.2
0.56	0.33	0.005	26.9
0.56 "b"	0.75	0.009	15.5
0.69	0.2	0.005	30.9
0.69 "b"	0.5	0.008	34.3

4. SUMMARY AND CONCLUSIONS

In this paper we have investigated flow and the dispersion of pollutant released from a ground level line source in several building packing densities, ranging from the sparse to the compact city models by means of wind tunnel measurement and CFD simulations. The aim is to contribute to the understanding of the relation between city compactness and exposure to air pollution.

The effects of different packing densities on flow and pollutant dispersion from a ground level line source at pedestrian level have been studied and some conclusions are listed below:

- In general the air entering the array through the lateral sides and that leaving through the open roof increase with increasing packing density. The exception is the array with the lowest packing density (0.0625) where the air was flowing out of the array through the lateral sides.
- The average concentration at pedestrian level increases with increasing packing density. This is due to the fact that increasing packing density means diminishing aspect ratios, which in turn implies smaller velocities and subsequently less ventilation.
- The lateral spread of the pollutant released from a ground level line source positioned at the beginning of the array decreases with increasing packing density. Therefore lower concentrations of pollutants are found close to the sides of the array. With this type of source as the dominant source, locating people at the less-polluted edge of the city can be a strategy for lowering people's exposure to pollutants.

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