Data driven and fuzzy techniques for wind speed calculation inside urban canyons

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ABSTRACT

Wind speed characteristics in the centre of a city differ than the ones in its suburban. Street canyon effects result in weak airflows in the centre of highly dense cities because of the combination of inertia and gravitational forces. A huge experimental campaign took place in the centre of Athens in order to create a database of the main parameters that affect wind speed characteristics. Previous studies aimed to calculate wind speed in urban canyons by using deterministic techniques. The agreement between experimental and calculated valued present a low accuracy, for most cases of ambient incidence wind flow, because of the incomplete description of the physical phenomena that determine wind flow inside street canyons. This paper present alternative data driven and fuzzy techniques able to estimate the wind speed in urban canyons. Four different relationships were estimated between inertia and gravitational forces and that were the criterion of clustering the input-output data. For each cluster using statistical analysis, the more probable wind speed inside the canyon, was calculated. Three different data driven prediction models were developed in order to calculate wind speed inside street canyons. These were a 3D graphical interpolation method, a decision tree method as well as a linear regression model. Using the results of the graphical interpolation model, a fuzzy estimation model has been developed as well. All methods have been compared against the experimental data. The values for wind speed derived from the fuzzy model followed closely the experimental data and predicted with sufficient accuracy the most probable wind speed in urban street canyons.

1. INTRODUCTION

Natural ventilation systems when appropriately used may contribute to fight problems of indoor air quality. They might decrease the concentration of indoor pollutants, improve thermal comfort conditions in indoor spaces and decrease the energy consumption or the need for air conditioning. Knowledge of the wind speed inside urban canyons is a necessary input to estimate the natural ventilation potential of urban buildings as well as thermal comfort in open areas. Numerical studies, field experiments and scaled physical models in wind tunnels are used in order to esteem wind speed values inside urban canyons (Vardoulakis et al., 2003). Various mathematical algorithms have been proposed for calculating the wind speed inside such canyons (Nicholson, 1975; Hotchkiss and Harlow, 1973; Yamartino and Wiegand, 1986). Recently after thorough research work (Georgakis and Santamouris, 2007) algorithms have been proposed in order to calculate the wind speed in canyon, when there is a coupling between the undisturbed wind flow and the flow inside the canyon. Such a situation occurs when wind speed outside the urban canyon is greater than the threshold limit of 4m/sec (Vardoulakis et al., 2003). For such a situation a secondary circulation feature driven by the above roof-imposed flow is remarked inside the urban canyon (Nakamura and Oke, 1988). Thermal and mechanical phenomena may play a very important role, in this secondary flow inside the canyon, and determine the final wind speed. Important temperature differences between the canyon walls and the air is the source of upward or downward flows that may be much more important than the flow induced by the wind above the canyon.

The local Grashof number, defined as, may describe buoyancy phenomena:

$$Gr = \frac{g\beta(T_{surf} - T_{air})H^3}{\nu^2} \quad (1)$$

Where $\beta=1/T_{air}$, Tair and T_{surf} are the mean air and surface temperature of the point (H(x),w) inside the canyon. H and w are the distances of point x, from ground level and from the left wall of the canyon, respectively. Inertia forces may be considered by using the Reynolds number,

$$\mathrm{Re} = \frac{Vh}{\nu} \quad (2)$$

Where V is the undisturbed wind speed measured outside the canyon, and v is the viscosity. For example if the flow inside the canyon caused exclusively by inertial forces Reynolds number is close to 3.400 (Hoydysh et al., 1974).

2. EXPERIMENTAL PROCEDURE

Field experiments were performed during the summers of 2001 and 2002 in the frame of the European Projects Urbvent and Reshyvent. Wind characteristics were measured in seven pedestrian street canyons in Athens. Due to the extended experimental procedure air and surface temperature were measured in different points inside each street canyon. The aspect ratio of the studied canyons varied around 1.7 and 3.3. Experimental procedure took place in each canyon for three days and for twelve or twenty-four hours per day. Detailed prescription of the followed experimental campaigns and the characteristics of each canyon can be found in (Santamouris et al, 2007).

3. DEVELOPMENT OF DATA DRIVEN MODELS

Highly uncertain boundary conditions and combination of complex phenomena, that were not of a deterministic nature, characterized wind flow inside canyons after the application of deterministic techniques for low ambient wind speeds (Ghiaus et al., 2006; Assimakopoulos et al., 2006; Jospisil et al., 2006). Deterministic models that do not consider thermal effects may not be appropriate to estimate the wind speed in a canyon especially when thermal phenomena are important. For the case where flow outside a canyon is very weak four simplified data driven techniques have been developed to estimate the wind speed near the canyon facades (Santamouris, et al., 2007). The proposed data driven techniques have been developed using the collected experimental data, from the seven different field experiments, and thus are valid inside the boundaries of the specific experiments. The necessity to develop more simplified data driven models was to predict the more probable wind speed at a point (H(x),w) inside a canyon. The impact of the main geometrical and climatic parameters inside urban canyons was studied by the use of principle components analysis. The target of this analysis was the best correlation between all independent parameters that characterize wind flow inside urban canyons, so its prediction to be possible. The main independent parameters was found to be the following: a) the geometrical characteristics (H(x),w) of the point where wind speed wanted to be estimate, b) the difference ΔT between surface and air temperature in the specific point and c) the ambient wind speed outside the canyon Vout. The data driven techniques that were developed based on the experimental data of this study were: a) Regression tree Viewer, B) Linear Correlation method and c) 3D Spline Interpolation Technique.

3.1 Linear correlation method

A simple correlation model of the form has been obtained:

$$V(x,H) = -0.537 + 0.957 H / w - 0.012 * \Delta T + 0.0039 * Vout \quad (3)$$

Where V(H(x),w) is the more probable wind speed inside the canyon at the specific point inside the canyon. All parameters of the algorithm have been already defined.

3.2 Decision tree method

Using decision tree methodologies, (Breiman te al., 1993), a flow chart algorithm has been developed to calculate the more probable wind speed inside the canyon at the point (H(x),w) inside the canyon. The independent variables of the decision tree were a) the ambient wind flow V_{out} outside the canyon, b) the height H(x) of the point, inside the canyon, were wind speed wanted to be calculated, c) the distance w of the same point from the left wall of the urban canyon, d) the difference ΔT between surface and air temperature at the specific point.

3.3 Spline interpolation technique

The developed reduced space has been used as input to a 3D spline interpolation technique (Sandwell, 1987.). A graphical representation of the three dimensional space V_{out}, H/w and ΔT, has been obtained, as mentioned above. The developed graphical methods close to the windward and the leeward facades, for perpendicular flow, are given in Figures 3 and 4 respectively.

4. DEVELOPMENTS AND DESCRIPTION OF FUZZY CLUSTERING

Experimental data from all canyons have been processed and a very important data set has been created. The prediction of the more possible wind speed was classified according to the direction of the ambient wind speed as: a) Parallel to the canyon axis, b) Perpendicular to the canyon axis, and c) Oblique to the canyon axis

For each of the above cases four data groups may be defined, (f.e. for the perpendicular flow): a) Wind angle 90 +/- 15 degrees (windward façade), b) Wind angle 180 +/- 15 degrees (windward façade), c) Wind angle 90 +/- 15 degrees (leeward façade), d) Wind angle 180 +/- 15 degrees (leeward façade)

For all specific position (H(x),w) inside the canyon where wind and temperature characteristics were measured, the local Gr as well as the Re number were calculated. Then four different clusters with specific (Gr, Re) were obtained. Clustering is a mathematical method to classify numerical data based on the identification of subgroups on a data set, called 'clusters', where all objects are described by similar characteristics. Fuzzy clustering is a quite modern, 'intelligent' technique considering that each individual member in the data set belongs to a cluster to some degree that is defined by a membership function, (Bezdek, 1981; Chiu, 1994). As shown in Figure 1 the four different clusters characterized by:

- ✓ Cluster I: were Reynolds number is very small and Grashof number is negative (figure 1 with blue triangles),
- ✓ Cluster II: were Reynolds number is small and Grashof number is close to zero (figure 1 with green circles),
- ✓ Cluster III: were Reynolds number is small and

Grashof number is positive (figure 1 with red crosswise),
✓ Cluster IV: were Reynolds number holds great positive values (figure 1 with yellow crosses),

When clusters of different flow regimes were defined, the probability density function of the air speed at the position (H(x),w), corresponding to each cluster, was calculated. A representative distribution for the whole set of data is given in Figure 2. It is pointed out that only data corresponding to ambient wind speeds lower than 4 m/sec have been considered. Thus for each cluster the more probable wind speed inside and outside the canyon was calculated. In parallel the corresponding temperature difference between the air and the canyon surfaces at the point where the wind speed is estimated, have been found. Thus, a reduced data space including the three above parameters, (more probable wind speed inside and outside the canyon and the corresponding temperature difference), has been created.

5. RESULTS FROM THE DATA DRIVEN METHODS FOR PERPENDICULAR FLOW

After the calculation of the more probable wind speed inside a canyon, based in three different techniques, a majority of conclusions derived. The results described in the following refer to the case of windward and leeward perpendicular to the canyon axis ambient wind flow. As depicted in Figure 3 for the windward facades, it has been found that three zones of the more probable wind speed occurred. For the lower parts of the canyon, (H/w<1.5) the more probable wind speed was less than 1 m/sec. For medium heights, 1.5<H/w< 2, the corresponding mean value was around 1.5 m/sec, while for the higher parts of the canyon, the wind speed increases considerably and may reach values close to 2.5 m/sec.

For the leeward facades, as depicted in Figure 4, much lower wind speeds have been found. For temperatures differences close to 0^0C there more probable wind speed was close to zero. For temperature differences up to 5^0C, the average more probable wind speed close to the leeward facades was around 0.5 m/sec. For higher temperatures differences, the corresponding value increased up to 1 m/sec.

The theoretical data derived from the above mentioned methodologies have been compared against the experimental data. The R^2 correlation coefficients was considered by the use the following algorithm:

$$R^2_{\Psi,Z,X,...} = 1 - \frac{\sum_{i=1}^{N} (\Psi_i - \Psi_{i,\varepsilon\kappa})^2}{\sum_{i=1}^{N} (\Psi_i - \overline{\Psi})^2} \quad (4)$$

The R^2 was equal to 0.96 for the 3D graphical interpolation model, 0.84 for the tree decision method and 0.74 for the linear correlation method. It is obvious that the 3D graphical interpolation model predicts the more probable wind speed inside the canyon with sufficient accuracy. The tree decision method although it is of sufficient accuracy for low speeds, it fails to predict high wind speeds inside the canyon. Finally, the linear correlation method, as expected, presents a limited accuracy. Similar results have been obtained for all the other cases of airflow.

6. FUZZY LOGIC FOR WIND SPEED CALCULATION INSIDE URBAN CANYONS

Prediction of the more probable wind speed, inside urban canyons, carried out also by the use of fuzzy logic. The application of fuzzy logic systems is an alternative method to predict wind speed inside urban canyons, by creating data driven algorithms exclusively based to experimental data **(**Jang, 1991; **Chiu, 1994; Toolbox Matlab V6p5)**. By the use of fuzzy logic sixteen different rules were developed and trained in order to predict the more probable wind speed inside an urban canyon. Neural networks were used for the development and the training of the sixteen fuzzy logic rules The input data were couples of experimental values of the temperature differences ΔT inside the canyon at the point (H(x),w) and of the ambient wind speed V_{out}. The data set was also concluded, for each of the above-mentioned couple, the corresponding wind speed value inside the canyon, at the same point.

7. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL WIND SPEED DATA

For the goodness of fit between the experimental measurements of wind speed inside a canyon and the ones raised from the application of the four different theoretical models, the t-test of the differences of mean values was applied taking into account the variation of the samples (Snedecor and Cochran, 1973). For the goodness of the fit the experimental values recorded inside a canyon were compared with the ones derived from the different data driven techniques, when wind incidence angle was perpendicular to the canyon's axis and very weak ambient flow. The differences of the mean values were not statistical important in all cases so the null hypothesis was valid. The theoretical wind speed values were smaller of the critical ones in the significant level of 0.05 for all methods. The Regression Tree Viewer technique, the Linear Method, the 3D Spline Interpolation and the Fuzzy Logic method found to be able to estimate with significant accuracy wind speed inside a canyon. These values are presented in Tables 1. The proposed data driven techniques have been developed using the collected experimental data and thus are valid inside the boundaries of the specific experiments.

8. CONCLUSIONS

New calculation methods have been applied in order to predict wind speed inside urban canyons, for the case of very weak ambient flow. In particular three data driven techniques have been developed to estimate the more probable wind speed near the canyon facades. The data driven methods were 3D Spline Interpolation, Tree Decision Method and Linear Correlation. The 3D Spline Interpolation Method was more sufficient in order to predict wind speed inside urban canyon. The developed methodologies were strictly valid inside the limits of the experimental data. Sixteen fuzzy rules were developed and trained in order to predict wind flow inside an urban canyon. The theoretical wind speed values followed closely the experimental data.

ACKNOWLEDGEMENTS

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Table 1: The t-test values for perpendicular wind flow outside a canyon less than 4 m/sec, respectively. Bold values correspond to the cases where the differences of mean values were not significant.

PERPENDICULAR WIND FLOW ABOVE A CANYON LESS THAN 4 m/sec				
DATA DRIVEN METHOD N	REGRESSION TREE VIEWER	LINEAR CORRELATION METHOD	3D SPLINE INTERPOLATION TECHNIQUE	FUZZY LOGIC
T-TEST VALUE	**0.67**	**0.02**	**0.02**	**0.65**

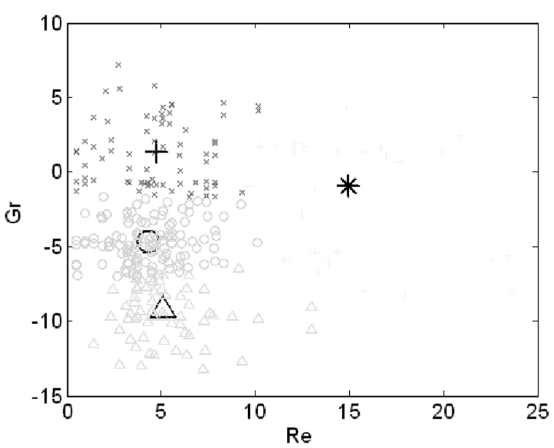

Figure 1 Distribution of the data as a function of their Reynold and Grashof numbers in four different clusters

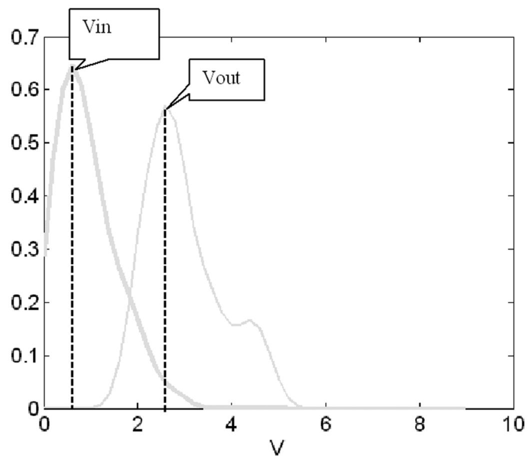

Figure 2 Probability density function of the wind speed inside and outside the canyon for a representative cluster

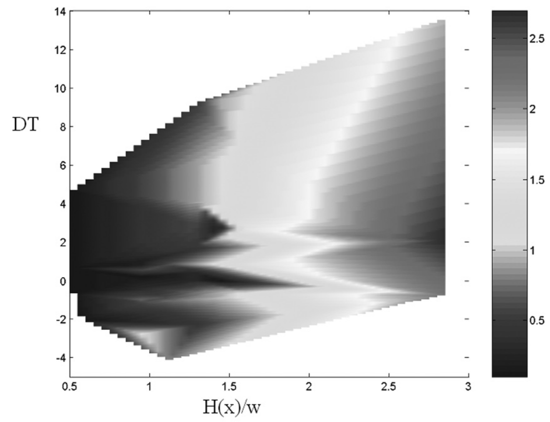

Figure 3 Developed graphical data driven model to predict the more probable wind speed close to the windward canyon facades

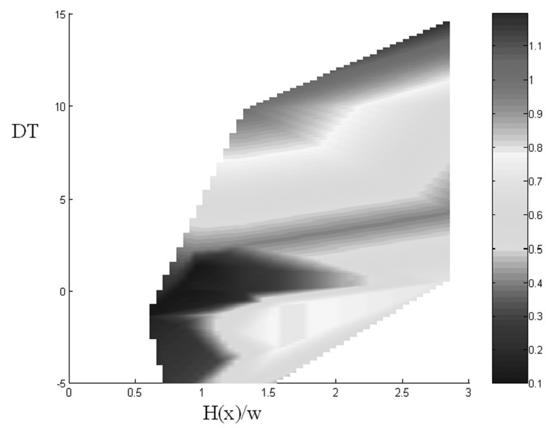

Figure 4 Developed graphical data driven model to predict the more probable wind speed close to the leeward canyon facades

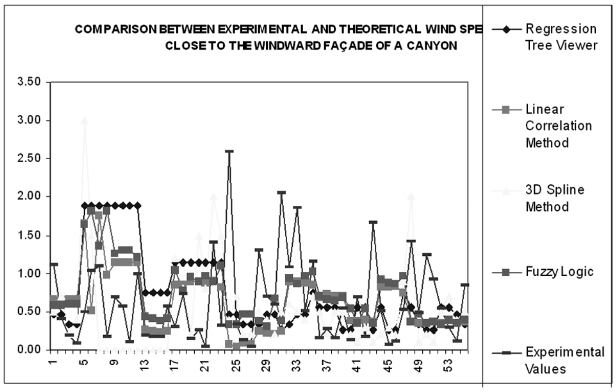

Figure 5 Comparison of the predicted against the experimental values of the more probable wind speed inside the windward façade of a canyon

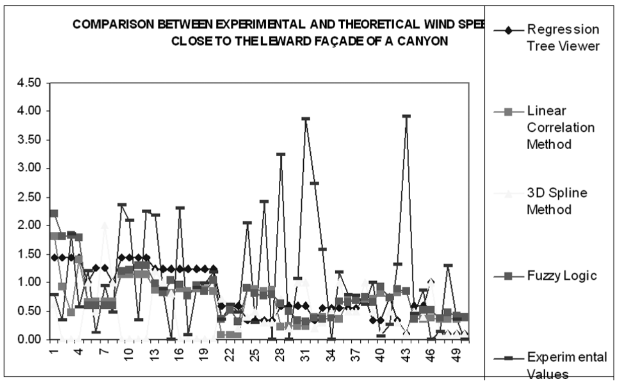

Figure 6 Comparison of the predicted against the experimental values of the more probable wind speed inside the leeward façade of a canyon

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