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On the impact of the urban environment on the potential of natural ventilation

M. Santamouris, E. Dascalaki, N. Klitsikas, K. Papakonstantinou, C. Georgakis

Group Building Environmental Studies, Physics Dept.,

University of Athens, University Campus 15784, Athens, Greece

ON THE IMPACT OF THE URBAN ENVIRONMENT ON THE POTENTIAL OF NATURAL VENTILATION

M. Santamouris, E. Dascalaki, N. Klitsikas, K. Papakonstantinou, C. Georgakis

Group Building Environmental Studies, Physics Dept., University of Athens, University Campus 15784, Athens, Greece

ABSTRACT

Knowledge and estimation of the wind speed and air flow characteristics, in a city, is of vital importance for passive cooling applications and especially in the design of naturally ventilated buildings. This study is referred to the analysis of the wind characteristics in urban canyons as a function of the free stream wind. The impact on the airflow rate calculation is discussed for an urban canyon. The goal of this study is to get a better insight of the impact of the urban environment on the ventilation effectiveness. For this reason a large number of data are collected including air temperature, wind speed and direction above and at various heights inside ten urban canyons in Athens. Two ventilation techniques are considered: single sided and cross ventilation and three different cases are studied regarding the incidence angle of the free stream wind to the canyon axis: (a) vertical incidence, (b) parallel incidence and (c) oblique wind. Finally a model is proposed for the simple calculation of the wind speed and air flow characteristics in urban canyons.

NOMENCLATURE

A_1	"lot" area occupied by each building, (m^2)
A_r	plan of roof area of the average building, (m^2)
H	mean height of the building in the canyon, (m)
h_b	representative building height, (m)
j	building density
L	canyon length, (m)
u	cross canyon air speed, (m/sec)

u_o wind speed above the canyon (at the point x=W/2 and z=H), (m/sec)

v along canyon wind component, (m/sec)

v_r wind speed at reference height, (m/sec)

W canyon width, (m)

w vertical canyon air speed, (m/sec)

z_o aerodynamic roughness length, (m)

z_r reference height, (m)

• incidence angle, (degrees)

1. INTRODUCTION

Urban canyons are characterised by three main parameters (Fig.1), namely: H, the mean height of the buildings in the canyon, W, the canyon width, and L the canyon length. Given these parameters, the geometrical descriptors are limited to three simple measures. These are the ratio H/W, the aspect ratio L/H and the building density j=Ar/A1 where Ar is the plan of roof area of the average building and A1 is the "lot" area or unit ground area occupied by each building.

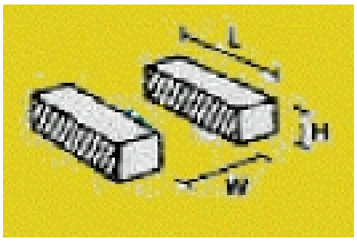

Figure 1. Height, Width and Length of a canyon

The flow field inside a canyon is a function of three main factors:

- The canyon geometry
- The wind characteristics (speed and direction) above the canyon
- The temperature distribution inside the canyon, especially in the cases of very low ambient wind speed

Knowledge of the air flow patterns in urban canyons is resulting either from numerical studies or from field experiments within real urban canyons or within scaled physical models in wind tunnels. Based on the incidence angle of the ambient wind on the canyon axis different flow patterns are observed.

1.1. Parallel Wind

Parallel ambient flow generates a mean wind along the canyon axis, [1,2], with possible uplift along the canyon walls as airflow is retarded by friction by the building walls and street surface, [3]. This is verified by Arnfield and Mills [4], who found that with no along canyon winds the mean vertical canyon velocity is close to zero. Measurements performed in a deep canyon, [5], have also shown an along flow of the same direction. The flow is characterised by an along speed almost parallel to the axis of the canyon and a downward incidence angle relative to the canyon floor between 0 and 30 degrees.

Regarding the relation between the free stream wind speed, U, and the along canyon velocity, v, Yamartino and Wiegand, [6], report that the along canyon wind component, v, in the canyon is directly proportional to the above roof along canyon component, through the constant of proportionality that is function of approach flow azimuth. The same authors found that v=Ucos• , at least to first order, where • is the incidence angle and U the horizontal wind speed out of the canyon. Nakamura and Oke, [2], report that for wind speeds up to 5 m/sec, the general relation between the two wind speeds appear to be linear: v=pU. For wind speeds parallel to the canyon axis and for a symmetric canyon with H/W=1, they found that p varies between 0.37 and 0.68 when v and U are measured at about 0.06 H and 1.2 H respectively. Low p values are obtained because of the deflection on the flow by a side canyon. Measurements performed in a deep canyon of H/W=2.5, [5], have not shown any clear threshold value where coupling is lost. Also, the correlation between the parallel to the canyon ambient speed and the along canyon wind speed inside the canyon was not clear, mainly because most of the data, corresponded to ambient wind speeds lower than 4 m/sec, where the relation between the two wind speeds is not clear. However, a statistical analysis of the data has shown that statistically there is a correlation between them.

1.2. Perpendicular Wind

When the predominant direction of the airflow is approximately normal (say $\pm 30^o$), to the long axis of the street canyon, three type of air flow regimes are observed as a function of the building (L/H) geometry, [7,8], and canyon (H/W) geometry.

When the buildings are well apart, (H/W>0.05), their flow fields do not interact. At closer spacing, (Fig.2a), the wakes are distributed and the flow regime is known as "Isolated Roughness Flow". When the height and spacing of the array combine to disturb the bolster and cavity eddies, the regime changes to one referred to as "Wake Interference Flow", (Fig.2b). This is characterised by secondary flows in the canyon space where the downward flow of the cavity eddy is reinforced by deflection down the windward face of the next building downstream. At even greater H/W and density, a stable circulatory vortex is established in the canyon because of the transfer of momentum across a shear layer of roof height, and transition to a "skimming" flow regime occurs where the bulk of the flow does not enter the canyon (Fig.2c). Because high H/W ratios are very common in cities, "Skimming Air Flow" regime has attracted considerable attention.

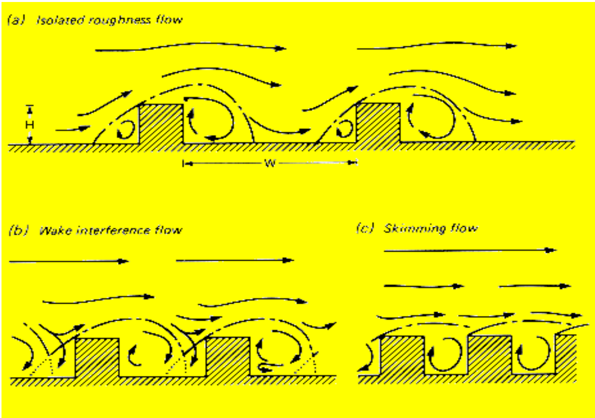

Figure 2. The flow regime associated with air flow over building arrays of increasing H/W

Transition between these three regimes occurs at critical combinations of H/W and L/W. Oke, [7], has proposed threshold lines separating the different flow regimes as a function of the buildings (L/H) and the canyon (H/W) geometry. The proposed threshold lines are given in Figure 3.

Numerous wind tunnel and field experiments have been performed and some of the main conclusions are:

The air flow in the canyon can been seen as a secondary circulation feature driven by the above roof imposed flow, [2]. If the wind speed out of the canyon is below some threshold value the coupling between the upper and secondary flow is lost, [2] and the relation between wind speeds above the roof and within the canyon is characterised by a considerable scatter.

Regarding, the relation between the wind speed out of the canyon and the corresponding vortex velocity, De Paul and Shah, report that for wind speeds higher than the threshold value, they have found that the speed of the vortex increases with the speed of the cross canyon flow.

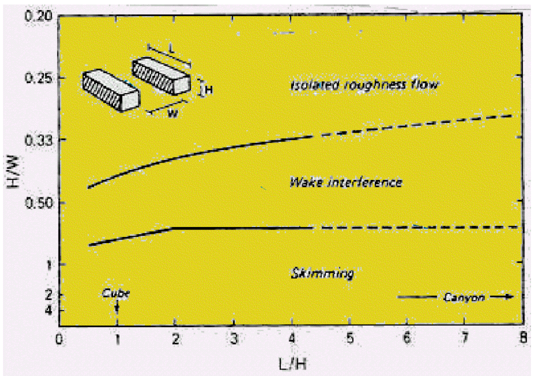

Figure 3. Threshold lines dividing flow into three regimes as functions of the building (L/H) and canyon (H/W) geometry

Regarding the direction of the vortex, it has to be expected that as the vortex is driven by a downward transfer of momentum across the roof – level shear zone, a flow normal to the canyon axis has to create a vortex where the direction of the air flow near the ground should be directly opposite to the wind direction outside the canyon, (Fig.4a). In deep canyons, wind tunnel research, [9], has found that two vortices are developed, an upper one driven by ambient airflow and a lower one driven in the opposite direction by the circulation above it, (Fig.4b).

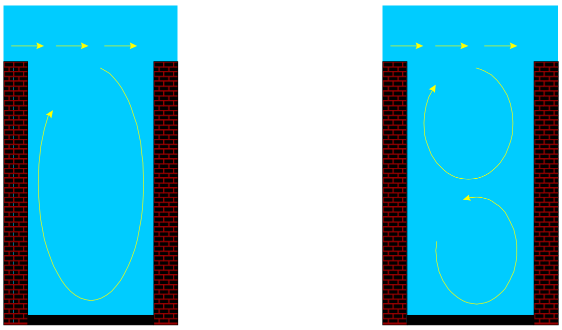

Figure 4. (a) Single vortex regime (b) Two vortices regime in deep canyons

As it concerns the air velocity inside the canyon, Nakamura and Oke, [2], report that for wind speeds up to 5 m/sec, the general relation between the two wind speeds appears to be linear, $u_{in}=pu_{out}$. For wind speeds normal to the canyon axis, and for a symmetric canyon with H/W=1, they found that p varies between 0.66 and 0.75 under condition that winds in and out are measured at about 0.06 H and 1.2 H respectively, where H is the height of the buildings.

As it concerns the length of the vertical displacement of the vortex in a canyon, very few studies have been performed. For normal wind speeds, Hoydysh and Dabberdt, [10], report that for a symmetric canyon the average vertical displacement of the vortex was of the same magnitude as the canyon width, while in a step up canyon the vortex was smaller and the mean vertical displacement was equal to 0.61 of the canyon width.

The end effects or the finite length canyon effects play an important role on the air flow distribution in canyons. Yamartino and Wiegand, [6], report that when $L/W \approx 20$, finite length canyon effects began to dominate over the vortex. Hoydysh and Dabbert, [10], report that intermittent vortices are shed on the building corners. These vortices are responsible for the mechanism of advection from the building corners to mid – block creating a convergence zone in the mid block region of the canyon, resulting in larger concentrations there, both at street level and aloft, (Fig. 5). Similar phenomena are reported by Santamouris et al, [5].

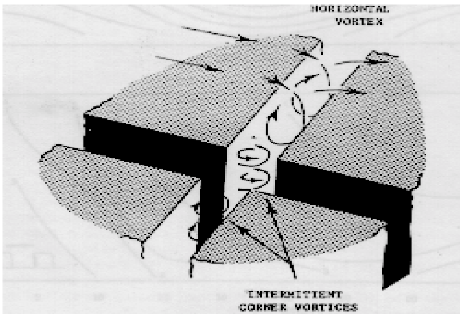

Figure 5. Intermittent vortices at the building corner

1.3. Oblique Wind

When the flow above the roof is at some angle of attack to the canyon axis, a spiral vortex is induced along the length of the canyon, a cork-screw type of action, [2]. Existing research on this topic is considerably smaller compared to the scientific information for perpendicular and along the canyon flows. Results are available through limited field experiments and mainly through wind tunnel and numerical calculations. Wind tunnel research carried out by Dabberdt et al, [11], Wedding et al, [1], have also shown that a helical flow pattern develops in the canyon.

2. MODELING THE AIR FLOW CHARACTERISTICS IN URBAN CANYONS

The objective of this work is to present an analysis of the wind characteristics in urban canyons as a function of the free stream wind. The impact on the airflow rate calculation is discussed for an urban canyon. The goal of this study is to get a better insight of the impact of the urban environment on the ventilation effectiveness. The assessment of the strategies will be done through simulations, using the AIOLOS software.

In the framework of the POLIS European research project, a vast measurement campaign was carried out in ten urban canyons in Athens, Greece. During this campaign a large number of data were collected including air temperature, wind speed and direction above and at various heights inside the canyons. These data will be used as inputs to the simulations for the assessment of effectiveness of different ventilation techniques in the urban environment.

The case of IPPOKRATOUS canyon is presented in the following paragraphs. The canyon has an NS orientation. Its height is H=21m and its width is W=12m. Wind speed measurements were taken at heights 8m (inside the canyon) and 21 m (outside the canyon), for a period of ten consecutive days in the summer 1998. Temperature was simultaneously recorded at the same heights. The time step of the measurements was 1minute.Two ventilation techniques were considered: single sided and cross ventilation. Three different cases were studied regarding the incidence angle of the free stream wind to the canyon axis:

- Vertical incidence (incidence angle:90^o or $180^o \pm 30^o$)
- Parallel incidence (incidence angle: 0^o or $270^o \pm 30^o$)
- Oblique wind (all other cases)

2.1. Flow Along the Canyon

2.1.1. Wind speed above the canyon < 4 m/sec

Type of Flow: Chaotic: There is no coupling between the undistributed and the wind speed inside the canyon. The maximum expected wind speed should not exceed 0.5 m/sec. This value (0.5 m/sec), may be used in ventilation models especially when the ambient speed exceeds 3 m/sec and the H/W ratio is low, (<1). For lower speeds a value close to 0.2 – 0.3 m/sec may be used. There is no predominant wind direction inside the canyon. Only when the ambient wind speed exceeds 3 m/sec, it may be considered that the flow is almost parallel to the axis of the canyon with a very small uplift component parallel to the walls of the canyon.

2.1.2. Wind speed above the canyon > 4 m/sec

Type of Flow: Mean wind along the canyon axis with possible uplift along the canyon walls.

Prediction of the along canyon wind speed v (z) [12]:

$$v(z) = U_o e^{z/Z_o} \quad (1)$$

where:

$$Z_o = h_b D^* / z_o \quad (2)$$

and

$$D^* = 0.1 h_b \quad (3)$$

or

$$v(z) = v_r \log[(z + z_o)/z_o]/\log[(z_r + z_o)/z_o] \quad (4)$$

<u>For Canyons with L/W< 20</u>

Type of Flow: Intermittent vortices are shed on the building corners. These vortices are responsible for the mechanism of advection from the building corners to mid block creating a convergence zone in the mid block region of the canyon.

Prediction of the wind speed: Use mean wind speed close to 0.4 m/sec. Prevailing direction: Parallel to the axis of the axis with a downward direction.

2.1.3. Prediction of the air flow rate

<u>For canyon with H/W<2 and L/W>20 IPPOKRATOUS</u>

- Single Sided Ventilation

When the free stream wind speed exceeds 4 m/sec the predicted airflow rates inside and outside the canyon are linearly correlated, as illustrated in Figure 6.

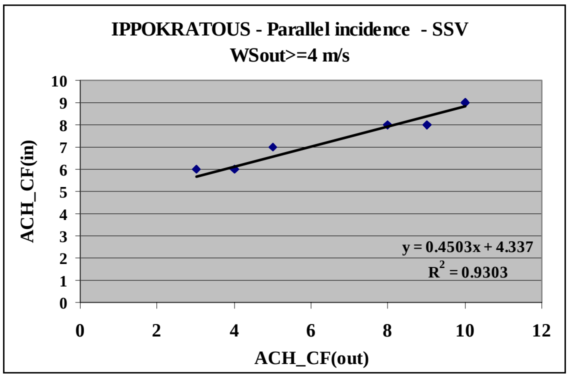

Figure 6. Parallel incidence – Single Sided Ventilation ($WS_{out} \geq 4m/s$)

- Cross Ventilation

When the free stream wind speed exceeds 4 m/sec the predicted airflow rates inside and outside the canyon are linearly correlated, as illustrated in Figure7.

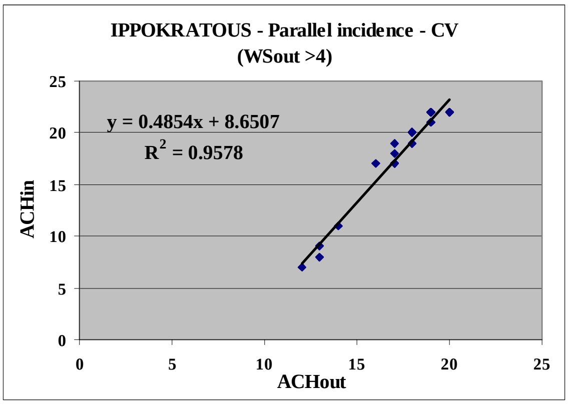

Figure 7. Parallel incidence – Cross Ventilation ($WS_{out} \geq 4m/s$)

2.2. Perpendicular Flow

2.2.1. Wind speed above the canyon < 4 m/sec

<u>For H/W > 0.7</u>

Type of Flow: Chaotic: There is no coupling between the undistributed and the wind speed inside the canyon. Thermal as well as mechanical influences play an important role in the canyon circulation. The maximum expected wind speed should not exceed 0.4 m/sec. This value (0.4 m/sec), may be used in ventilation models especially when the ambient speed exceeds 3 m/sec. For lower speeds a value close to 0.2 m/sec may be used. There is no predominant wind direction inside the canyon.

2.2.2. Wind speed above the canyon > 4 m/sec

<u>For Canyons with H/W< 2 and L/W>20</u>

Type of Flow: A stable circulatory vortex is established in the canyon.

Prediction of the cross canyon u and vertical, w, air speeds [6]:

$$u = u_o(1-\beta)^{-1}[\gamma(1+k\gamma) - \beta(1-k\gamma)/\gamma]\sin(kx) \quad (5)$$

and

$$w = -u_o(1-\beta)^{-1}ky[\gamma - \beta/\gamma]\cos(kx) \quad (6)$$

where:

$$k = \pi / W \quad (7)$$

$$\beta = \exp(-2kH) \quad (8)$$

$$\gamma = \exp(ky) \quad (9)$$

$$y = z - H \quad (10)$$

For Canyons with H/W>2 and L/W>20

Type of Flow: Two vortices are developed, an upper one driven by ambient airflow and a lower one driven in the opposite direction by the circulation above.

Prediction of the cross canyon u and vertical, w, air speeds:
For the lower part of the canyon use a mean wind speed close to 0.3 m/sec.
For the upper parts use the following expressions:

$$u = u_o(1-\beta)^{-1}[\gamma(1+k\gamma) - \beta(1-k\gamma)/\gamma]\sin(kx) \quad (11)$$

and

$$w = -u_o(1-\beta)^{-1}ky[\gamma - \beta/\gamma]\cos(kx) \quad (12)$$

For Canyons with L/W<20

Type of Flow: Intermittent vortices are shed on the building corners. These vortices are responsible for the mechanism of advection from the building corners to mid block creating a convergence zone in the mid block region of the canyon.

Prediction of the wind speed: Use mean wind speed close to 0.4 m/sec. Prevailing direction: Parallel to the axis of the axis with a downward direction.

2.2.2. Prediction of the air flow rate

IPPOKRATOUS

- Single Sided Ventilation

As illustrated in Figure 8, when the temperature difference of the air inside and out of the canyon is in the range from 2 to 3 C (the air temperature in the canyon is higher that the free stream air temperature), the difference between the predicted airflow rates appears to be a linear function of the wind speed outside the canyon. For wind speed lower than 2 m/sec, the buoyancy-related phenomena dominate, resulting to an under-prediction of the airflow rate when free stream data are used. For ambient wind speed exceeding 2 m/sec the wind effect supersedes the buoyancy, resulting to an over-prediction of the airflow rate when free stream data are used.

As illustrated in Figure 9, when the free stream air temperature exceeds the canyon temperature, the free stream wind velocity is above 4 m/sec and exceeds the canyon wind speed by at least 2 m/sec, the difference between the predicted airflow rates appears to be a linear function of the wind speed outside the canyon. In this case, the wind effect supersedes the buoyancy, resulting to an over-prediction of the airflow rate when free steam data are used.

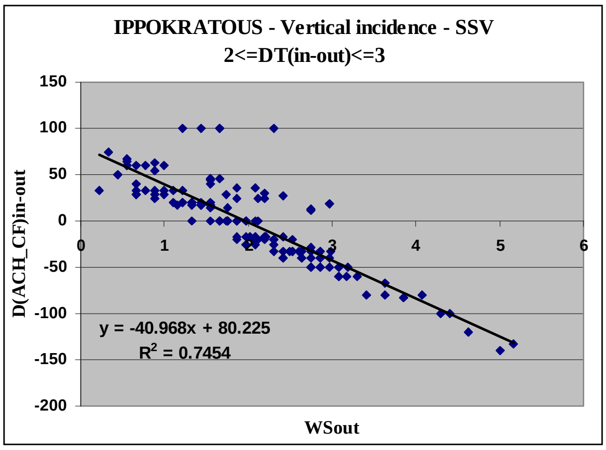

Figure 8. Vertical incidence – Single Sided Ventilation (2C≤DT(in-out)≤3C)

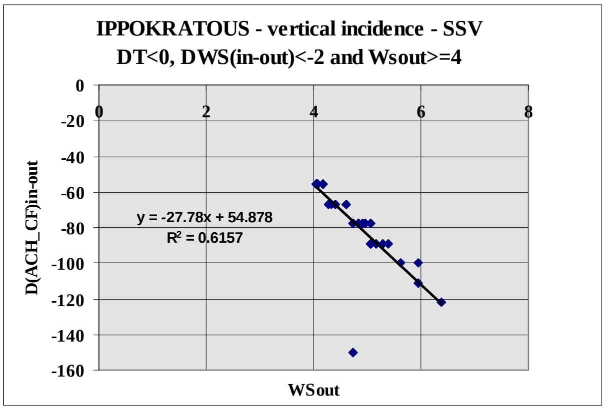

Figure 9. Vertical Incidence – SSV (DT(in-out)<0, DWS(in-out)<-2m/s, $WS_{out}\geq 4m/s$)

2.3. Oblique Flow

2.3.1. Wind speed above the canyon < 4 m/sec

Similar to the perpendicular flow.

2.3.2. Wind speed above the canyon > 4 m/sec

For Canyons with L/W>20

Type of Flow: A spiral vortex is induced along the length of the canyon, a cork-screw type of action.

Prediction of the cross canyon u and vertical, w, air speeds:

$$u = u_o(1-\beta)^{-1}[\gamma(1+k\gamma)-\beta(1-k\gamma)/\gamma]\sin(kx) \tag{13}$$

and

$$w = -u_o (1-\beta)^{-1} ky[\gamma - \beta / \gamma]\cos(kx) \qquad (14)$$

<u>For Canyons with L/W<20</u>

Type of Flow: Intermittent vortices are shed on the building corners. These vortices are responsible for the mechanism of advection from the building corners to mid block creating a convergence zone in the mid block region of the canyon.

Prediction of the wind speed: Use mean wind speed close to 0.4 m/sec. Prevailing direction: Parallel to the axis of the axis with a downward direction.

3. CONCLUSIONS

In the preceding paragraphs the characteristics of air flow – wind speed and air flow rate - inside urban canyons are defined through a proposed model. To get a better insight of the impact of the urban environment on the ventilation effectiveness a large number of data are collected including air temperature, wind speed and direction above and at various heights inside ten urban canyons in Athens. Two ventilation techniques are considered: single sided and cross ventilation and different cases are studied regarding the incidence angle of the free stream wind to the canyon axis.

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