

Canyon effects: Calculation of wind speed in an urban street canyon with the aid of a semi-empirical model based on experimental data

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ABSTRACT

The microclimate and dispersion in urban street canyons has become a subject of intense scientific research in recent years since complex flow patterns evolve leading many times to bad comfort conditions for the pedestrians and the inhabitants. Within that frame, the main aim of this study is the creation of a semi-empirical algorithm for accurate wind speed computation inside street canyons.

A big experimental campaign took place in Athens in the summer of 2001 where measurements were taken in five different urban street canyons in the framework of the Urbvent European Research project. The experimental data set includes wind speed and direction measurements within and above the canyon, on the rooftop of the buildings, as well as wind speed measurements near the building walls at several heights at 30 sec intervals. The experiment lasted three days at each canyon.

The experimental data were grouped into different categories based on the wind speed and incidence angle on the canyon axis. Following that a semi-empirical model was created for each wind direction and wind speed category based on already existing algorithms.

Comparison between measured and computed wind speed values, derived from the semi-empirical model, resulted into agreement.

1. EXPERIMENTAL PROCEDURE FOR WIND SPEED RECORDING INSIDE AND AT THE TOP OF THE CANYONS

The experimental campaigns, which took place in each of the five canyons (Table 1), included

the following measurements:

- Type A) The meteorological station of the University of Athens was placed in the centre of each urban canyon for three days, for twelve hours per day. The mobile meteorological station was installed on a vehicle equipped with a telescopic PT8 Combined Collar Mast Assembly with extended height of 15.3 meters. On the telescopic mast anemometers were attached at four different heights (3.5 – 7.5 – 11.5 – 15.5 meters) in order to record and storage every 30 seconds wind speed and direction in the middle of the canyon.

These types of measurements have been performed with the following instruments:

- a) Wind speed in the middle of the canyon was measured with A100K Pulse output anemometers,
- b) Wind direction in the middle of the canyon was measured with W200 Porton Windwane ($\pm 300^{\circ}$ range) anemometers.

- Type B) At the same time wind speed on three orthogonal axes was measured near the facades of the canyon, as well as wind speed and direction outside the canyon, with the following instruments:

- c) Wind speed measurements near canyon facades.

A three-axis anemometer was used to measure the three components of wind speed inside the canyon adjacent to the facades. The anemometer was mounted on the exterior façade of a building facing into the canyon at a distance of 3 m from the wall.

- d) Wind speed and direction measurements at

Table 1: Description of the experimental sites, definition of the measurement points, the experimental period of every canyon.

Street Canyon		Ermou	Miltiadou	Voukourestiou	Kaniggos	Dervenion
Orientation from the North	Degrees	92	45	45	12	327
Canyon width	Meters	10	6	10	8	7
Canyon length	Meters	200	50	100	70	200
Buildings height	Meters	20	12	30	28	23
Canyon aspect ratio	H/W	2	2	3	3.5	3.3
Wind speed and direction inside the canyon	Meters from ground	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5	3.5-7.5-11.5-15.5
Height of the two	Meters					
Three-axis anemometer	from ground	7.5-10.5	8.0-8.0	5.0-8.0	5.0-10.0	20.0-10

the top of the canyon.

A cup anemometer was placed at a distance of 6 m above the top of the canyon to measure the wind speed and direction out of the canyon.

2. DESCRIPTION OF THE ALGORITHMS USED IN THE DEVELOPED SEMI-EMPIRICAL MODEL

The air flow in the canyon has to be seen as a secondary circulation feature driven by the above roof imposed flow (Nakamura and Oke, 1988). If the wind speed out of the canyon is below some threshold value the coupling between the upper and secondary flow is lost, (Nakamura and Oke, 1988), and the relation between wind speeds above the roof and within the roof is characterized by a considerable scatter. End effects or finite-length canyon effects, play an important role in the airflow distribution inside canyons. For canyons with $L/W \approx 20$ (Yamamoto and Wiegand, 1986) was reported that, finite-length canyon effects begin to dominate over the vortex. Similar phenomena reported by Santamouris et al., (1999). Thus, prediction of the airflow in high aspect ratio canyons may concentrate on cases where end effect does not dominate the flow.

The experimental data collected from all the street canyons were used for deriving the new semi-empirical model based on the theoretical approaches presented above. The model uses as inputs the orientation of the canyon, the geometrical characteristics of the canyon which are

width, height and length of the canyon without intersections. A file with airflow data (concluding wind speed and direction data) outside the canyon is the input file of the model. The user defines the coordinates (x, y) of a point and the model predicts a wind speed value at that coordinates.

The flow chart of the model is presented in Figure 1.

- **The first criterion**, is whether the aspect ratio of the canyon (H/W) is greater than 0.7, if it is a canyon situation is formed otherwise, the space between the buildings is not a street canyon.
- **The second criterion**, is if the ratio of the building length between main intersections and the width between buildings (L/W) is greater than 20. If the ratio L/W is less than 20 then, the end effects dominate inside the canyon and extended experimental analysis indicated that a wind speed value of 0.5 m/s could be considered as mean (Results of the European Projects URBVENT Part 1, 2004). If it is greater than 20, it means that there is a wind circulation in the canyon and the calculations of the model continue.
- **The third criterion** of the model regards wind speed values outside the canyon.

When the wind speed outside the canyon is less than 4 m/s extended analysis of the experimental data resulted in Empirical models A and B. When the direction of the undisturbed wind is along the main axis of the canyon, the values from Table 2 can be used

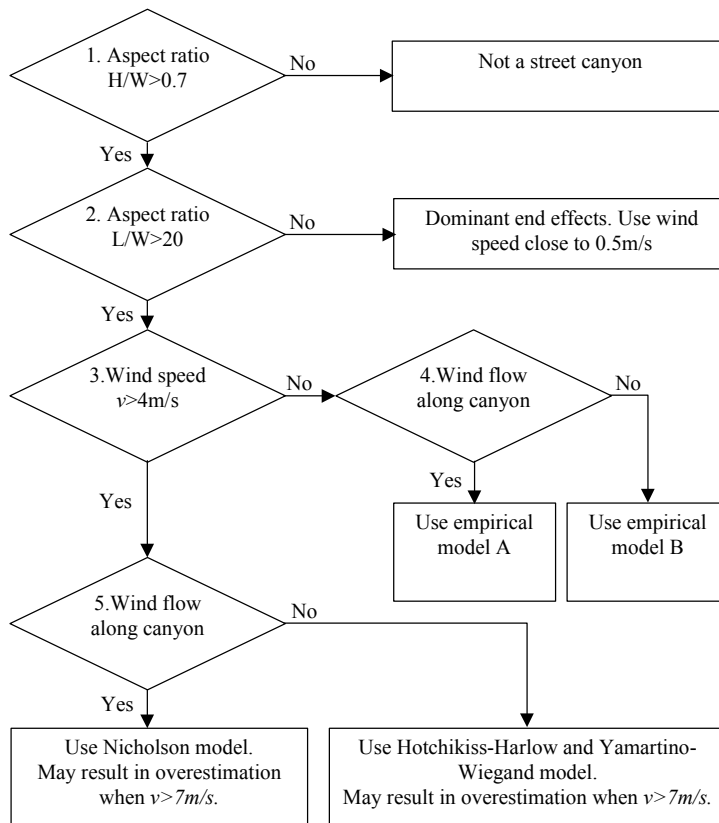


Figure 1: Flow-chart of the algorithm for estimating wind speed inside street canyons.

Table 2: Values for along canyon wind speed inside the canyon (Empirical model A).

Wind speed outside canyon (U)	Typical values in the centre of the canyon	
	Lowest part	Highest part
U=0	0 m/s	0 m/s
0 < U < 1	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster
1 ≤ U < 2	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster
2 ≤ U < 3	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster
3 ≤ U < 4	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster

(Empirical model A). When the direction of the undisturbed wind is perpendicular or oblique to the canyon, the values from Table 3 (Empirical model B) can be used.

- **The forth criterion** of the model regards winds' direction outside canyon.

When the wind speed was higher than 4 m/sec and the incidence angle of the wind was parallel to the main axis of the canyon, The logarithmic law (Nicholson, 1975) used to describe variation of mean wind u with height z in the free surface layer above roof

Table 3: Values for perpendicular/oblique canyon wind speed inside the canyon (Empirical model B).

Wind speed outside the canyon (U)	Wind speed inside the canyon		
	Near the windward facade of the canyon		Near the leeward facade
	Lowest part	Highest part	
U=0	0 m/s	0 m/s	0 m/s
0<U<1	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade
1<=U<2	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade
2<=U<3	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade
3<=U<4	0 m/s	75% of the corresponding maximum wind speed value recorded at the top of the canyon, for this cluster	50% of the calculated wind speed value close the windward façade

tops:

$$\bar{u} = \frac{u^*}{k} \cdot \ln\left(\frac{z + p_d + z_0}{z_0}\right) \quad (1)$$

where u^* was the frictional velocity, k was the Karman's constant (0.38), p_d was the zero-plane displacement, z_0 was the aerodynamic roughness length.

In the obstructed sublayer $0 \leq z \leq h_b$ the following exponential law describes the variation of wind with height below roof tops:

$$u_p = U_0 \cdot \exp\left(\frac{y}{z_2}\right) \quad (2)$$

and:

$$z_2 = 0.1 \cdot h_b^2 / z_0 \quad (3)$$

Where U_0 was a constant reference speed, z_2 was the roughness length for the obstructed sub-layer and y was the height from ground in which wind speed could be calculated.

When wind speed outside canyon was higher than 4 m/s and the wind's incidence angle was perpendicular/oblique to the main axis of the canyon the following algorithms were used:

Hotchkiss and Harlow, (1973), proposed a model to calculate values for the cross and vertical wind speed component (u, v). The model considers incompressible flow, absence of sources or sinks of vorticity within the canyon, and appropriate boundary conditions for the simple two-dimensional rectangular notch of

depth H and width W . They propose the following algorithms:

$$u = \frac{A}{k} \cdot [e^{ky}(1+ky) - \beta \cdot e^{-ky}(1-ky)] \cdot \sin(kx) \quad (4)$$

and

$$v = -A \cdot y \cdot (e^{ky} - \beta \cdot e^{-ky}) \cos(kx) \quad (5)$$

where

$$k = \pi / W \quad (6)$$

$$\beta = \exp(-2kH) \quad (7)$$

$$A = ku_0 / (1 - \beta) \quad (8)$$

$$y = z - H \quad (9)$$

and u_0 is the wind speed above the canyon and at the point $x=W/2, z=H$.

This model was tested by Yamartino and Wiegard, (1986), with very high success. The same authors have proposed the following expression to calculate the along canyon component, $w(z)$:

$$w(z) = w_r \cdot \log[(z + z_0) / z_0] / \log[(z_r + z_0) / z_0] \quad (10)$$

Where w_r was the wind speed values measured by the cup anemometer outside canyon at z_r height level and z_0 was the surface rough-

ness.

The horizontal wind speed inside the canyon was:

$$v_h = (u^2 + v^2)^{0.5} \quad (11)$$

and the total wind speed inside canyon at any point (x, y) was:

$$v_t = (v_h^2 + w^2)^{0.5} \quad (12)$$

The agreement between the experimental measurements of wind speed inside the canyon and the ones computed from the theoretical model was tested with the t-test statistical method (Georgakis et al., 2004). The comparison of the two values led to the conclusion that the model's prediction could be characterized as satisfactory.

3. GRAPHIC PRESENTATION OF THE AIR-FLOW DATA

The experimental results of the study are given in the form of box-plots. A box-plot is a graphic representation of data distribution that shows the locations of percentiles. The line in the middle of the box is the median, or the 50th percentile of the sample. The lower and upper lines of the box are the 25th and the 75th percentiles, representing the lower and upper quartile, respectively. The length of the box represents the interquartile range. The lower and upper "whiskers" show the range of data, if there are no outliers. Data are considered outliers if they are located 1.5 times the interquartile range away from the top or bottom of the box.

The bold line depicts the average calculated value.

4. DISCUSSION

4.1 Parallel flow

The box plot result analysis, presented in Figures 2-5, indicated a very good agreement between experimental and semi-empirical model values, for the case when the ambient flow was less than 4 m/sec and parallel to the main axis of the canyons. The computed average values for the four height levels of 3.5-7.5-11.5-15.5 meters and for the different heights near to each canyons facades, are very close to the average

measured values for the respectively heights. This analysis indicated a very good agreement between experimental and model values.

The box plot analysis, presented in Figures 6-9 is for the case when the ambient flow was greater than 4 m/sec and parallel to the main axis of the canyons. For Miltiadou and Kaniggos canyons their aspect ratio L/W were less than 20 (Table 1). One of the first criteria in the semi-empirical model, was that only if the aspect ratio L/W was greater than 20, the calculations of the model could take place, otherwise end effects dominate and the mean wind speed inside canyon at any height level is close to 0.5 m/sec. Thus for both of these canyons the calculated average wind speed was 0.5 m/sec. For the other two canyons Voukourestiou and Dervenion a very good agreement between experimental and semi-empirical model values is depict. For Ermou canyon lack of experimental wind speed values, due to technical problems during the experimental procedure, obstruct a representative box plot analysis.

4.2 Perpendicular/Oblique flow

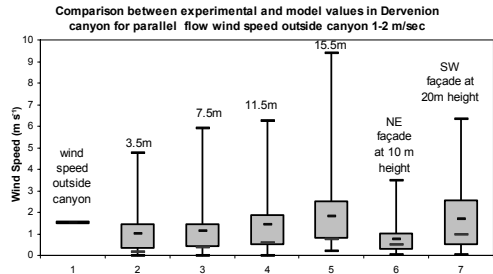
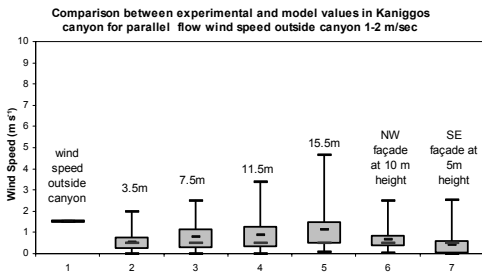
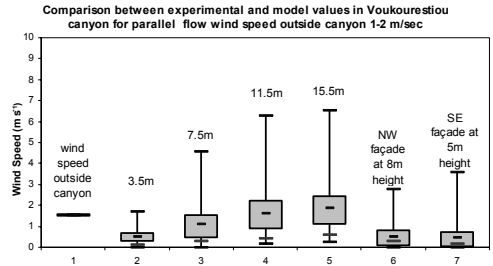
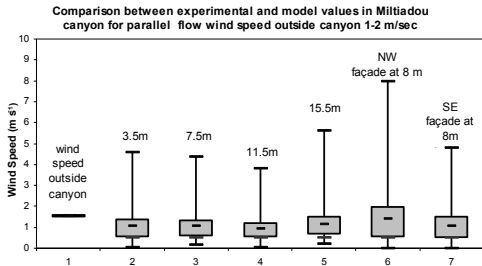
The algorithms used for the perpendicular flow were the same with the ones used for the oblique flow, even if ambient wind speed was greater or less than 4 m/sec.

The box plot analysis, presented in Figures 10-13, indicated a very good agreement between experimental and semi-empirical model values, for the case when the ambient flow was less than 4 m/sec and perpendicular to the main axis of the canyons.

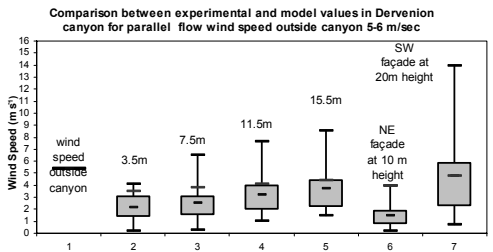
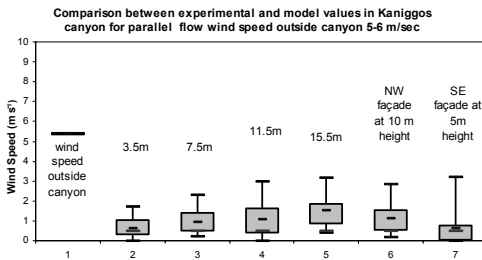
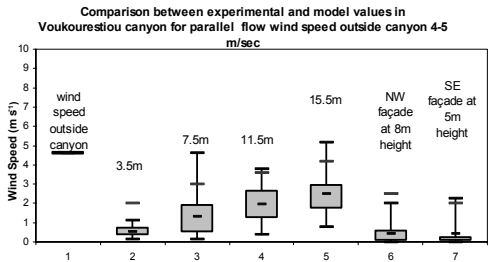
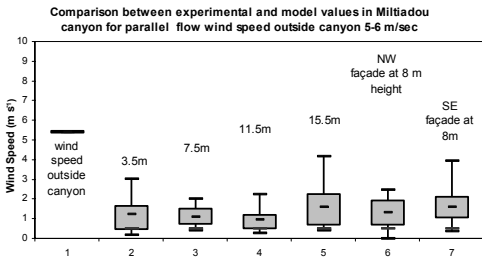
The box plot analysis, presented in Figures 14-17 is for the case when the ambient flow was greater than 4 m/sec and oblique to the main axis of the canyons. The agreement between experimental and computed mean values was satisfactory. For Ermou canyon lack of experimental wind speed values, due to technical problems during the experimental procedure, obstruct a representative box plot analysis.

5. CONCLUSIONS

- For types of flow average wind speed values measured inside canyons indicated stratification proportionally to wind speed values measured outside canyon.

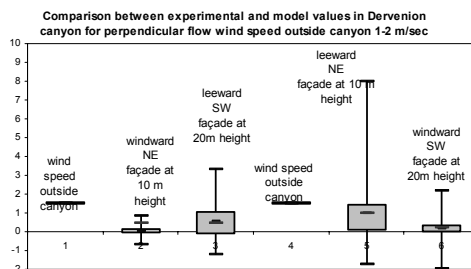
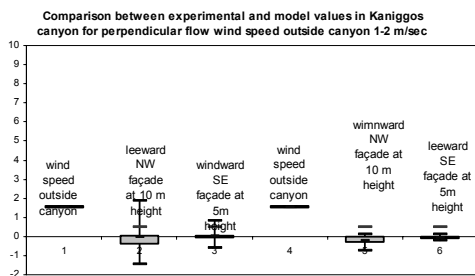
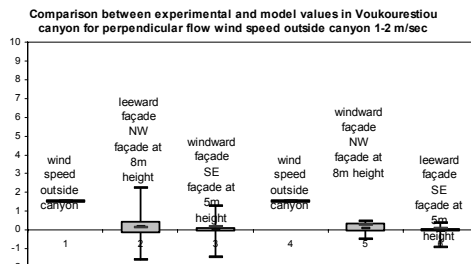
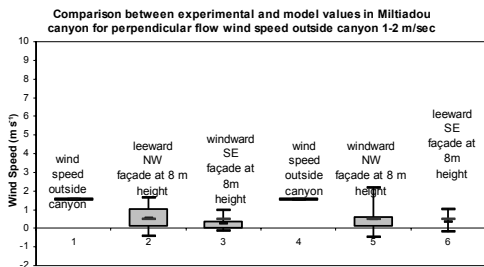


Figures 2-5: Experimental and computed vales of wind speed in the centre of the canyons and near the canyons facades, for incidence angle parallel to the main axis of the canyon, and wind speed outside canyon less than 4 m/sec.

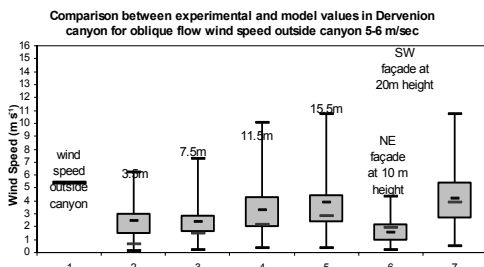
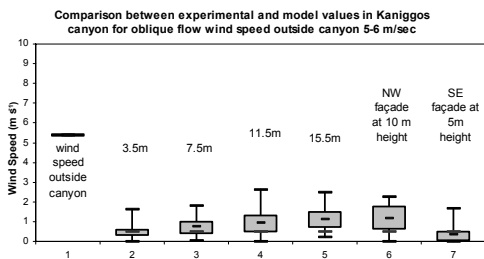
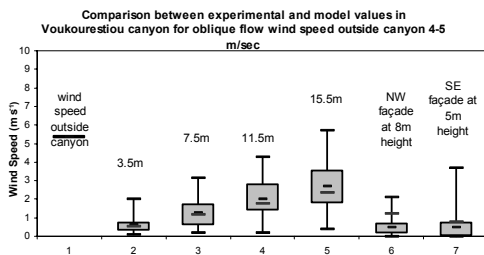
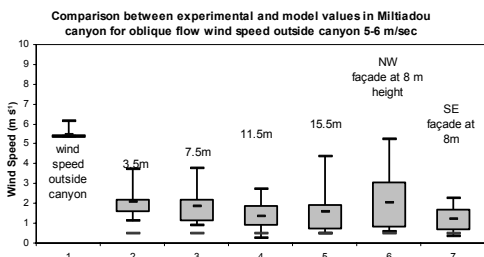


Figures 6-9: Experimental and computed vales of wind speed in the centre of the canyons and near the canyons facades, for incidence angle parallel to the main axis of the canyon, and wind speed outside canyon greater than 4 m/sec.

- Computed wind speed values inside canyons indicated stratification proportionally to wind speed values measured outside canyon.
- When the aspect ratio L/W was greater than 20, the calculations of the model could take place, otherwise end effects dominate and the mean wind speed inside canyon at any height indicated stratification proportionally to wind speed values measured outside canyon. This was proved in Miltiadou and Kaniggos canyons.
- Model tends to overestimate inside canyon velocities compared to experimental ones for the cases of parallel flow and ambient flow



Figures 10-13: Experimental and computed wind speed values near the canyons facades for perpendicular incidence angle to the main axis of the canyon, and wind speed outside canyon less than 4 m/sec



Figures 14-17: Experimental and computed wind speed values in the center of the canyons and near the canyons facades for oblique incidence angle to the main axis of the canyon, and wind speed outside canyon greater than 4 m/sec.

greater than 4 m/sec. For ambient wind less than 4 m/sec and wind incidence angle parallel to the main axis of the canyon the model tends to underestimate wind speed velocities inside canyons.

- In perpendicular/oblique flow the model

compares well to experimental wind speed values, independently the measured ambient wind speed values.

- In deep the canyons such as Dervenion and Voukourestiou, there was a very good agreement between experimental and computed

values for perpendicular/oblique type of flow, and for ambient wind speed greater than 4 m/sec. This model is a good practical tool for deep canyon cases.

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